

Woven Textiles

Principles, Technologies
and Applications

Second Edition



Edited by Kim Gandhi



THE TEXTILE INSTITUTE BOOK SERIES

Woven Textiles

The Textile Institute Book Series

Incorporated by Royal Charter in 1925, The Textile Institute was established as the professional body for the textile industry to provide support to businesses, practitioners and academics involved with textiles and to provide routes to professional qualifications through which Institute Members can demonstrate their professional competence. The Institute's aim is to encourage learning, recognise achievement, reward excellence and disseminate information about the textiles, clothing and footwear industries and the associated science, design and technology; it has a global reach with individual and corporate members in over 80 countries.

The Textile Institute Book Series supersedes the former 'Woodhead Publishing Series in Textiles' and represents a collaboration between The Textile Institute and Elsevier aimed at ensuring that Institute Members and the textile industry continue to have access to high calibre titles on textile science and technology.

Books published in The Textile Institute Book Series are offered on the Elsevier web site at: store.elsevier.com and are available to Textile Institute Members at a substantial discount. Textile Institute books still in print are also available directly from the Institute's web site at: www.textileinstitute.org

To place an order, or if you are interested in writing a book for this series, please contact Matthew Deans, Senior Publisher: m.deans@elsevier.com

Recently Published and Upcoming Titles in The Textile Institute Book Series:

New Trends in Natural Dyes for Textiles, Padma Vankar Dhara Shukla, 978-0-08-102686-1
Smart Textile Coatings and Laminates, William C. Smith, 2nd Edition, 978-0-08-102428-7
Advanced Textiles for Wound Care, 2nd Edition, S. Rajendran, 978-0-08-102192-7
Manikins for Textile Evaluation, Rajkishore Nayak Rajiv Padhye, 978-0-08-100909-3
Automation in Garment Manufacturing, Rajkishore Nayak and Rajiv Padhye, 978-0-08-101211-6
Sustainable Fibres and Textiles, Subramanian Senthilkannan Muthu, 978-0-08-102041-8
Sustainability in Denim, Subramanian Senthilkannan Muthu, 978-0-08-102043-2
Circular Economy in Textiles and Apparel, Subramanian Senthilkannan Muthu, 978-0-08-102630-4
Nanofinishing of Textile Materials, Majid Montazer Tina Harifi, 978-0-08-101214-7
Nanotechnology in Textiles, Rajesh Mishra Jiri Militky, 978-0-08-102609-0
Inorganic and Composite Fibers, Boris Mahltig Yordan Kyosev, 978-0-08-102228-3
Smart Textiles for In Situ Monitoring of Composites, Vladan Koncar, 978-0-08-102308-2
Handbook of Properties of Textile and Technical Fibres, 2nd Edition, A. R. Bunsell, 978-0-08-101272-7
Silk, 2nd Edition, K. Murugesh Babu, 978-0-08-102540-6

The Textile Institute Book Series

Woven Textiles

Principles, Technologies and Applications

Second Edition

Edited by

K. L. Gandhi



The Textile Institute



ELSEVIER

WP

WOODHEAD
PUBLISHING

An imprint of Elsevier

Woodhead Publishing is an imprint of Elsevier
The Officers' Mess Business Centre, Royston Road, Duxford, CB22 4QH, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States
The Boulevard, Langford Lane, Kidlington, OX5 1GB, United Kingdom

© 2020 Elsevier Ltd. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

ISBN: 978-0-08-102497-3

For information on all Woodhead publications
visit our website at <https://www.elsevier.com/books-and-journals>

Publisher: Matthew Deans
Acquisition Editor: Brian Guerin
Editorial Project Manager: Joshua Mearns
Production Project Manager: Joy Christel Neumarin Honest Thangiah
Cover Designer: Victoria Pearson

Typeset by SPi Global, India



Contributors

S.C. Anand University of Bolton, Bolton, United Kingdom

B.K. Behera Indian Institute of Technology Delhi, New Delhi, India

K.L. Gandhi The Textile Institute, Manchester, United Kingdom

J.M. Hardcastle The Textile Institute, Manchester, United Kingdom

Pramod Kumar Hari Department of Textile Technology, Indian Institute of Technology, Delhi, India; ENSAIT Textile engineering School, Roubaix, France

M. Amirul “Amir” Islam Bally Ribbon Mills, Bally, PA, United States

Ahmad Rashed Labanieh ENSAIT Textile engineering School, Roubaix, France

S. Rajendran University of Bolton, Bolton, United Kingdom

Nicola A. Redmore School of Art, Design and Architecture, The University of Huddersfield, Huddersfield, United Kingdom

J.P. Singh Department of Textile Technology, UPTTI Kanpur, Kanpur, India

Pammi Sinha University of Leeds, Leeds, United Kingdom

Part One

Yarns and weaving technology

Types and properties of fibres and yarns used in weaving

1

Pramod Kumar Hari

Department of Textile Technology, Indian Institute of Technology, Delhi, India

1.1 Introduction

Woven fabrics consist of interlacements of yarns in two mutually perpendicular directions. Their structure permits a variation in the length and distribution of interlacements, resulting in a range of fabric deformations. Such control also offers scope for the generation of a diverse range of patterns and properties in fabrics. Triaxial fabrics are a special class of woven fabrics in which the warp threads constitute two sheets inclined at different angles, instead of being vertical. The weft thread is interlaced horizontally with the warp; this configuration thus has yarns in the fabric in three axes, hence the term 'triaxial' fabrics.

The building block of a woven fabric is yarn but the basic unit is fibre. Strength, extension, fineness, length, and surface properties are some of the primary attributes of fibres which, using different types or blends of fibres, create a wide spectrum of useful and desirable physical and mechanical properties in the yarn and fabric produced. There are two basic types of fibres or filaments used in yarn:

- discontinuous fibres, that is, short/staple fibres (including most natural fibres); and
- continuous fibres (such as silk and synthetic fibres).

Natural fibres have traditionally offered a variety of physical and mechanical properties. Using a natural, regenerated, and synthetic filament yarn increases the range of physical and mechanical properties available and, indeed, allows functional properties to be tailor-made for a particular end use. Man-made filaments can be modified by texturing to alter bulk or stretch, or cut to the desired length to produce staple fibres which, either alone or blended with other fibres, are then blended as spun yarns. Knowledge of fibre properties enables a design engineer to select the proper materials to create fabrics for specific end uses.

1.2 Types of natural and regenerated fibres

Cotton, wool, flax, and silk are the most important natural textile fibres, followed by fibres such as jute and kenaf. Natural fibres vary in length and in their other properties. They are not consistent and contain unwanted impurities from their original source. Such fibres need to be processed to remove these impurities and reduce the variation

in their length. Such fibres can be made coherent, continuous, and load bearing by providing sufficient twist to the strand.

The mechanical properties of silk fibres are a combination of high strength, extensibility, and compressibility. Jute and kenaf are strong fibres, exhibiting brittle fracture and with a small extension at break; they have high initial modulus but show very little recoverable elasticity. Cotton is the most important natural cellulosic textile fibre. Length and fineness are important measures of fibre quality. Cotton fibres range in dimensions from a length of 5–1.5 cm and a linear density of 1–3 dtex. Amongst its many important properties, cotton fibre is hydrophilic and porous; on immersion in water, it swells and its internal pores fill with the water. Chemical modification can add many desired properties to a cotton fabric, including colour, permanent press, flame resistance, soil release, and antimicrobial properties.

Regenerated fibres are manufactured from natural polymers. Two of the most widely used regenerated fibres are rayon and acetate. There is a wide variety of different rayon fibres, including regular rayons, high-tenacity rayons, low wet modulus rayons, high wet modulus and modal rayons, high-strength/high-elongation rayons, polynosic rayons, flame-retardant rayons, high absorbency (alloy rayons), hollow rayons, and cuprammonium rayons. High-tenacity rayons are used where strength, toughness, and durability are required. These fibres are dimensionally stable when used as reinforcement in tyres, conveyor belts, drive belts, and hoses. Other applications for this type of rayon include industrial sewing threads, tent fabrics, and tarpaulins.

A range of cross-sectional shapes such as round, flat, Y-shaped, E-shaped, U-shaped, T-shaped, and irregular (crenulated) shaped fibres are produced in rayon. It is generally accepted that the crenulated structure is formed by greater shrinkage of the fibre skin than of the core. Given its aesthetic properties, particularly its silk-like sheen, finer denier fibres are used for shawls, scarves, blouses, and coat linings. Blends with cotton, polyester, and flax help overcome inherent defects such as poor dimensional stability and mushy hand. Polynosic rayon fibres have high wet and dry strength, low elongation (8%–11%), relatively low water retention and a very high wet modulus of 1 g/den. They have the firm and the crisp hand of cotton in fabrics.

Cellulose acetate and triacetate textile fibres produce fabrics with an excellent hand, good dyeability, softness (comfort), and draping quality. The traditional market for cellulose acetate and triacetate fabrics is women's apparel. Acetate yarns are used for both tricot knit and woven constructions. Principal products within women's apparel include dresses, blouses, and lingerie. Acetate has replaced rayon as a liner in men's suits and in nonapparel applications such as curtains. Cellulose triacetate offers a unique combination of 'ease-of-care' and aesthetic properties. A particularly important application of triacetate is in surface-finished fabrics such as fleece, velour, and suede-like fabrics for dresses. Triacetate is also desirable for print fabrics as it produces bright sharp colours. Cellulose acetate and triacetate fibres are blended with nylon and polyester for numerous end uses to compensate for the lower strength and durability of the weaker acetate and triacetate fibres. Yarns of this type, which are textured by air entanglement and bulking processes, have unique characteristics and aesthetics which permit their use in upholstery fabrics. Triacetate-nylon blended filament yarns are lightweight with good strength and bulk and are useful in producing silk-type woven

fabrics, such as plain taffetas, fine crepes, and delicate jacquard figured styles for blouse and lingerie wear.

1.3 Types of synthetic fibres

An understanding of the chemistry and physics of natural textile fibres led to the creation of a range of man-made fibres such as viscose, rayon, nylon, polyester, acrylic, and polypropylene. These synthetic fibres provide a range of specific properties, depending on the purpose. Because they are manufactured and synthetic fibres can be produced consistently and are free of natural impurities. Synthetics have much to offer in terms of ease of care and durability but the problems of garment comfort, fabric cover, lustre, drape, and garment tailorability have been major obstacles limiting the types of woven apparel fabrics made from 100% synthetic filament yarn. Instead, man-made/synthetic filaments are often cut into regular short lengths (staples) so that they are compatible with natural fibres and can be blended and spun into yarns with the right mix of properties for apparel applications.

1.3.1 Polyester

Polyester fibre, specifically polyethylene terephthalate (PET), is the most important synthetic fibre worldwide in terms of production volume [1] due to its low cost, excellent performance, and the ease with which it can be processed. Amongst its properties, PET is a strong fibre (5 g/decitex). Polyester fibres need to be treated with surface finishes or lubricants to allow high-speed processing. The various processing steps such as drawing, bulking, and spinning would be impossible without spin finishes which alter the frictional properties of the fibre.

Polyester technology is responsible for a large number of products that range from cotton-blended staple to high-performance tyre cord. Drawn filament yarn can be treated in a number of ways. It can simply be twisted on a ring frame, or bulked by a process such as false-twist texturing. Many apparel filament yarns need to be textured to give desirable aesthetic properties, particularly for women's wear markets. The principle of false-twist texturing is to create minor side-to-side variations across a filament yarn, causing the yarn to bend during controlled thermal shrinkage to create a 3D structure with a bulky feel. For industrial use, such as for tyre cord, high-tenacity yarns are drawn under conditions where low heat shrinkage, low extension, and high modulus products are produced. Polyester staple fibre can also be crimped to blend with cotton, wool or other natural fibres at the carding stage to prepare appropriate yarn blends. PET staple blends with wool and cotton are highly successful but, in a low twist yarn, the fibre has many loose ends and pill formation can take place.

Synthetic fibres like PET and nylon are normally round in cross section (while natural fibres have different cross sections). These fibre shapes affect yarn and fabric aesthetics in terms of feel, drape, handle, and appearance. Trilobal polyester yarns glitter because incident light reflects off the fibre surface. By contrast, octalobal yarns produce fabrics with an opaque matte effect, as light is effectively absorbed by multiple

reflections off the many acute angles in the yarn. Sharp-edged filaments have the same prized rustle and high frictional characteristics of pure silk. Flat rectangular filaments give fabrics an unpleasant slimy handle. Synthetic fibres, in general, and PET, in particular, are hydrophobic materials. PET has a moisture regain of 0.4% at 65% RH and rapidly builds up static electrical charges by friction to give a very unpleasant electric shock. Static charges can also lead to the attraction of dust and dirt, and, to avoid these problems, polyester is blended with wash-fast hydrophilic materials.

1.3.2 Polyamides (including nylon)

Polyamide textile fibres include nylon 6.6 and nylon-6. Excellent mechanical properties, strength, fatigue resistance, and good adhesion to other materials such as rubber are some of the reasons for the predominance of polyamide fibres in a wide range of applications. Nylon fibres, for example, offer a number of attributes such as high strength, abrasion resistance, lustre, chemical and oil resistance, washability, elasticity, and dyeability in a wide range of colours. In general, most nylon fibre products require high strength and round cross sections. However, for textile and carpet applications, fibres with modified cross sections have been developed to achieve different aesthetics (such as lustre, opacity, and better insulation).

Polyamides are used for women's hosiery, intimate apparel, and stretch fabrics such as blouses, dresses, lingerie, ski apparel, and swimwear. Polyamides have also been used for house furnishings such as bedspreads, carpets, curtains, and upholstery. Other technical applications include truck and airplane tyres, seat belts, parachutes, ropes, fishing lines, nets, sleeping bags, tarpaulins, tents, sewing thread, ropes, monofilament fishing line, and dental floss. High strength, toughness, and abrasion resistance are also the main factors for selecting polyamide fibres for a wide range of military applications. In the area of general apparel, polyester has gained considerable significant market share at the expense of polyamides because of its easy-care characteristics.

1.3.3 Acrylic

Acrylics exist in a range of cross sections, from almost perfectly round to dog-bone-shaped. Dry-spun acrylic fibres have a lower bending modulus due to their dog-bone-shaped cross section; as a result, a softer yarn with better fabric aesthetics can be obtained at a comparable fibre denier. The dog-bone-shaped cross section prevents the fibres from packing closely to give a bulky yarn. Acrylics have a high resistance to sunlight, making continuous filament acrylics valuable in outdoor applications such as for tents and awnings.

In the general apparel markets, continuous filament acrylics and modacrylics find use as artificial fur; the fibres in these applications are made in a coarse denier with a special cross section and surface modification to simulate natural animal hairs. Continuous filament yarn in very fine deniers is valued as a silk replacement for high-fashion dress fabrics, satins, and poplins or to produce a cloth suitable for surface rising to give a suede or fine velour effect. Fine-denier filaments may also be used to produce fabrics with very high filament density and low air permeability, useful

as an insulating material, for example, in quilted interliners for parkas and outerwear for skiing. Other prominent uses for acrylics include rugs, curtains, and upholstery.

1.3.4 Polypropylene

Some properties, such as toughness, low density, and chemical stability are inherent to all polypropylene products. Others, such as colour stability, UV, and thermal stability result from the use of additives. The quality of polypropylene fibre has been improved to enhance properties such as lightweight, mouldability, light stability, colouration, flame resistance, and antistatic properties. Polypropylene is increasingly used for automotive interior furnishings while for furniture, the current trend is to produce upholstery with a polypropylene tufted fabric of medium-denier using both air-textured and draw-textured yarn.

Woven fabrics from low denier polypropylene fibre (<1.5 dpf) are effective for thermal protection. They provide good aeration during perspiration and are waterproof. In apparel, their use can prevent skin dryness and body odour from perspiration, thus providing comfort and personal hygiene. Its major usage lies in winter wear, sportswear for hiking and skiing, work clothes, and underwear. A smaller amount of this fibre is used in blends with nylon or acetate fibres for fashion wear. Polypropylene fibre itself does not ignite but shrinks, melts, and pulls away on exposure to a flame, thus making it a more fire-retardant fibre than most synthetic fibres. A high-shrinkage fibre fabric processed at high temperature gives greater fibre density and bulk. There are two types of high-shrinkage polypropylene staple: cotton and wool types. Cotton staple is typically a 0.13 tex filament and 38 mm long. Wool staple is typically a 0.39 tex filament and 60 or 90 mm long. High-shrinkage polypropylene fibre is mixed with conventional fibres in spinning to yield a fluffy yarn.

1.4 Key fibre properties and how they are measured

To be suitable as a textile yarn, a fibre must have some essential and other desirable properties. The most important fibre characteristics [2] affecting fabric appearance, properties, and performance include:

- length/linear density (fineness)
- cross-sectional shape
- surface characteristics
- crimp
- moisture content/regain
- shrinkage
- lustre/colour
- strength
- stiffness (flexibility)
- elastic recovery
- tenacity/elongation
- abrasion/chemical/flame resistance.

The moisture regain and tenacity/elongation of fibres are given in [Tables 1.1 and 1.2](#). The following sections focus on fibre length/linear density, cross section, and crimp.

Table 1.1 Moisture regain for fibres

Fibre	Moisture regain (%)
Wool	13.6
Silk	11.0
Rayon	11.0
Linen	8.75
Cotton yarn	7.0
Cellulose acetate	6.5
Nylon	4.5
Cellulose triacetate	3.5
Acrylic	1.5
Polyester	0.4

Table 1.2 Tenacity/elongation for fibres

	Tenacity (g/den)	Elongation (%)
Nylon (regular)	4.5–5.0	25–18
Nylon (high tenacity)	6.5–7.7	20–14
Nylon (staple)	3.8–4.5	37–25
Dacron polyester	4.4–5.0	22–18
Dacron polyester	3.0–3.9	40–25
Orlon acrylic	4.7–5.2	17–15
Orlon acrylic	2.0–2.5	45–20
Viscose (regular)	1.5–2.4	30–15
Viscose (high tenacity)	2.4–4.6	20–9
Acetate rayon	1.3–1.5	30–23
Wool	1.0–1.7	35–25
Cotton	2.0–5.0	7–3
Silk	2.2–4.6	25–10

1.4.1 Fibre length and fineness/linear density

Length is a very important parameter for staple fibres affecting processability, as well as governing the physical and mechanical properties of the spun yarn itself. The lengths of staple fibres used in the production of spun yarns vary. Examples are:

- for polyester/viscose, 31–51 mm (for ring spinning) and 60–90 mm (for a worsted system)
- for cotton, 20–45 mm (for ring spinning).

Length variability is generally high for natural fibres (40% for cotton), but it should be as low as possible to improve yarn regularity. Longer fibres are advantageous since they require less twist for the desired yarn strength than shorter fibres. The low twist makes it possible to produce bulkier yarns.

The linear density, that is, the fineness of fibres, is expressed in decitex for natural fibres or denier for synthetic fibres. Examples include cotton (1.4 decitex); silk (1 decitex); wool (1.7 decitex); and synthetic fibres (0.7–1.6 dpf). Many important properties of a yarn, such as packing and flexural rigidity, are influenced by fibre linear density. Finer fibres have a greater specific surface area which helps to improve the cohesion between fibres and gives better capillary action within the yarn structure. The total potential area of contact between fibres is governed by the specific surface area (surface area/unit volume) of fibres. The cohesion between fibres depends on the degree of interfibre contact generated by lateral pressure as a result of twist or wrapping. Torsional resistance of fibres also increases rapidly with increase in linear density. A coarser fibre is more difficult to twist and, once twisted, stores a higher level of torsional strain energy than finer fibres. This may be manifested in a yarn in the form of kinks and snarls in a relaxed state.

The uniformity of a yarn improves with a greater number of fibres in the yarn cross section. For a given linear density of yarn, there will be a greater number of finer fibres in the yarn cross section. A uniform yarn automatically reduces the variation in other properties too. To spin a yarn successfully there should be a minimum number of fibres in the yarn cross section (40–90 for ring spinning; 100 in rotor spinning).

Rigidity and cohesion contribute significantly to yarn strength. Strength is needed to withstand the spinning and weaving processes and to give strength to the fabric. Flexibility and fineness enable the fibres to be spun and woven to give the fabric its unique draping characteristics. Bending rigidity is proportional to the square of linear density of fibres. An increase in the linear density increases resistance to bending which makes the fibres stiffer. Fibres having a linear density of <0.33 tex are flexible enough to be used in apparel products. For industrial applications, the linear density ranges between 0.66 and 1.66 tex or more. Higher linear density is also used to improve the abrasion resistance of yarn and fabric.

1.4.2 Fibre cross section

A fibre's cross section affects fabric appearance, hand, drape, flexibility, and moisture transport. It also affects cohesion, bending rigidity and the packing of fibres in a yarn. Cotton fibre has a U-shaped cross section with a thin cuticle and a primary wall on the outside, and a hollow collapsed lumen inside. Jute fibre has a polygonal shaped cross section. Synthetic fibres can be designed with any cross-sectional shape such as a circular, trilobal/multilobal, hollow shape, etc. The cohesion of circular cross-section fibres is generally higher than those with noncircular cross section due to the greater surface area of contact between adjacent fibres. Cohesion depends on cross-sectional shape, fineness, and the flexural and torsional rigidity of fibres.

1.4.3 Fibre crimp

Natural fibres like cotton have crimp which facilitates processing and improves yarn bulk. Crimp (3.5–5.5 per cm) needs to be introduced in synthetic fibres to aid processing. Crimp geometry in staple fibre prevents fibres getting too close to each other and enhances yarn bulk. Fibre crimp also improves fibre cohesion.

1.5 Comparing fibre properties

The different properties of some common fibres are compared in [Table 1.3](#). Polyester fibres have the best performance in the range of highly desired properties, followed by nylon, acrylics, cellulosics, and wool. Acrylic fibres score more poorly than polyester or nylon but are superior to wool and the cellulosics. Acrylic fibres are poorer than polyester in terms of strength, abrasion resistance, wash–wear performance and wrinkle resistance. Acrylic fibres rank highest in the categories of useful and specific properties. Some of the properties in these two categories are considered more important for nonapparel markets, such as good resistance to sunlight degradation for drapery. In summary, acrylic fibres exhibit a well-rounded combination of performance properties with no major deficiencies. However, for woven apparel, the key properties of good wash–wear performance, abrasion, and wrinkle resistance favour the use of polyester–cotton blends or cross-linked resin-finished cotton fibres.

Table 1.3 Comparative properties of common fibres, measured on a scale of 1–5, with 5 being the best

	Polyester	Nylon	Acrylic	Wool	Cellulosics
Category 1: Highly desired properties					
Abrasion resistance (durability)	4	5	3	3	3
Strength (durability)	4	5	3	2	3
Wash–wear performance	5	3	3	1	1
Wrinkle resistance	5	3	3	4	1
Pill resistance	3	1	3	3	5
Category 2: Useful properties					
Bulk (cover)	3	3	5	4	1
Water transport (HS comfort)	3	2	5	3	4
Static resistance	2	1	4	5	5
Speed of drying	5	5	5	1	1
Category 3: Properties for specific applications					
Resistance to burning	5	5	3	5	1
Resistance to degradation by dry heat	5	3	5	5	3
Resistance to degradation by wet heat	3	4	5	2	4
Resistance to degradation by Sunlight	3	3	5	2	3
Resistance to insects	5	5	5	1	1
Resistance to microorganisms	5	5	5	1	1

1.6 New types of fibre

There are a number of emerging types of fibre, some of the most important of which are discussed below.

1.6.1 Polyester fibres based on terephthalic acid

Polybutylene terephthalate (PBT) differs only slightly from PET in chemical composition but more substantially in its properties such as its higher crystallization rate and lower melting point. It can be melt-spun at lower temperatures and is inherently whiter than PET. As a fibre, it is much more elastic and has excellent resilience and recovery from small deformations. It dyes easily with disperse dyes at the boil, unlike PET, and resists photooxidative yellowing. Resilience and ease of dyeing are assets for carpet fibre.

Another polyester, polytrimethylene terephthalate (PTT), is a fibre with excellent recovery properties. Carpets made from PTT show excellent resilience due to the unique spring-like crystal structure of the fibre. It has a lower static charge and is resistant to stains. It is also used in intimate apparel and inner linings for clothing, and in the automotive and upholstery industries.

1.6.2 Microfibres

One of the most important developments in recent years has been in the technology to extrude extremely fine filaments of <1.0 denier while maintaining the strength, uniformity, and processing characteristics expected by textile manufacturers and consumers. Microfibres are fibres finer than 1.2 dtex for polyester and finer than 1.0 dtex for polyamide. Normal polyester filament yarn is around 3–5 dpf, while a typical polyester microfibre is only 0.5 dpf. Such fine fibres in the form of yarn give excellent textile properties, being very flexible, and giving a soft hand and excellent drape to fabrics. Microfibres also lend themselves very well to fabric aesthetics. Dyed fabrics have solid bright colours due to the fine size of individual filaments. The vulnerability to damage from ironing is one disadvantage, the thermal capacity of the tiny filaments being so low that it is easy to overheat them. They can snag easily and need to be handled with care in processing.

The high density of filaments in typical microfibre fabrics makes them inherently windproof and waterproof. There are only tiny gaps for air to move through and the fabrics are largely unwettable since surface tension prevents water from penetrating the interstices in the fabric. Such fabrics are comfortable to wear as water vapour from perspiration evaporates easily. Microfibre fabrics also have heat-insulating properties. A 0.5 dpf polyester filament (density 1.4 g/cm^3) has a diameter of about $7 \mu\text{m}$, right in the middle of the infrared (IR) wavelength (2–20 mm). Radiation is efficiently scattered by the microfibrils and the radiation loss of body heat is reduced. As a result, microfibrils are used in outdoor clothing and sportswear (e.g. skiing or mountaineering).

1.6.3 Bicomponent fibres

Bicomponent fibres are filaments made up of different polymers. There are many geometrical arrangements. The three main configurations are:

- side-by-side
- core–sheath
- multiple cores (or ‘islands in a sea’).

So-called ‘splittable pie’ configurations are also used in the production of microfibres. Side-by-side bicomponent fibres can be used to produce self-bulking yarns. After drawing and relaxing, two PET polymers of different molecular weights (spun as a side-by-side heterofil) curl up like a bimetallic strip and give a spiral crimp. The core–sheath configuration is adaptable because many different polymers may be applied as a sheath over a solid polyester core, thus giving a variety of modified surface properties while maintaining all the major fibre and textile properties of PET. The multiple core or ‘islands in a sea’ type of heterofil is of interest in connection with microfibres. Hollow fibres are a type of core–sheath heterofil in which the core is composed of air. For end uses like fabric interlinings, it is desirable to stabilize a filled hollow fibre structure by incorporating an additional thermally bondable bicomponent fibre.

1.6.4 Technical/high-performance fibres

There are many kinds of technical textile products produced according to particular applications [3,4]. The variety of textile structures in technical textiles is thus much larger than it is in apparel textiles. There is also a wider range of materials from which fibres can be manufactured. Examples are glass, ceramic, and basalt filaments. Glass filament yarn can be textured, folded or cabled and finds application in aerospace, automotive, marine, civil, sporting goods, and in the electrical/electronics industries. The ceramic filament is resistant to very high temperature (2000–3000°C) and finds application in thermocouples, furnace curtains/lining, seals and gaskets. Basalt filament finds application in high service temperature and high-performance machinery, automobiles, shipbuilding, aviation, cryogenic technology, and on sea platforms.

Aramid and high-performance polyethylene filaments are organic polymeric materials. Aramid filaments are used in bulletproof jackets, helmets, automotive, electrical/electronic, and medical applications. These filaments are also used in ropes and cables, sailcloth, and tennis racket strings. High-performance polyethylene filaments are also used in ropes, nets, and ballistic protection. Carbon is another useful quasi organic-based polymer. Its strength is its thermal stability and it has application in rockets, satellites, aircraft, fishing equipment, golf clubs, automobiles/bicycles, machinery parts, and corrosion resistant equipment.

High-modulus, high-tenacity (HM-HT) fibres with a fully extended well-oriented structure is produced in two contrasting ways. The first involves manipulation of rigid rod molecules into fibres that are already highly oriented in the as-spun state, as in the case of poly(phenylene terephthalamide) or Kevlar. The other method for manufacturing HM-HT fibres results from the ease with which flexible, inert chain molecules can be pulled out into a fully extended, oriented form by imparting very high draw ratios.

Ultrahigh-molecular weight polyethylene (UHMWPE) fibres such as Spectra and Dyneema fall into this category.

When processed into fibres, oriented thermotropic liquid crystalline polymers (TLCP) such as Vectran (a wholly aromatic polyester) are characterized by very high specific tensile properties and intrinsically low density compared with metals, ceramics, and carbon. However, they have inherent weaknesses in shear and compression. The key application areas for LCP fibres include hard armour (vehicles, helmets), soft ballistic protection (vests), cut protection (gloves) and a variety of composite uses that include honeycomb structures, pressure vessels, and rubber reinforcement.

1.6.5 Biodegradable/medical fibres

Biodegradable polyesters comprise a diverse field, but the best-developed fibre (monofil) market is in resorbable surgical sutures, which slowly disappear in vivo and do not need subsequent surgical removal. Biodegradable yarn/fibres are also used for disposable items such as wipes. These yarns are environmentally friendly and hydrolysable at temperatures up to 50°C. Polylactic acid fibre (PLA) silk is used as an implantable suture and as a scaffold for ligament tissue engineering and is produced by electrospinning to 50–500 nm in diameter. Polycaprolactone (PCL) alginate is used to fabricate scaffolds for tissue engineering.

1.6.6 Electro-conductive fibres

Electro-conductive yarns are used as sensors, for data transfer, wireless communication, and for electromagnetic shielding in intelligent and smart textiles. These are core spun yarns in which the core is a conductive filament. Technical textile yarns such as reflective, luminescent, phosphorescent, photoluminescent, and electroluminescent yarns find application in areas such as reflective clothing, road signs, and markers. Such yarns are produced by lamination of a silver transfer film onto polyester.

1.6.7 Smart fibres

Fibres are flexible, mechanically strong one-dimensional structures that can be converted into a variety of two- and three-dimensional flexible structures such as ligaments (artificial muscles), woven fabrics, nonwoven webs, and membranes. Smart fibres, which can change shape in response to various stimuli from the environment, open up new applications in areas such as apparel which allows heat and moisture release in warm weather but retains heat at lower temperatures [5].

1.6.8 Eco-friendly^a

The natural fibre is appreciated for its traditional authenticity. Although cotton production is natural but it consumes scarce resource water, so it is not eco-friendly. The lotus fibre is more durable than cotton or linen when it is not dyed. The lotus fabric is the first natural microfiber, the most eco-friendly in the world. It is amazingly

^a<http://www.fibre2fashion.com/interviews/sector-pulse/samatoa/awen-delaval/293-1/>.

resistant, soft, and sustainable. An important thing to know is that each stem harvested needs to be used on the same day. Stems also need to be moistened; they are stored in the water and cleaned. The spinners are trained in meticulous movements to break the stem. The yarn is the result of this patient and rigorous application.

The banana fabric, on the other hand, is another amazing natural fabric that is completely biodegradable and recyclable. The fibre is extracted from the trunk of the banana plant. The fibres from the banana stems have been used to create table cloths, saris, and kimonos. The banana fabric is especially great for raincoats and outerwear.

The kapok fabric is a new and uniquely sustainable fabric. This delicate process has been developed by the skills of Cambodian women. The kapok fabric interests fashion designers to make innovative clothes and underwear. This fabric is particularly suited for jackets, life-saving appliances, insulation, aviation suits, and other moisture-resistant clothing.

1.7 Yarns and their properties

A textile yarn is a continuous linear assembly of fibres or filaments which exhibits suitable characteristics such as good specific tensile strength and high flexibility [6]. The various parameters used to characterize a yarn are given in Table 1.4. Some of these properties are discussed in more detail below.

1.7.1 Linear density

Linear density, yarn count, yarn number, and yarn size are all expressions of the ‘finess’ of a yarn. A yarn or fibre’s fineness cannot be expressed in terms of diameter because its diameter is not stable and uniform along its length and its cross-sectional

Table 1.4 Yarn characterization

Parameter	
Dimensional parameters	Linear density Diameter
Structural parameters	No. of filaments in cross section
	Twist per cm
	Wrap density
	Core content
	Core–sheath ratio
Special treatment	
Fibre parameters	Length
	Linear density
	Crimp
	Cross-sectional shape

shape may not be circular. Consequently, it is expressed either by measuring the mass of a known length of yarn or by measuring the length of a known mass of yarn. These two basic methods for expression of linear density of any textile strand are known as:

- the direct system (mass/length)
- the indirect system (length/mass)

These systems are discussed in more detail below.

In the direct system, the linear density of plied yarn is the simple summation of linear densities of the individual components, that is, linear density (R) = $T_1 + T_2 + T_3 + \dots + T_N$, where $T_1, T_2 \dots T_N$ are the linear densities of n individual components expressed in tex. The tex system has units measured in grams per 1000m. As an example, 20tex means that the mass of 1000m of yarn is 20 g. The higher the value, the coarser the yarn. Prefixes such as kilo and deci are used when the numbers become too large or too small to express fineness.

- 1 ktex = 1000tex
- 1 decitex = 1/10tex
- 1 militek = 1/1000tex

Another expression of fineness for continuous filament yarn is the denier, which is expressed as the mass in grams per 9000m. As an example, a 3 denier yarn means that the mass of 9000m of yarn is 3 g. In the jute system, mass is expressed in pounds (lb) per 14,400 yards (yd); a 12-lb yarn count indicates that 14,400yd of yarn has a mass of 12 lb.

In the indirect system, fineness is expressed as the ratio of the number of standard lengths per unit mass. A higher designated number indicates a finer yarn. Thus, in the English system, an 840-yd length (Hank) per pound refers to the fineness of the yarn. A '30's' yarn indicates that a 1lb. mass will be 30 times 840yd in length, that is 25,200yd. of yarn. In the metric system, the number of units of 1000m is determined in 1 kg of yarn. In the indirect system the relationship is: $1/R = 1/T_1 + 1/T_2 + \dots + 1/T_k$, where $T_1, T_2 \dots T_k$ are the linear densities of k individual components. Units of linear density are given in Table 1.5 and conversion from one system to another is shown in Table 1.8.

The number of filaments in a yarn is generally specified in the case of a filament yarn. It can also be found by taking the ratio of the yarn to filament linear density:

$$n = n_t / (n_f / 9) \quad (1.1)$$

Table 1.5 Units of linear density

	System	Mass	Length	Unit	Symbol
Direct	tex	g	1000 m	g/1000m	Tex
	denier	g	9000 m	g/9000m	Den
	jute	lb	14,400 yd	lb/14,400 yd	Lb
Indirect	English	lb	840 yd	No. of 840 yd./lb	Ne
	metric	kg	km	No. of km/kg	Nm

where n is the number of filaments/fibres, n_t the yarn linear density (tex), and n_f the fibre linear density (den). A filament yarn designated as 130/24, refers to 130 denier with 24 filaments in the cross section.

1.7.2 Yarn diameter

It is sometimes necessary to know the approximate diameter of a yarn even though it is well known that yarn diameter cannot be estimated accurately due to the highly compressible nature of the material. Diameter, however, gives an idea of the extent of cover achievable, or the closeness of yarn packing in a fabric. Fabric thickness also depends on yarn diameter. Yarn diameter in terms of linear density in tex for a general case is given as

$$d = \frac{1}{280.2} \sqrt{\frac{T}{\phi \rho_f}} \quad (1.2)$$

where d is the yarn diameter (cm), T the yarn linear density (tex), ρ_f the fibre density (g/cm^3), and ϕ the yarn packing coefficient.

Numerical examples:

1. Calculate the yarn diameter of a 10tex cotton yarn, with yarn packing coefficient of 0.65, fibre density of 1.52 g/cm^3

$$d = \frac{1}{280.2} \sqrt{\frac{T}{\phi \rho_f}}$$

where d is the yarn diameter (cm), T the yarn linear density (tex), ρ_f the fibre density (g/cm^3), and ϕ the yarn packing coefficient.

$$d = \frac{1}{280.2} \sqrt{\frac{10}{0.65 \times 1.52}} = 0.01135 \text{ cm}$$

2. Calculate the diameter of a 40 worsted yarn with yarn packing coefficient of 0.6, fibre density of 1.32 g/cm^3

Tex of worsted yarn = 22.145 (see [Table 1.8](#))

$$d = \frac{1}{280.2} \sqrt{\frac{T}{\phi \rho_f}}$$

$$d = \frac{1}{280.2} \sqrt{\frac{22.145}{0.6 \times 1.32}} = 0.01813 \text{ cm}$$

3. Calculate the diameter of 27 denier nylon monofilament yarn, fibre density of 1.14 g/cm^3 $\phi = 1$ for monofilament yarn.

$$d = \frac{1}{280.2} \sqrt{\frac{T}{\phi \rho_f}}$$

$$d = \frac{1}{280.2} \sqrt{\frac{3}{1 \times 1.14}} = 0.005789 \text{ cm}$$

4. Calculate the diameter of a 30 tex polyester/cotton (67/33) blend yarn, take fibre density 1.38 for polyester and 1.54 for cotton. Yarn packing coefficient as 0.6
Using Eq. (1.3) for blended yarn, $\frac{1}{\bar{\rho}} = \sum_1^n \frac{p_i}{\rho_i}$.

$$\frac{1}{\bar{\rho}_{blend}} = \sum_1^n \frac{p_i}{\rho_i} = \frac{0.67}{1.38} + \frac{0.33}{1.54}$$

Therefore, average density of blend, $\bar{\rho} = 1.43 \text{ g/cm}^3$

$$d_{cm} = \frac{1}{280.2} \sqrt{\frac{T}{\phi \rho_f}} = \frac{1}{280.2} \sqrt{\frac{30}{0.6 \times 1.43}} = 0.1492$$

5. Calculate the diameter of 20 tex polyester/wool (80/20) blend yarn, take fibre density 1.38 for polyester and 1.32 for wool. Yarn packing coefficient as 0.6

$$\frac{1}{\bar{\rho}_{blend}} = \sum_1^n \frac{p_i}{\rho_i} = \frac{0.80}{1.38} + \frac{0.20}{1.32}$$

Therefore, average density of blend, $\bar{\rho} = 1.3676 \text{ g/cm}^3$

$$d_{cm} = \frac{1}{280.2} \sqrt{\frac{T}{\phi \rho_f}} = \frac{1}{280.2} \sqrt{\frac{20}{0.6 \times 1.3676}} = 0.01762$$

1.7.3 Yarn packing

Packing of fibres in a yarn is an important structural parameter which affects the porosity and bulk (specific volume) of a yarn. It influences properties such as compressibility and water/air transport, etc. Compressibility influences flattening of yarn in a woven or knitted structure. Porosity affects the flow of liquid due to capillary action while yarn bulk affects thickness. Packing depends on the physical/mechanical properties of the fibres, their arrangement in the yarn structure, and the level of twist. The extent of packing of fibres in a yarn's cross section is expressed by a packing

Table 1.6 Packing coefficient values for various yarn

Type of yarn	Packing coefficient
Monofilament	1.00
Tape	1.00
Multifilament	
Untwisted	0.25
Regularly twisted	0.60
Hard twisted	0.90
Staple yarn	
Soft twisted	0.33
Hard twisted	0.60
Ring	0.50–0.60
Rotor	0.35–0.55
Air jet	0.50–0.70
Friction	0.30–0.55
Wrap	0.40–0.70

coefficient. Some typical values for different yarn types are given in Table 1.6. The packing coefficient is defined as.

$$\text{Packing coefficient} = \frac{\text{specific volume of fibre}}{\text{specific volume of yarn}} = \frac{\text{density of yarn}}{\text{density of fibre}}$$

For blended yarns, average fibre density is given by the following:

$$\frac{1}{\bar{\rho}} = \sum_{i=1}^n \frac{p_i}{p_{fi}} \quad (1.3)$$

where $\bar{\rho}$ is the average fibre density, p_i the mass fraction of the i th component, p_{fi} the fibre density of the i th component, and n the number of components of the blend.

1.7.4 Yarn twist

Twist is quantified by the number of turns present in a unit length of yarn. Hence, a 20tpi means 20 turns per inch length of yarn. The unit length can be inches, centimetres, or metres. The basic purpose of twist is to induce structural integrity or coherence in a staple spun yarn so that it makes the yarn strong enough to withstand various kinds of stress. In the case of multifilament yarns, the twist is primarily introduced to bind the filaments together so that it facilitates processing by preventing a tendency for filament fraying. As well as processability and strength, twist also influences many other properties of yarn. Hence, depending on the end use, an optimum twist level is selected. The two most important aspects of twist are its direction and level (i.e. intensity).

Table 1.7 Specific volume of different types of yarn

Yarn	Specific volume (cm ³ /g)
Spun	
Cotton	1.10
Nylon	1.45
Polyester	1.30
Filament	
Nylon	1.35
Polyester	1.16

The direction of surface fibres/filaments looking up the yarn determines the direction of the twist. If the inclination of the surface fibres matches the centre portion of the letter ‘S’, it is termed an ‘S’ twist; the reverse is true for ‘Z’ twist. Most spun yarn has a Z twist. In a single yarn, twist direction does not influence the property of the yarn. If a plied structure is made from single yarns, the ply twist direction is generally opposite to the direction of the single yarn twist. This gives a balanced (torque free) structure when an optimum level of ply twist is chosen with respect to the single twist. However, ply twist in the same direction as a single yarn is introduced for special end uses. Plied yarns are usually designated by a number, such as 30/4, meaning that four groups of 30 single yarns have been plied together to form a single twisted structure. The specific volume of a yarn is mainly a function of twist, though fineness, crimp, flexural rigidity, and length of staple fibres do have some influence. Some typical values of the specific volume of different types of yarn are given in [Table 1.7](#).

1.8 Types of yarn for spinning

There are two main types of yarn: filament and spun yarns. Filament yarns in the medium to fine count range are used in fabrics for apparel. Filament yarns in the very fine count range are more appropriate for hosiery and also for carpets, sportswear, and as industrial yarns for technical textiles. Spun yarns are suitable for shirts, trousers, suits, home textiles, and bed linen ([Table 1.8](#)).

1.8.1 *Filament yarns*

With the exception of natural silk, continuous filament yarns are man-made. They can be sourced from natural polymers such as paper pulp to produce viscose, rayon, etc., or from synthetic polymers such as polyester, polypropylene, polyethylene, polyamide, etc. A filament yarn can be either monofilament or multifilament. There are also flat yarns.

Monofilament yarns can be solid or hollow. Monofilament yarns have a single filament with a cross section which can vary depending on the end use. It is normally circular but can be altered to a range of other shapes (e.g. triangular, multilobal,

Table 1.8 Conversion formula for different numbering systems

Convert into known	Tex	Decitex (dtex)	Denier (den)	Metric no. (Nm)	English cotton no. (Ne)	Worsted English count (Nw)
Tex		$10 \times \text{tex}$	$9 \times \text{tex}$	$1000/\text{tex}$	$591/\text{tex}$	$885.8/\text{tex}$
Decitex (dtex)	dtex/10		$0.9 \times \text{dtex}$	$10,000/\text{dtex}$	$5910/\text{dtex}$	$8858/\text{dtex}$
Denier (den)	den/9	den/0.9		9000/den	5314/den	7972/den
Metric number (Nm)	1000/Nm	10,000/Nm	9000/Nm		$0.59 \times \text{Nm}$	Nm/1.1288
English cotton no. (Ne)	591/Ne	5910/Ne	5314/Ne	$\text{Ne} \times 1.69$		Ne/0.6666
Worsted English count (Nw)	885.8/Nw	8858/Nw	7972/Nw	$\text{Nw} \times 1.1288$	$0.6666 \times \text{Nw}$	

serrated, oval or dogbone-shaped). A noncircular cross section prevents close packing and helps wicking. Monofilament diameters are typically in the range of 0.1–2 mm. The filament yarn is chopped to a suitable length to produce staple fibres, and these staple fibres are spun alone or blended with natural fibres into yarn.

Continuous filaments are invariably used as a multistrand and termed a multifilament yarn. A multifilament yarn consists of a bunch of monofilaments with a nominal twist to provide coherence to the structure. Alternatively, fibres in multifilaments can be held together by intermingling or entanglement. A noncircular cross section prevents the close packing of multifilament yarns.

Flat filament yarns can be textured to increase bulk or extension by false twisting, intermingled by an air-jet or crimped by a stuffer box. Flat yarns can be twisted or interlaced to produce different effects. Tape yarn is produced by splitting up a thin ribbon-like narrow width of the polymer film. Tape yarns are used, for example, for making fabric for packaging applications. A tape yarn can be further split or fibrillated mechanically to produce a regular network of interconnected fibres, a texture similar to multifilament yarn.

1.8.2 Spun yarns

Yarns made by using short fibres (natural fibres such as cotton, wool, jute, coir, etc.), staple fibres (rayon, polyester/nylon/acrylic/polypropylene) or a blend of different fibres are designated as spun yarns. Short staple spun yarns are a linear assembly of short discontinuous fibres. Such an array of fibres cannot sustain any load unless coherence is provided by generating transverse forces. This is achieved by a twist or

fibre/filament wrapping. Twisted yarns are hairy due to the projecting fibre ends but the yarn surface typically shows fibres in a helical configuration. Twisting in a spun yarn is achieved by conventional ring spinning, or by more unconventional methods using rotor spinning, friction spinning, air-jet spinning, and hollow spindle wrap spinning [7]. These yarns have different structures and properties.

A yarn made using a mixture of two or more different fibres is called a blended spun yarn. The proportion of different components in the yarn depends on the desired physical and mechanical properties. The most common blends are polyester–cotton, polyester–viscose, and cotton–viscose, usually in proportions of 67:33 or 50:50. A yarn designated as PC (67,33) is a 67% polyester and 33% cotton fibre blended spun yarn.

A spun yarn can either be single, or two or more of such yarns can be twisted to achieve certain desirable effects, that is, to create a plied or folded yarn. These effects can be to increase strength or reduce hairiness or to create colour effects by twisting single yarns of different colours. Plied/folded yarns are an assembly of several individual yarns helically wrapped around each other to form a coherent structure. Several plied yarns are twisted (generally in the opposite direction to the twist in the plied yarn) to form a cable yarn.

1.9 Short staple spinning yarns

Short staple spinning uses 25–50 mm fibres during yarn formation by employing the following techniques.

1.9.1 *Ring spun yarns*

The structure of ring spun yarns gives them visual, tactile, aesthetic, and elastic fabric properties suitable for a wide range of end uses. The fibres which form the body of yarn lie parallel along the Z/S twist helix (usually ‘Z’ twisted). The yarn can be carded or combed, with the latter having lower hairiness, a higher uniformity, and strength due to longer and more parallel fibres. In compact ring spinning, the single ribbon of fibres is compacted before twisting to further reduce hairiness and increase yarn strength. These yarns can be spun from most natural or man-made fibres, or from a blend of short staple fibres in the 25–50 mm range, and to a wide count range (5–300 tex). Two ribbons of fibres separated by a small distance can be ply twisted to give a siro spun yarn, usually in the 20–100 tex (2×10 – 2×50) count range. These yarns are less hairy and more uniform and are equivalent to ply yarns.

1.9.2 *Rotor spun yarns*

Rotor spun yarns are bulky two-layered yarn structures. The core comprises a bulk of parallel fibres aligned with the Z twist helix, with an outer layer of wrapper fibres along the core length. The fibres in a rotor yarn are less packed than in a ring yarn. Rotor yarn is known to be 5%–10% bulkier than a ring yarn. They can be spun to a moderate range from coarse-to-medium (25–100 tex) yarn counts.

1.9.3 Friction spun yarns

Friction spun yarns have a core–sheath element. The surface of this yarn is similar in appearance to a ring spun yarn. Outside fibres in these yarns have a uniform surface appearance along a Z twist helix. The core fibres are disposed in parallel and do not contain any twist. Friction spun yarn has a high extensibility due to the large proportion of hooked and disoriented fibres in the sheath and the low level of tension at which the yarn is spun. Friction spun yarns are the weakest yarns due to the presence of highly disoriented and folded sheath fibres with a low degree of packing. The yarns are spun in a coarse count range (over 40tex).

1.9.4 Air-jet spun yarns

Air-jet spun yarns have a two-layered yarn structure. The core fibres have no twist and are wrapped with fibres as in a rotor spun yarn. Air-jet yarn is less extensible due to the untwisted, straight and parallel arrangement of core fibres constituting 90% of the yarn. The bending rigidity of an air-jet yarn is high due to the clustering effect of core fibres tightly wound by binding fibres which offer very little freedom of movement. Air-jet spun yarn's abrasion resistance is small, causing disintegration of the yarn once the wrapper fibres are broken. These yarns are spun in the fine count range (7–15tex).

1.10 Long staple spinning yarns

Long staple spinning uses 51–215 mm fibres during yarn formation using the following techniques.

1.10.1 Wrap spun yarns

Wrap spun yarns consist of two component yarns, with a core of parallel, untwisted staple fibres and a binder wrap of either a filament yarn or staple fibres on the outside. The wrap provides cohesion to the staple fibre core by radial pressures along the wrap helix. The yarn has low hairiness. Surface fibre wrapping is carried out by hollow spindle wrap spinning. The yarn has a bulky and crimped appearance though under tension it is lean and smooth. These yarns are spun in the coarse to medium count range (higher than 16tex).

1.10.2 Self-twist spun yarns

In self-twist spun yarns, two fibrous strands are separately false twisted by alternating an S and Z twist along their length. They are then plied together by an untwisting torque of single to alternating Z and S twists to create a twofold yarn. These yarns are spun in the medium to coarse count range (20–100tex).

1.10.3 Twistless spun yarns

Twistless spun yarn is formed by felting or adhesive bonding of fibres. An entanglement process consolidates an assembly of fibres in the form of a felted yarn. This type of yarn is well suited for carpets. For technical textile applications, staple fibres are bonded to a core filament (glass, polypropylene, nylon, or polyester) with a polypropylene resin binder.

1.10.4 Core spun yarns

Core spun yarn is a sheath–core yarn formed by twisting fibres as a sheath around an existing core of either a filament or staple spun yarn. These are two-layered structures, the core filament yarn normally providing strength and durability. Elasticated core yarn is used for stretch comfort. These yarns can be produced by ring spinning, friction spinning, wrap spinning, and self-twist spinning.

1.10.5 Ply yarns

Ply yarns are produced by twisting two or more yarns. Doubling or plying helps to achieve special physical characteristics by exploiting the direction and level of the twist in plying. Twisting in a direction opposite to the single yarn enables fibres to orient along the plied yarn axis. This makes the plied yarn smoother, more uniform, lustrous, stronger, more extensible, and less hairy. Twist lively plied yarn is produced by twisting in the direction of the single yarn.

1.10.6 Fancy yarns

Fancy yarns are made with a distinctive irregular profile which is different from basic single and folded yarns. This profile enhances the visual and textural properties of the fabric. Fancy yarns are also termed novelty yarns, speciality yarns, effect yarns and fashion-oriented yarns, and can incorporate deliberate ‘defects’ or variations distributed randomly or in a predefined order, along with colour to give visually and texturally attractive difference to the fabric. Colour effects along the yarn length are introduced by twisting different coloured yarns, spinning blended dyed fibres, or by irregularly printing/dyeing spun yarns.

Fancy yarns are invariably used to create fashion fabrics. They are used in ladies outerwear, mens jackets, knitwear, ties, furnishings, curtains, and upholstery. Typical fancy yarns include snarl, spiral, loop, chenille, slub, and nep. Fancy effects can also be created by changing fibre specifications such as type, length, denier, cross-sectional shape, crimp, initial modulus, colour, lustre, affinity for dyes, and shrinkage, etc. A deliberate difference in length, denier, cross section, and modulus of component fibres can be exploited to position them at predetermined zones of the yarn cross section, with short and coarse fibres occupying the yarn surface. For increased lustre, fibres with a flat cross section, such as trilobal and ribbon-shaped yarns, are often

employed. Slubs of varying dimensions can be produced by using differential fibre length in the core and effect components.

Blending of regular polyester fibres with cationic dyeable polyester can be used to get attractive colours, contrast and fancy effects. Similarly, a blend of fibres having varying shrinkage when combined with colour difference can also give fancy effects. Manufacture of fancy yarns often involves plying and cabling together different yarns of varying count and twists. The density (tpi) and direction of twist (S/Z) are often manipulated during plying and cabling so as to create particular effects. Differences in individual yarn fineness are employed to make corkscrew and spiral yarns. If the direction of twist in the component yarns is kept different, the plying operation will produce an unbalanced twisted spiral yarn.

One of the most popular and well-known fancy yarns is slub yarn which has been used in various types of apparel such as suits and shirts. Corkscrew, spiral, chenille, gimp, loop, snarl, and boucle have all found acceptance in apparels and for the production of furnishings and upholstery. Cotton melange yarn has been highly successful in enhancing the appeal of knitted garments such as T-shirts, etc.

1.11 Physical properties of woven fabrics

Fabric cover, mass, specific volume, and thickness are important physical properties and can be determined based on yarn count, thread spacing, and yarn crimp [8].

1.11.1 Fabric cover

In fabric, 'cover' is measured as the fraction of total fabric area covered by the component yarns. For a circular cross-section yarn, the cover factor is given as

$$\frac{d}{p} = \frac{E\sqrt{T}}{280.2\sqrt{\phi\rho_f}} = \frac{K}{28.02\sqrt{\phi\rho_f}} \quad (1.4)$$

$$K = E\sqrt{T} \times 10^{-1} \quad (1.5)$$

where T is the yarn tex, d is the yarn diameter in cm, E is the number of threads per cm = $1/p$, K is the cover factor, and ϕ is the yarn packing coefficient.

For $d/p = 1$, the cover factor is maximum and given by

$$K_{\max} = 28.02\sqrt{\phi\rho_f} \quad (1.6)$$

Fractional fabric cover is given by

$$\frac{d_1}{p_1} + \frac{d_2}{p_2} - \frac{d_1 d_2}{p_1 p_2} = \frac{1}{28.02} \left[K_1 + K_2 - \frac{K_1 K_2}{28.02} \right]$$

Multiplying by 28.02 we get a fabric cover factor

$$K_1 + K_2 - \frac{K_1 K_2}{28.02} \quad (1.7)$$

1.11.2 Fabric mass

Fabric mass [expressed as grams per square meter (gsm)] is a very commonly used parameter and is given [9] by

$$\text{gsm} = [T_1 E_1 (1 + c_1) + T_2 E_2 (1 + c_2)] \times 10^{-1} \quad (1.8)$$

$$\text{gsm} = \sqrt{T_1 [(1 + c_1) K_1 + (1 + c_2) K_2 \beta]} \quad (1.9)$$

where E_1, E_2 are ends and picks per cm; T_1, T_2 are warp-and-weft yarn tex; K_1 and K_2 are the warp-and-weft cover factors, c is the fractional crimp and $d_2/d_1 = \beta$. In practice, the comparison between different fabrics is usually made in terms of GSM. A fabric engineer tries to optimize the fabric parameters for a given GSM.

1.11.3 Specific volume

The apparent specific volume of fabric, v_F , is calculated using the following formula:

$$v_F = \frac{\text{fabric thickness (cm)}}{\text{fabric mass (g/cm}^2\text{)}} \quad (1.10)$$

where fabric mass (g/cm^2) = $10^{-4} \times \text{gsm}$
and

$$\text{Fabric packing factor, } \gamma = \frac{v_f}{v_F} \quad (1.11)$$

where v_f and v_F are fibre and fabric specific volume, respectively. A knowledge of fabric specific volume helps in calculating the packing of fibres in the fabric. Such studies are useful in evaluating fabric properties such as warmth, permeability to air or liquid.

1.11.4 Thickness

Fabric thickness for a circular yarn cross section is given by $h_1 + d_1$ or $h_2 + d_2$, whichever is greater:

$$h_1 = \frac{4}{3} p_2 \sqrt{c_1} \quad (1.12)$$

$$h_2 = \frac{4}{3} p_1 \sqrt{c_2} \quad (1.13)$$

When the two threads project equally, then $h_1 + d_1 = h_2 + d_2$ and, in that case, the fabric's *minimum thickness* is given by

$$\text{Minimum thickness} = 1/2(h_1 + d_1 + h_2 + d_2) = D; h_1 = D - d_1$$

Such a fabric produces a smooth surface and ensures uniform abrasive wear. In a fabric with a coarse thread in one direction and a fine thread in the other, maximum crimp is obtained for the coarse thread by stretching the fine thread straight. In this case, the fabric's *maximum thickness* is given by

$$\text{Maximum thickness} = D + d_{\text{coarse}}, \text{ since } h_{\text{coarse}} = D$$

1.11.5 Packing of yarns in fabric

The maximum number [9] of warp-and-weft yarns in a fabric depends on the weave-and-yarn count. For plain weave, the maximum number of threads which can be packed in a fabric depends on the following equation:

$$\sqrt{1 - \left(\frac{p_1}{D}\right)^2} \sqrt{1 - \left(\frac{p_2}{D}\right)^2} = 1 \quad (1.14)$$

where p_1 and p_2 are the spacing between the neighbouring warp-and-weft yarns, respectively, and D is the sum of the yarn diameters.

Numerical examples:

1. Calculate the fabric mass, fabric specific volume, and fabric cover factor for a cotton square fabric made from 30tex and 25 threads per cm. Take yarn packing coefficient 0.65 and 1.52 g/cm^3 density of cotton fibre.

$$p_1 = p_2 = \frac{1}{25} = 0.04 \text{ cm}$$

$$d_1 = d_2 = \frac{1}{280.2} \sqrt{\frac{T}{\phi \rho_f}} = \frac{1}{280.2} \sqrt{\frac{30}{0.65 \times 1.52}} = 0.01966 \text{ cm}$$

In a square fabric, $d_1 = d_2$, since $h_1 + d_1 = h_2 + d_2$, therefore $h_1 = d_1 = h_2 = d_2$

Using $h = \frac{4}{3}p\sqrt{c}$ gives

$$d/p = \frac{0.01966}{0.04} = 0.4915 = \frac{4}{3}\sqrt{c}$$

Therefore $c = \frac{9}{16} \times (0.4915)^2 = 0.1359$

Crimp percent = 13.6

$$h_1 = h_2 = \frac{4}{3}p\sqrt{c} = \frac{4}{3} \times 0.04 \sqrt{0.1359} = 0.01966 \text{ cm}$$

Fabric thickness $= h + d = 0.01966 + 0.01966 = 0.03932 \text{ cm}$

$$\text{Also } K_1 = K_2 = d/p \times 28.02 \sqrt{\varphi \rho_f} = h/p \times 28.02 \sqrt{\varphi \rho_f} = 4/3 \times 27.85 \sqrt{c}$$

$$K_1 = K_2 = 37.2 \sqrt{c} = 37.2 \times \sqrt{0.1359} = 13.72$$

$$\text{Fabric cover factor} = 13.72 \times 2 - (13.72 \times 13.72)/28 = 20.72$$

$$\text{Fabric mass (g/m}^2\text{)} = 2 \times [TE(1 + c)] \times 10^{-1} = 2 \times [30 \times 25(1.136)] \times 10^{-1} = 170.4$$

$$\text{Fabric mass (g/cm}^2\text{)} = 0.01704$$

$$\text{Fabric specific volume} = \frac{0.03932}{0.01704} = 2.3$$

2. Calculate the maximum threads per cm in a square jammed plain weave cotton fabric. The warp-and-weft yarn tex is 20, yarn packing coefficient 0.65 and cotton fibre density 1.52 g/cm^3

$$d_1 = d_2 = \frac{1}{280.2} \sqrt{\frac{T}{\varphi \rho_f}} = \frac{1}{280.2} \sqrt{\frac{20}{0.65 \times 1.52}} = 0.016057 \text{ cm}$$

$$D = 2d = 0.032114 \text{ cm}$$

$$\text{Using } \sqrt{1 - \left(\frac{p_1}{D}\right)^2} + \sqrt{1 - \left(\frac{p_2}{D}\right)^2} = 1$$

$$\sqrt{1 - \left(\frac{p}{D}\right)^2} + \sqrt{1 - \left(\frac{p}{D}\right)^2} = 1$$

$$2 \times \sqrt{1 - \left(\frac{p}{D}\right)^2} = 1$$

$$\text{Therefore } p = D \times 0.866 = 0.032114 \times 0.866 = 0.027812$$

$$\text{Threads per cm} = 1/p = 36$$

1.12 Mechanical properties of woven fabrics

Woven fabrics are subjected to a combination of in-plane extension/tension, shear, compression, bending in a perpendicular plane and out-of-plane buckling deformations [10]. The tensile properties of woven fabrics depend on the yarn and the fabric structure, that is the yarn twist, yarn strength, weave, crimp, and cover. The degree of yarn twist affects fabric elongation. A reduction in twist improves cover and reduces air permeability.

An increase in picks/cm and twist density within a normal limit significantly improves both tensile strength and surface durability, but a reduction in pick density improves the tear strength in the filling direction. The breaking strength of a textile fabric is enhanced by an increase in the strength of its component yarns and the number of yarns per unit width. Fabrics made from ring-spun yarns give a higher breaking load than those made from open-end yarns, though the effect of scouring and bleaching in increasing the breaking load is more pronounced with the former.

Cloth strength is affected by the degree of binding of cross threads which aid inter-fibre frictional force and contribute to tensile strength. The degree of binding is dependent on the density of weave and cloth setting. The elongation at break increases with the increase in these variables. The tensile strength of a fabric decreases with an increase in the fabric cover. Crimp decreases the strength of the yarn and fabric. The initial modulus of the fabric decreases with an increase in the crimp. The straightening of longitudinal threads during tension applies compressive forces at the points of contact with the cross-yarn. If the cross-yarn jams before crimp exchange is complete, then a reduction in fabric strength and extension occurs.

The buckling, bending, and drape characteristics of woven fabric influence its performance during the making-up process and in the actual use of the garment. These properties are important, particularly when the fabric is limp, resulting in large-scale deformation even when a small force is applied. The engineering concept of buckling helps to explain the behaviour of fabric during garment manufacturing as well as during its use as a garment. The folding of a garment, bending of sleeves, bending of trouser legs, cutting and sewing operations, etc., all involve buckling phenomena. In bending, a woven fabric exhibits initial nonlinearity due to frictional restraint, followed by the linear deformation-recovery behaviour of the material. The puckering tendency of a cloth during stitching shows similar behaviour as does formability, a measure of the ability of a fabric to absorb compression in its own plane without buckling. The formability value is used as a direct indicator of the likelihood of seam pucker occurring during the sewing of a garment.

Fabrics are subjected to bending deformations in most uses. Bending is a very common phenomenon during the use of garment fabrics. Additionally, it has some influence on the drape of upholstery, furnishings, and curtain fabrics. Creasing and wrinkling of fabrics and garments are also associated with bending deformation. Bending resistance is made up of the bending resistance of threads lying in the direction of bending, frictional restraint and interaction between the threads. The four main factors directly influencing minimum bending rigidity $G_{\min}$ are fibre tensile modulus, fibre linear density, yarn linear density, and the number of threads per unit cloth width [11].

Interfibre adhesion can increase elastic fabric stiffness considerably. Textile yarns, being visco-elastic, exhibit time-dependent effects such as stress relaxation. This causes decay in the interyarn force at the cross-over point and results in setting. In addition, fabrics can be set by finishing treatments to relax internal stresses in the fabric and lower its internal energy level.

1.13 Effects of fibre and yarn properties on the use and application of woven fabrics

The physical and mechanical properties of a fibre, as the unit cell of a textile material, clearly contribute to a fabric's mechanical properties. However, according to the spinning system used, the yarn structure and properties can be varied considerably to alter packing, surface, and mechanical properties. The fabric itself imposes another set of variables, such as sett and weave, to further diversify the overall list of fabric properties.

The use of textiles for apparel, home furnishing, and industrial/technical applications depends on a unique combination of required properties. Fabrics for apparel, for example, require comfort, hand, drape, breathability, easy care, durability/abrasion, aesthetics, dyeability and, of course, tailorability. The requirements of fabrics for home textiles (such as curtains and upholstery) are drape, aesthetics/colour/design and resistance to stain/soiling and degradation from light. Fabrics for industrial and technical applications require specific characteristics which usually include strength and durability. This section reviews some of these properties and how they are influenced by fibre and yarn properties.

In general, spun yarns of either single or blended fibres are the major building materials in woven fabrics. Continuous filament yarns are used either as textured or as core spun yarns. There needs to be maximum packing of yarn in fabric for several applications. The properties of a textile which govern its conformation to a technical specification are the function of the yarn network (interlacement, diameter, and spacing), thickness, and mass. A large group of fabric properties are more dependent on pore structure than on yarn network, for example, resistance to the flow of liquids, gas, and light.

Woven fabrics are made from interlaced yarns which are flexible. The yarns are made by twisting together long, thin, flexible, and strong fibres. The properties of yarn and fabric depend largely on the properties of the constituent fibres. Textiles are low-density materials and contain a large proportion of air within their total structure and thus the characteristic textile properties arise from two basic fabric elements: fibre and air. Another set of attributes rely on the interchange in yarn and interstices geometry: tear resistance, fabric drape, and sewability. Fabric strength and extension is a function of crimp and yarn twist. It is very important to have an in-depth knowledge of the principles involved in the selection of raw materials and their conversion to desired yarns and fabric structures, followed by dyeing and finishing. Additionally, knowledge of polymers and coating helps when designing technical fabrics for different applications.

1.13.1 Creasing and wrinkling properties

In practical use, textile fabrics are subjected to a wide range of complex deformations such as bending, folding, creasing, and wrinkling which may be added deliberately during manufacturing or produced by body movement during use. Of these, wrinkling and creasing can affect the aesthetic characteristic of a fabric. The ability of a fabric to resist creasing or wrinkling and to recover from such deformations is determined by many factors, the most important being the mechanical properties of its fibres, such as

their tensile strength, bending and torsion, the geometrical and constructional parameters of the yarn and fabric, and the presence or absence of finishing agents on or within the fibre.

Resistance and recovery from creasing are largely influenced by the type of fibre, yarn, and fabric structure. Bending elasticity plays an important role in the creasing phenomenon of a fabric. Amongst the commonly used textile fibres, linen exhibits creases easily due to a very high degree of orientation of cellulose in the fibre. Cellulosic materials are highly susceptible to creasing. The materials which resist creasing also resist deformation and therefore they behave as a rigid material. Ideally, a fabric which is deformed should recover from its deformation rapidly. Wool is well known for its very good elastic recovery and therefore has the ability to resist and recover from creasing.

1.13.2 Shear properties

Shear behaviour is one of the most important characteristics contributing to the performance and appearance of woven fabrics. Shear properties influence drapeability, pliability, and hand behaviour of apparel fabrics. The study of shear behaviour of fabrics has special significance, particularly for mass-produced apparel. This is mainly because cloth is deformed in all directions during handling on machines, as well as in actual use. In fact, the ability of a fabric to be deformed by shearing distinguishes it from other flat flexible materials such as paper and polymer thin films. Shear angle is one of the main criteria for characterizing the formability of fabrics. This property enables a 2D fabric to undergo complex deformations and helps a 3D garment to conform to body contours, imparting the desired mechanical comfort.

1.13.3 Compression properties

Compression is defined as a decrease in intrinsic thickness with an increase in pressure – intrinsic thickness being the thickness of the space occupied by a fabric subjected to barely perceptible pressure. Compression of fabrics is an inevitable phenomenon during fabric handling and processing. Compressive properties are concerned with the surface smoothness, softness, and fullness of a fabric. The compressive properties of textile materials have direct relevance to bulk and handle of fabrics. In a woven construction, warp-and-weft yarns are compressed due to inter-yarn pressure. The softness of a fabric is determined by its compressibility which depends on the compressibility of the yarn and the fabric construction. Compressibility of fabric is an integral component of fabric hand.

Tailorability of cloth significantly depends on fabric compressional behaviour. Compressibility of fabrics significantly influences drapeability. When a fabric is draped on the edges of a contour, there is compressional deformation at the point of bending. Fabrics with higher compressional energy give a higher drape coefficient. A highly compressible fabric has high compressional energy and can absorb or withstand compressive forces to a greater extent at the deforming points. This prevents folding at the deforming points and a higher drape coefficient results.

1.13.4 Abrasion properties

Abrasion is a kind of wear in which rubbing away of component fibres and yarns of the fabric takes place. During abrasion, a series of repeated applications of stress takes place. Therefore abrasion resistance is the capacity to absorb energy. The abrasion resistance of a fabric is dependent on many factors including fibre properties, yarn structure and size, fabric mass and geometry as well as fabric finish (including lubricating and sizing agents used). For hydrophilic fibres, the amount of moisture present also affects abrasion resistance.

1.13.5 Fabric comfort

The subjective feeling of fabric comfort is a complex result of psychological and physiological responses of the human body and the physical properties of the fabric. Comfort [12] has two attributes: mechanical (evaluated by visual and tactile means) and thermal (assessed by the permeability of fabric to air, water, and heat). Comfort is evaluated in part by fabric hand – a traditionally subjective evaluation made by judging the feel of a fabric between the fingers. The fabric hand is expressed by an index – total hand value (THV) – based on a combination of mechanical properties derived from tensile strength, shear, bending, compression, surface friction, and the surface deformation recovery of fabric at low stress. These fabric properties are also useful for tailorability and formability, that is, the forming and sewing of flat fabric pieces into 3D-shaped garments. Thermal comfort is evaluated in terms of air permeability, thermal insulation capacity, water repellency, and water vapour transmission.

Fabric characteristics such as fibre type, yarn linear density, thread (yarn) density, weave type, and yarn twist affect fabric hand since these constructional parameters determine fabric surface characteristics, which significantly contributes to the perceived touch of a fabric. Surface properties also help to judge the smoothness and crispness of a fabric. Geometrical roughness is another important factor affecting the perceived softness of a fabric. For a given fabric construction, the denier, cross-sectional shape, and crimp of the fibres influence the softness of the final product. Very fine filaments are effective for good draping, antcrease properties and softness of handle, but these yarns are more susceptible to abrasion than coarse-filament yarns. The desired softness of handle can also be achieved through modified fibre cross section.

1.14 Effects of fibre and yarn properties on woven textiles: Apparel and sports textiles

In the apparel market, polyester in staple or filament form has a clear advantage because of its easy-care qualities and low cost. Although 100% polyester has limited appeal because of its less desirable handle, it is extremely popular in blends with cotton. Filament yarns are used for outdoor clothing applications or where a fur-like or silky appearance is desired. Fibres with enhanced or modified properties are in great

demand. Yarn bulk is enhanced by using bicomponent or biconstituent fibres. Pilling is reduced by producing fibres that are more brittle, while a yarn with exceptionally soft handle is produced by using fine-denier fibres or fibres treated with special friction-reducing finishes. Abrasion resistance is enhanced by modifying the spinning conditions to produce a denser filament microstructure.

Sports textiles are textiles used in sports goods and in sportswear. Sportswear is clothing, including footwear, which is worn for sport or exercise. It includes shorts, tracksuits, T-shirts, polo shirts, and trainers. Sportswear is also often worn as casual fashion clothing. For most sports, athletes wear a combination of different items of clothing. These should have protective properties against variable atmospheric conditions during use as well as for protection against physical damage. In addition, they require a high tear strength, resistance to abrasion, shape stability, and colour fastness. Almost every piece of sports clothing is designed to be lightweight so the athlete is not encumbered by its weight. The best athletic wear for some forms of exercise, for example, cycling, should not create drag or be too bulky. On the other hand, it should be loose enough so as not to restrict movement. Various physically dangerous sports require protective gear, for example, for fencing, American football, or ice hockey.

Garments should allow the wearer to stay cool in hot weather and warm in cold weather. In cold climates, the best athletic wear should not only provide warmth but also transfer sweat away from the skin. For activities such as skiing and mountain climbing, this is achieved by using layering. Moisture transferring materials must be worn next to the skin, followed by an insulating layer and wind and water resistant shell garments. The waterproof fabric prevents the penetration and absorption of liquid water. The term 'breathable' implies that the fabric is actively ventilated. Breathable fabrics passively allow water vapour to diffuse through them yet prevent the penetration of liquid water. Water-resistant and moisture-permeable materials may be divided into three main categories: high-density fabrics, resin-coated materials, and film-laminated materials. These are selected according to the finished garment requirements in casual, athletics, ski or outdoor apparel.

Densely woven waterproof breathable fabrics consist of cotton or synthetic micro-filament yarns with compacted weave structure. One of the most famous waterproof breathable fabrics, known as Ventile, was manufactured by using long staple cotton with minimal space between the fibres. Usually combed yarns are woven parallel to each other with no pores for water to penetrate, and Oxford weave is preferred. When the fabric surface is wetted, the cotton fibres swell transversely, reducing the size of pores in the fabric and requiring very high pressure to cause penetration. Therefore, waterproofing is provided without the application of any water repellent finishing treatment.

Densely woven fabrics can also be produced from microdenier synthetic filament yarns. The individual filaments in these yarns are $<10\mu\text{m}$ in diameter so that fabrics with very small pores can be engineered. The use of superfine or microfibre yarns makes the production of dense fabrics possible enabling capillary action which gives the best wicking properties. The wicking behaviour of a fabric is dependent mainly on the base fibre's moisture properties. While most fabrics, both natural and synthetic, have the ability to wick moisture away from the skin, not all of them are fast-drying

and air permeable (two factors which have a direct influence on cooling and perceived comfort). High-tech synthetic fabrics are lightweight and capable of transporting moisture efficiently and dry relatively quickly. It is generally agreed that fabrics with moisture wicking properties can regulate body temperature, improve muscle performance, and delay exhaustion. While natural fibres such as cotton may be suitable for the clothing worn for low levels of activity, synthetic fabrics made of nylon or polyester are better suited for high levels of activity. They absorb much less water than cotton, but can still wick moisture rapidly through the fabric. No single fibre or a blend of different fibres provides an ideal sportswear fabric: the right type of fibre should be in the right place. A two-layer structure is better, with a synthetic fibre layer close to the skin with high wicking properties (e.g. a microdenier polyester, which is ideal for wicking perspiration away from the skin) and an outer layer usually of cotton or rayon which absorbs and evaporates.

1.15 Future trends

Electronic-textile (e-textile) technology holds out the promise of truly wearable computers as well as inexpensive large-scale computational devices. New fibres are being created for inclusion in e-textiles, including battery, conductive, and mechanically active fibres. Methods are being developed to attach discrete components to e-textiles, including processors, microphones, and speakers. In the category of wearable computing, a garment providing the user with precise location information within a building is being developed. Virtually all woven e-textiles are expected to use the new fibre batteries and solar cells that have been developed.

Conductive woven fabrics are being made by utilizing metallic conducting wires as flexible wearable electrical circuits; the properties of these nanotube-based yarns can be leveraged to produce more robust systems far lighter and more flexible than metallic wires. As a step in the direction towards the creation of nanotube-based electronic components for fabric applications, supercapacitors have also been woven into a textile fabric. The capacitors have capacitances and life cycles comparable to commercially available supercapacitors. Since nanotubes are also known to have effects similar to piezoelectric materials, such materials can be integrated into structures to produce sensors that monitor stresses. Chemo-, piezo- and thermo-resistive fibres are now available in a textile compatible form and their integration into fabrics and garments is being actively pursued.

1.16 Sources of further information and advice

The best source of information is the internet. The following list of links to fibre producers, machinery manufacturers and technical textiles producers gives plenty of innovative information, of interest to both academics and industry:

- <http://www.ibena.de/techtex/english/fabric/fabric.html>
- <http://www.innovationintextiles.com/>

- <http://ec.europa.eu/enterprise/sectors/textiles/research-innovation/technical-textiles/>
- <http://www.technicaltextilesguide.com/>
- http://www.huntsman.com/textile_effects/eng/Technical_Textiles/Technical_textiles/index.cfm?PageID=629
- <http://www.technical-textiles.net/html/j20050119.557671.htm>
- <http://www.aramid.com/>
- <http://www.highbeam.com/doc/1P3-618128741.html>
- <http://www.ascendnif.com/>
- <http://www.universalfibres.net/industrialFibres.php>
- <http://www.ifai.com/>
- <http://www.sagezander.com/>
- <http://www.torayusa.com/tomac/products/synthetic.htm>
- <https://www.bing.com/images/search?q=yarn+numbering+conversions&qpv=yarn+numbering+conversions&FORM=IGRE>

References

- [1] J.E. McIntyre, *Synthetic Fibres: Nylon, Polyester, Acrylic, Polyolefin*, Woodhead Publishing, Cambridge, 2004.
- [2] C. Gordon, *Handbook of Textile Fibres*, Woodhead Publishing, Cambridge, 1984.
- [3] R. Alagirusamy, A. Das, *Technical Textile Yarns: Industrial and Medical Applications*, Woodhead Publishing, Cambridge, 2010.
- [4] A.R. Horrocks, S.C. Anand, *Handbook of Technical Textiles*, Woodhead Publishing, Cambridge, 2000.
- [5] M. Jassal, A.K. Agrawal, Functional smart textiles using stimuli-sensitive polymers, in: N. Pan, G. Sun (Eds.), *Functional Textiles for Improved Performance, Protection and Health*, Woodhead Publishing, Cambridge, 2011.
- [6] C.A. Lawrence, *Fundamentals of Spun Yarn Technology*, CRC Press, Boca Raton, FL, 2002.
- [7] J. Lünenschloss, K.J. Brockmanns, *Textil Praxis International*, (1985) (February), Stuttgart, Konradin Verlag.
- [8] F.T. Peirce, *J. Text. Inst.* 28 (1937) T45–112.
- [9] L. Weiner, *Textile Fabric Design Tables*, Technomic, Lancaster, PA, 1971.
- [10] B.K. Behera, P.K. Hari, *Woven Textile Structure: Theory and Applications*, Woodhead Publishing, Cambridge, 2010.
- [11] J.D. Owen, *J. Text. Inst.* 59 (1968) 313.
- [12] S. Kawabata, M. Niva, Y. Yamashita, *Int. J. Cloth. Sci. Technol.* 11 (2–3) (1999) 134.

Yarn preparation for weaving:

Winding

2

K.L. Gandhi

The Textile Institute, Manchester, United Kingdom

2.1 Introduction to yarn preparation

When a fabric is to be woven on any loom, whether it is a handloom or a power loom, two sets of yarns are required. One set of yarns, called warp yarn, is used in the length-wise direction and the other set of yarn, called weft yarn, is used in the horizontal direction. The warp yarns are put on a package called a weaver's beam which is put at the back of the loom as shown in Fig. 2.1A. The number and length of warp yarn to be put on the weaver's beam depend on the quality of the cloth, i.e. the number of warp yarns/cm, also called ends/cm, width of the fabric and the length of fabric to be produced from the weaver's beam. Fig. 2.1B shows the front of the looms as the fabric is produced [1].

In order to produce a weaver's beam with a few hundred to a few thousand numbers of warp yarns and their length (m) on the beam, the spun yarns on small packages produced during the spinning process undergo the following yarn preparation processes for weaving purposes:

- winding
- warping
- sizing.

During the spinning process, as the yarn is produced, it is generally wound on a package called a spinner's package. The length of yarn put on this package can be from a few hundred to a few thousand metres depending on the length and diameter of the spinning package as well as the count, i.e. linear density of the yarn. These small packages produced on the ring-spinning machine are mostly unsuitable for the efficient running of the next processes, i.e. warping, twisting, and weft winding (pirn winding), making a winding process necessary.

The sizing process is optional and is carried out mostly for single spun cotton yarns. Woollen and worsted warp yarns are normally produced as twofold yarns (two yarns twisted together). As such, they do not require a sizing process, in which case only winding and warping preparatory processes are carried out.

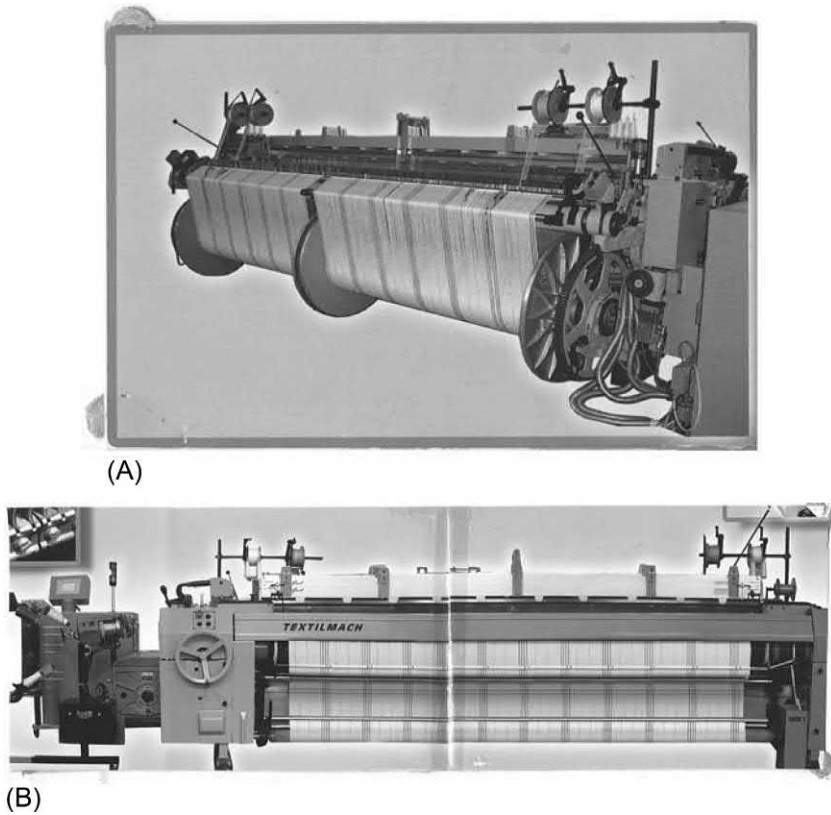


Fig. 2.1 (A) Back and (B) front of loom.

2.2 The winding process

Winding is a process of transferring yarn from one package to another or from a number of small packages (spinner's packages, spools or hanks) to a big package (Fig. 2.2) [2], i.e. a cone or cheese that is more suitable for the next processes such as warping or knitting or for any other suitable use such as on shuttle-less looms.

Winding is also important in removing defects in the yarn. During the spinning process of traditionally spun staple yarns, for a variety of factors, some defects or imperfections, such as a thick place, thin place, slub or nep, are induced into the yarn. The length and thickness of these defects can vary significantly (Fig. 2.3) [3]. If not removed from the yarn which is going to be used as warp or weft during weaving or knitting, these defects will get woven/knitted and produce a defective fabric. These defects or irregularities from the yarn are therefore removed during the winding process (also called 'yarn clearing'). Not every defect is removed from the yarn. The degree of clearing of such defects is dependent on what the yarn is going to be used for.

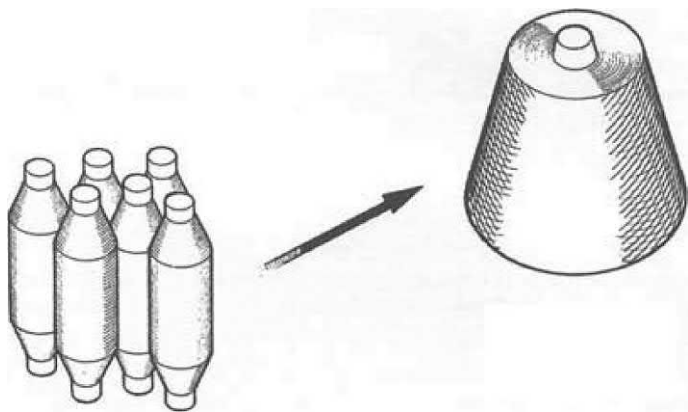


Fig. 2.2 Yarn from spinner’s packages onto cones.

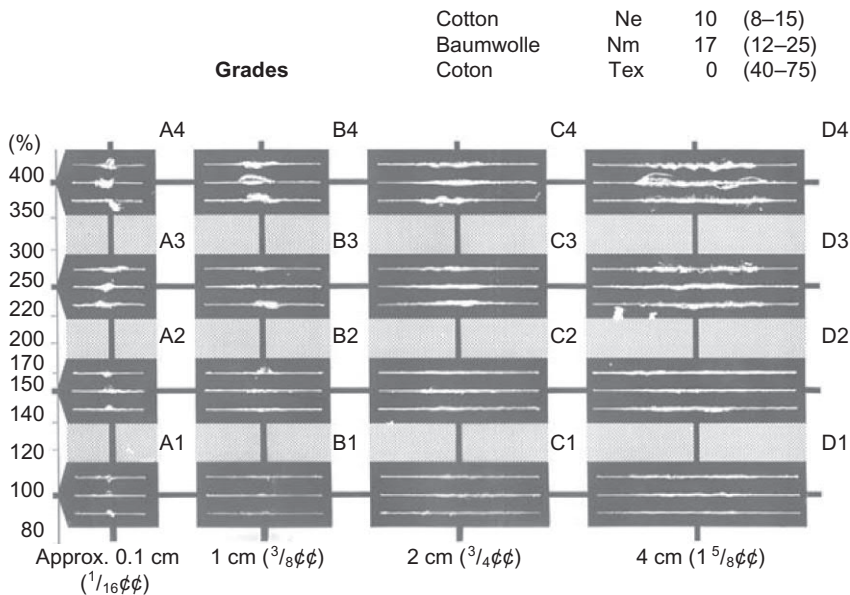


Fig. 2.3 Defects in yarns of different length and thickness.
Courtesy of Uster Technologies AG.

When spun, filament yarns are not produced by twisting of fibres during their production. As a result no yarn irregularities, i.e. thick or thin places, are induced during the spinning process. The winding process for such yarns is carried out to produce bigger packages, if these are required, by transferring yarn from a number of small packages onto big packages suitable for the next process.

2.2.1 Clearing yarn defects during winding

Thick places/slubs in the yarn having a diameter bigger than the normal diameter of yarn are removed either mechanically by a device called a slub catcher or electronically using optical or capacitance sensors.

2.2.1.1 Mechanical clearers

When cleared mechanically, the yarn is made to pass through a small slit with a definite opening depending on the degree of the clearing. Thick places [4,5] and slubs larger than the opening of the slit are arrested, cut, and replaced by a knot or a splice (Fig. 2.4A and B). Thin places are usually removed by applying tension to the yarn during the winding process. On a traditional manual winding machine, the yarn is made to pass between the two discs (Fig. 2.4B and C) [5,6]. Suitable weights are added on the top disc. As the yarn passes between the discs it is subjected to tension and the thin places, having a breaking strength lower than the tension applied, are broken and replaced by either a knot or splice.

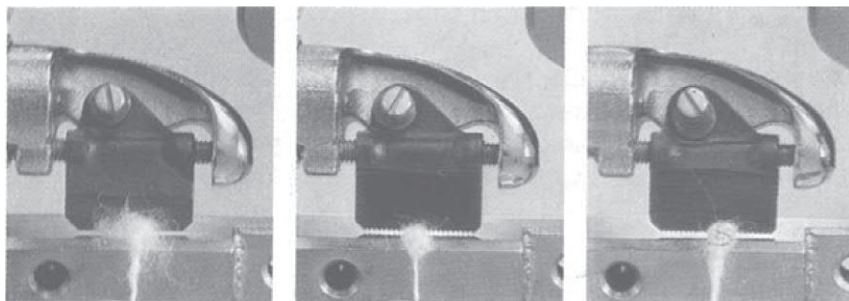
All modern automatic winding machines are equipped with very efficient tension devices. Oerlikon Schlafhorst offer on their Autoconer 5 a very precise and unique tension control: Autotense FX (Fig. 2.5A) [7]. The yarn tension in cN and its variations are permanently recorded by a sensor and adjusted to the desired level by the electromagnetic tensioner. The yarn tension is measured online and adjusted to the required level in a closed control loop.

The Savio Machine offers a unique tension device called TensorFlex (Fig. 2.5B) [8] on their Automatic winder Orion E/I. The tension sensor (Tensor) continuously detects actual winding tension since it is positioned immediately before the drum. The Tensor interacts, through the head computer, with the yarn tension to vary the pressure exerted on the yarn as required. The operating range of the yarn tensioner can be set on the machine's computer. When the yarn tensioner reaches the minimum value of this range, it can, if so required, activate the preset speed reduction curve. The Tensor has no moving parts that could influence operation and therefore provides correct reading and correction of tension.

Another electronic yarn tension device (Fig. 2.5C) [6], called TENS CONTROL, with an 'on-line' tension sensor, is available in the market. With this device, it is possible to constantly control and regulate the yarn tension from the beginning to the end of the package formation, independently from the tension variations coming from the feeder bobbin. On the computerized digital terminal in the drive end, it is possible to set the desired yarn winding tension, which is in turn controlled by a special online electronic tension sensor located on each single winding spindle, which again operates a motorized tension device. With this continuously regulating system, the tension device sets in at the slightest variation, keeping yarn tension within the set parameters.

2.2.1.2 Electronic clearers

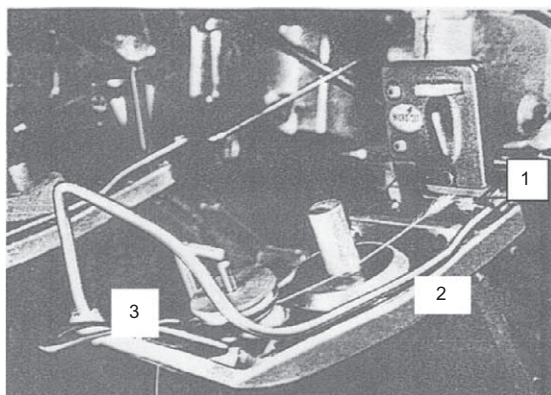
In the capacitance clearer, the yarn passes through an air-spaced condenser. The change in the capacitance is related to the mass of the material between the plates. If the mass changes to values beyond preset limits, the cutter operates, thus cutting



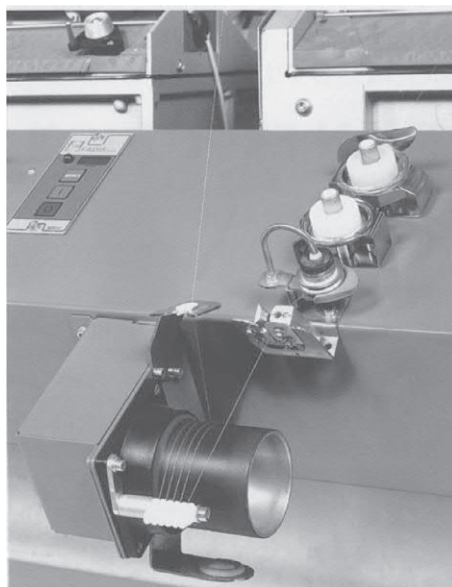
(A)

Key

- 1 – Slub catcher
- 2 – Waxing unit
- 3 – Disc tensioner



(B)



(C)

Fig. 2.4 (A) Mechanical slub catcher, (B) slub catcher, and (C) disc tensioning and waxing.

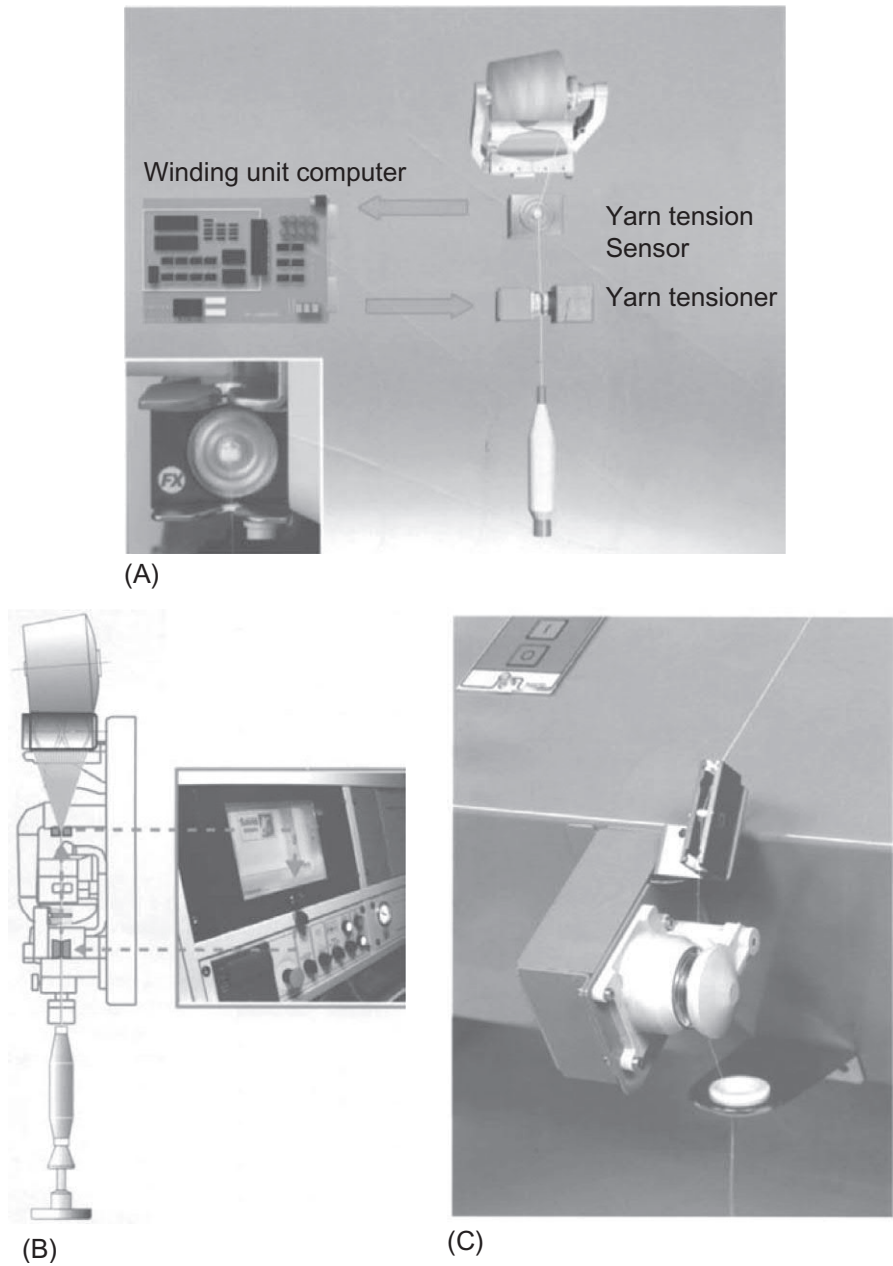


Fig. 2.5 (A) Autotensor, (B) TensorFlex, and (C) tension device TeNS CoNTrol.

the yarn. It is the mass of the material that is measured and not the physical dimensions, i.e. width or diameter of the defect [9].

In the photoelectric or optical electronic clearer, the device measures the diameter or profile of the yarn. The yarn is scanned by a light source. The scanned portion interrupts the beam, which thus changes the signal from the photoelectric cell. If limits are exceeded, the cutter is brought into operation. Almost all modern winding machines are equipped with electronic clearers. Fig. 2.6 shows yarn clearer units on Savio winding machines [8].

Knitting yarns are subjected to a lot of friction during the knitting process and, to reduce it, yarn is usually waxed during the winding process. Fig. 2.4C shows a modern tension and waxing device [6] equipped with large diameter feed roller to eliminate the tension variations and two waxing units.

The winding process is carried out not only for transferring the yarn from a number of small spinning packages onto bigger packages such as cones and cheeses. It is also carried out, when required, for transferring yarn from bigger packages such as cones onto small ones, i.e. pirns or weft bobbins for use during weaving as weft yarn. In this case the defects from the yarn have generally already been removed when preparing the cones on the winding machine. In some cases, the yarn is wound from bigger packages produced on an open end spinning machine onto weft packages (pirns) without clearing the defects. Equally, it is common to produce weft bobbins on the spinning frame which are taken straight for weaving.

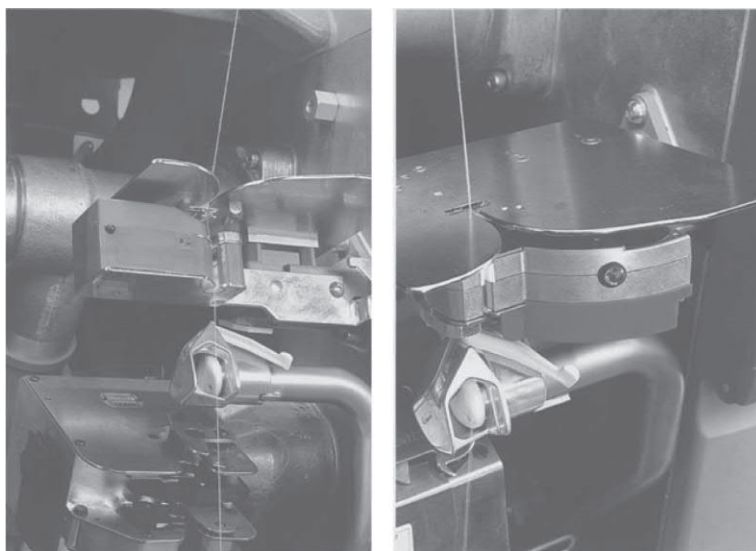


Fig. 2.6 Electronic clearers.

2.3 Types of winding machines

The following types of winding machines are commonly available:

- *Drum winding machines*: these produce packages called cones, cheeses, etc.
- *Hank winding machines*: these unwind hanks, skeins, etc., produced on reeling machines.

Fig. 2.7A shows a hank to cone winding machine SINCRO with electronic yarn guide, a

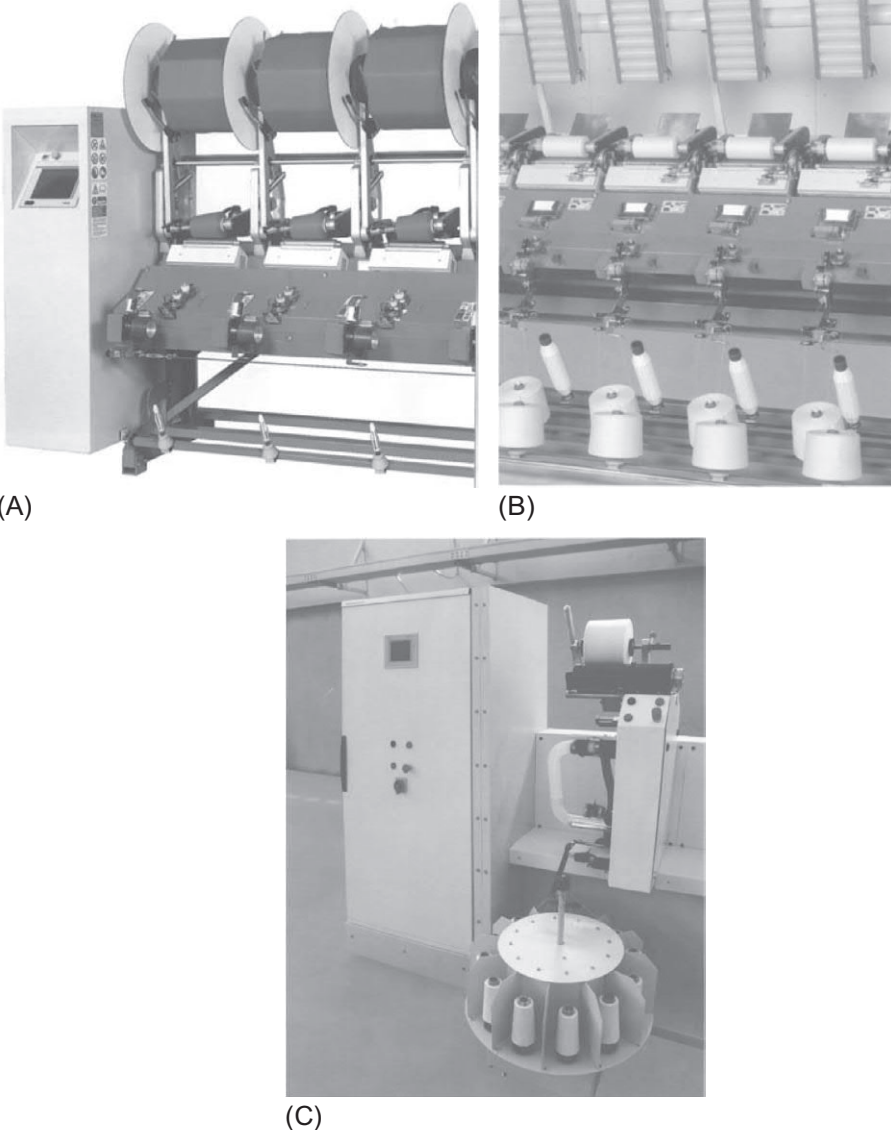


Fig. 2.7 (A) Hank to cone winding, (B) assembly winder, and (C) econoflex residual package.

precision crossing angle, a positively driven bobbin, and an unwinding speed of up to 1000m/min [6].

- *Assembly winding machines*: these assemble yarns from two, three or more packages onto one larger package. Fig. 2.7B shows an assembly winder model SINCRO B from Fadis, Italy [6]. The machine is equipped with a three-ply creel with an individual yarn sensor, TENS CONTROL, an online tension device, yarn cutter, and automatic doffing. Fig. 2.7C shows an Econoflex residual package winder [10] for winding expensive residual yarn left on packages such as cones and cheeses in the warping section. The model is completely automatic and changes the feeding package automatically each time the yarn breaks or ends, reducing the amount of hard waste.

2.3.1 *Winding mechanisms*

Irrespective of the type of winding machine, two mechanisms essentially are involved in the transferring of yarn from one package onto the desired one. These are:

- the rotational movement to the package onto which the yarn is wound
- guiding of the yarn on the package being rotated.

This mechanism is called traversing of the yarn from one side of the package to the other and back. This process continues all the time. Every type of winding machine named above has a rotary and a traversing mechanism.

2.3.2 *Cone and cheese winding machines*

There are two types of winding machines to wind the yarn in cone or cheese form. These are:

- drum winding machines
- precision winding machines.

2.3.3 *Drum winding machines*

On a drum winding machine, the rotary movement to the package, whether it is a cone or a cheese, is provided by the frictional contact between the package and the revolving drum surface. The traversing mechanism is provided by the grooves cut into the drum (Fig. 2.8A) [5]. When the package is brought in contact with the drum, the yarn enters the grooves (Fig. 2.8B) [8] and is guided from one side to the other of the package and back again to continue the process. As the yarn lies in and travels with the groove, moving at approximately the same speed, it is not subject to abrasion likely to cause injury and its properties are unimpaired.

Since the surface of the package is driven with the surface of the drum which has a constant speed, the yarn speed on such machines is always constant. However, the revolutions of the package decrease as the package diameter increases. This kind of winding, normally classed as random winding, is carried out for most staple-spun yarns and is not suitable for continuous filament yarns as the friction between the package and the drum tends to damage the yarn surface. When the yarn breaks as

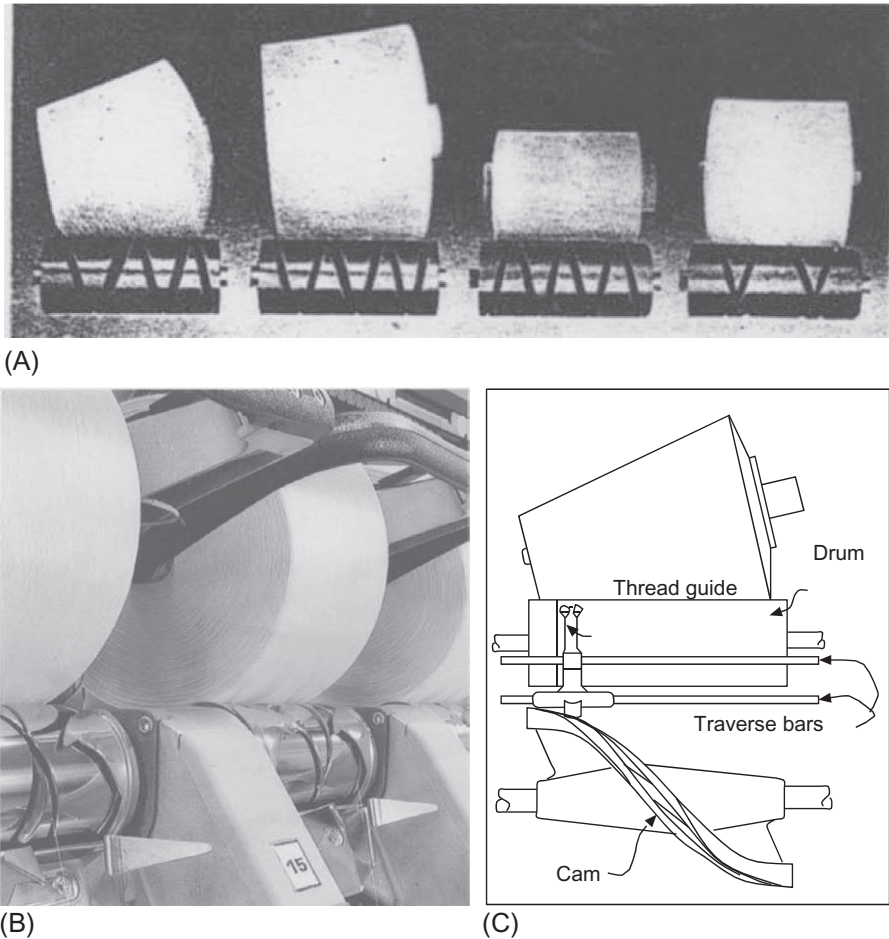


Fig. 2.8 (A) and (B) grooved drums and (C) drum winder with cam traverse.

a result of removal of the defect or any other reason, i.e. when the supply package runs out, the package is lifted off the drum and the winding process stops.

The characteristics of random winding are as follows:

- As the package diameter increases, the angle of wind remains the same but wind per double traverse decreases.
- Yarn speed throughout the build of the package remains constant.
- Minimum tension variation occurs during unwinding of the package in subsequent processes.
- The process is capable of producing large diameter packages.
- If dyeing takes place, dye liquid penetration is not very ideal.

2.3.4 Drum winding machines with cam traversing mechanism

Fig. 2.8C shows the traverse to the yarn achieved with the help of a grooved cam [5] which is mounted on the camshaft rotating at a definite speed. The grooved cam has a small pin positioned into it and to which is attached a thread guide. When the camshaft rotates, the pin is guided in the grooved path of the cam, which transfers the motions to the thread guide from one side to the other and back again, thus traversing the yarns on the package.

There exist important relationships between the traverse and the winding speed [11]. The greater the number of coils of yarn in the width of the traverse, the higher the winding speed possible. It is usual, therefore, to operate the traverse mechanism at the maximum speed, to keep this speed constant, and to alter the number of coils or winds by varying the speed of the driving drum, thus altering the ratio between the traverse and the drum speed. The characteristics of the yarn, the type of yarn package, and the subsequent purposes for which the package is required are factors which determine the most satisfactory ratio and, in conjunction with the maximum traverse speed, determine the production of which the machine is capable.

2.3.5 Precision winding machines

On these machines, the package is inserted onto a spindle which is rotated at a uniform speed measured in revolutions per minute. When the spindle rotates, the package rotates and the yarn is wound on it. The traverse to the yarn is provided by an independent mechanism and usually involves a specially designed cam with a groove mounted on a shaft (Fig. 2.9) [5]. A small pin with a thread guide lies in the groove. When the shaft rotates, the cams rotate and the small pin (thread guide) is guided in the groove to transfer motion to the thread guide, thus traversing the yarn on the package.

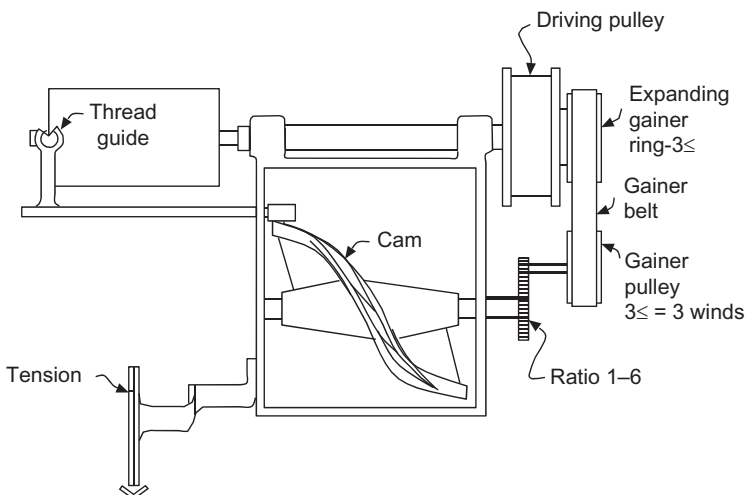


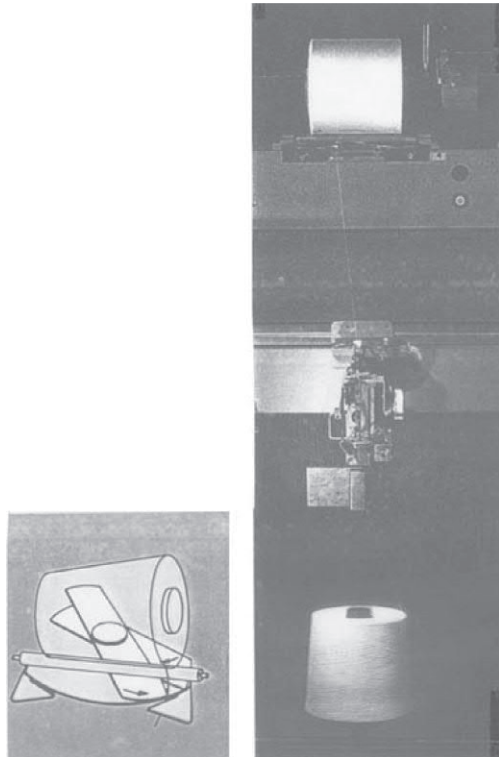
Fig. 2.9 Cam traverse mechanism.

On these machines, since the package is fixed on the spindle which has a uniform speed in revolutions per minute, the yarn speed increases as the package diameter increases. Precision winding is mostly suitable for continuous filament yarns where the package is rotated independently and there is no frictional contact with any surface. There are some precision winding machines on which the spindle speed decreases as the package diameter increases, in which case the yarn speed is kept constant. This indirectly helps to keep the yarn tension constant through the build of the package. Fig. 2.10 shows a different mechanism of traversing the yarn on the Schaerer Precision Cross Winder [12] using counter-rotating propeller blades. It is easy to change the traverse length.

Precision winding offers some of the following advantages:

- higher density of packages
- no pattern zones
- reduced end breakage rate
- higher density of the package gives advantages in twisting operation, i.e. cost of twisting, dyeing, etc.
- easy overend unwinding
- regular dye liquid penetration
- excellent for winding continuous filament yarn.

Fig. 2.10 Counterrotating propeller blades traverse mechanism on a precision winder.



2.4 Terminology commonly used in the winding process

2.4.1 *Wind*

During the winding process, the package rotates, whether by the friction of the drum or when mounted onto a spindle and the yarn is traversed on the package from one side to the other and back. In one stroke of the single traverse, a certain number of coils are wound on the package and this number is defined as the wind. The wind is therefore defined as the number of coils wound around the package in a single traverse.

2.4.2 *Wind ratio*

This is defined as the number of coils wound on the package per double traverse. This can be found by counting the number of times the package is revolved to traverse and return the yarn to the same point.

2.4.3 *Random wound package*

This kind of package is mostly produced on a drum winding machine. The wind ratio, i.e. the number of coils per double traverse, decreases as the package diameter increases but the angle of wind remains the same (Fig. 2.11A) [6].

2.4.4 *Precision wound package*

This is mostly wound on a precision winding machine where the package is driven independently. The number of coils per double traverse (wind ratio) remains constant from the start to the finish of the package, i.e. as the package diameter increases, the angle of wind decreases (Fig. 2.11B) [6].

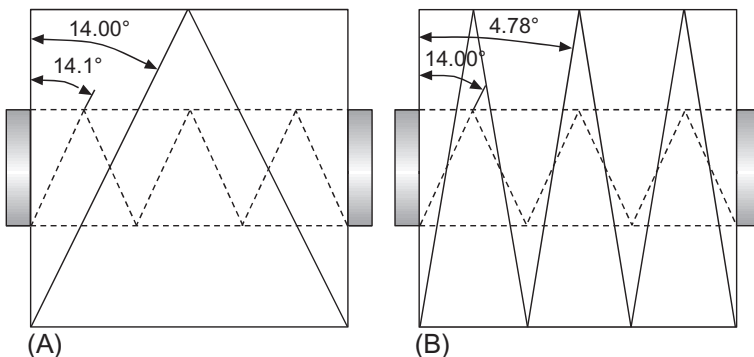


Fig. 2.11 (A) Random wound and (B) precision wound package.

2.4.5 Angle of wind

This is the angle between the direction of yarn lay on the package and a perpendicular drawn to the package axis (Fig. 2.11). It is formed by the ratio of two components: speed of yarn guide (traverse velocity)/surface velocity of the package, and is defined as $\tan Q$. The quality of the package during winding is determined by several variables, the most important being the angle at which the yarn is wound onto the package. As a rule, the higher the wind angle, the better the package. The maximum wind angle is determined quantitatively by the package configuration, the properties of the yarn material and the process conditions connected with the winding operation [13].

The normal range of winding angle is 30–50 degrees. Minimum package density is reached when the winding is 90 degrees or the two sets of threads are perpendicular. Compact packages for warping, shuttleless weaving are normally wound with the angle of wind of about 30 degrees. A change in winding angle from 30 to 55 degrees reduces the package density by about 20%–25%. Too low an angle of wind will produce a deformed package of ‘diabolo’ shape when coils will tend to run towards the middle of the package. On the other hand, too large an angle of wind will produce a stitching (webbing) effect when the coils tend to slip over the edges of the package thus causing end breaks during unwinding of the yarn from the cone.

2.4.6 Overend unwinding

Overend unwinding occurs when the yarn is unwound, but the package remains stationary (Fig. 2.12B) [2]. It can be compared with side unwinding when, during unwinding of the yarn, the package rotates (Fig. 2.12A).

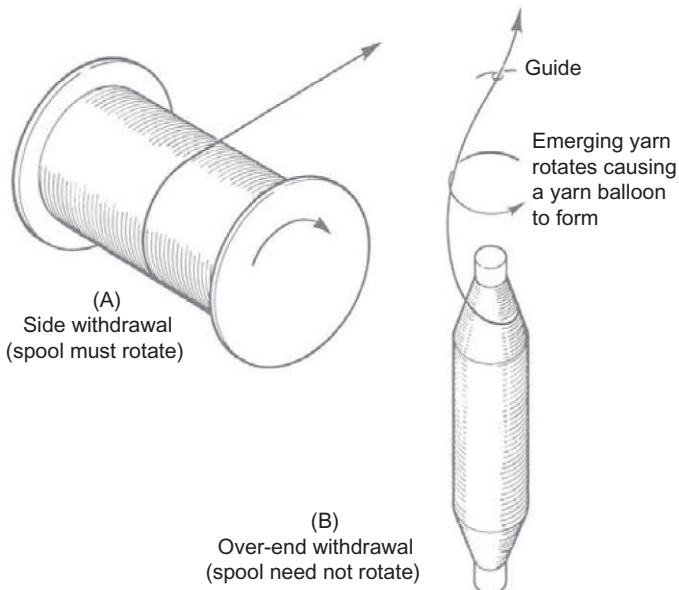


Fig. 2.12 Over and side unwinding.

2.4.7 Open wind

During winding, when each succeeding coil of yarn lies nearest to the preceding coil, the package is said to have an open wind. This will occur when the wind per double traverse happens to be a whole number.

2.4.8 Close wind

If the adjacent coil of yarn lies adjacent to the preceding one, then the package is said to have a close wind. This will occur when wind per double traverse happens to be a whole number, plus or minus a small quantity called gain.

2.4.9 Patterning (ribboning)

This is a sort of defect which occurs during winding on a random winding machine when the wind per double traverse becomes exactly an integer. Some coils of yarns tend to superimpose on each other thereby creating a sort of short band or a ribbon. If a package with such a defect is used in subsequent processes such as knitting, warping or weaving, they adversely affect the unwinding properties of the yarn. During unwinding of the yarn at high speed, the coils of yarn from the ribbon tend to slough off in a bunch and cause a machine stoppage.

Almost all random winding machines are equipped with antipatterning devices of one form or another. The method most commonly employed is that of periodically varying the speed of the driving motors through a control switch which interrupts and restores the current at suitable intervals. The variation in speed of the driving rolls which this action brings about breaks up the synchronism between the rolls and the cones due to the time lag which occurs before the cones respond to the changed speed of the driving rolls [11].

2.5 Cone types and build

Cones produced by modern high-speed winding machines differ in build and taper according to the type of material and the purpose for which they are used. There are generally three main types [11]:

- cones produced with a close wind on spindle machines with individual cam and reciprocating traverse
- cones with convex base and increasing taper
- cones with little taper, built up with a uniform or slightly accelerated traverse.

The last two types are of open wind and are produced on machines of the drum or driving roll type.

In order to facilitate the overend withdrawal of fine and delicate yarns used, for example, in hosiery, cones of about $9^{\circ} 15'$ taper, built up with a convex base and increasing taper, are used. For warping, cones of smaller taper around 5° , which contain a greater length of material, are generally used. They are built with a uniform

traverse and there is a tendency for the degree of taper to decrease as they increase in size. There is evidence that cones with an accelerated taper of $4^{\circ}20'/9^{\circ}15'$ give good results when used on shuttleless weaving machines [14].

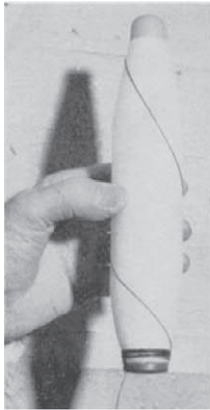
2.6 Manual, semiautomatic, and fully automatic winding machines

During the ring spinning process, when the ring bobbins have reached their full size on the spinning frame, they are ready to be taken out from the ring spindles. The process is called doffing of the packages and involves running the ring rail down and then running on some wraps of yarn around the base of the bobbins so as to be sure that the end will not be broken in removing the full bobbin from the spindle. During this process, the yarn wraps around the bobbin as shown in the Fig. 2.13A. This is referred to as back wind. However, all these extra wraps of yarn must be removed by the winder before this is put on the supply spindle of the winding machine. When hundreds of bobbins are handled by the operator during the working shift, much of his/her time is wasted in removing the back wind, thereby affecting productivity significantly. The choice of buying a manual winding machine, or using a semiautomatic or fully automatic winding machine to replace some or all of these tasks, depends on the type of activities the particular company is engaged in, i.e. in the production of coarse, medium or fine fabrics, etc. and other requirements.

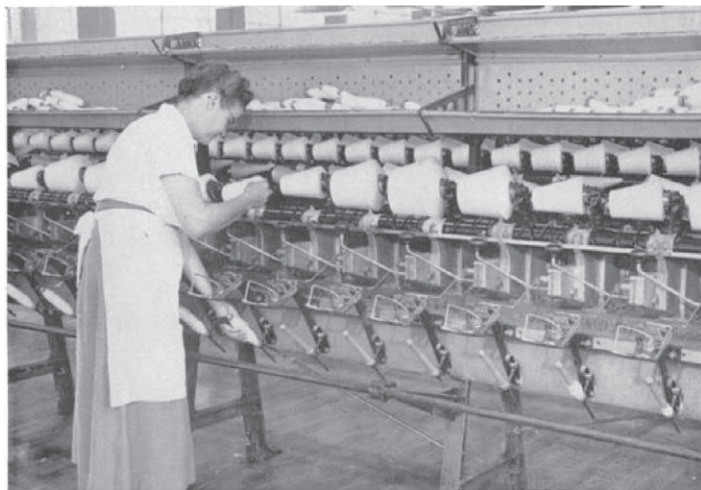
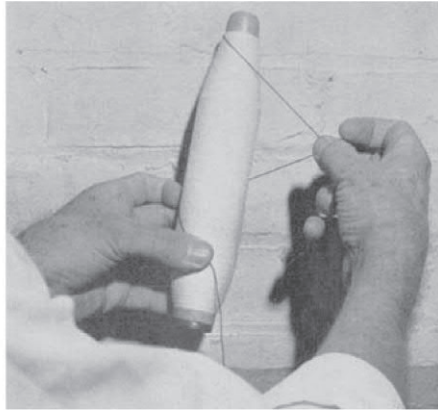
2.6.1 Manual winding machines

One of the greatest disadvantages of a manual winding machine is the number of operations which have to be performed by a winder by hand per day. This depends on factors such as yarn quality, size of the supply package, winding speed, etc., which determine the workload, i.e. number of spindles that can be allotted to a winder. On a manual winding machine, almost all the operations are carried out by the operator. These include [5]:

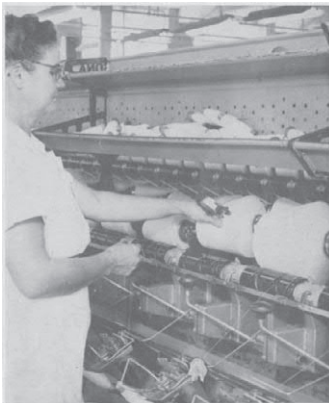
- removal of the backwind from the spinning package (Fig. 2.13A)
- positioning of the package on the spindle and passing of the yarn through the tension device and slub catcher which eliminate thin and thick places from the yarn (Fig. 2.13B)
- positioning of the yarn on the cone to commence winding (Fig. 2.13C)
- when a yarn breaks as a result of the removal of the thick or thin place, or when the supply package runs out, taking the yarn from the running supply package, passing it through the tension device and slub catcher, locating the free end of yarn from the cone and knotting it with the end of yarn from the supply package to commence winding (Fig. 2.13C)
- when the cone or cheese package becomes full size, removing it from the cone or cheese holder, taking a new empty cone or cheese package and starting the whole process of guiding the yarn from the supply package onto the cone/cheese (Fig. 2.13D)
- cleaning the machine.



(A)



(B)



(C)



(D)

Fig. 2.13 (A) removal of back wind (wraps of yarn have been unwound from the base of the bobbin on the left), (B) operator feeding the spindle with new package after removal of the back wind, (C) operator trying to join the end from the cone with the end from the package and (D) operator doffing.

2.6.2 *Semiautomatic winding machines*

On these machines, some of the above operations are carried out automatically and some manually. The automatic operations might include:

- feeding of the supply package onto the winding spindle
- automatic knotting of the yarn from the supply package with the yarn from the cone in case of the yarn breaking as a result of removal of thick or thin places
- automatic knotting when the supply package runs out and a new end from the supply package is tied to the end from the cone
- doffing of the cone, i.e. removal of the cone when it becomes full.

2.6.3 *Fully automatic winding machines*

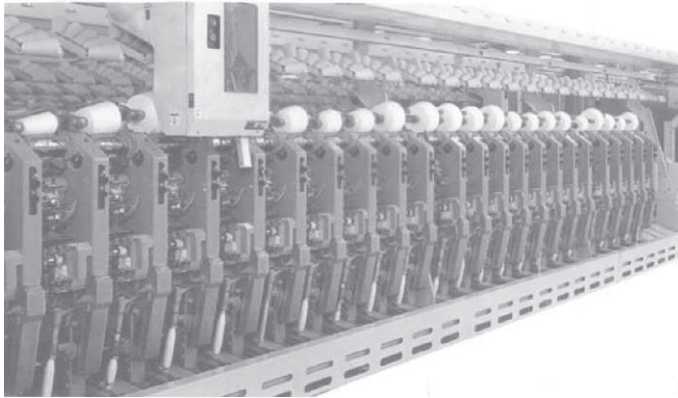
On a fully automatic winding machine all of the following functions are performed automatically:

- removal of the backwind from the spinner's package
- feeding of the supply package to its appropriate spindle
- joining of the two ends, i.e. from the package and the cone or cheese either by putting a knot or a splice when a defect is removed or when the supply package finishes
- doffing, i.e. replacing the full cone (when it has reached its desired diameter) with an empty cone to commence winding.

Fig. 2.14A shows a Murata fully automatic winding machine equipped to carry out all of the above actions. The automatic doffer as shown in the figure keeps on patrolling the spindles and doffs the cone when required [15]. On modern winding machines, yarn speeds are adjustable from 300 to 2000 m/min, depending on yarn type, bobbin build, and machine specification. Fig. 2.14B shows a typical automatic backwind removal unit equipped on a fully automatic winding machine. Spinner's packages are dumped into the unit and, after removal of the backwind, the mechanism automatically feeds the packages onto the spindles.

2.7 Hazards from knots during weaving and knitting processes

During the winding process, each time a defect such as a thin, thick place or a slub is removed, or when the spinner's supply package is finished and replaced with a new one, the yarn end from the cone and the supply package is commonly joined either by a fisherman's knot or a weaver's knot, depending on the circumstances. The fisherman's knot is considered to be more reliable and acceptable in most cases other than for coarse yarns used on fine gauze applications. Its knot diameter is three to four times that of the yarn. The weaver's knot, on the other hand, is considered less stable but has the advantage of a diameter of two to three times the yarn diameter and is thinner than the fisherman's knot. This makes it easier to process subsequently through confined spaces. If not knotted properly, knots do tend to untie during the weaving



(A)



(B)

Fig. 2.14 (A) Murata fully automatic winding machine with automatic doffer patrolling the spindles and (B) automatic back wind removal unit equipped on a fully automatic winding machine.

process. Technically speaking, a knot itself can be considered a defect and hazard in subsequent processing of the yarn during knitting or weaving. The only point in its defence is that a knot is much smaller in diameter and length than many of the yarn defects which can extend to over a centimetre in length as well as having a larger diameter.

2.7.1 Frequency and behaviour of knots during weaving

The frequency of knots introduced during winding usually depends on the yarn count, weight of yarn on the spinner's package, and the degree of the clearing. It is estimated that on average about 15–35 knots/kg of the yarn are introduced during winding. When transferred to weaving, this represents 10–20 knots/m of warp. It is believed that while weaving cotton warp yarns, knots cause about 20%–50% of all the warp breaks which include:

- knot slippage
- jamming of knots between reed wire
- entanglement with other warp threads.

With woollen warps, it is believed that up to 40% of all breaks are attributed to knots.

2.7.2 Behaviour of knots during knitting

During knitting, knots either catch in the knitting elements or jam between knitting elements as well as causing temporary interruption of yarn feed thus breaking the yarn, and sometimes even knitting needles. Assuming a knitting machine with 24 feeders each using a weighing 2 kg, of 50 metric count, which normally might contain between 40 and 50 knots, the total number of knots will be 960–1200. If the yarn usage per loop was 0.2789 cm, with 1800 needles and machine speed of 654 rpm, it is anticipated that a knot will run through the needles of the knitting machine every 19 s with the probability of a defect being caused by the knot. During finishing, knots cause holes if the fabric is to be sheared. Fig. 2.15 shows the appearance of knotted and spliced yarns of the same quality and their effect when knitted or woven into the fabric.

2.8 Yarn splicing for knot-free yarns

In order to get rid of the problems caused by knots, practically all modern winding machines are equipped with a splicing technique which joins the two ends of yarn without knotting. Fig. 2.16 shows the different techniques of splicing the yarns [16–18].

2.8.1 Pneumatic splicing

In this method, the two ends from the supply package and the cone to be spliced are inserted into a chamber and then overlapped to join them together by means of a strong current of compressed air. The splicing time and air pressure are determined according to fibre type and yarn characteristics. The splicing operation consists of the vertical application of air to the fibres and simultaneous rotational movement of the air to twist/untwist the yarn.

Pneumatic splicing can be applied to a wide range of fibre and yarn types without precise adjustments or settings, thus facilitating efficient winding.

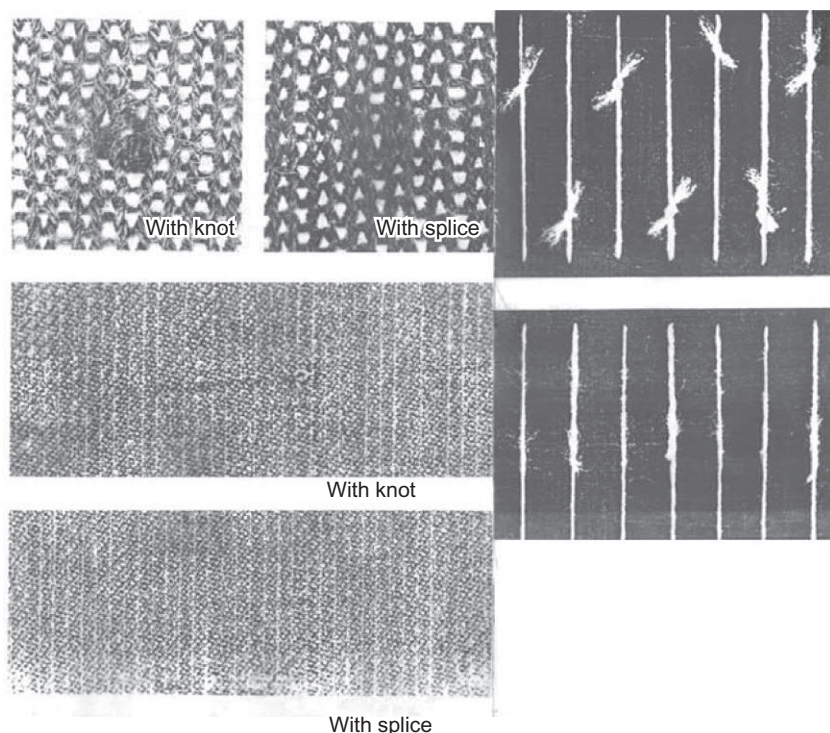


Fig. 2.15 Knotted and spliced yarns when woven and knitted into a fabric.

2.8.2 Mechanical splicing

In this process, the yarn ends are untwisted to open the fibres. The two ends are overlapped and then twisted together again to essentially the same twist level as in the basic yarn. The technique is ideal for short staple fibres. For long staple yarns, it is somewhat difficult to separate fibres at the yarn ends, which has a negative effect on the binding of fibres. Different twisting wheels are required for opening and twisting of yarns of different twist levels and made from different staple length fibres. It is also not possible to splice plied yarns as opening by untwisting is not possible.

2.8.3 Electrostatic splicing

In this method of splicing the yarn, ends are separated and untwisted in the opening zone. The opened yarn ends are then spread out evenly in an electrostatic field, after which they are intermingled and bound again by a pole change, while the twist is simultaneously inserted corresponding to the twist in the basic yarn. The method has some limitations. For yarn containing a large number of fibres in the cross section,

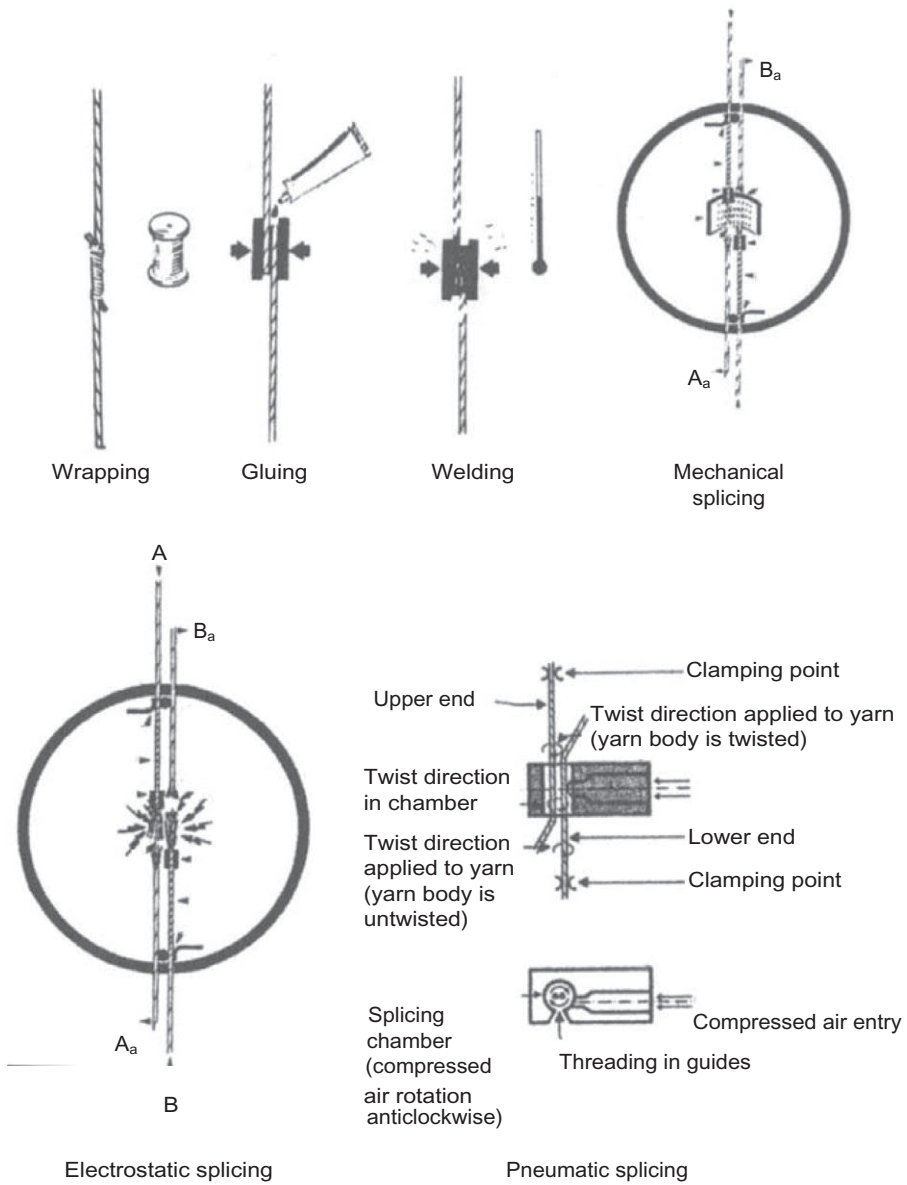


Fig. 2.16 Different splicing techniques.

the intermingling of fibres at the yarn ends is a problem as fibres obstruct one another. Secondly, plied yarns cannot be spliced due to difficulty in opening fibres at the yarn ends by mechanically untwisting. Thirdly, the time taken for splicing is quite long, thus decreasing winding machine efficiency.

2.8.4 Gluing

In this technique, yarns are overlapped and glued together. The process takes a long time and produces a rigid joint.

2.8.5 Welding

In this process, the two ends are welded together by heat and are suitable for polyamide yarns.

2.8.6 Wrapping

The two ends of the yarn are overlapped and an auxiliary thread is wrapped around them. This process is normally suitable for joining carpet yarns used on tufting machines. It takes more time and produces a bit thicker, more rigid joint that is stronger than a knot.

2.9 Applications of splicing techniques

Splicing can be applied to a variety of yarns such as:

- long and short staple yarns (wool, cotton, synthetics)
- plied yarns of cotton, wool, synthetics, and blends
- siro spun yarns
- woollen spun yarns
- core yarns
- open-end yarns.

It has been conclusively proved that spliced yarns play a significant role in reducing the cost of production and the number of fabric defects caused as a result of yarn breakages during the weaving and knitting process. Knot-free yarns have also helped to reduce the processing costs during warping and sizing processes.

2.10 Developments in the yarn preparatory processes

Over the years, in the preparatory processes winding, warping, and sizing there have been some revolutionary developments in the design of their machines leading to improve the:

- ergonomic standards of the machines,
- increased flexibility and productivity,
- automation to reduce man power requirement,
- noise levels,
- energy consumption,
- waste reduction and
- make machines more user friendly.

The overall aim has been to provide the best price-performance ratio to the user. As the years have gone by the levels of revolutionary developments in the preparatory machines have reached almost to their saturation limit. However, the machinery manufacturers still do their best to incorporate incremental developments in one form or the other in their respective machines.

An account of the incremental developments incorporated by the manufacturers of different preparatory machines used in the winding, warping, and sizing processes is presented in this and the following chapters on warping and sizing. The author has been a regular visitor to ITMA exhibition since 1979 and the information presented in the chapters is based as witnessed and collected in different forms from ITMA 2015.

2.10.1 Automatic winder *PROCESS CONER II QPRO*

Murata Machinery, Ltd. from Japan exhibited their latest Automatic Winder *PROCESS CONER II QPRO* Plus incorporating some incremental developments, all leading to High quality, High productivity, Energy reduction, and Easy operation and maintenance (Fig. 2.17A and B) [19].

2.10.2 Stable winding at high speed

- The winder realizes stable winding from start to end of the winding process by giving instantaneous feedback of yarn tension from the bottom to package by PC Module.
- The unit activates the bobbin automatic centring function which allows for the yarn unwinding at higher speeds to offer 15% more production in total.
- The drum motor, splicer, and suction mouth are independently driven to optimize the splicing cycle.
- The 'system of Tension feedback' from the PC Sensor to PC Tensor, enables a very precise control over the unstable yarn tension at the start and end of the winding process
- Feedback is performed so that a uniform tension for the winding by any bobbin can be maintained. Regardless of the shape of a bobbin, high-quality winding is realized.

2.10.3 *PC Bal-Con*

The winding unit is equipped with a unique device called *PC Bal-Con* (Fig. 2.18A and B) [19] which moves along the bobbin, creating a ballooning in order to maintain a uniform winding tension from start to end of the winding process. Whenever changing the bobbin size, the height of the *Bal-Con* can be adjusted without using any tools. Along with *Auto Bobbin Centring Function*, this contributes improvements in productivity. The unit provides the following advantages:

- High-speed winding
- High productivity
- Sloughing suppression
- Hairiness reduction
- Reduced hairiness generation
- Reduced nep generation.

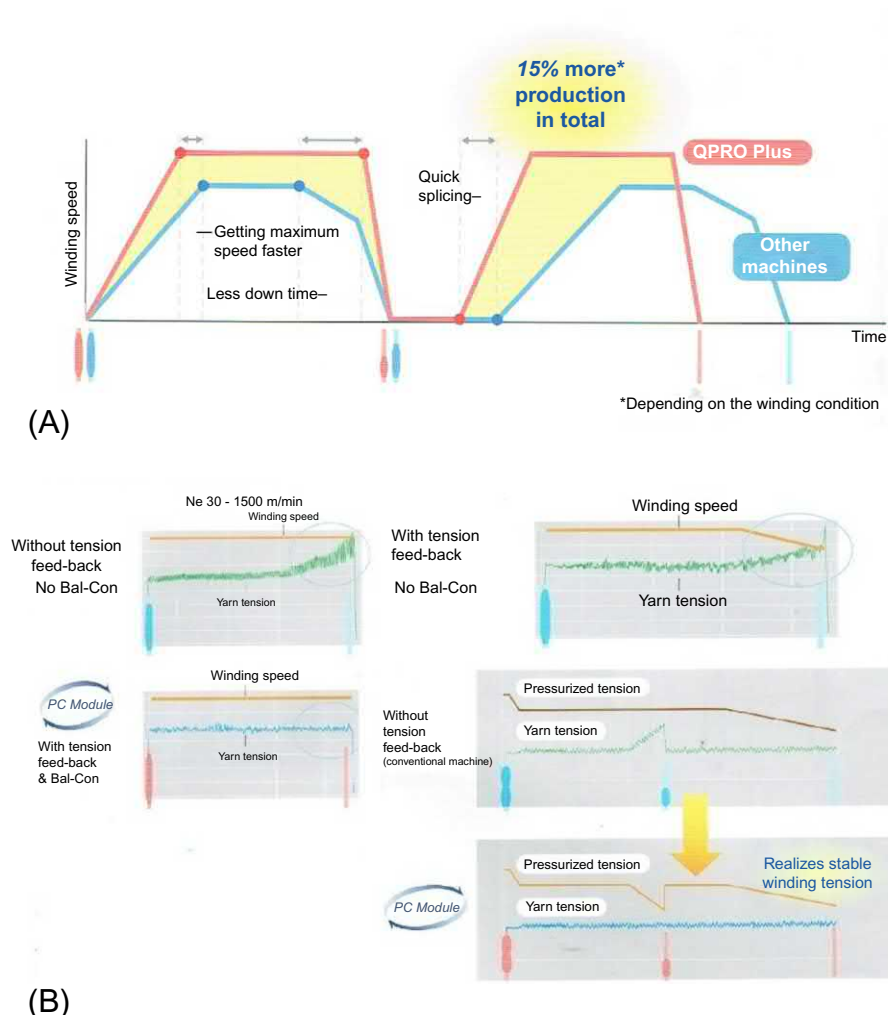


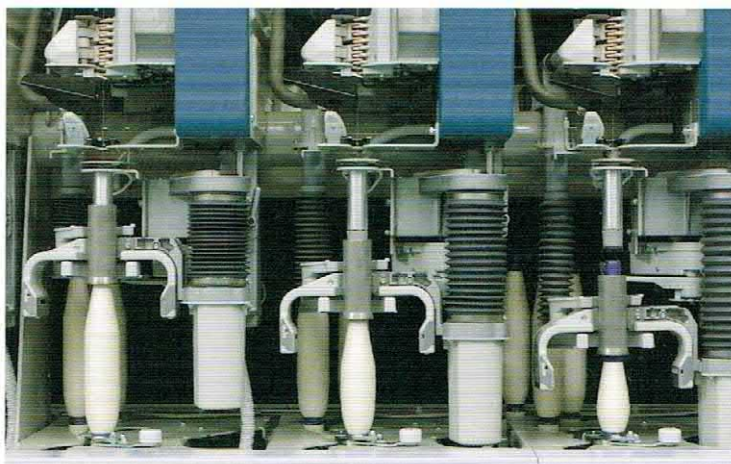
Fig. 2.17 (A) Even and stable winding. (B) Uniform tension for winding.

2.10.4 Slough suppression

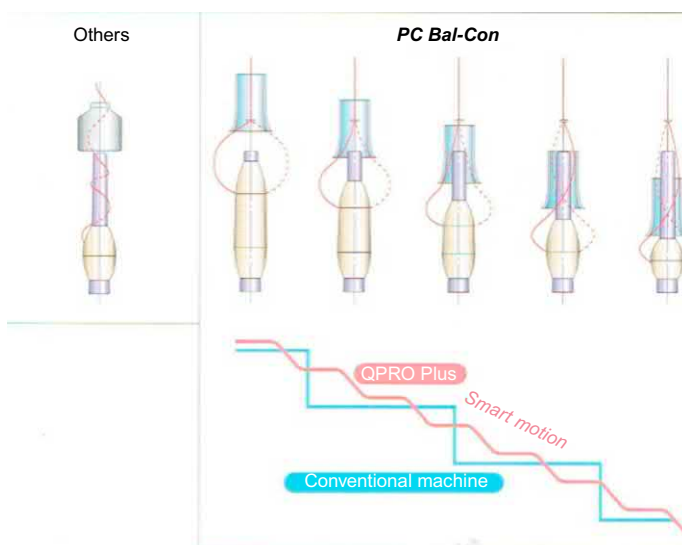
When unwinding the supply bobbin, the Bal-Con minimizes the contact between the yarn being unwound and the yarn layer on the bobbin. This results in a remarkable suppression during high-speed winding of undesirable tension in the package (Fig. 2.19) [19].

2.10.5 Auto bobbin – Centring function, less hairiness

The bobbin is continuously held in the ideal position by the sensor sensing the bobbin position. The bobbin can be maintained at the centre of the Bal-Con by the sensor (Fig. 2.20) [19].



(A)



(B)

Fig. 2.18 (A) PC Bal-Con. (b) QPRO Plus and conventional machine.

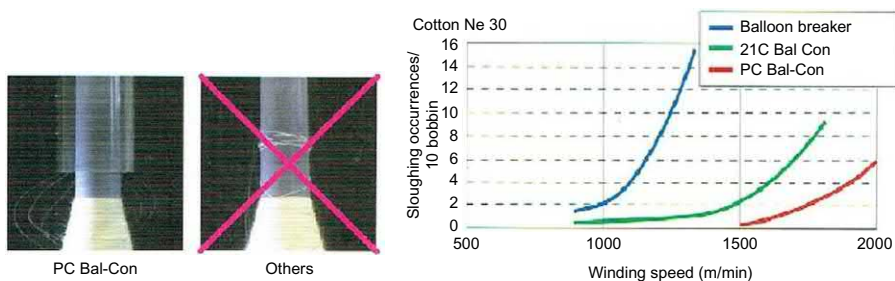


Fig. 2.19 Slough suppression during winding.



Fig. 2.20 Auto Bobbin Centring Function.

2.10.6 Less hairiness

The chase surface does not generate hairiness as a result of noncontact with the unwound yarn, and hairiness is reduced in all sections, from the top to the bottom of the bobbin (Fig. 2.21) [19].

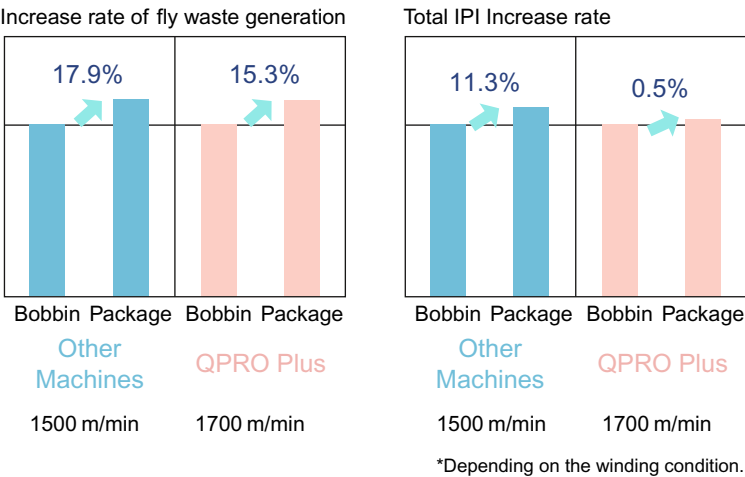


Fig. 2.21 Comparison of QPRO Plus winder with other machines-less hairiness.

2.10.7 Clear package – PC module

PC Sensor continuously monitors yarn tension and sends feed back to PC Tensor and PC Bal-Con. Their combination realizes stable winding tension. Package density is made uniform (Fig. 2.22) [19].

2.10.8 PLC 21 – The Perfect Length counter (optional) and kink preventing system – Hard waste reducer

The Perfect Length counter is a noncontact photoelectric type and precisely detects the length of yarn to be wound without making contact with yarn. Based on the detected data, the VOS (Visual On demand System) controls the winding length of a package to rewind at a uniform speed so that a precise fixed length winding ($\pm 0.3\%$) can be realized (Fig. 2.23) [19].

Accuracy holds the bobbin end at the optimum timing in order to minimize waste yarn, prevents kink generated when the yarn is spliced, and as a yarn waste reduction device, prevents yarn on the bobbin side from being sucked in the joint pipe more than necessary.

Conventional machine

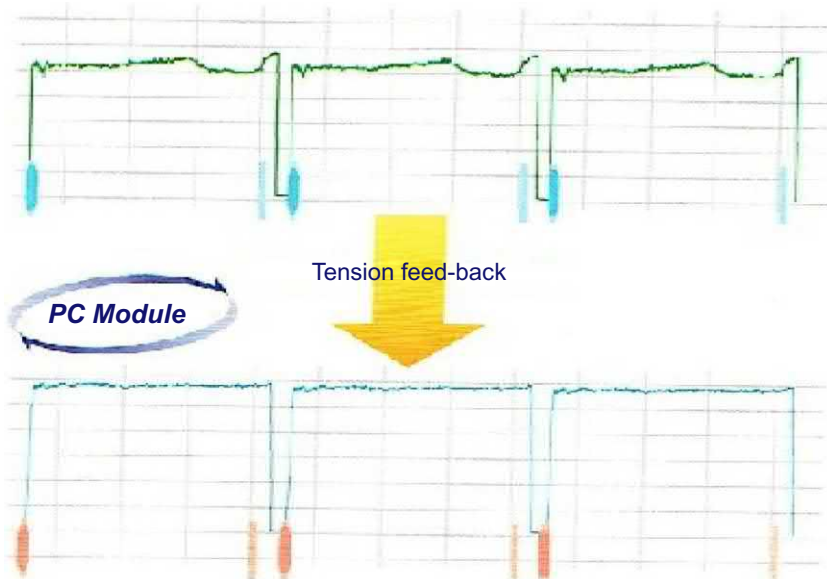


Fig. 2.22 Monitoring of the yarn tension by PC Sensor.

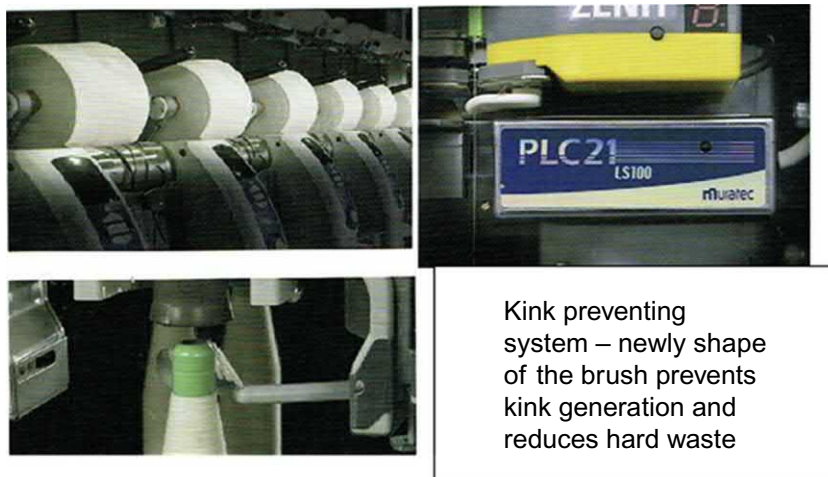


Fig. 2.23 Length counter and kink preventer.

2.10.9 Power saving design

The machine-based design minimizes pressure loss of the blower and in addition, each device of the unit is modularized and independently driven to suppress electrical power consumption thus offering outstanding energy saving performance with high-speed operation (Fig. 2.24) [19].

2.10.10 Smart guide panel

The smart guide panel build in each unit is an LED display and remarkably improves visibility, this lights blue to indicate a full bobbin. When the LED lights to red, it indicates a maintenance call and informs of the trouble spots (upper, middle, and lower sections) in the machine base (Fig. 2.25) [19].

2.10.11 Automatic doffer – AD

The automatic doffer achieves a top travelling speed 52 m/min. The packages doffed in a 10-s cycle are automatically loaded into either the conveyor or the shelf installed at the rear of the machine (Fig. 2.26) [19].

2.10.12 Waxing device

Stable and uniform waxing is made possible by a rotary-driven positive motor (Fig. 2.27) [19]. When wax is not being applied, the motor stops and saves energy. It is available for both S twist and Z twist directions.

Can use wax with max. 45 mm in length up to 3 mm in thickness, and is equipped with a wax remaining alarm.

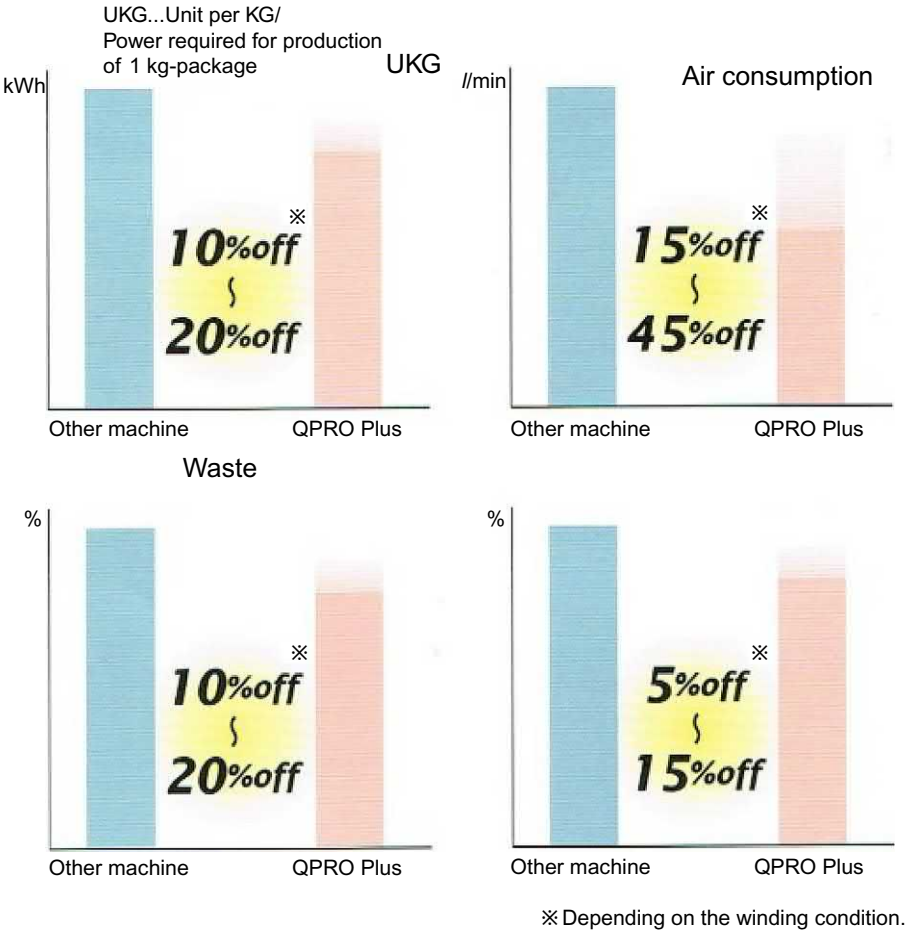


Fig. 2.24 Power and waste saving on QPRO Plus and other winding machines.

2.10.13 Splicer

The winding machine can be equipped with air splicer or water splicer or hot splicer or with a three-tier nozzle type of splicer as per the customer’s requirements (Fig. 2.28) [19].

2.10.14 Multigrooved drum

Muratec’s multigrooved drum has a control system that switches the drum groove to the diameter at which patterning (ribboning) occurs and produce the quality package to facilitates the unwinding (Fig. 2.29) [19].

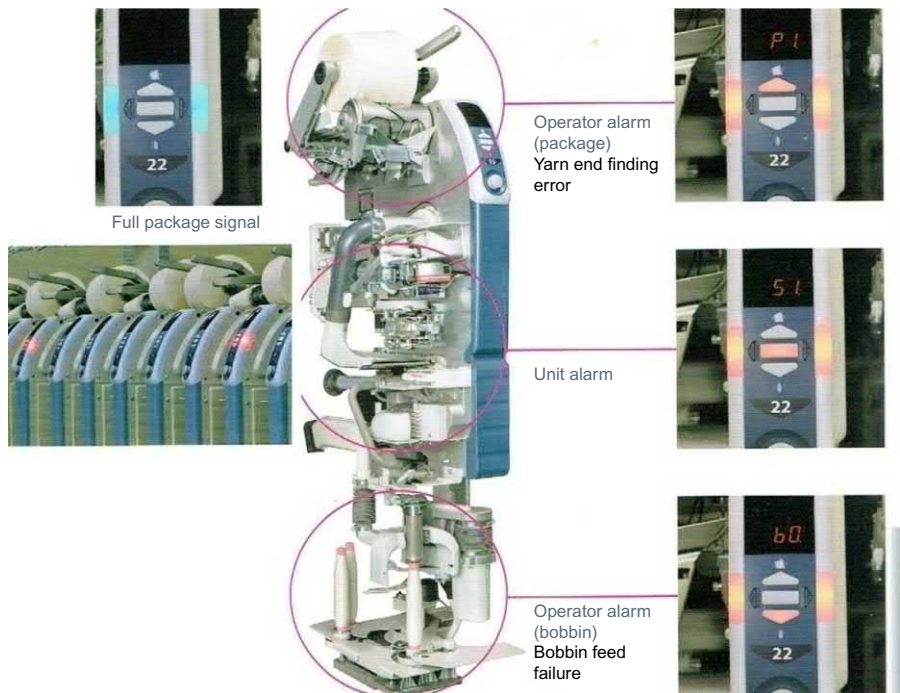
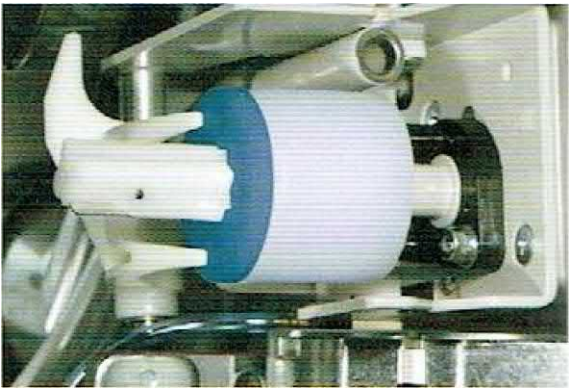


Fig. 2.25 The smart guide panel for improving the visibility.



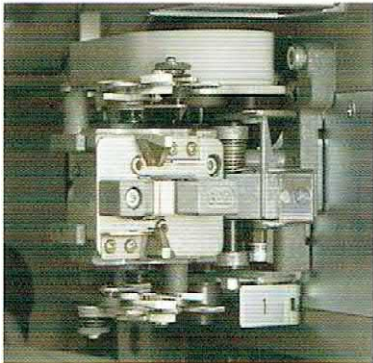
Fig. 2.26 Automatic doffer with a speed of 52 m/min.

Fig. 2.27 Stable and uniform waxing.

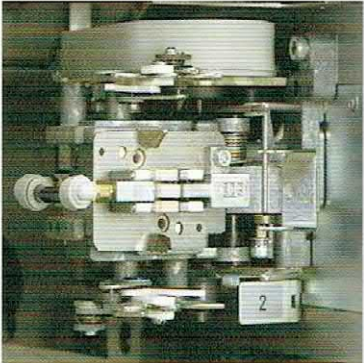


Air Splicer

Core spandex yarn type (optional)

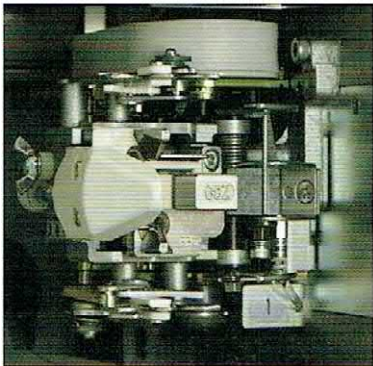


Three-tier nozzle type (optional)



Water Splicer

(optional)



Hot Splicer

(optional)

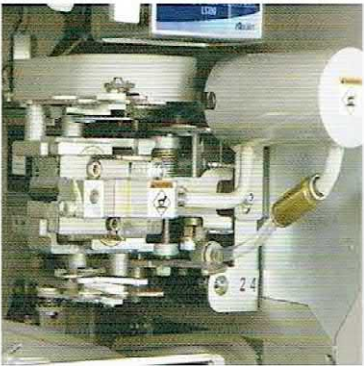


Fig. 2.28 Air, water, and hot splicer.

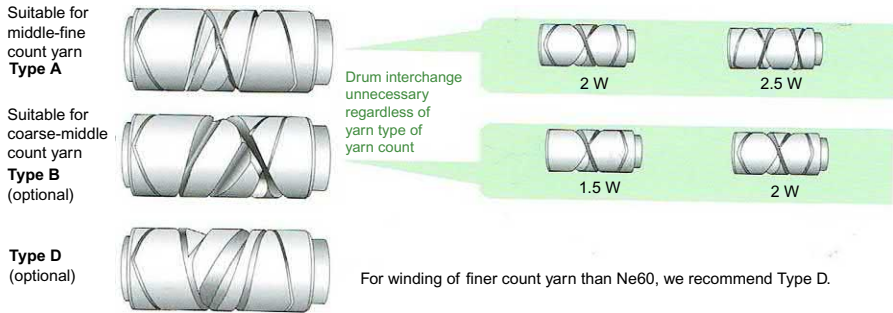


Fig. 2.29 Different types of multigrooved drums with changing drum grooves diameter.

2.11 Saurer Schlafhorst – Autoconer 6

SAURER Schlafhorst presented at ITMA 2015 their new Autoconer 6 [20] E³ – Energy, Economics, Ergonomics – offering triple added value comprising energy saving, highest kg/m² output and biggest staff savings. The Autoconer 6 offers the following interesting new incremental developments incorporated in the newly designed winder.

2.11.1 New eco-drum-drive system

With the provision of the latest drive and bearing technology, the new eco-drum-drive system saves a huge amount of energy costs. The unproductive downtime drops to zero thus offering massive productivity gains.

2.11.2 MultiJet: Reduction in compressed air consumption with new MultiJet

With this system, it is possible to set the frequency of the ‘puff’ pulses for cleaning the winding unit to match the demand. The consumption is controlled centrally at the informant which results in conserving valuable compressed air (Fig. 2.30) [20].

2.11.3 Yarn pick-up, new suction tube: Flow-optimized to conserve yarn

The new suction tube with its aerodynamic internal and external design offers convincing, highly efficient air guidance. This guarantees the utmost reliability in the upper yarn pick-up offering reduced energy and waste costs. Fig. 2.31 [20] shows the reduction in energy consumption due to vacuum reduction with secure yarn end pick-up.

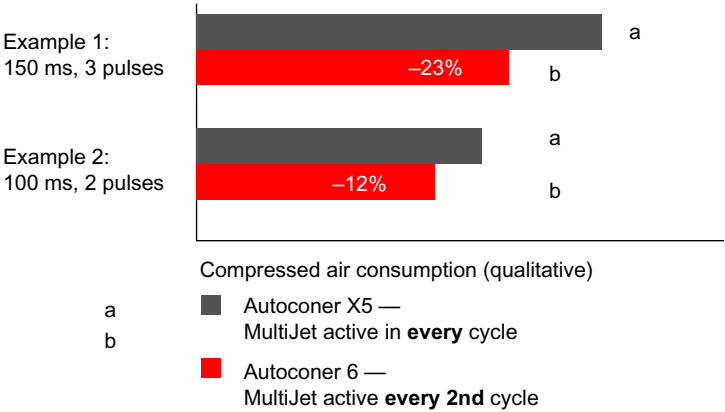


Fig. 2.30 Comparison between Autoconer 6 and Autoconer X5 in energy consumption with the new MultiJet system.

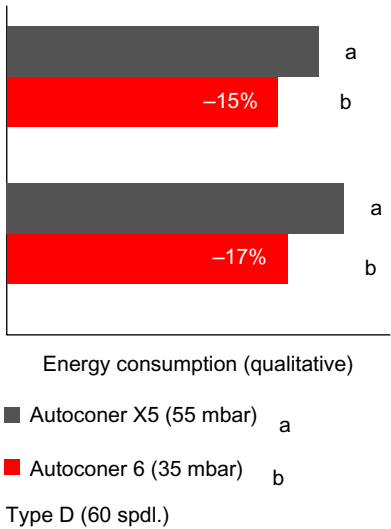


Fig. 2.31 Energy consumption on Autoconer 6 and Autoconer X5.

2.11.4 Maximum productive capacity

Autoconer 6 offers 6% more productivity right from the start as a result of Short cycle times, top acceleration, short braking, high-speed winding process as well as more kg/m² (Fig. 2.32) [20]. With the Eco-Drum-Drive-System tuned to maximum capacity, the unproductive downtime drops to zero and energy costs are reduced significantly.

2.11.5 New yarn tension control

For regulating the yarn tension an innovative tension control is provided (Fig. 2.33) [20]. A sensor at a reference winding unit determines the typical tension progression and the yarn tension curve. This information is transmitted to the other winding units

Higher productivity (m²)

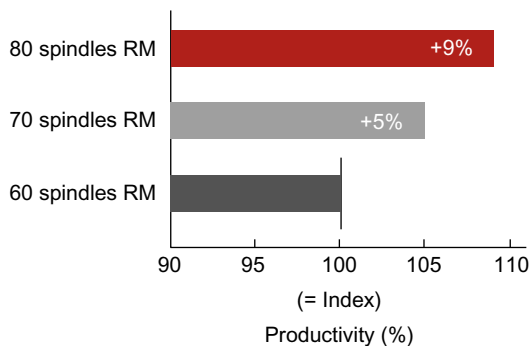


Fig. 2.32 Short cycle time effect on the increase in productivity.

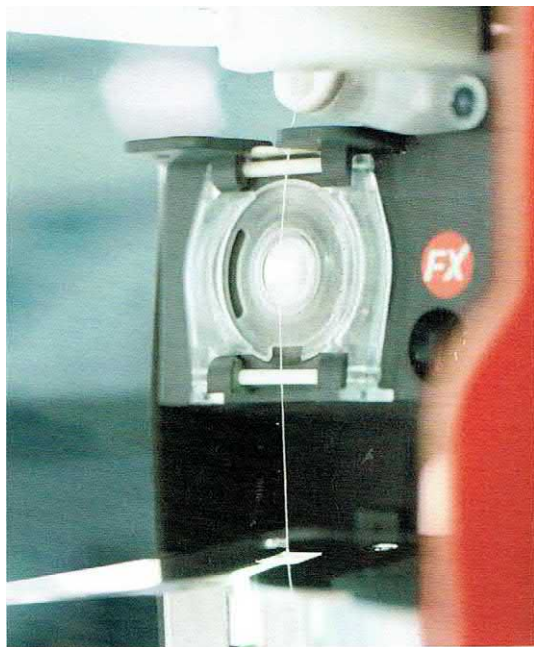


Fig. 2.33 New yarn tension control for regulating yarn tension.

via the informator to influence the yarn tension. The electronic yarn tension control produces a package with much more homogeneous package density compared with a winder without a yarn tension control system.

2.11.6 Balloon control with Speedster FX

Yarn balloon during unwinding of the yarn from beginning to the end of the package is controlled by the provision of smartest winding turbo – Speedster FX which ultimately facilitate minimum yarn tension stress at maximum winding speed throughout bobbin



Fig. 2.34 Control of the balloon with Speedster FX.

unwinding (Fig. 2.34) [20]. This ultimately results in fewer tension breaks, less negative centrifugal force and up to 6% more productivity.

2.11.7 Package doffing – X-Change

An intelligent high-tempo package doffing unit X-Change doffs all common package and tube formats within a very short time, with intelligent advance request mode with a high travel speed of 43 m/min and 10-s doffing time thus providing maximum doffer capacity with minimal manual effort (Fig. 2.35A and B) [20].

If the tube magazine of a winding unit is empty, X-Change automatically fetches an empty tube of the same format from a neighbouring magazine and starts package doffing straight away resulting into cutting of waiting time and speed up production.

2.12 SAVIO automatic winder Eco PulsarS

Savio Macchini Tessile S.P.A. from Italy exhibited their latest winding machine Eco PulsarS (Fig. 2.36) [21] with some very interesting incremental developments purposing a revolutionary concept of the winding process, offering energy saving up to 30%, including room air conditioning, together with improved production performances, high-quality packages, utmost flexibility, and enhanced productivity up to 10%.

The combination of the new features and design of the EcoPulsarS has created an environment in which each part of the winding machine can operate at its optimum

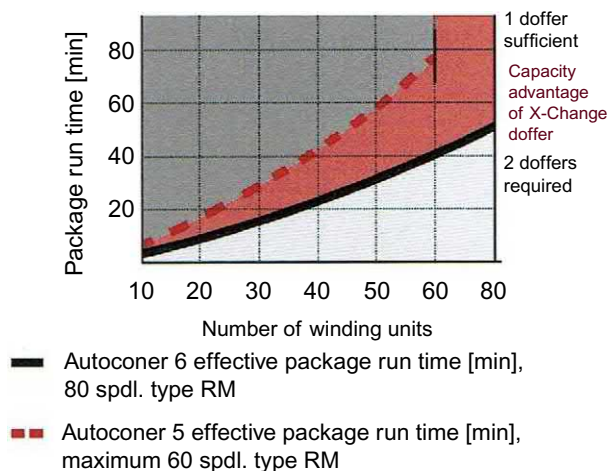


Fig. 2.35 (A) Effective package run time on Autoconer 6 and Autoconer 5. (B) X-Change doffer.

(A)



(B)

level and without limitations. Spindles and bobbin feeding systems set independently the level of suction required. Suction is generated as needed and used without losses. The winder is designed to handle natural, synthetic, and blended staple yarns ranging in count from 286 to 4 tex (Ne 2–147).

The newly developed Controlled Cut System, Yarn Tension Control System, Waste Collection and Separation System, and Upgrading Splicing solutions, each contribute to the overall reduction of the process downtime. The automatic winder Eco PulsarS offers some of the following novel developments in its design.



Fig. 2.36 Savio automatic winder Eco PulsarS.

2.12.1 Controlled Cut System

The electronic clearer intervention represents a critical factor for the full control of the 'cut yarn end'. The high-speed winding process, lively and/or elastomeric core yarns, can create a 'spring-like-rebound' of the yarn end; yarn might be trapped on package flanks and adaptors. In this case, the splicer cycle becomes uncertain and with low efficiency rate, because of the difficulty to retrieve the end.

The 'Controlled Cut System' (CCS) with its yarn cut function, separated from the electronic yarn clearer detection, has an independent smart cutter, which works in synchronism with the winding process. In this way, the cut is controlled, being done only when the yarns is perfectly aligned with the middle drum traverse stroke. This assures that the yarn end can be easily found and retrieved during the subsequent splicing

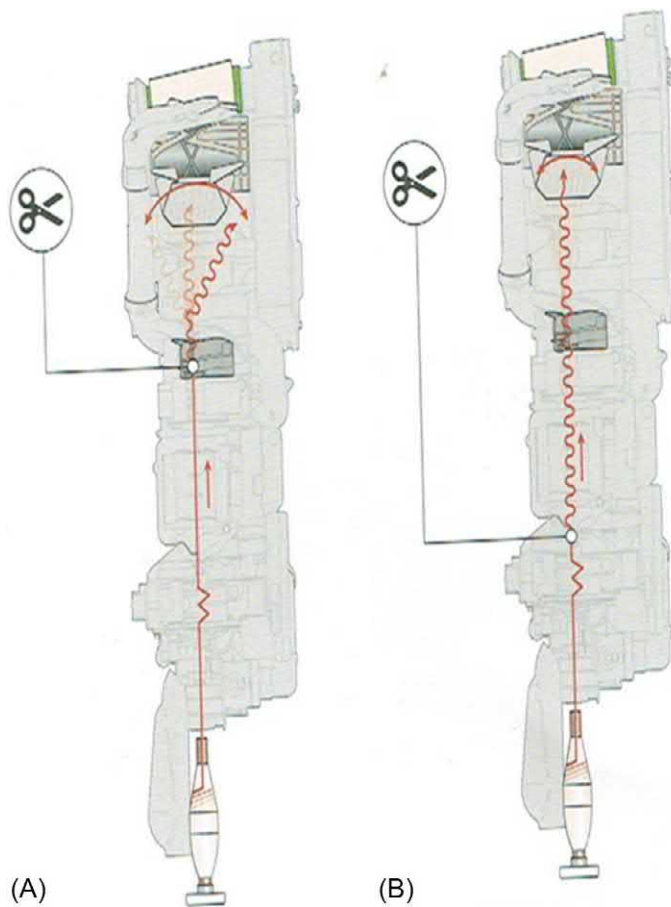


Fig. 2.37 (A) Yarn cut function along with clearing and (B) separated from clearing.

cycle, with minimum suction, avoiding unnecessary repeating cycles that might damage the package quality.

Fig. 2.37A and B [21] shows the yarn cut function along with clearing and separated from clearing respectively. The provision of CSS guarantees that the hard waste generation is reduced, the cycle efficiency is increased, and the operator intervention minimized.

2.12.2 New tensioning system

Yarn tension (Fig. 2.38) [21] is controlled by a variable interference system, which works in synergy with the tension sensor. A precise set motor adjusts the interference in order to maintain the set tension. The system ensures total control of the yarn in all conditions, even in the case of slub or core/elastomeric yarns. A combination of fixed

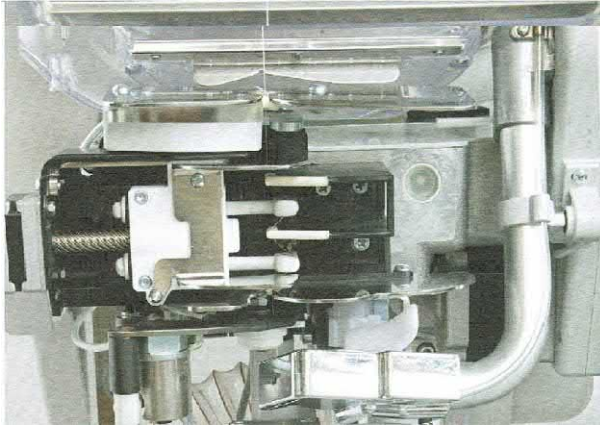
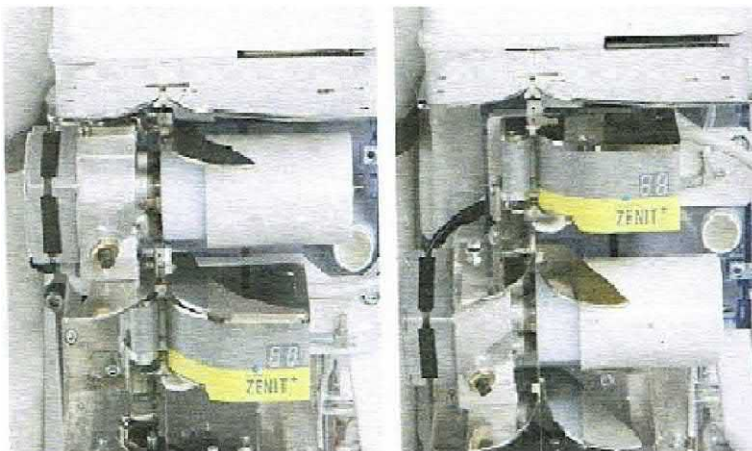


Fig. 2.38 The new yarn tensioning system.

and moveable ceramic fingers traps stabilizes the yarn allowing higher winding speeds. The friction points have been reduced in order to preserve the overall quality of yarn.

2.12.2.1 *Waxing*

A dedicated step motor on the PulsarS new winding system allows a very fine wax uniformity on the yarn. It is possible to optimize the waxing, as both sense of rotation and speed are settable. It is also possible to select the position of the waxing device above the clearer or under the clearer as shown in the [Fig. 2.39 \[21\]](#).



Above the clearer

Below the clearer

Fig. 2.39 Waxing unit.

2.12.3 Up graded splicing solutions

Air and Moistair boasts a Duo Air Feeding System, for yarn tail preparation and splicing (Fig. 2.40) [21]. The separation allows the individual setting of the most appropriate value of air pressure and makes these splicers able to easily process any different fibres and blends combination.

2.12.3.1 Air splicer

Settings are completely centralized in the PC and the main application range are Cotton 100% and blends, Cotton compact yarns, Fancy yarns, Core yarns, Synthetic and artificial yarns, Wool 100% and blends, and Silk.

2.12.3.2 Moistair splicer

The innovative air splicer uses a very small quantity of water (spray). It is endowed with a water valve with a dosage setting to moisturize the splice. Settings are completely centralized in the PC with consistent uniformity of splice in each different spindle. Settings are completely centralized in the PC and offer fast and simple change as well as consistent uniformity of splice in each different spindle. The application range includes short and long staple yarns, TENCEL, elastic single and dual core yarns, very fine cotton yarns, coarse and slub yarns.



Fig. 2.40 The innovative air and Moistair splicer.

2.12.4 Suction on Demand System – Energy saving up to 30%

Provision of the ‘individual and independent suction unit per spindle’ represents a real break-through vs the conventional system (Fig. 2.41) [21]. The yarn suction is created and managed individually, only when required by the individual spindle and bobbin feeding system. The self-sufficient units can individually optimize the suction required according to the process, and to the cycle mode and status. Each unit operates at optimum suction values without influencing the rest of the machine.

All of the above improvements in the machine design offer better efficiency, a smooth winding process, an overall superior package, and yarn quality. Since the suction is generated only when needed, up to 30% savings in energy costs are achieved and theoretically, there are no limitations on the number of spindles per each machine.

2.12.5 Suction on Demand System – Smart and flexible cycle

The Suction on Demand System (SDS) gives the possibility of smart cycle settings in terms of suction values and timing relevant to potential different splicers attempts. The cycle time is also adjustable, in accordance with processed yarn type (Fig. 2.42) [21]. The smart flexibility is coupled with the flexibility coming from the individual and independent movements of each cycle devices thus offering the following:

- Greater productivity.
- Consistent package quality.
- Power and compressed air savings because unnecessary splicing cycle are avoided.
- Minimum wear of the parts.
- Minimum yarn waste.

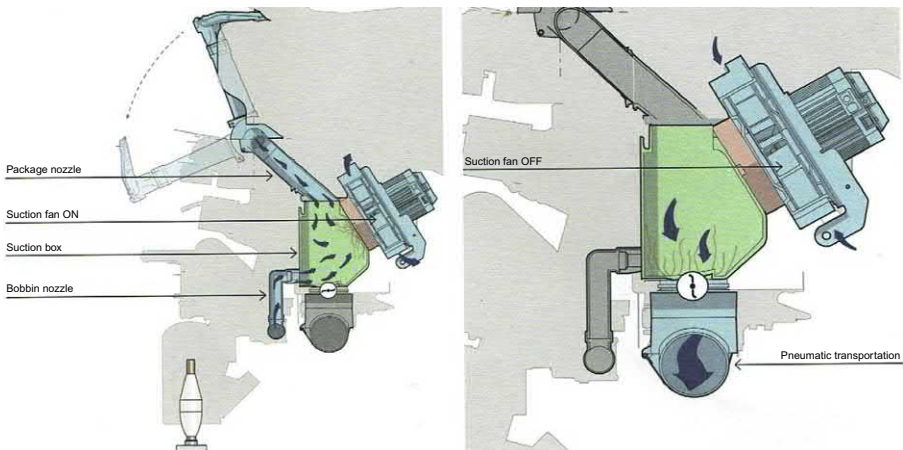


Fig. 2.41 Every single suction fan collects its spindle yarn waste and dust in a dedicated suction box. The individual spindle waste is evacuated when required through a centralized pneumatic transportation, to guarantee the cleaning with the lowest energy consumption.

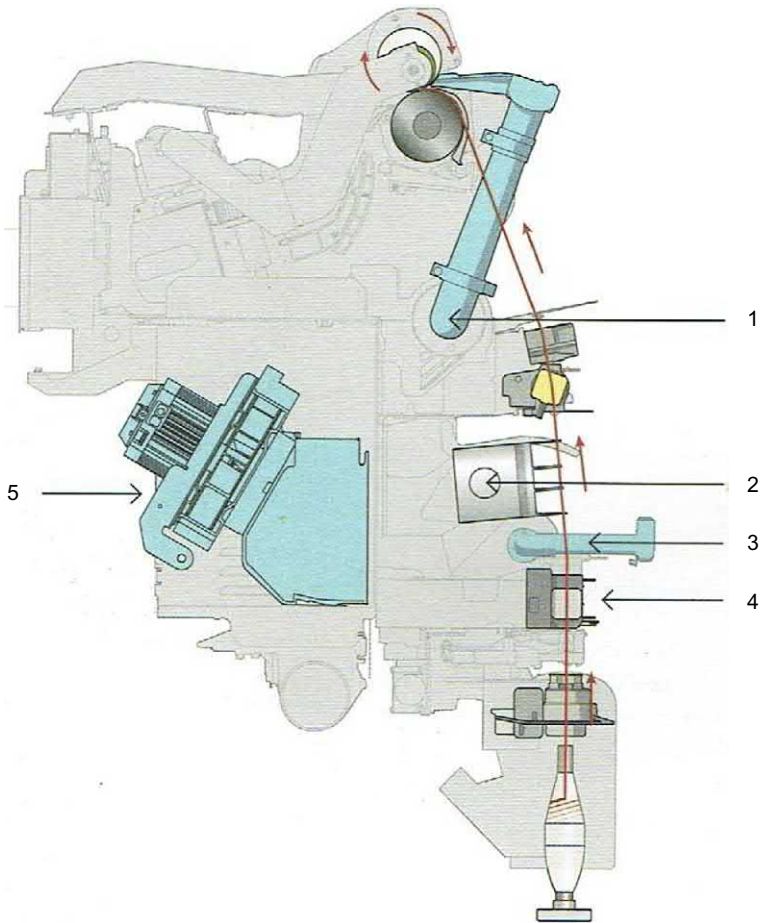


Fig. 2.42 1 – Independent movement of the package yarn suction nozzle, 2 – independent movement of the splicer, 3 – independent movement of the bobbin yarn suction nozzle, 4 – independent movement of the yarn tension device, and 5 – suction fan.

2.12.6 Computer aided tension (CAT)

The winding tension is detected continuously by the Tensor, which interacts with the yarn tensioner device, through the machine PC, in order to adjust the load on the yarn as required. The Tensor, being positioned just before the drum detects on line the real winding tension (Fig. 2.43) [21].

2.12.7 End finder station

Yarn bobbins coming from the ring frame are automatically delivered to the end finder stations located along the machine. Each end finder station has its dedicated suction box. Through PC settings the system allows a dedicated and specific suction tunings

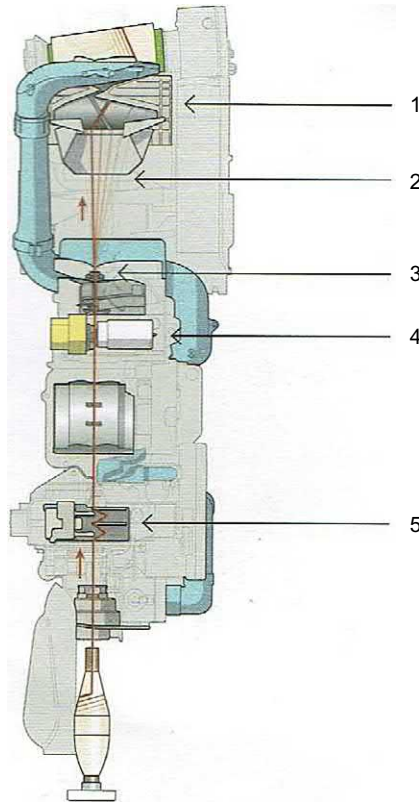


Fig. 2.43 1 – Drum, 2 – traverse, 3 – tension sensor (TENSOR), 4 – waxing device, and 5 – yarn tension.

without any compromise with other services. Each end finder station is positioned along the spindle housing. The machine can be equipped with different numbers of end finder stations depending on capacity for longer ring frames.

2.12.8 Savio identification system (SIS)

It is an identification system of the spinning frame spindle and control of bobbin quality. Each bobbin delivered by the ring frame is numbered and recorded in the PC. The winding head reads the code of the bobbin peg on the process and identifies the position of the spinning spindle which has generated it.

In the presence of 'Off standard' alarms, the winding process is interrupted and the bobbin is rejected and delivered to a dedicated area, allowing the operator intervention for removing it and recognizing the spinning spindle. The smart Backup Station (optional) is able to remove the faulty yarn bobbin.

References

- [1] Joint Stock Company, Textilmach, Russia From Brochure.
- [2] P.R. Lord, M.H. Mohamed, *Weaving: Conversion of Yarn to Fabric*, Merrow Publishing, Watford, 1973.
- [3] Uster Classimat Grading of Yarn Faults.
- [4] Schlafhorst Autoconer Leaflet.
- [5] J.W. Stribling, *Work Load Calculations for Winding Machines*, Universal Winding Company, Leesona Bulletin 139-A, 1952.
- [6] Fadis Textile Machinery, Italy, General Catalogue.
- [7] Oerlikon Schlafhorst, Autoconer 5 Bulletin.
- [8] Savio Macchine Tessili, Automatic Winder Orion E/I, Italy.
- [9] J.E. Booth, *Textile Mathematics*, The Textile Institute, Manchester, 1977.
- [10] GRG Industries Leaflet, www.grgindustries.com.
- [11] G.A. Bennett, *Introduction to Automatic Weaving*, Harlequin Press Co. Ltd, Manchester, 1948.
- [12] Schaerer Precision Winder Leaflet.
- [13] F. Hebbeling, *Text. Res. J. USA* 39 (9) (1969) 799.
- [14] J.B. Aitken, *Automatic Weaving*, Columbine Press, London, 1964.
- [15] Murata Winding Machine, Bulletin.
- [16] J. Lünenschloss, J. Thierhoff, Knottless yarn-joining, *Int. Text. Bull.* 1 (1985) 30–31.
- [17] Schlafhorst-Dokumentation, *The Theory and Practice of Splicing*, vol. 1, S. Schlafhorst & Co, Germany, 1985.
- [18] B.C. Goswami, R.D. Anandjiwala, D.M. Hall, *Textile Sizing*, Marcel Dekker, New York, 2004.
- [19] Muratec, Murata Machinery Ltd, Japan, General Catalogue 21P8T2 15-09-7(NS) – Automatic Winder, Process Coner II QPRO Plus, November 2015.
- [20] Saurer, Schlafhorst – Germany, General Catalogue, Autoconer 6 – The Best Original Ever (149-641-107/Schlafhorst/WIN/15-10/AC6/EN).
- [21] Savio Macchine Tessili S.P.A., Italy, Savio Sustainable Solution, General Catalogue – Eco PulsarS Automatic Winder.

Yarn preparation for weaving:

Warping

3

K.L. Gandhi

The Textile Institute, Manchester, United Kingdom

3.1 Introduction

Warping is the second stage of the processes used after winding. The process involves transferring yarn from a predetermined number of tubes, cones, or cheeses positioned on the creel onto a warper's beam or a weaver's beam. Winding involves either preparing a package called a weaver's beam which is set up on the back of the weaving machine, or preparing a number of packages called warper's beams which are then sent to the next process known as sizing. There are normally two methods of warping employing different technologies:

- direct warping or direct beaming (also sometimes known as beaming)
- indirect warping/sectional warping

Both methods can be used for spun or continuous filament yarns, depending on the circumstances and the quality of fabric to be produced.

3.2 Direct warping

This method of producing cotton warps is used mainly when the yarn to be woven requires application of starch which is applied in the next yarn preparation process known as sizing, after which it is sent to the loom for weaving. However, as mentioned above, the method can also be employed in the production of beams from continuous filament yarns. A warping machine consists of two units (see Figs 3.1 and 3.5 [1, 2]):

- warping creel
- head stock

The number of cones that should ideally be put on the creel to produce a number of warper's beams can be worked out by a simple calculation. For example, a fabric with 20 ends/cm and 100cm in width is to be produced. This means that the total number of warp yarns in the fabric width will be 2000 and a weaver's beam with 2000 ends would be required and positioned at the back of the loom. If the length of fabric to be produced is 20,000m, this length of yarn would have to be put on the weaver's beam. In actual practice, a small percentage of contraction takes place during the weaving process and is added to the above warp length.

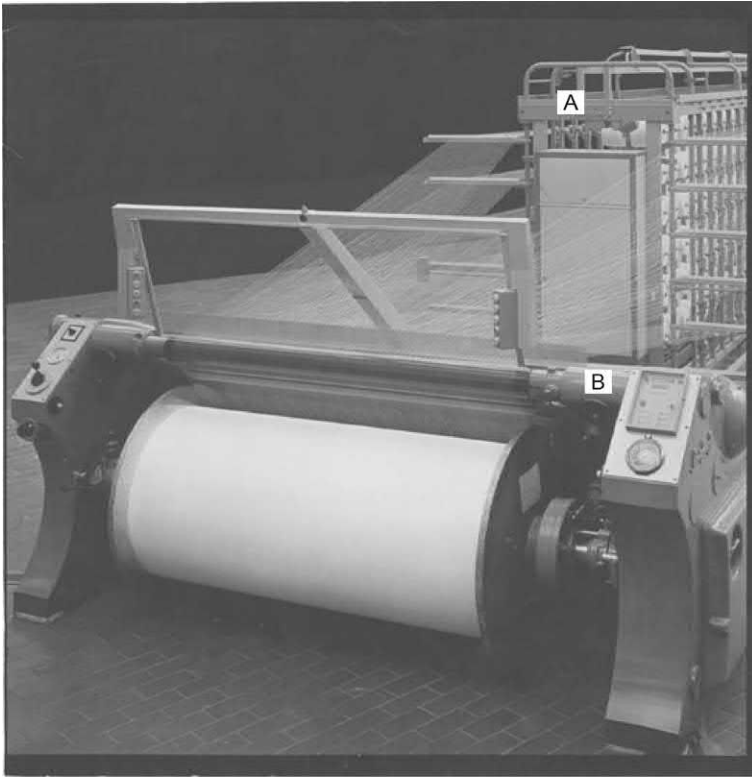


Fig. 3.1 Direct warping machine (A – Creel and B – Head stock).

If the yarn for the above fabric was a single cotton yarn, it will have to be sized after warping. However, the preparation for sizing would be done in the warping department. A number of warper's beams are produced and sent to the sizing department to produce a weaver's beam ready to be positioned at the back of the loom. How many warper's beam should be produced? There is no written formula to obtain the answer. It depends on the skill and experience of the person handling the job. However, it also depends on factors such as the creel capacity, that is, how many cones it can take, as well as how many cones are available. If the creel capacity was, say, 400 cones and we were to process the above fabric with 2000 ends, it would be reasonable to take 400 cones and fill the whole creel (see [Fig. 3.5](#)).

3.2.1 The direct warping process

In the direct warping process, an end from each of the packages positioned on the creel is drawn from the warp stop motion and tensioning unit located on the creel. It is brought forward to the headstock of the machine located in front of the creel, passed through an expandable V shape comb ([Fig. 3.2](#)) [1] and over the measuring roller. The

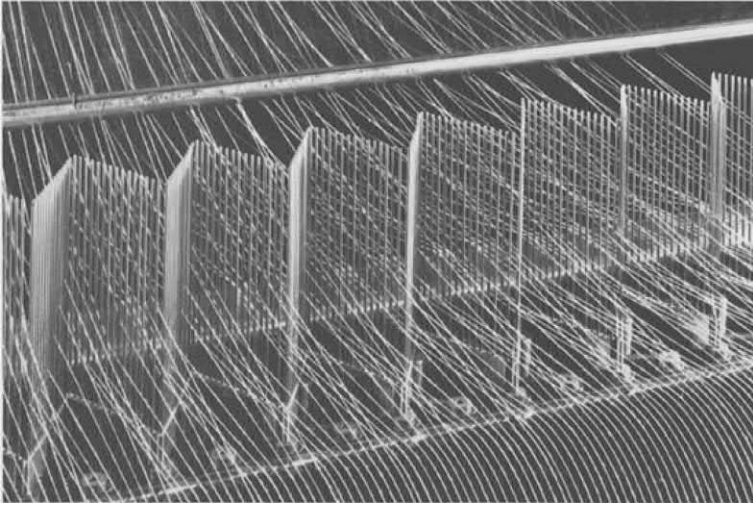


Fig. 3.2 V-shaped expandable comb.

process is complete when all the packages in a sheet form are wound on to a warper's beam (Fig. 3.1). Typically, a 20,000 m length of warp containing 400 ends is wound onto the first warper's beam. After this, the warp is cut, the full beam taken out and a new beam put in (Fig. 3.3) [1]. Since 2000 ends are required on the weaver's beam, five warper's beams, each with 400 ends and 20,000 m length of warp, will have to be produced. The process is repeated after each beam is produced.

In the above case, the five warper's beams will be sent to the sizing department and positioned on the creel at the back of the sizing machine (Fig. 3.4) [1]. Warp ends are collected from all five beams and passed through the sizing machine. In all, 2000 ends in sheet form are wound onto the weaver's beam. A number of weaver's beams can be made from the given length of warp on the warper's beams.

3.2.2 Drive to the warper's beam

Two methods of driving the warping beam are available. The majority of warping machines are drum driven, where the rotational motion to the warper's beams is imparted by the frictional contact of the drum (Fig. 3.5) [2]. As the beam diameter increases, its rotational speed decreases. This means the warp's linear speed remains constant which maintains constant tension on the warp sheet from the beginning to the end of the warping process.

On some warping machines, the beam is driven by a spindle or with gears (Fig. 3.1). In order to keep the tension uniform throughout the warping process, as the beam diameter increases, its rotational speed decreases and the yarn speed remains constant.



Fig. 3.3 Full beam being taken out (doffed) and new one put in.

3.2.3 Beam warping for yarns not requiring size application

If the yarn to be processed is a twofold yarn or another type which generally does not require any application of starch, then beam warping can be carried out in two stages. In the first stage, a number of warper's beams with the desired number of warp ends and warp length on each beam are produced on the direct warping machine. In the second stage, all the warper's beams are positioned on a frame and the warp ends from all the beams are

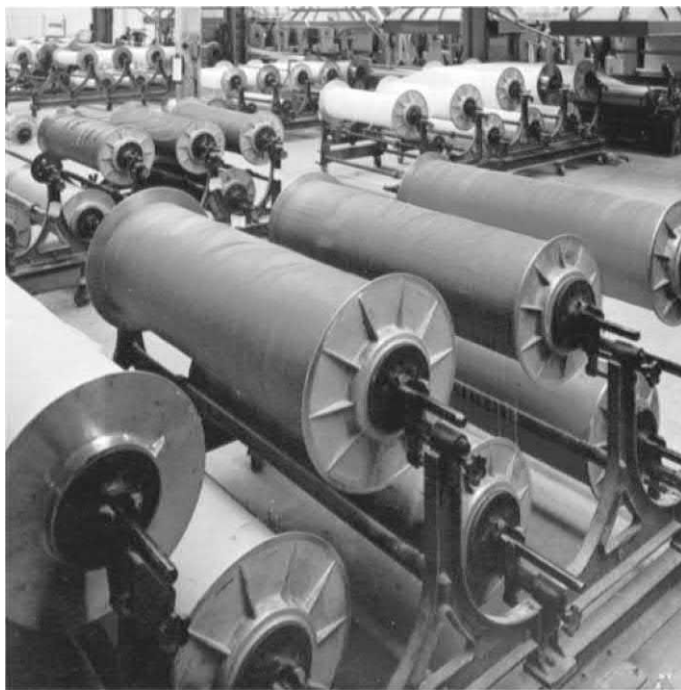


Fig. 3.4 Warper's beams at the back of sizing machine.

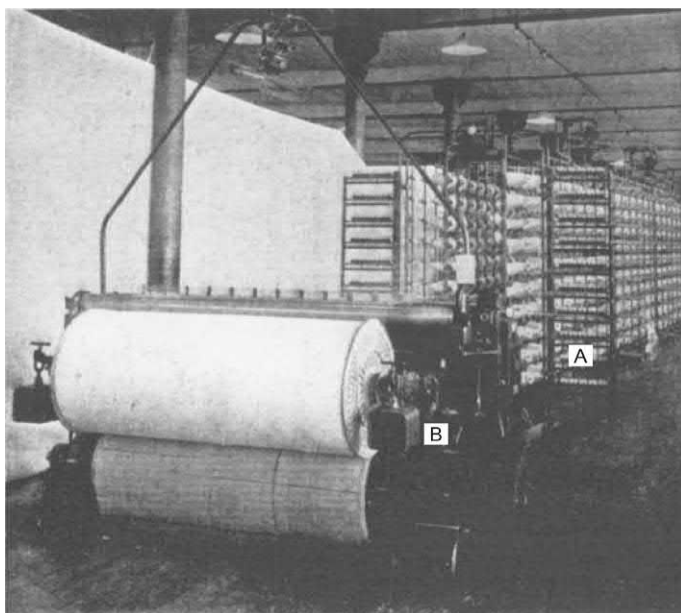


Fig. 3.5 Drive to warper's beam with frictional contact of drum (A – Creel and B – Head stock).

simultaneously unwound and transferred onto either a single weaver's beam or a number of beams which are then ready to be positioned at the back of the loom for weaving.

3.3 Indirect/sectional warping

This method of warping is generally carried out for yarns under the following conditions:

- where there is no need for any application of starch, such as twofold cotton or woollen/worsted warps
- for shorter runs of high-class goods
- for coloured yarns, that is, patterned warps for wool and worsted fabrics, etc.
- where a small number of cones is to be used because of the quality of the fabric to be produced, mostly coloured warps

Compared to direct warping, the number of cones used is generally much smaller. A sectional warping machine consists of three basic units:

- creel
- winding drum
- the beaming unit

Warper's beams are not produced in this process and the warp is directly transferred from the drum onto the weaver's beam(s).

The process involves two stages:

1. Warping of a number of sections with the required number of yarns onto a conical drum.
2. Beaming off, that is, transferring the yarns from all the sections in a sheet form onto a weaver's beam.

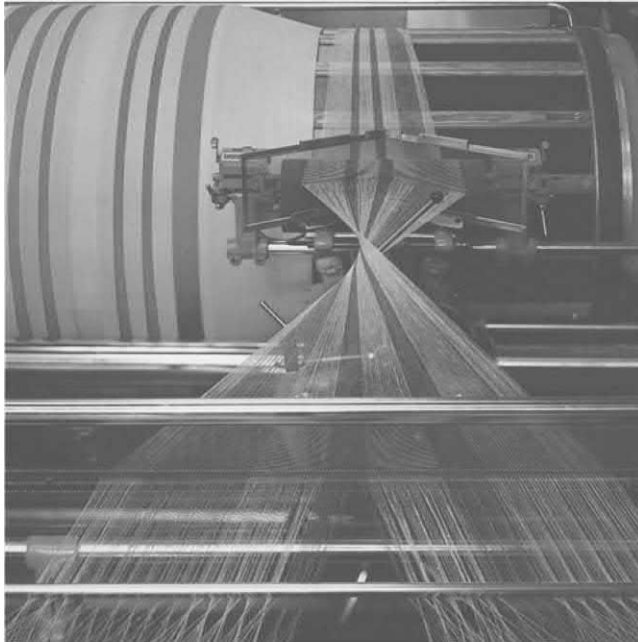
An example is the need to produce a fabric 5000m in length, 100cm wide with 20ends/cm, and 100 available cones or cheeses. To produce this fabric requires a weaver's beam with 2000 ends and 5000m length of warp. To produce this weaver's beam, 100 packages will be positioned on the creel (Fig. 3.6B). Yarn from each package is drawn through the tension and thread stop motion, brought forward to the front of the machine, and condensed into sections with a small width by passing through one or two different reeds (Fig. 3.6A and B). A section containing 100 ends and 5000m in length will be wound onto the conical drum (Fig. 3.6A [3] and B [4]). When the desired length of section has been wound, it is cut and another section adjacent to the previous section is wound for the same length (Fig. 3.6A). Since the total number of ends required on the weaver's beam is 2000, the process is repeated until 2000 ends of the same length have been wound onto the drum. In total, there will be 10 sections wound onto the drum.

3.3.1 Beaming off

The next stage, known as beaming off, consists of transferring the yarn from all the sections in a sheet form from the conical drum onto a weaver's beam (Fig. 3.6C [3] and D [4]). Whether the entire length of the warp yarn is transferred from the drum onto a single weaver's beam or a number of beams, depends on the production planning, that is, how many looms are to run from the same quality of warp.

3.3.2 Waxing of warp

Sometimes a coating of wax is applied to certain types of warp yarns, for example, woollen yarn, during the beaming off process to improve their weavability. The warp sheet is passed over a revolving roller loaded with liquid wax as shown in Fig. 3.6E [3] and is then wound onto the weaver's beam.



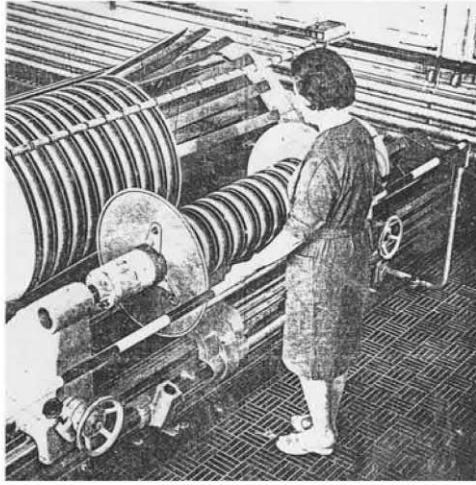
(A)



(B)

Fig. 3.6 (A) Sectional warping starting a new section, (B) sectional warping with section being wound on to drum,

Continued



(C)



(D)



(E)

Fig. 3.6, cont'd (C) beaming off from drum onto weaver's beam, (D) beaming off of solid warp from drum to weaver's beam, and (E) waxing of warp.

(B), (D) From HUYS machinery & Vanhevel n.v., Tiegem, Belgium, Brochure – a new generation of section warping machines.

3.4 Warping creels

A creel is basically a metal frame of varied design to accommodate a few hundred tubes, cone, or cheese packages. The frame is fitted with package holders. The number of package holders on the creel frame can vary from 100 to 800 and more in exceptional cases, their number representing the capacity of the creel. The creel is equipped with a tensioning device and thread stop motion through which each running yarn is passed. In modern machines, these devices are equipped with automatic control and centralized tension variation. Depending on the area of application, package type and size of the processed material, and the space conditions, a creel must satisfy various requirements. The following types of modern creel design are available from various manufacturers:

- single-end creel
- fixed frame creel
- magazine creel
- duplicate creel
- creel with removable bobbin trucks (RT)
- swivelling frame creel

3.4.1 *Single-end creel*

This type of creel is generally used when the factory requires the running of short lengths of warp or where it is necessary to make frequent changes in yarn counts or quality. Only one cone holder is provided for each package. When the packages are exhausted, the empty cones are removed and replaced with fresh ones. During this period, the warping machine remains idle.

3.4.2 *Fixed frame creel*

Fixed frame creels are often used in pairs enabling one creel to be running, whilst the other is being preloaded. Fig. 3.7 shows the design of a fixed creel (FC) with a fixed double-sided package frame [5]. By opening the tensioned frames which are mounted on ball bearings, the distance between the package top and the yarn tension units can be adjusted, depending on the ballooning of the yarn. The creel can be hydraulically opened and closed by means of a push button. Another widely used new fixed frame creel is available from Huys & Vanhevel, Belgium. The model FC [4] has two designs:

- fixed creel outside (FCO)
- fixed creel inside (FCI)

These feature a fixed steel construction with suspended tensioned frames (Fig. 3.8). By moving the tensioned frames laterally, a loading gangway is created between the packages and the tensioners. Similarly, the distance from the package to the tensioner can be adjusted for optimal yarn balloon formation.



Fig. 3.7 Fixed creel.

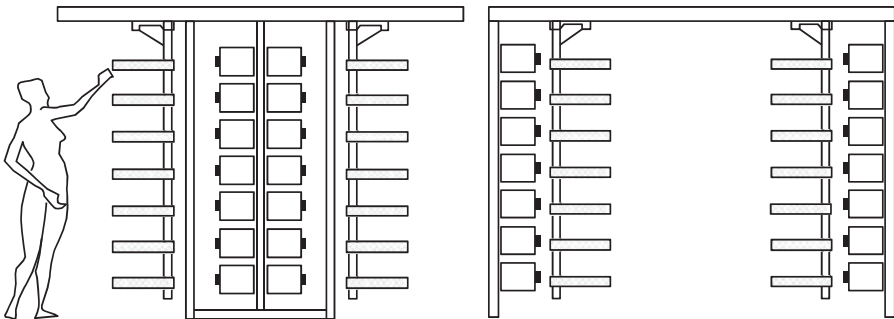


Fig. 3.8 Fixed creel with outside (left) or inside (right) yarn sheet.

3.4.2.1 FCO type (exterior yarn sheet)

The FCO type comprises a fixed central package frame with movable exterior tensioner frames. This is the most widely used construction with easy yarn sheet access which facilitates rapid yarn break repairs.

3.4.2.2 FCI type (inside yarn sheet)

The FCI type comprises a fixed exterior package frame with central movable tensioner frames. This solution provides minimum deviation in angles and is, therefore, particularly suitable for fine and delicate yarns.

3.4.3 Magazine creel

The magazine creel is most effective when long runs of a single count or quality are required. Two cones/holders are provided for each yarn, one for the running yarn and the other for the reserve cone. The tail end of the running cone is tied to the leading end of the reserve cone, so that when the running cone finishes unwinding, the yarn from the reserve package starts and continuity is thus provided without stopping the machine. There will be few leftover packages. This also allows replenishment of the cone holder on the creel with the reserve cones as required. Depending on the application, the creel may be configured for exterior or inside draw off. Fig. 3.9 shows model GP-M [6] of a magazine creel made by Benninger AG, Switzerland.

3.4.4 Duplicate creel

The use of this type of creel is the same as that of the single-end creel, that is, where it is necessary to change the quality of the material or yarn counts either at relatively short intervals or when frequent changes are necessary. The design places two creels side by side. The headstock of the warping machine can be moved from one creel to the other. Whilst the running creel is being used, the duplicate creel with the desired yarn quality is prepared ready for use. The headstock is moved to the made-up creel so the warping process may be started without any waste of time. The spare creel then becomes available for the positioning of new packages.

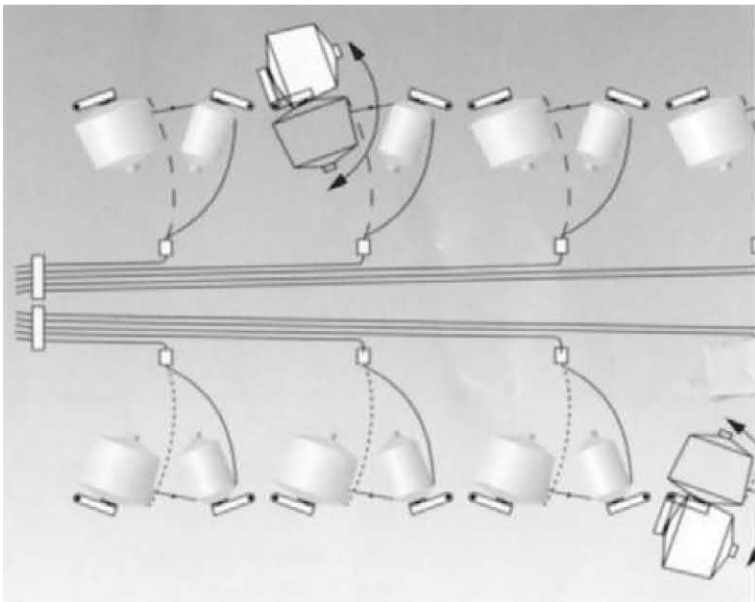


Fig. 3.9 Magazine creel GP-M for continuous production.

3.4.5 Creel with RT

The design of this creel is almost identical with that of the FC. However, the fixed bobbin frame is replaced by removable package trucks [5] or trolleys in the centre of the creel (Fig. 3.10). Individual trucks can be taken out of the creel. The design of this creel also allows the use of a set of spare trucks. These can be loaded with packages outside the creel whilst warping is carried with the other set. This increases the flexibility and productivity of the warping process. The downtime is reduced to that required to move the trucks in and out and to knot the yarns with the finished set. This creel design is particularly useful when there is insufficient room to permit the use of two standard creels. The creel can be hydraulically opened and closed by means of push buttons.

3.4.6 Swivelling frame creel

Fig. 3.11A shows the design of a swivelling frame creel-type CS [4] which is marketed by the huys Matthys Group-from Belgium. This design permits the setting up of other packages when the machine is running. The next set of packages, running for a different quality of fabric, can be loaded on to the creel whilst the warping machine is still running the previous set. When the running packages are empty, the package frame can be rotated to bring the new set of packages into the active position. The rotating frames have a locating catch for ease of positioning. The creel is particularly suited for large packages of filament yarn. This creel is available in two versions:

- With an exterior yarn sheet: this type is used when the yarn run needs to be accessible for the repair of broken ends.
- With an inside yarn sheet: used with heavy packages to facilitate handling and accessibility.

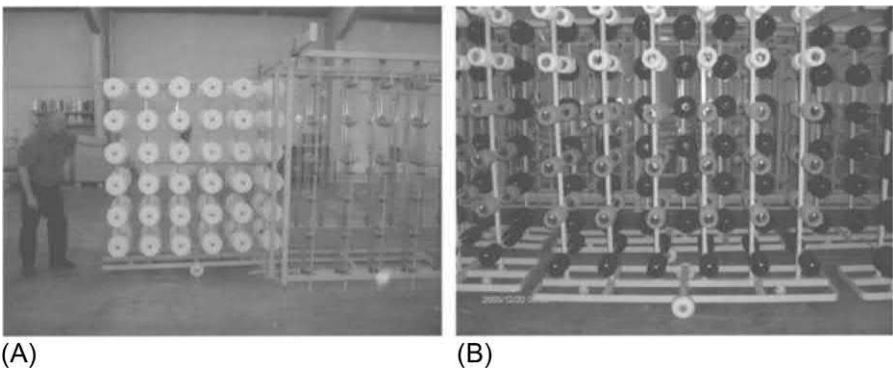


Fig. 3.10 Creel with removable package trucks: (A) creel with removable bobbin trucks and (B) spare trucks to increase flexibility and speed for warping.

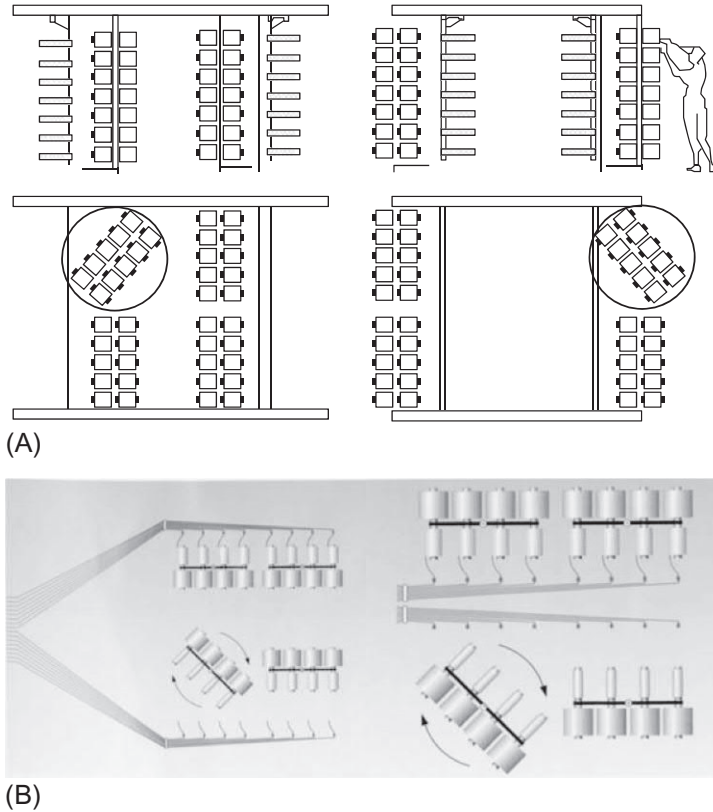


Fig. 3.11 (A) Swivelling frame creel and (B) swivelling frame creel GP-D.

Fig. 3.11B shows another model of swivelling frame creel GP-d [6] in two versions from Benninger. This creel is ideal for package sizes between 5 and 25 kg. The segments are turned manually but an automatic option is also available.

3.5 Tensioning units of creels

All modern creels are equipped with a tensioning unit for each package. These can be mechanical or electronic. A number of different tensioning units are available, covering a large range of yarn types and counts. The simplest is the disk tension device [7] as shown in Fig. 3.12A. The thread is drawn from the package, through an eyelet and led around two small pins before going forward from the creel. If an increase in tension is needed, weighted disks are placed on top of the yarn as shown in Fig. 3.12B. This method is generally suitable for cotton and wool. However, for

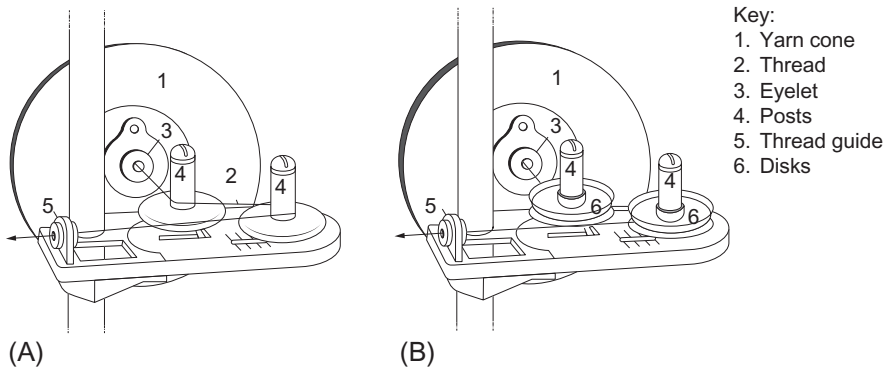


Fig. 3.12 Disc tension device.

sensitive yarns such as filament and silk, the steel posts or pins are fitted with porcelain adapters.

There are various types of tensioning device:

- self-compensating tensioner-type DTR
- adjustable disc tensioner-type DT
- mechanical self-compensating tensioner.
- electronic tension units.
- Tsudakoma new tensioner device.

3.5.1 Self-compensating tensioner-type data terminal ready

Fig. 3.13A shows a self-compensating tensioner-type data terminal ready (DTR) fitted on a warping machine [4]. It is designed to maintain a constant yarn tension on a given setting with cops, conical, or cross-wound packages and to maintain a constant yarn tension from full to empty packages, regardless of speed or package size. The decrease in diameter of the package during warping is compensated by the tension unit so differences in tension are kept to a minimum. Tension peaks are absorbed by the hydraulic damping action of the compensating wing, enabling smooth running of the yarn sheet. Different types are available to suit a large range of yarn counts.

3.5.2 Adjustable disc tensioner-type DT

This tensioner DT (Fig. 3.13) has been developed for technical applications with high tensions [4]. The yarn is deflected over a ceramic roller with a large deflecting radius of 12mm. It is ideal for fibreglass, industrial, or heavy filaments and spun yarns.

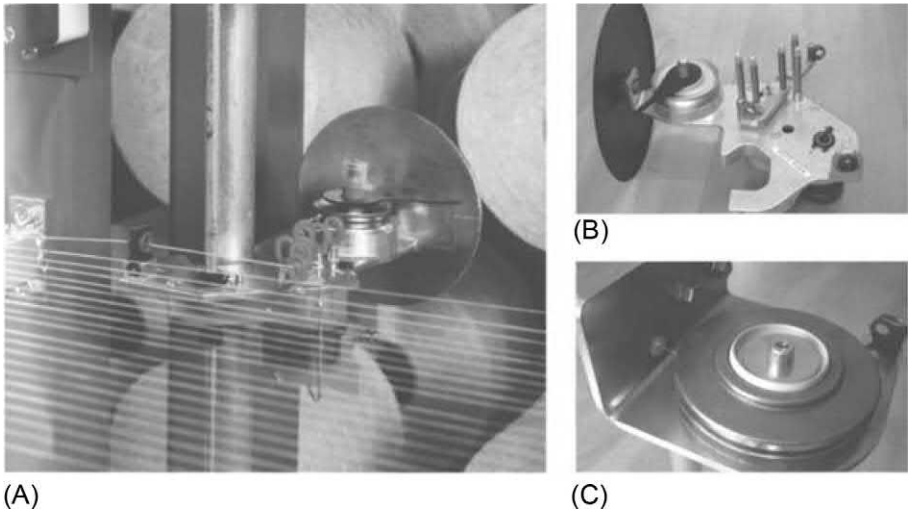


Fig. 3.13 Self-compensating tensioner, (A) DTR-1000, (B) DTR-Z, and (C) DT-tensioner.

3.5.3 Mechanical self-compensating tensioner

Two different mechanical self-compensating tension units, V001 and V002, are offered by VTA, Belgium (Fig. 3.14A and B) [5]. These units keep the tension constant, independently of the various colours on the creel, the different types and counts of yarn or the difference in diameter between the various packages. When at standstill, the tension units return to their starting position, thus keeping the yarn stretched.

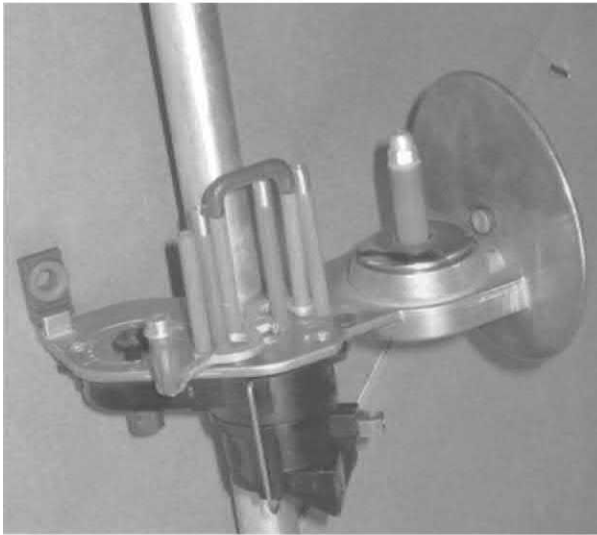
3.5.4 Electronic tension units

Most modern warping machines are equipped with different types of electronic tension units for packages on the creel. Fig. 3.15 shows an electronic tension unit [5] from VTA equipping a modern warping machine creel. It has the following features:

- fully programmable tension control
- stores 999 styles
- custom application for quick installation
- automatic profile of tension from front to back
- constant tension across the yarn sheet
- constant tension regardless of speed
- computer calibrated
- motion sensors for detecting broken ends
- individual end identification
- programmable response time to reduce lost ends
- touch screen



(A)



(B)

Fig. 3.14 (A) Mechanical tensioner V001 and (B) mechanical tensioner V002.

3.5.5 Tsudakoma new tensioner device

Tsudakoma have introduced a new type of tensioner unit (Fig. 3.16A) on their creel TVC-e Creel [8]. The figure shows the two-rod type, but three-rod and four-rod types are also available. A rod tensioned system with a movable rod is used. By setting three positions for the movable rod at stopping, running, and opening, the tension is equalized and yarn breakage may be easily repaired. This device breaks the yarn according to the machine stop/start setting to prevent the yarn from loosening in acceleration and

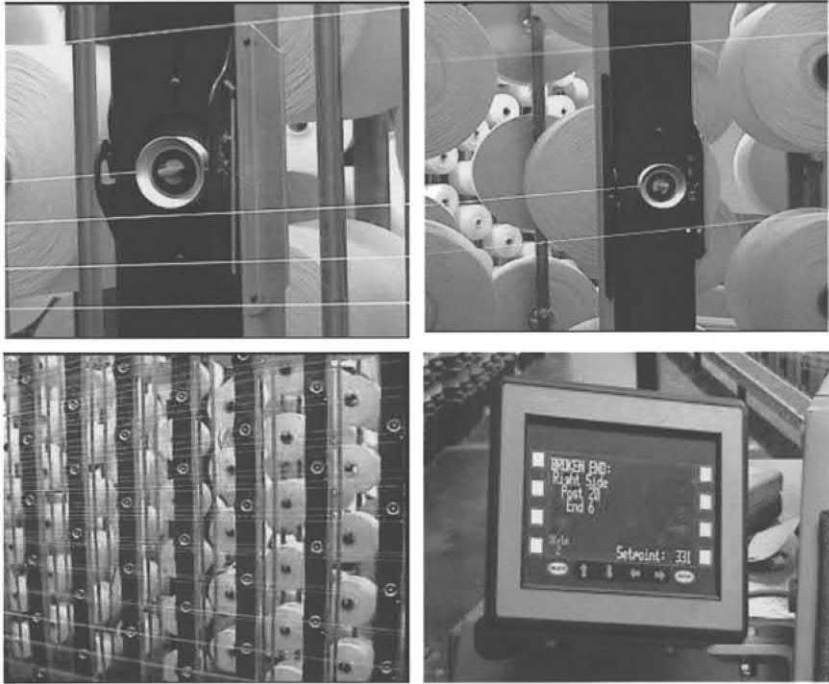


Fig. 3.15 Electronic tension unit.

deceleration. An optional tension control device is also available. The creel tension is detected on the warper's main body section. From the beginning to the end of the package, the combined use of the rod position control and the speed control draws out the yarns at a stable tension for winding on the beam.

The Tsudakoma tensioner unit also includes a device for automatic adjustment for ballooning distance. This unique device calculates the optimum distance between the yarn package and the tension rod based on the yarn package diameter, which is detected by the yarn package diameter sensor (Fig. 3.16B). The tension rod is then brought close to the yarn package [8]. As the distance between the package and the tension rod is maintained so as to prevent multiple balloons, yarn breakage is decreased.

3.6 Thread stop motion

Every warping machine is equipped with a thread stop motion. In the event of a thread breaking, the stop motion immediately stops the machine before the broken thread becomes lost under subsequent layers of yarn on the beam. A light at the stop motion

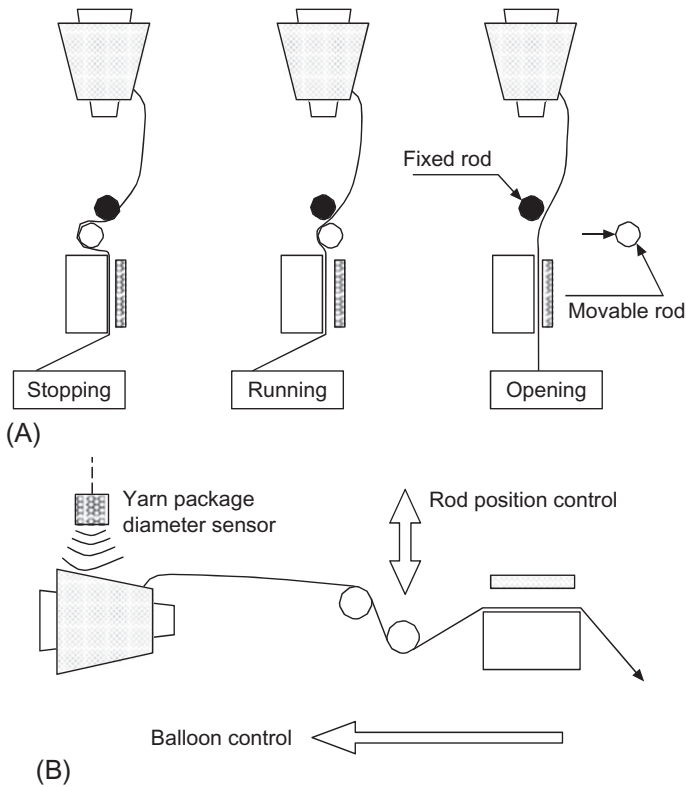


Fig. 3.16 (A) Two-rod tensioner and (B) automatic adjustment for balloon distance.

unit illuminates to identify the exact location of the break and assists the operator in repairing the broken end. Whenever an end breaks, the operator locates the broken end from the cone, passes it through the tension unit and thread stop motion and takes it forward to the beam, tying it with the broken end from the beam. The same process is carried out when any cone or cheese is finished and the machine stops.

Huys (Belgium) offer two types of modern warp stop motion/detection systems:

- FRD-O
- ECD-16

The first type uses a mechanical dropper to generate the stop motion signal. A LED lamp on each stop motion rack indicates the vertical position of the yarn break. The ECD-16 type (Fig. 3.17) is based on the magnetic reed contact. Because this contact is hermetically closed, the sensor is not sensitive to dust or other environmental conditions [4].

Another modern yarn break electric stop motion, with drop needles and dust-proof contactors or electric stop motion with ceramic eyelets and a vertical drop, is offered

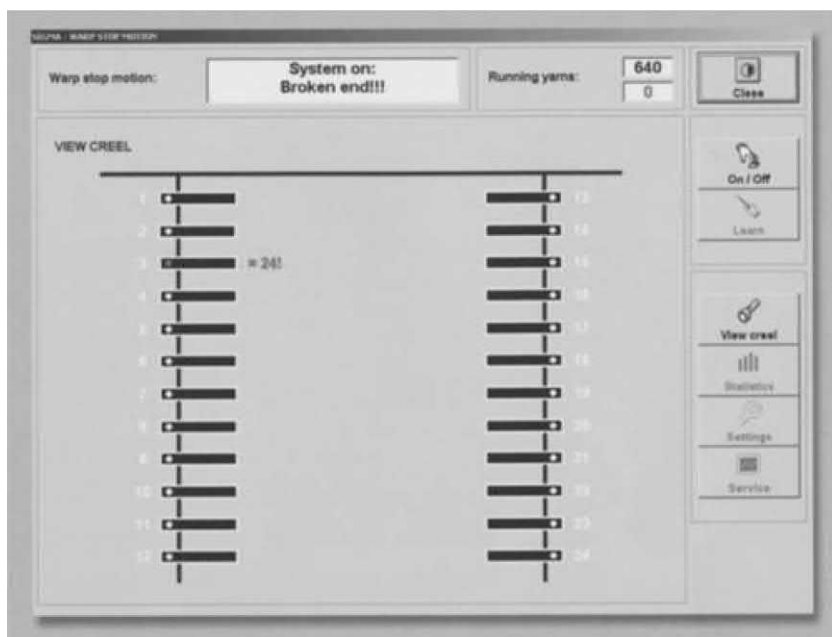


Fig. 3.17 Warp stop motion.

by VTA Belgium (Fig. 3.18) [5]. Benninger offers a unique broken yarn detection device called FILGARD (Fig. 3.19) on their Ben-Creel [6]. When an end breaks, two prominent LEDs flash on the outside of the stop motion assembly, clearly indicating the tier with the broken end. A digital display on the electrical panel shows the tier and the number of the broken end. Repeated end breaks at the same position are specially signaled, which enables troublesome packages to be identified with certainty and replaced if necessary. The minimum tension detection is only 3 cm, which allows even the finest yarns to be monitored. The detector needle can be adapted to cope with divergent yarn counts.

3.7 Single-end warping machines

Traditional warping methods all have their strengths and weaknesses. Even after many years of technological improvement in the design of warping machines, the basic principles and ways of producing warps have not changed. It remains necessary to prepare and use a considerable number of packages, whether in the form of bobbins, cones, or cheeses, which constrains the process.

Customer requirements are changing rapidly for a variety of reasons. For example, the demand for small quantity orders of specialized products at short notice is becoming very common. New production techniques with high flexibility are continuously

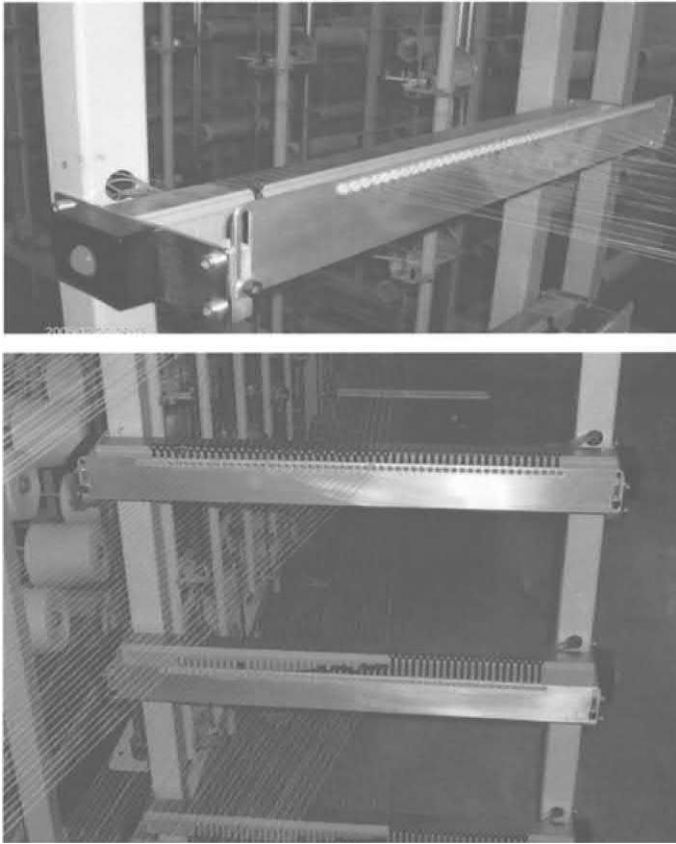


Fig. 3.18 Yarn break detector.

being introduced into the industry. Firms engaged in the production of fancy and patterned fabrics cannot afford to follow the traditional method of warping to produce 10–20 m of fabric as a sample. The answer to this problem is single-end warping technology which has come into the market in the last few decades.

This requires a minimum single package to prepare a sample warp of the desired density. It is equally possible to produce a patterned warp in any sequence according to the design of the fabric. The process is highly automated and dramatically increases the efficiency of sampling and small volume production. In addition to the use of single-end warping by the fashion and design industry, the equipment is ideal for academic institutions actively engaged in running courses in the field of woven textile design.

A number of manufacturers are marketing single-end warping machines. [Fig. 3.20](#) shows a Lutan [9] model which is available in two versions: v 3.6 and v 5.0 from CCI TECH, Inc. in Taiwan. This can produce warp lengths from 11 to 200 m with a

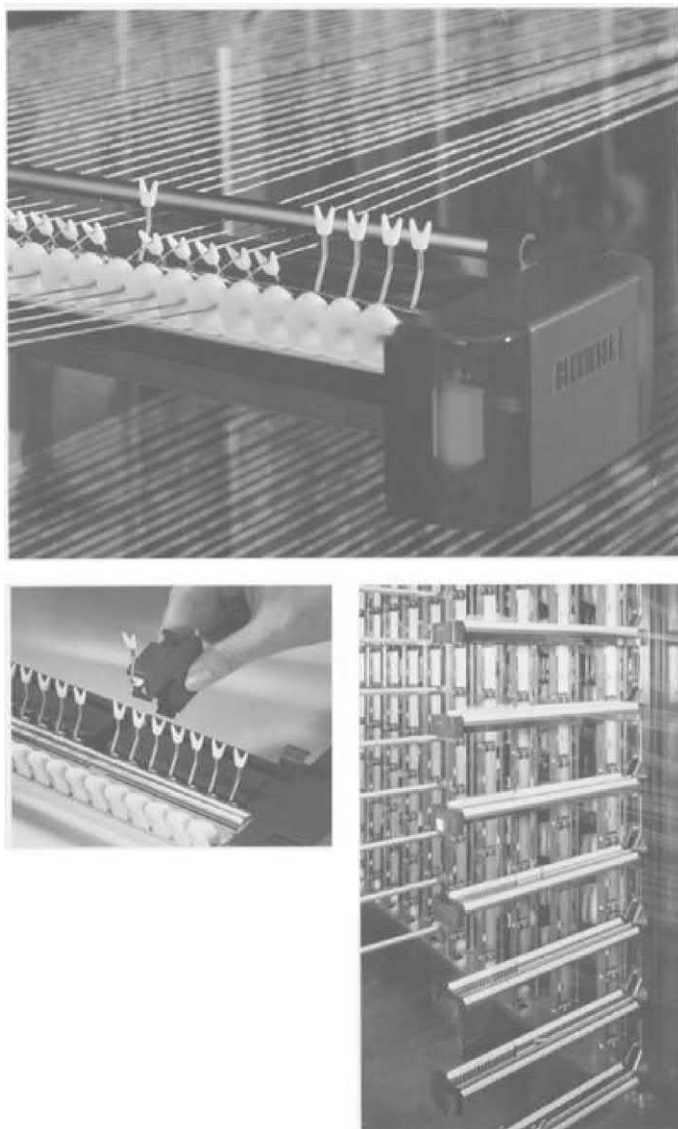


Fig. 3.19 FilGARD yarn detector.

working width of 2200 mm on model v 3.6, and 15–500 m on model v 5.0. In the simplest version, a stationary creel accommodates one package of each colour. Changing of the colour is automatic and allows any possible warp arrangement to a maximum of eight colours. [Fig. 3.20](#) shows a patterned warp wound on a drum which is then transferred to the weaver's beam positioned in front of the drum.

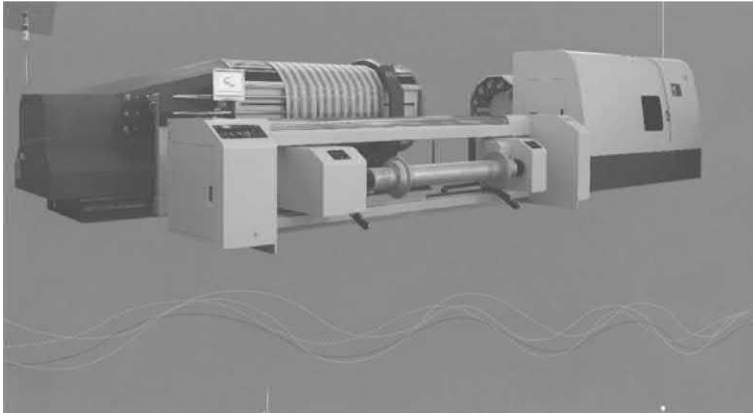


Fig. 3.20 Lutan single-end warping machine.



Fig. 3.21 Single-end warper VMI 601.

3.8 Newly designed single-end sample warper VMI 601

Rabatex Industries from India offer their newly designed sample warper VMI 601 (Fig. 3.21) [10] with the option of either a stationary creel VMI 701 or a Rotary Creel VMI 801 along with optional accessories – accumulator with control panel for stationary creel and rotational creel having eight ends with IRO ROJ – Italy make accumulator and control panel.

The sample warper is designed to produce warps with short lengths less than 100 m. The single-end sample warper reduces the sampling cost and eliminates yarn wastage to produce ‘replica’ of the sample fabric one would like to weave in bulk.

The single-end sample warper has the following technical features:

Drum circumference	7000 mm
Warping width	1900–2600 mm
Warping length	7–105 m
Warping speed	1000 m/min
Thread pickup speed	500 m/min
Thread change speed	500 m/min
Number of thread feeder	8 ends
Max. beam flange dia.	600–1000 mm

3.8.1 Rotary creel VMI 801

The unique creel can accommodate maximum of 8 ends that can be warped for at the same time which increases the warping efficiency significantly (Fig. 3.22A) [10]. The creel is precisely synchronized by a variable frequency digital AC drive and quick response thread accumulator.

3.8.2 Stationary creel VMI 701

It can hold maximum of eight different colours of warp and is programmable for various patterns selection (Fig. 3.22B) [10]. The specially developed sensor does not allow miss or double end. There is an option of thread accumulator available with eight cone holder frame.

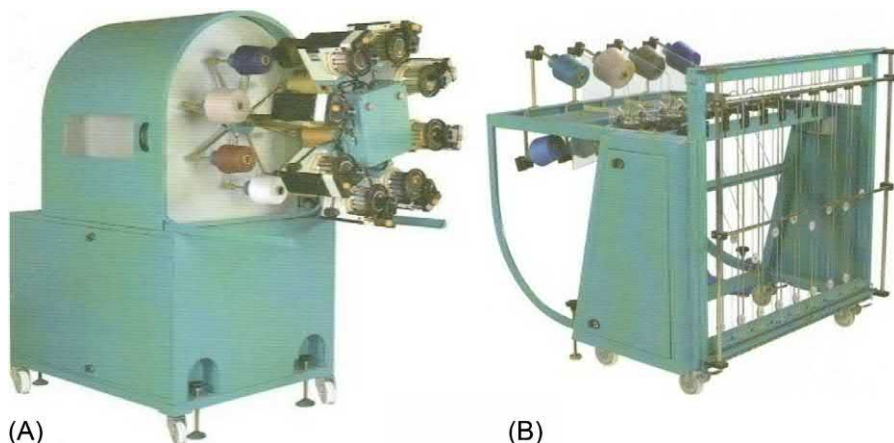


Fig. 3.22 (A) Rotary creel and (B) stationary creel.

3.9 Developments in sectional and direct warping machines

At Itma 2015, there were 19 exhibitors promoting their sectional warping machines and 21 exhibitors direct warping machines. However, majority were providing technical information, etc. about their machines through catalogues whilst very few exhibited their actual machines. As already stated in the previous chapter that in so far as radical developments in the preparatory machines are concerned, in author's views, these appear to have reached near to their saturation limits.

However, at every Itma, one gets an opportunity to see some incremental developments which the machinery manufacturers tend to incorporate in their latest models of winding, warping, sizing, and weaving machines. The general emphasis adopted by most leading manufacturers of these machines is to show improved machine design, production data logging, quality monitoring, and automation through the use of microprocessors and electronics as an integral part of the machines. Use of microprocessors and electronic controls is now almost taken for granted for use in every aspect of yarn preparation machines and this has been clearly reflected in the last few ITMAS and more so was evident at ITMA 2015.

The following sections cover the salient features/incremental developments in the sectional and direct warping machines that were being promoted by some leading manufacturers at ITMA 2015.

3.10 Sectional warping machines

Karl Mayer from Germany were marketing their two new models PROWARP (Fig. 3.23) [11] and ISOWARP (Fig. 3.24) [11] of the sectional warping machines offering new interesting features incorporated in the two models.

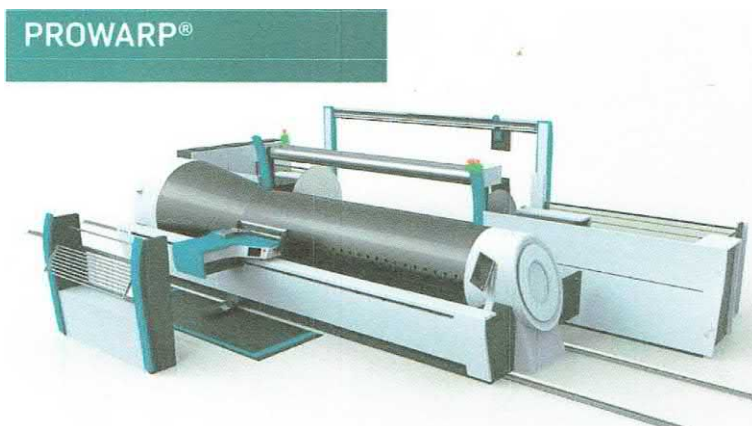


Fig. 3.23 Karl Mayer sectional warper PROWARP.



Fig. 3.24 Karl Mayer sectional warper ISOWARP.

3.10.1 PROWARP

The manufacturer was offering a study in concept and design in the shape of its new, stylish flexible PROWARP sectional warper (Fig. 3.23) [11]. Equipped with ‘best of’ technology the Warper is intended to offer maximum design flexibility throughout the production process, that is, the rotating direction of the warping drum on this new innovative machine can be adjusted to suit the warping requirements of the client. It can cater for a broad range of applications: during beaming, yarns can be processed for producing shirtings, whilst technical yarns as well as all kinds of materials and material combinations equipped with the latest communication, measuring, and control technology.

The newly designed machine offers:

- up to 5% higher efficiency in weaving
- up to 30% more performance in warp preparation
- beaming speed of max. 500 m/min
- beam diameter from 800 to 1250 mm
- working width of 2200–5600 mm
- tensile force values variable from 20 to 1800 N during warping

3.10.2 ISOWARP

ISOWARP sectional warping machine (Fig. 3.24) [11] ideally suited for shirting and sheeting application provide:

- up to 30% increased performance in warp preparation for weaving
- possible to achieve up to 3% greater efficiency in weaving
- warping speed of 800 m/min and beaming speed of 200 m/min
- working width up to 2200 mm and warp beam diameter of 1000 mm
- yarn tensile force 600 N during warping



Fig. 3.25 Lasertronic Plus sectional warper.

3.11 Lasertronic Plus sectional warping machine

Prashant Gamatex under Technical Collaboration with Gamatex s.r.l, Italy were claiming to present Asia's first and most advanced sectional warper Lasertronic Plus (Fig. 3.25) [12] with cradle-type beaming and laser technology. The machine is incorporated with a highly accurate, online pitch measuring device. The system incorporates continuous measuring and monitoring of yarn built-up by a contact-less laser sensor system right from the first section and offers a very high accuracy.

The newly designed warper offers the following interesting features.

3.11.1 Kick back-type feeler roller for compact beam

A feeler roll guided by pneumatic closed loop A/C servo drive is provided on warp table to offer high precision, uniform, compact, and tidy warping (Fig. 3.26) [12]. This actuates controlled pressure over warp section on drum. On stopping of warping operation, the feeler roll retracts automatically so as to avoid partial abrasion on yarn resulting in the formation of a compact package at low thread tension.

3.11.2 Programmable leasing device

Pneumatic leasing device (Fig. 3.27) [12] is provided to ensure precise and smooth operation and is programmed by programmable leasing control (PLC) for tilting the split rod frame simultaneously for seven lease operations.

3.11.3 Section tension control

This control features guarantees unvarying thread tension at all the times, regardless of package diameter and speed (Fig. 3.28) [12]. The required yarn tension in warp section once set is continuously monitored by load cell which in turn gives signal to creel PLC in close loop of main machine PLC, thus regulates the yarn tension precisely.



Fig. 3.26 Kick back feeler roller for compact beam.



Fig. 3.27 Programmable leasing device.

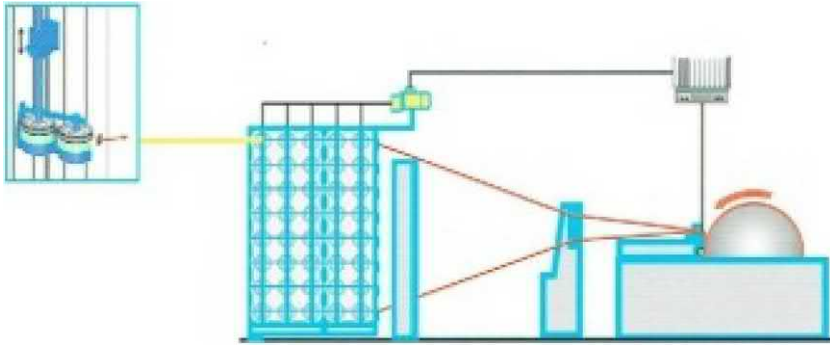
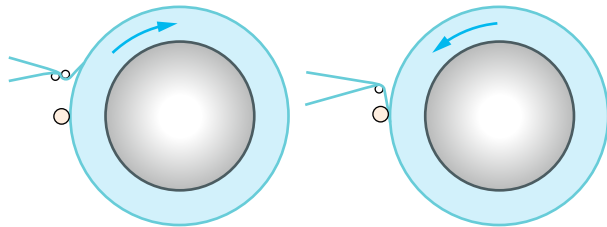


Fig. 3.28 Section tension control.

Fig. 3.29 Reverse drum rotation.



3.11.4 Reverse drum rotation

Reverse drum rotation makes everything easy to reach. It minimizes the distance between fix-reed to drum surface and thereby avoids yarns spreading. It also simplifies the entering of seven lease, which saves considerable time whilst warping (Fig. 3.29) [12].

3.11.5 Adjustable waxing device

It features:

- three roll waxing devices with wax container tray and storage tank (Fig. 3.30) [12]
- waxing speed is variably adjustable for uniform wax throughout the length
- rear guide roll to maintain uniform wax contact area irrespective of yarn diameter built-up
- to bypass the waxing process, wax roller with tray can be lowered pneumatically

3.12 COMSAT sectional warping machine UNI-EVO

COMSAT from Spain offer their sectional warper UNI-EVO (Fig. 3.31) [13] with fast synchronized machine movements, in conjunction with the high warping and beaming



Fig. 3.30 Adjustable waxing device.



Fig. 3.31 COMSAT sectional warper UNI-EVO.

speed providing maximum productivity and warping of a diverse range of yarns from coarsest to the finest. Warping speeds up to 1200m/min can be achieved. Beaming speed up to 300m/min with a maximum tension of 8000N, special configuration up to 200m/min with a maximum tension of 12,000N is available. The sectional warper offers the following salient features incorporated in the newly designed machine.

3.12.1 Automatic warp section control

The device guarantees an identical length and tension of the yarns independent of the bobbin diameter and the warping speed. It allows speed changes in the middle of the warping process and keeps the tension constant during the acceleration and stop of the machine.

3.12.2 Automatic beam tension control

With this device a constant tension during the entire beaming process is assured without affecting any external factors. It allows speed changes in the middle of the beaming process.

3.12.3 Minimum loss of yarns

Through an effective system of hydraulic brakes, a fast stop action is obtained, minimizing the loss of yarns inside the warping drum. The split up of the warp stop motions installed on the creels speeds up the warp stop when a yarn is broken.

The broken yarn memorization in the warping process and its repair in the beaming process, avoids warping defects when a yarn is lost on the drum.

3.12.4 Other features

These include

- partial stops in the beaming process for placement of separation markers
- minimum turn at slow speed during the final section achieved due to the drum inertia compensation
- alignment of the warping table to reduce the angles of the yarns coming from leasing device
- using the simple system of recipes built into the software of the machine, it can accurately reproduce previously produced beams which results into reduced machine set up times and eliminating the possibility of faulty data entry

3.12.5 Optional devices

The following devices are offered as optional devices:

- Press roller device – it increases the beam hardness without increasing the winding tension (Fig. 3.32A) [13].
- Antistatic device – to eliminate antistatic charge accumulated on the yarn (Fig. 3.32B) [13].
- Waxing device – totally independent group for the waxing of warp, with pump and lever detector. Waxing speed is synchronized with winding speed (Fig. 3.32C) [13].
- Printer – it prints the most relevant data of each beam (Fig. 3.32D) [13].

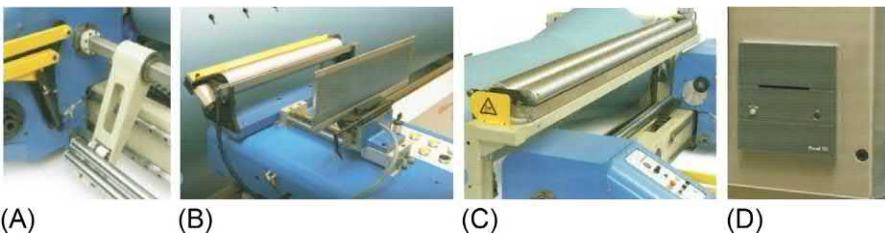


Fig. 3.32 Optional devices: (A) press roller, (B) antistatic, (C) waxing device, and (D) printer.

- Warp section rotating device – allows the construction of symmetrical warp sections.
- Working with two creels – reduces machine downs time.
- Semiautomatic leasing device – automatic stop and opening for lease and sizing splits and allows working with odd yarns of warp section.
- Weighing of the beam – obtains the gross and net weight of the beam.
- Direct beaming from creel – allows directly beaming from the creel without previously warping on the drum.
- Regenerative beaming:
 - Motor braking providing energy saving.
 - Rewinding of the warp to the drum.
 - Beaming low tension.

3.13 Developments in direct warping machines

Karl Mayer offer their latest universal model of the direct warping machine WARPDIRECT (Fig. 3.33) [14] for staple yarns. It has high-production performance with warping speeds up to 1200m/min, working width 1800–2400mm and beam diameter 800–1400m. It ensures perfect warping quality provided by intelligent press roll system and optimal yarn depositing device, meaning.

- completely cylindrical beams
- precise yarn arrangement
- same warping length for all beams
- reduced maintenance costs

WARPDIRECT offers the following salient features.

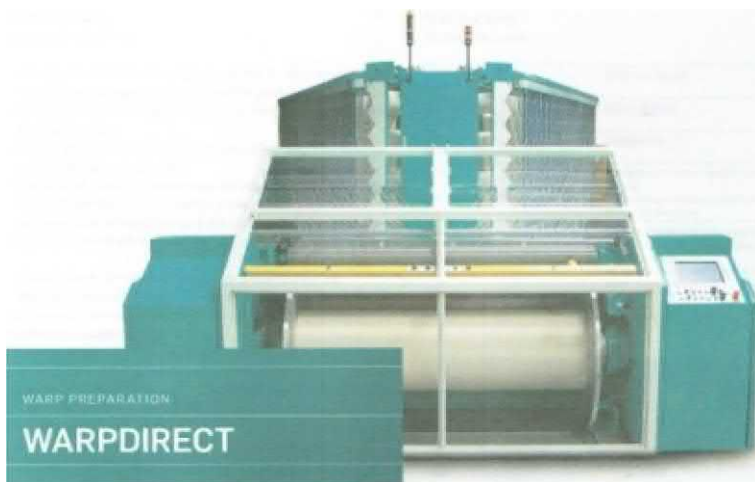


Fig. 3.33 Karl Mayer Direct warping machine ‘WARPDIRECT’.

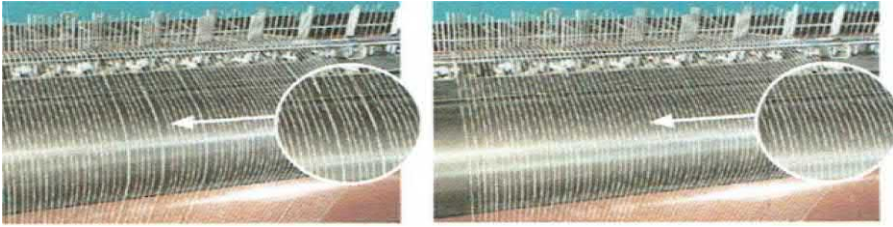


Fig. 3.34 Consistent optimal yarn arrangement during warping.

3.13.1 Consistent optimal yarn arrangement

The machine has a unique consistent optimal yarn arrangement system: during stopping or starting, the threads between the shaft and the reversing roller may get crossed (Fig. 3.34) [14]. During sizing, this quite often results in yarn breaks. The automatic detangling function ensures that the thread arrangement is reestablished immediately after start-up.

3.13.2 Indirect pressure with active kickback

The increasing yarn batch on the beam shifts the pressure roll backwards against the resistance set for the contact pressure. This indirectly acting pressure ensures that completely cylindrical yarn packages are achieved at all times. Since the press roll is hydraulically driven, it will swing out of the way immediately on braking (Fig. 3.35) [14]. This prevents any kind of friction between roll and yarn.

3.13.2.1 Other interesting features

These include:

- Computer – controlled length measuring system provides length accuracy of 0.1%.
- The indirect pressure system and precisely aligned press roll ensures absolutely cylindrical beams.

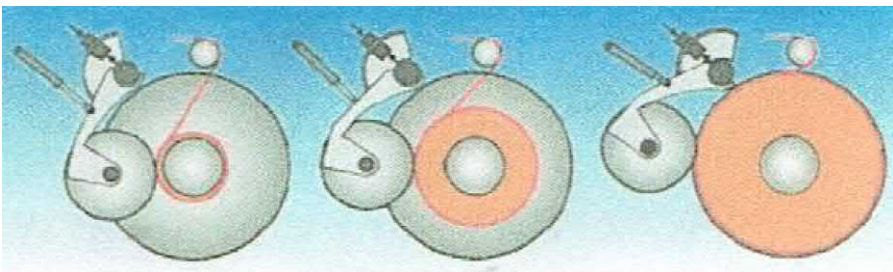


Fig. 3.35 Indirect pressure device with active kickback on 'WARPDIRECT'.

- Lap-protecting press-roll function when stopping due to the press roll (kickback system) swinging out of the way within seconds.
- Reduced maintenance costs.

3.14 COMSAT direct warping machine – ‘UNI-EVO DIRECT’

COMSAT from Spain offer their UNI-EVO DIRECT warping machine (Fig. 3.36) [15] incorporating interesting incremental developments thus providing high productivity of beams of medium density along with the following novel technical features:

- warping speeds up to 400m/min with tension up to 3000N
- beams with a 1000mm maximum diameter
- antiyarn crossing device with blowing
- hydraulic beaming brake
- pressing and waxing device
- possibility of working with two creels simultaneously
- waxing device
- zigzag reed adjustable in width and oscillation of the zigzag reed speed and constant tension during the full beaming process

3.15 Selvage warper

COMSAT offer their interesting Selvage Warper S-200 (Fig. 3.37) [15] for filling of the selvage bobbins, with standard creels for 12, 24, or 36 bobbins with the following technical data:

- 0.18 Kw motor
- signalling operator at thread break

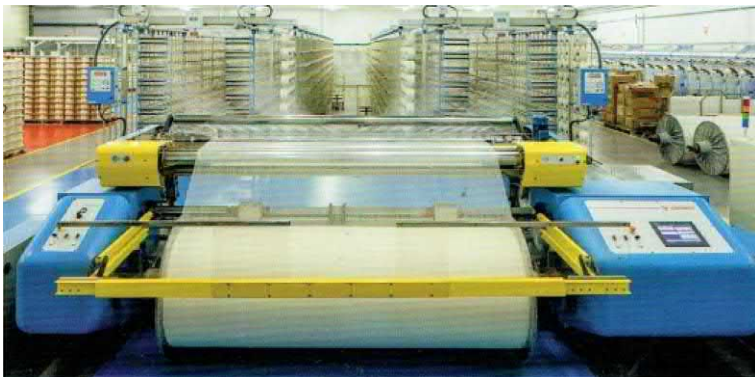


Fig. 3.36 COMSAT direct warping machine UNI-EVO.

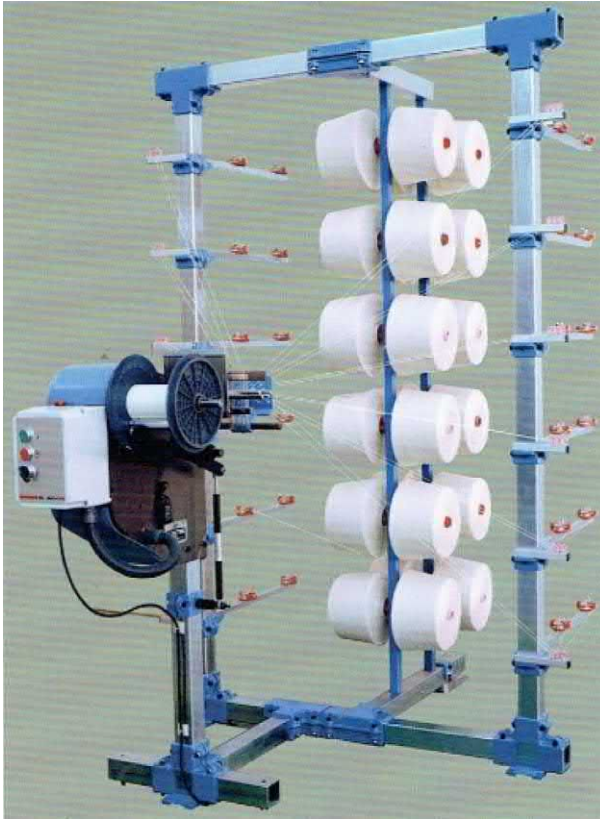


Fig. 3.37 COMSAT – selvage warper.

- warp stop motion
- oscillation
- automatic stop at filling
- press group for uniform winding
- universal system tensioner

3.16 T-Tech, direct warping machine – TW30F

T-Tech Japan Corp. offer their latest direct warping machine TW30F (Fig. 3.38) [16] with some new incremental developments incorporated in the machine which enables to achieve quality warping for a wide range of yarns kinds: chemical and synthetic, nontwist and high twist, and super fine to thin yarns by holding the yarns with the nip roll. Some of the novel features include:



Fig. 3.38 Direct warping machine TW30F from ttj – Japan.

3.16.1 Fixed-position stop system for fluff

When any fluff, broken filament, fluff ball, or loop is detected, the machine is stopped at a fixed position. Defects on yarns are easily removed ([Fig. 3.39](#)) [16].

3.16.2 Take-up tension control system

The take-up tension can be easily set with touch-key operation of the T-machine data station (MDS) with the nip tension control system and the roll tension control system. When the take-up tension control is provided, the tension is more accurately controlled by feedback control.

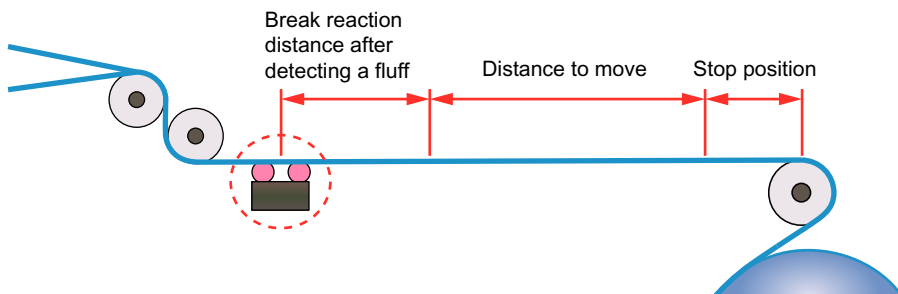
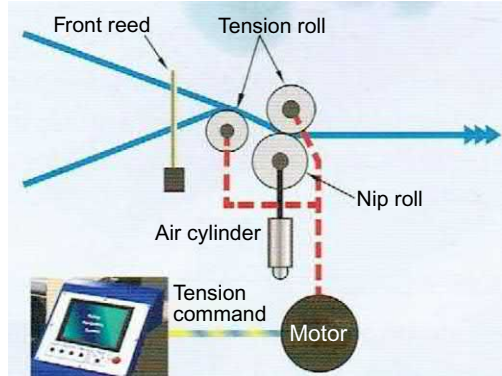


Fig. 3.39 New fixed position stop system for fluff.

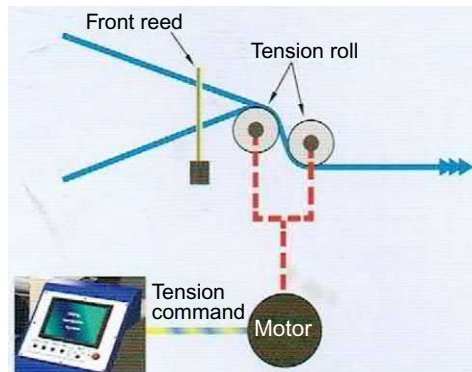
Fig. 3.40 Nip tension control system.

3.16.2.1 Nip tension control system

By holding the yarn with the nip roll, high quality of warping is possible for a wide range of yarn kinds without damaging the yarn due to slippage of the running yarn on the roll (Fig. 3.40) [16]. When the warper is stopped, the nip roll positively releases the yarn immediately even during an emergency stop, so the yarns will never be damaged. The contact angle of the tension roll that is close to the creel is variable to adjust the sheet looseness after stoppage. The system responds to all yarn kinds and is specially efficient for twisted yarns and other yarns that require high tension.

3.16.2.2 Roll tension control system

The motor that drives the two tension rolls positively controls the tension (Fig. 3.41) [16]. Because the roll that is close to the creel has a swing structure to change the contact angle, the friction between the yarn sheet and the roll is adjusted according to the yarn kind and the system is best suited for nontwist yarns.

Fig. 3.41 Roll tension control system.

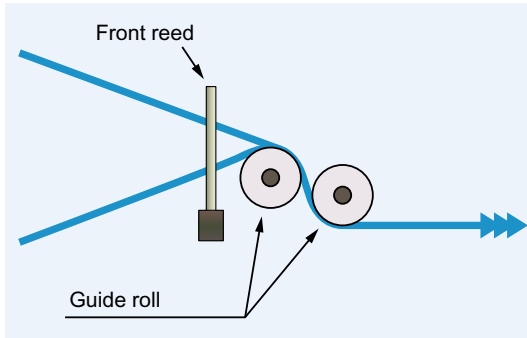


Fig. 3.42 Guide roll system.

3.16.2.3 Guide roll system

Two guide roll negatively rotate to arrange the yarns into a sheet (Fig. 3.42) [16]. The take-up tension can be adjusted with the creel pensioners and the system is ideal for nontwist and low-twist yarns.

3.17 Take-up tension indicator

The T-MDS displays the take-up tension [16] during the warping process thus helping to maintain the desired tension for the production of quality beams.

3.18 Tension setting and control in increments of 1 N

Delicate yarns, such as super-fine yarns, require the tension to be set according to the yarn fineness. Setting in increments of 1 N allow finely tuned setting and control. Delicate yarns, such as super-fine yarns, require the tension to be set according to the yarn fineness.

3.19 Beam inertia compensator

The beam braking pressure appropriate for the winding diameter reduces excess tension during deceleration.

References

- [1] Schlafhorst warping machine, MZD, Brochure, W.Schlafhorst & Co, D 4050 Monchengladbach, Germany.
- [2] G.A. Bennett, *Introduction to Automatic Weaving*, Harlequin Press, Manchester, 1948
- [3] Schlafhorst warping and beaming machine, DSB, Brochure, W.Schlafhorst & Co, D 4050 Monchengladbach, Germany.
- [4] Huys & Vanhevel n.v., Westdorp 69a, 8573 Tiegem, Belgium, Brochure, SIGMA new generation of section warping machines.

- [5] V T A Creels, Heirbaan 14-8570 Ingooigem, Belgium, Creels and Tension units, Brochure.
- [6] Benninger AG, Fabric Strasses, 9240, Uzwil, Switzerland, Brochure—BEN-CREEL.
- [7] A.L. Landau, *Warping and Slashing, Sizing Part 1, International Text Book, Scranton, PA, 1949.*
- [8] Tsudakoma Corporation,-5-18-18, Nomachi, Kanazawa, 921-8650 Japan, Brochure, A 03QVH 05HE.
- [9] LUTAN Single-End Warping Machine, Brochure, CCI Tech, Chaun-Choung Lutan Corp. No.184-3, Zhongxing N.St., Sanchong Dist., New Taipei City 24158, Taiwan.
- [10] Rabatex Industries, Plot 9, Opp Road 9, Kathwada, Ahmedabad 382 430, India, General Catalogue.
- [11] Karl Mayer, Textilmaschinenfabrik GmbH, Bruhlstrase 25, 63179 Obertshausen, Germany, PDF Catalogue Technical Documentation Sheets on PROWARP & ISOWARP.
- [12] Prashant Gamatex Pvt Ltd, Plot 4, Phase 1, GIDC Estate, Vatva, Ahmedabad, India, Technical Catalogue, Lasertronic Plus.
- [13] COMSAT, Zona Industrial Puiguriger, PO Box 68, 08540 Centelles, Barcelona, Spain, General Catalogue Sectional Warpers, Uni EVO.
- [14] Karl Mayer, Textilmaschinenfabrik GmbH, Bruhlstrase 25, 63179 Obertshausen, Germany, Technical Information Leaflet, Warp Preparation-WARP DIRECT.
- [15] COMSAT, Centelles, Spain, General Catalogue, Direct, Sectional Warpers, Creels.- UNI EVO DIRECT.
- [16] T-Tech Japan Corp. (ttj), Tsudakoma Corp, Technical Catalogue TTJ041505E Single-End-Sizing System, Warper TW30F, pp. 12–13.

Yarn preparation for weaving: Sizing

4

K.L. Gandhi

The Textile Institute, Manchester, United Kingdom

4.1 Introduction

It is almost impossible to weave single spun warp yarn from cotton, viscose, polyester blends, and acrylic/wool blends without the application of size (starch). Most single spun yarns are, therefore, sized to enable successful weaving of warp yarns. The application of starch, an adhesive material, is carried out in a process called sizing (slashing). Although sizing is a complex process which is key to successful weaving, it is also considered to be a nonvalue-added process. First, the single spun warp yarns are sized, and after the yarn has been woven into fabric, the protective coating of starch is later removed by a de-sizing process. This enables the selected finishing cycle to be completed without problems, but obviously adds to the cost. Weft yarn is never sized. Correct sizing can help in making cloth from low-grade cotton, even where older machinery is used. However, even with new machinery, inadequate sizing will cause serious trouble during the weaving process with resultant losses in material, quality, and production time.

In this chapter, the author covers only the basic information related to the technology of warp sizing. No attempt is made to cover the chemistry and technology of sizing in any depth. For detailed information on this technical subject, the reader is referred to the books: *Textile Sizing* by Bhuvnesh C. Goswami, R. Anandjiwala, and David. Hall, *Sizing of Spun Yarns* by Henry Hacking, *Technology of Warp Sizing*, edited by J.B. Smith, *Warp Sizing Mechanisms* by T. Ramsbottom, *Textile Warp Sizing* by Paul V. Seydel and *Weaving: Technology and Operations* by Allan Ormerod and Walter Sondhelm, along with other references given at the end of this chapter.

It is generally thought that sizing is carried out in order to increase the strength of the yarn, but this is not entirely true. There is no correlation between tensile strength alone and the end breaks occurring during the weaving process. The efficiency of sizing treatment cannot be judged by an increase in the breaking strength of the yarn. Flax yarns have a higher strength than cotton and wool but are difficult to weave. The strength of the yarn is many times greater than the normal tension imposed on it by the loom parts during the weaving process and yarn does not usually break because of a lack of tensile strength. On the loom, the warp yarns are subjected to a wide range of mechanical stresses, the most significant being bending, fatigue, oscillating tension, and frictional resistance.

4.1.1 Reasons why single spun yarns in their unsized state cannot be woven

The efficiency of the sizing machine at the weaving stage is largely judged by a single criterion, which is the warp breakage rate. A warp break on the loom will occur only when the resistance of the weakest spot in the yarn is less than the tension generated in it. High tension is caused mainly by imperfections in the yarn which create obstructions to the crossing of the warp ends during the shedding process and in their passage through the drop wires, healds, and reed. Among the imperfections which are induced during the process of yarn manufacture, the presence of loose fibres called hairs, which protrude from the yarn surface, is considered to pose the most serious difficulties in weaving spun yarns in their unsized state. Yarn hairiness is affected by factors such as fibre properties, spinning parameters, and yarn properties.

Hairiness arises from three classes of fibres:

1. Fibres whose ends project from the yarn.
2. Fibres which reach the outer layer of the yarn and then arch into loops emerging from the yarn.
3. Fibres which are only attached to the yarn core, and in the majority of cases, are wound round outside it. These fibres are classified as wild fibres [1, 2].

The length of these protruding hairs can vary from 1 to 5 mm or above. The greater the number of hairs per metre, the more hairy the yarn will be. Yarn hairiness, measured by the number of hairs per metre, can be tested on the Shirley hairiness meter. This equipment does not give a figure representing total hairiness but counts the number of hairs exceeding 3 mm in length when the standard setting is used. It appears that hairs emerging more than 3 mm in length from the yarn surface are more susceptible to entanglement with adjacent yarns during weaving. Fig. 4.1A and B shows the difference in appearance between the same yarns with and without hairiness.

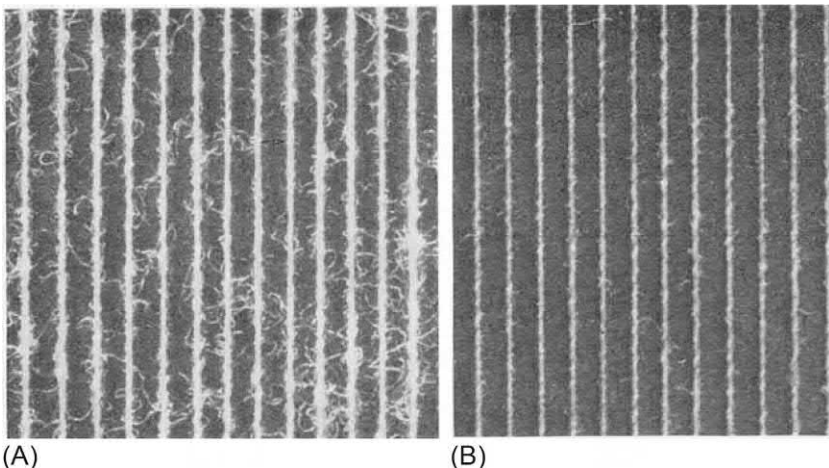


Fig. 4.1 (A) Yarn hairiness before and (B) after singeing.

Properties such as abrasion resistance, breaking strength and elongation, and hairiness in twofold spun yarns are considerably better than in single spun yarns. Sizing is not, therefore, essential when weaving twofold spun yarns, although in many cases even these yarns may be sized for better performance.

4.1.2 Weaving trial on unsized warp yarns

A research project conducted a full-scale weaving trial on unsized warp yarns. A beam containing 1600 ends of 38 tex yarn was prepared. The ends were drawn with one end per heald eye and two ends per dent, weaving plain cloth with 16 ends and picks/cm on a standard Picanol loom running at 220 picks/min (rpm). Fewer than 1500 picks had been woven before the effect of yarn-on-yarn and reed-on-yarn abrasion was clearly noticed as follows [3]:

- Behind the heald shafts, protruding hairs from adjacent ends were interlocked and prevented the formation of a clear shed (Fig. 4.2A and B). Fig. 4.2B shows the fibres being pulled out from the yarn structure.
- Accumulations of detached fibres from the yarn structure as a result of yarn-on-yarn abrasion and the reed-on-yarn abrasion were forming beads in between the front heald and the reed (Fig. 4.2C).
- Behind the healds, a cloud of detached pieces of fibres were thrown into the air by the upward movement of the warp yarns, forming a reservoir for further obstructions. These detached (wild fibres) and broken fibres were seen to be collecting on the loom parts and on the healds. Some fibres fell on the warp and were quickly wrapped around the yarn (Fig. 4.2D and E).

As the weaving progressed, a considerable degree of obstruction was caused by the beads formed on many of the warp ends across the entire width of the warp (Fig. 4.3). Beads also formed at the back of the healds where ends had interlocked. Obstructions were cleared by hand but these became so numerous that after 4000 picks, weaving had to be abandoned. It is noteworthy that for 4000 picks inserted, only one warp break occurred and this was directly caused by one of the beads (Fig. 4.4B (i)). The main deduction seems to be that the yarn was able to withstand the normal weaving tensions and did not suffer significantly from fatigue in its passage from the beam to the fell of the cloth, despite being unsized.

During the formation of the beads, it was observed that in the initial stage of their formation (Fig. 4.4), they were not firmly attached to the yarn. A bead, while still small, could slide from its place of formation under the influence of the reed, but as the bead increased in its length and width, it became fixed on the yarn and travelled forward along with the parent yarn. The size of the particular bead and the movement of the reed put the end under high tension which resulted in its breaking. Beads as big as 15×3 mm in size were formed on the yarn.

Some of the beads were seen to behave in a typical manner, that is, due to yarn-on-yarn abrasion, the ends adjacent to the one carrying the beads detached some of the loose fibres from the outer surface of the bead. This resulted in the loose fibres being discarded, either falling under the loom, or, as was observed in some cases, wrapping themselves around the yarn itself or interlocking the two ends. Fig. 4.4B(iv) shows the

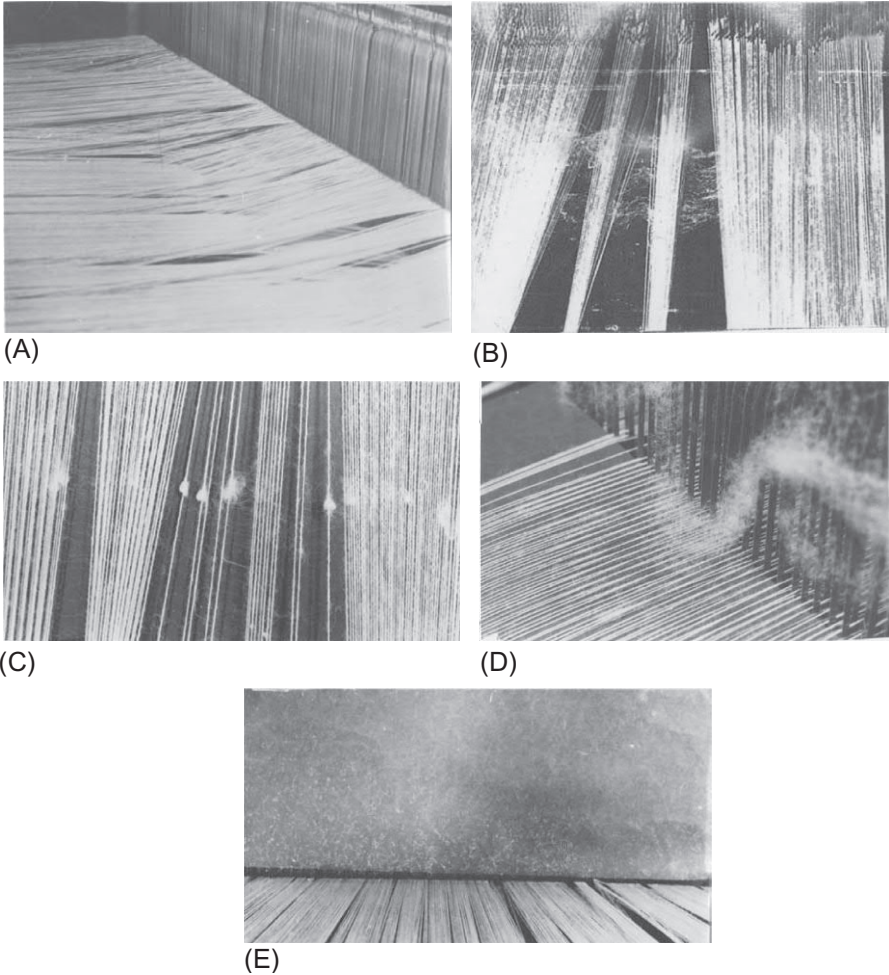


Fig. 4.2 (A) Protruding hairs interlocking with warp during shedding and preventing clear formation of shed, (B) fibres being pulled out during shedding, (C) formation of beads on warp between front heald and reed, (D) detached fibres settling on heald parts and intermittently falling on the warp yarns, and (E) clouds of detached pieces of fibres thrown into the air during shedding.

appearance of a typical bead from which the fibres had been detached. This bead initially had more or less the same appearance as the one shown in [Fig. 4.4B\(ii\)](#) or (iii). The structure of the beads formed in the course of weaving unsized warp was analyzed to prepare a Baer-sorter diagram in order to find out the effective length of the fibres. This was found to be 20mm ([Fig. 4.4](#)).

This analysis clearly showed that these long hairs must have been pulled out from the structure of the yarn and not merely broken off. It became clear that the protruding

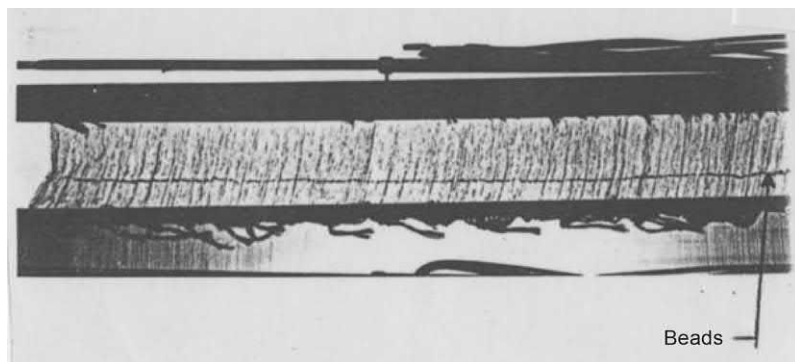


Fig. 4.3 Beads formed in front of reed across the whole width of warp as a result of reed-on-yarn abrasion.

hairs from adjacent ends interlocked and, during the crossing of the warp (shedding), threads were put under tension which either pulled the hair completely from the yarn structure, or after a certain length had been pulled out, caused it to rupture. The severity of entanglement depends on the amount of yarn-on-yarn abrasion, reed-on-yarn abrasion, and heald-on-yarn abrasion during the weaving process and the number of ends and picks/cm.

Thus, it was concluded that because of the hairiness of the yarn, unsized single spun warp yarns, cannot be woven unless they are treated to improve their hairiness, yarn-on-yarn, and reed-on-yarn abrasion resistance. After the treatment, the protruding hairs will not become entangled with each other nor will they be peeled off from the yarn surface during the reed-on-yarn abrasion, which causes the formation of beads.

4.1.3 Effect of singeing on yarn hairiness and weavability

Singeing sewing threads and fabrics burns the protruding hairs to achieve a better appearance in the end products. It is considered desirable to carry out this process to remove the protruding hairs from the yarn and then study the weavability behaviour. As an example, a 37-tex break-spun yarn was singed at a speed of 130m per minute. Fig. 4.1A and B shows the hairiness of the yarn before and after singeing. The decrease in yarn strength and breaking extension was found to be insignificant.

4.1.3.1 Weaving trial on singed unsized yarn

A large-scale trial was conducted in which a beam with 1600 ends from 38-tex singed yarn was prepared to produce a plain cloth with 15.7 ends and picks/cm. A standard Picanol loom running at 220rpm was used. It was observed that no difficulty was experienced in weaving the warp. Even in the unsized condition, the warp sheet divided clearly and in the absence of hairiness, yarn-on-yarn abrasion did not cause

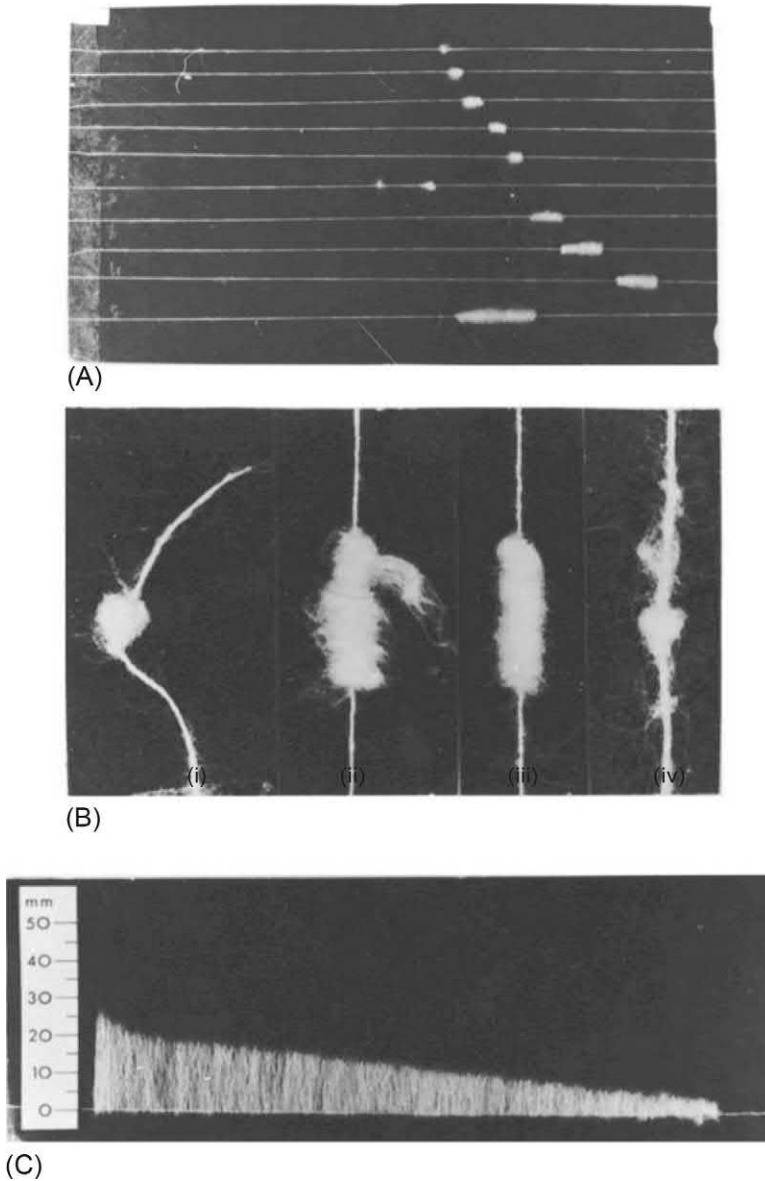


Fig. 4.4 (A) Different stages of bead formation, (B) various beads, and (C) Baer-sorter diagram of fibres removed from beads.

any entanglement of the adjacent warp ends (Fig. 4.5C–E). There was no formation of beads on any of the warp ends across the entire width of the warp. A total of 50,000 picks were inserted and only five warp breaks recorded. Compared to this performance, the trial on unsinged and unsized warp as described earlier had to be abandoned after only 4000 picks [3].

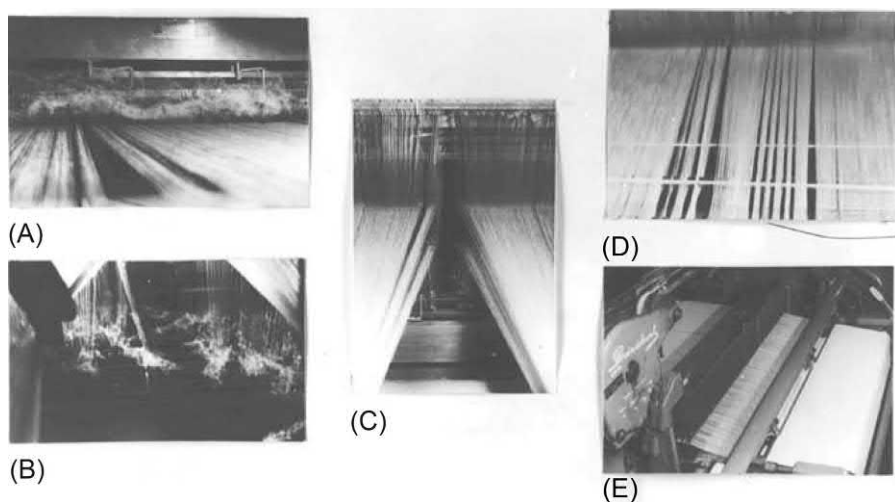


Fig. 4.5 (A) and (B) fibre removed from unsinged sized yarn with only 0.8% of size collected on top and bottom of the heald shafts, respectively, (C) and (E) heald shafts free from fibre deposit when weaving singed unsized yarn, and (D) singed unsized warp at the back of the loom free from entangled fibres.

In another weaving trial, an unsinged sized warp had only 0.8% of size applied to it. During weaving, a significant number of fibres were detached from the warp as a result of yarn-on-yarn abrasion (Fig. 4.5A and B). This significant undersizing caused many problems during weaving. The trials confirmed that it is the initial hairiness of the yarn which impedes the weaving of spun yarns in their unsized state. An ideal percentage of size must be applied to single spun yarns to improve their abrasion resistance and fatigue properties if weaving results of a high standard are to be obtained.

4.1.4 The sizing process

Preventing the protruding hairs from entangling with each other and improving the yarn's abrasion resistance is achieved by applying an adhesive (starch) paste around the yarn surface. This is prepared by boiling suitable starch material in water along with other ingredients which are used to enhance the film properties. The process known as 'cooking' prepares the size paste to a viscosity which will have a significant effect when applied to the yarn.

The application of the adhesive involves immersing the warp yarns in the size paste. The surplus is squeezed out, the warp sheet is dried, then the yarns are separated and wound onto the weaver's beam. After drying, a film of starch is left around the yarn surface and it is this film which improves the abrasion resistance of the yarn. It also enhances its tenacity and fatigue properties as well as the elasticity to withstand the stresses of the weaving process.

4.1.5 Size ingredients for yarns

The main ingredients used in sizing cotton warps are adhesives (starches) and lubricants/softeners.

4.1.5.1 Starch adhesives

Most adhesives used in sizing are starches. Starch is a hydrophilic polymer which is readily influenced by moisture or water. The adhesion capacity of the sizing product is important. Starch, a natural product obtained from several sources, is still the major sizing ingredient in the formulation of size paste along with other materials, the use of which depends on many factors. Starch is used for fibre-to-fibre cementing action and for laying the protruding hairs firmly on the yarn surface. A number of natural starches are available, that is, sago, potato (farina), maize, tapioca, wheat, and rice. Starches vary widely in their physical properties, exhibiting differing adhesion, viscosity and other characteristics. The most commonly used are sago and maize. In general, sizes of low viscosity are chosen as they are easier to handle, the take-up of paste is smaller and thus the drying of the warp sheet is easier. It is also more economical and achieves better penetration into the sheet and into individual yarns. However, high viscosity is an advantage in certain applications where only a low, or very low, concentration is necessary and the yarn is of a type in which surface coating rather than a high degree of penetration is of value.

4.1.5.2 Modified starches

Modified or water-soluble starches have a number of advantages over unmodified starches. These include uniformity, size consistency, ease of removal, and a shorter preparation time. While the modified starches as a whole have adhesive properties similar to those of the natural starches from which they are derived, they fall short in their film-forming properties. To compensate for this, other film-forming substances such as water-soluble ethers and polyvinyl alcohol (PVA) are used as film strengtheners and binders with modified starches. Starch ethers are excellent water-soluble sizing materials. Solvitoses are important members of this group which require mild de-sizing treatment.

4.1.5.3 Thin boiling starches

Thin boiling starches are also known as soluble, high-fluidity, or oxidized starches. Fluidity is the reciprocal of viscosity, so a starch with low viscosity has high fluidity. Once the thin boiling starch mixture has reached its required viscosity, it will remain more stable than a raw starch mixture, reducing only slightly in size viscosity. Most of the soluble starches are made from corn starch but other starches may also be used. Starch is added to water and is usually treated with chemical agents which tend to oxidize the starch while it is in a water solution. These starches usually produce a more flexible film and are suitable for the sizing of fine counts of yarn.

Thin boiling starches are converted to more soluble types by acid hydrolyses. These are necessary when sizing heavy yarns for penetration and binding power. In principle, they are used to obtain more weight or a thicker film on the yarn. They need less cooking time than regular starches to stabilize the viscosity [4–6].

4.1.5.4 *Size materials for synthetic/filament yarns*

Filament yarns are composed of continuous filaments aligned in parallel rows which run straight except when they are coiled by the insertion of a twist, giving the yarns an appearance of evenness, smoothness, and the absence of hairiness. Most of the filament yarns may not require sizing. However, sizing improves their efficiency by a further 15%–20%. Sizing improves the frictional resistance of the yarn and bonds the filaments which prevent the peeling back and intermingling of any broken filaments which are present on the yarn before weaving or may break during weaving. In order to achieve this, the selected size must have sufficient adhesion to the fibre to make the filaments cohere.

Requirements for sizes for the treatment of synthetic yarns are different for continuous filament and for spun yarns. Continuous filament yarns (a) have a strong cohesion due to continuity of their filament, (b) possess good elastic behaviour to cyclic extension, and (c) have a higher degree of elongation. Spun yarn has a greater capacity than continuous filament yarn for absorbing size. The traditional starch-based size material suitable for spun yarn has inadequate adhesion to smooth synthetic fibres and cannot be used successfully on synthetic yarn/filament yarn.

Size materials adapted to the specific properties of the fibres are used for synthetic yarns. The choice of the correct size material depends on the type of synthetic yarn, that is, polyamide, polyester, etc. A satisfactory size recipe for filament yarn, in addition to providing a good adhesion to the yarn, should possess good film-forming properties. It should also impart strength, elasticity, resilience, and lubricating properties to the yarn [7].

The film-forming materials used for filament yarns are generally high polymeric substances capable of being dissolved in water or some other suitable solvent. They are classified into three main groups:

- natural polymer (protein group)
- regenerated polymer
- synthetic polymer

Table 4.1 lists the classification of sizing materials available for the sizing of filament yarns [8].

4.1.5.5 *Sodium carboxymethyl cellulose*

This is a cellulosic adhesive, water soluble, and capable of being easily removed from the cloth during finishing. It is supplied in a range of viscosities and has a high film strength and considerable adhesive power. It can be mixed with PVA and in conjunction with modified starch and PVA, can be used on spun viscose and acrylic fibre.

Sodium carboxymethyl cellulose (SCMC) produces a tough, clear, and flexible film. It tends to absorb and hold moisture so its water binding ability makes the need for high

Table 4.1 Classification of sizing materials.

Generic name	Examples	Fibre
Natural polymers	Gelatin Modified starches	Acetate and viscose Viscose, glass
Regenerated polymers	Gums SCMC ^a	Viscose Viscose
Synthetic polymers	PAA ^b Vinyl copolymers ^c PVOH (PVA) ^d	Polyamide, acrylic Polyester, acetate, acrylic Viscose, acetate, polyamide, glass

^aSodium carboxymethyl cellulose.^bPolyacrylic acid.^cAcrylic copolymers, vinylacetate copolymers, styrene copolymers.^dPolyvinyl alcohol.

humidity in the weaving room less critical than with other sizes. In solution, the viscosity of SCMC is decreased by raising the temperature and increased by lowering it [4, 5].

4.1.5.6 Polyvinyl alcohol

PVA is synthesized from petroleum and produces size films that are very strong, have good abrasion resistance and are easily de-sized in hot water. It is basically a synthetic polymer resin and can be used satisfactorily on spun yarns in conjunction with soluble starches.

4.1.5.7 Polyacrylic acid for sizing

This is an excellent adhesive for spun nylon yarns and can be used in the sizing of hydrophobic fibres and their blends such as nylon, acrylics, acetate, polyester, etc. The size gives good binding to these fibres and can also be made water insoluble, permitting their use in water-jet weaving applications [9].

4.1.5.8 Lubricants and softeners

When applied on its own, starch tends to make the yarn somewhat harsh and brittle which is detrimental to the yarn during the weaving process. To overcome this, lubricant/softener materials are added to the size paste. Their use reduces friction between yarn-on-yarn, reed-on-yarn, and heald-on-yarn, which facilitates the beat-up of the weft. They also reduce the dusting-off due to easier and better separation in shedding. Softeners give a soft handle to the yarn, and help decrease the brittleness of size film, reduce abrasion resistance, increase elasticity, improve size penetration, and reduce the sticking of yarns in the warp sheet and on the drying cylinders. Softeners also tend to lubricate a yarn and allow it to slide through the various parts of a loom without chafing. The most common lubricants are tallow, spermaceti, and paraffin wax. Emulsified tallow and soluble mineral oils are sometimes used [5, 10].

Tallow is probably more extensively used as a softening agent than any other material. It acts as a lubricant as well as a softener. Its proportion in the size paste is

generally between 8% and 10% of the dry weight of the adhesive used. Other common softeners such as castor oil, glycerine, and paraffin wax are also used. Glycerine is an excellent softener as it possesses the desired softening qualities and is hygroscopic in nature, thus maintaining a high regain in the yarn. Caution is required in the use of softeners. If used in quantities in excess of 8%–10% in weight of the starch, they will tend to weaken the size film and its strength and abrasion resistance.

4.2 Characteristics of a good sized yarn

The primary characteristics of a good size are

- tensile strength and elongation
- flexibility
- adhesion
- proper viscosity
- removability
- consistency
- abrasion and sticking resistance

The secondary characteristics of a good size are

- transparency
- resistance to mildew and bacteria
- cost
- lack of odour
- softness
- lubrication
- noncorrosive and nonabrasive to machine parts

The most important of these characteristics which contribute the most to weavability in sized warp yarns are

- substrate adhesion
- elongation
- flexibility
- viscosity
- desizability
- abrasion resistance

4.3 Size mixtures: Composition and quality

Size mixtures, their composition, and the quantity to be applied to the yarn depend on many factors and conditions and may vary significantly. The most important factors to be considered are

- Type of yarn (i.e., counts, material, and turns/metre): a size mixture may be required to size a high-twisted, high count yarn efficiently, while another mixture may be required for a soft, low-twist, low count yarn. Each yarn is used for an entirely different purpose and should

fulfil all the requirements. The size mixture for each type of yarn is varied for the appropriate characteristics.

- Fabric parameters (ends and picks per centimetre): the higher the number of picks per centimetre in the fabric, the greater is the amount of heald-on-yarn and reed-on-yarn abrasion for each inch of woven cloth. This is because the warp yarns are not drawn forward as rapidly as they are in cloth having a low number of picks per centimetre, and the reed moves forward and backward a greater number of times during the beat-up operation. During this operation, the reed dents severely abrade the warp yarns. Similarly, the higher the number of ends per centimetre in the warp, the greater is the yarn-on-yarn abrasion and friction during the shedding process when the healds change their positions. Therefore, if yarns are to withstand the strain and abrasion forces under such conditions, they will normally require a greater amount of size.

There is no single sizing ‘recipe’ which is valid for all processes. A recipe suitable for the sizing of all cotton-warp yarns, or blends or synthetic yarns cannot be formulated because of the multiplicity of the fabric constructions and yarn compositions and the different types of weaving machinery. The size recipe and the amount of size deposited on a yarn will vary according to the abovementioned conditions, along with the type of loom used.

4.3.1 Quantity of size mixture applied to the yarn

It has been established that it is impossible to weave single spun yarns without the application of size. The question arises as to the quantity of size applied to the yarn. If too little is applied, the warp would perform better than in an unsized state but problems would remain which prevent successful weaving. If too much size is applied, it will seriously affect breaking extension and flexibility, so leading to an increased number of warp breaks and a loss of productivity. This suggests that there is an ideal amount of size application for optimum results in weaving.

If the warp breakage rate were studied in similar warps sized to varying percentages, it would be found, as shown in Fig. 4.6 that the warp breakage rate is reduced as the percentage of size is increased [6]. This is due to reduction in yarn hairiness and a significant improvement in the yarn abrasion resistance due to the coating of size film as well as to an increase in yarn strength.

The reduction in warp breakage rate with an increase in the addition of size reaches a point beyond which any further addition of size will not show a significant improvement in yarn performance on the loom. In fact, it will tend to increase the number of warp breaks. An excessive size add-on leads to an increased penetration of the size inside the yarn structure, which significantly decreases the yarn’s breaking extension. Between the two extremes, a certain size percentage gives the minimum breakage rate and this percentage is called the optimum or ideal size percentage for application to the yarn. The curve plotting the breakage rate against the percentage of size on the warp is defined as the ‘sizing-weaving curve’. Warp breaks are generally expressed as breaks/1000 ends/10,000 picks.

The weaving efficiency, which is inversely proportional to the warp breakage rate, reaches its peak when the warp breakage rate is at its minimum. The highest weaving efficiency consistent with the optimal addition of size is usually achieved by trial and

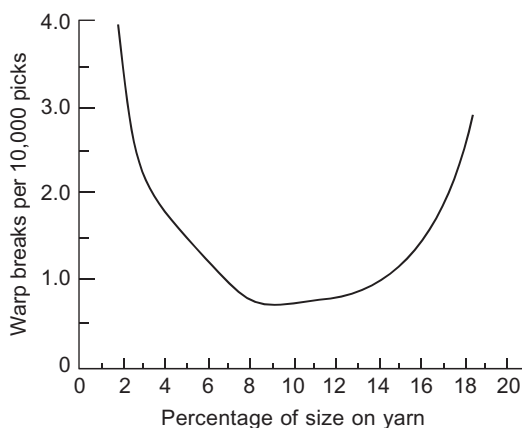


Fig. 4.6 Sizing-weaving curve.

error [11]. In practice, it is not simple to identify the ideal size percentage for achieving optimum weaving results for a particular fabric style. The relationship between warp breaks and the amount of size on the yarn will vary greatly, depending on the composition of the size, the type of yarn, the fabric particulars, pickup of size paste from the size box, type of loom, and many other factors.

4.4 Effect of size on adhesion between fibres in the yarn structure

On the basis of information gathered while weaving unsized yarn, it is obvious that sufficient interfibre adhesion is required to prevent the hairs being pulled out. This is achieved by adding a suitable percentage of size to the yarn. The size forms bonds between the fibres (Fig. 4.7A) and the strength of the bonds depends on the type of size used. A breakdown between fibre and size or in the size itself reduces the adhesion between fibres, making them liable to be pulled out from the yarn structure. This causes yarn breakage. An investigation into the value of this function of sizing was carried out. The amount of force required to extract individual hairs from unsized yarn and from yarn with different degrees of sizing, using sago as the adhesive, was taken as the criterion to evaluate the effect of size on adhesion between fibres. This force was measured on the Instron tensile strength tester, as shown in Fig. 4.7B.

A single hair, over 3 mm in length, was taken at random from a 20 cm length of yarn surface and gripped by the jaws. As can be seen from the figure, when the hair is pulled, it does not remain perpendicular to the yarn axis as the force increases. The angle between the hair and the yarn axis changes constantly and is difficult to observe at the instant when the hair either breaks or is detached. Therefore, the force required to pull the hair is defined as the component at right angles to the yarn of the tension in the hair.

Results from 100 tests carried out are summarized in Table 4.2. Some hairs were pulled out completely, but others broke only when partially extracted. With unsized yarn, some hairs, between 5 and 20 mm in length, were pulled out without registering

Fig. 4.7 (A) Size film bonds being formed between fibres and (B) hair being pulled out from the yarn.

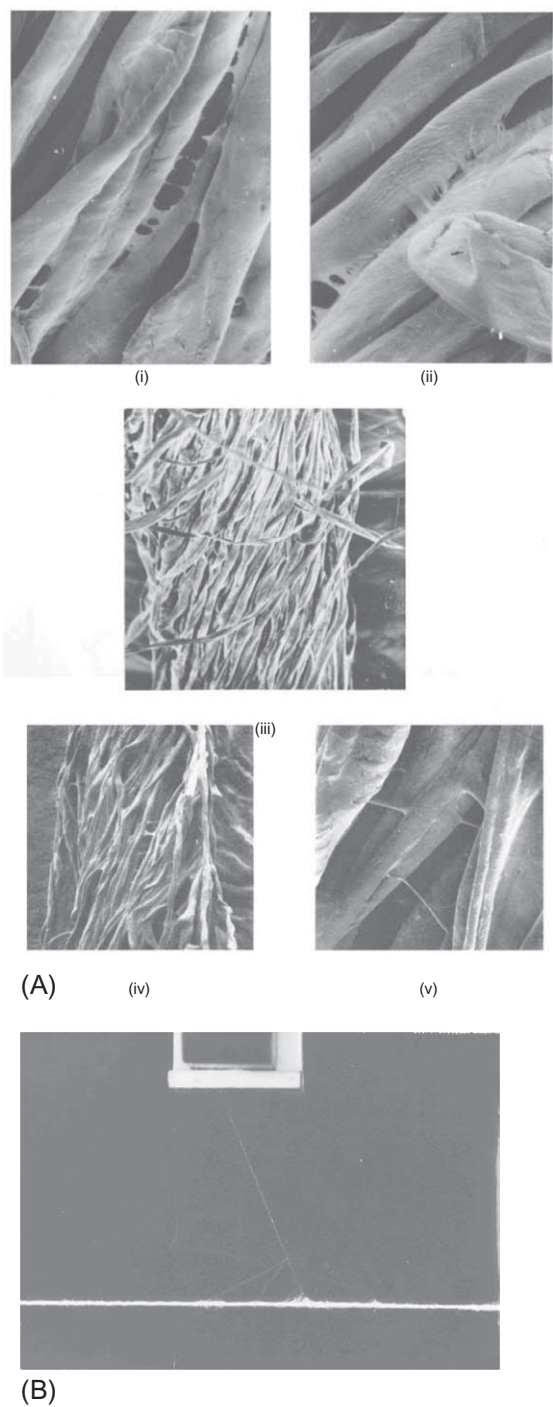


Table 4.2 Force required to pull or break a hair from the yarn structure following single-end sizing.

Force required to			% Hairs		Average length of hairs removed from yarn when	
Size added to yarn (%)	Pull out the hair (gf)	Break the hair (gf)	Pulled out	Broken	Pulled (cm)	Broken (cm)
0	2.0	3.7	54	46	1.30	1.23
7	2.6	4.18	16	84	1.16	1.0
14	3.0	4.0	7	93	1.0	0.78
21	4.4	4.78	5	95	0.9	0.7

Size formulation: sago/tallow (10:1). Yarn: cotton, open-end spun, 38 tex.

any force. It is presumed this could happen with loose hairs (wild fibres). The number of hairs completely pulled out from the unsized yarn with a force of 0.1–1.0 gf was found to be 33%. With an addition of 7% size, all hairs were anchored to the yarn and none of the hairs were pulled out or broken from the sized yarn in the above range of force. Although a significant increase in the average force required to pull out or break a hair from sized yarn was observed when compared with unsized yarn, it was found that this increase was not proportional to the amount of size added to the yarn. No significant difference was observed between yarn with 14% of added size and that with 21% in respect of the ratio of the number of extracted to broken hairs or to their average length.

The results suggest that beyond a certain point, the further addition of size does not significantly increase adhesion between fibres. Thus, any additional amount of size added to the yarn in excess of that ideally required will not serve any useful purpose. It is also likely to decrease the yarn’s breaking extension, so leading to a higher warp breakage rate during weaving.

4.5 Size paste preparation: Cooking

Size preparation (also known as cooking) is carried out in large wooden or stainless steel kettles fitted with suitable types of agitators to stir the paste.

Depending on the concentration of the size paste, the required quantity of water and size materials are mixed in the kettle and the solution is cooked by injecting steam. The viscosity is controlled and when the size is cooked to the required degree, it is transferred to storage tanks from where it is then pumped into the size box to the sizing machine.

Pressure cookers are also used for cooking size paste. These substantially reduce the cooking time for starch, especially for unmodified starch. Water and size ingredients are added to the vessel and boiled. The steam inside is allowed to build up

the pressure to a desired level which is maintained for the required period. When the cooking is complete, the paste is transferred to a storage tank from where it is pumped to the sizing machine.

A number of size preparation systems have been developed to allow quick cooking of starches to a reasonably low and stable level of viscosity. These systems have been automated to a certain extent and are effective not only with starch, but also with ingredients which are not easy to mix.

4.5.1 Preparation of size paste when supplied in liquid form

Some sizes are supplied in liquid form for special usage. These are not heated during preparation and the vessels required can be very simple. From a main storage tank of size, specified quantities are passed to a preparation vessel, mixed with water and (if necessary) a suitable lubricant, and then after agitation the size will be ready for use.

4.6 Sizing machines

Fig. 4.8A shows a typical two-cylinder sizing machine which was in use a few decades ago but is now obsolete. Cylinders of different dimensions were used but the typical arrangement was a large cylinder about 7 ft. in diameter and a smaller one with diameter of about 4 ft. The width varied according to the width of the sizing machine and the production requirements of the individual mill. The cylinders were steam heated and the drying temperatures varied from 100°C to 105°C, depending on the yarn count, density of the warp being sized, the machine speed and the percentage of size applied, etc.

Fig. 4.8B is a schematic diagram of a modern seven-cylinder sizing machine for spun yarns [12]. Most modern machines, depending on various factors, are capable of working at 100–120 m/min. On any sizing machine, the warp has to pass through five zones or sections: the creel, the size box, the drying cylinders, the leasing section, and the headstock.

4.6.1 Creel section

This is the first section of a sizing machine and is located at the back of the machine to accommodate the warper's beams. There are various creel designs commonly in use on modern sizing machines. In the over/under creel design, the beams are positioned as shown in Fig. 4.9A. This type of creel is preferred when the warper's beams commonly used for sizing of spun yarns of cotton and synthetic fibres are exactly the same length [6]. Warp ends in sheet form are drawn from the first and second beams, then drawn forward and combined with the third beam. The process is continued until all the ends have been collected from all the beams in sheet form which is then fed into the following section of the machine, which is the size box.

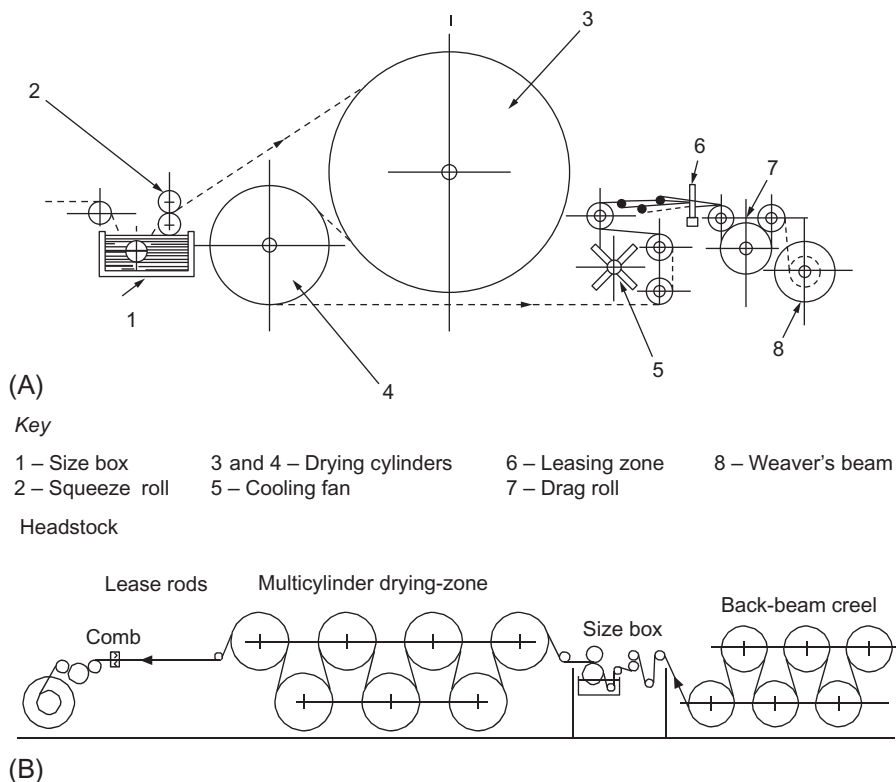


Fig. 4.8 (A) Schematic layout of two-cylinder sizing machine and (B) schematic layout of a modern seven-cylinder sizing machine.

When the warp is drawn forward from the back beams, it is leased. Lease strings are placed between the yarn sheets from each beam and the yarns are drawn forward until the lease strings reach the headstock of the machine. At this point, the lease strings are removed and split rods (lease rods) are inserted in their place [13]. Fig. 4.9b shows other designs [6] of creel, methods of collecting warp ends from the back beams and feeding all the yarns in a sheet form to the size box.

4.6.2 Size box

The size box (Figs 4.8A and 4.10A) consists of an immersion roller, steam-heated pipes, and a pair of rollers known as the size roller and the rubber-covered squeeze roller [12, 14]. The configuration of the size box may vary, but its basic function is to apply the size paste to the yarn. As the warp sheet enters the size box, it is passed under the immersion roller which impregnates the warp sheet with the size solution. The immersion roller can be raised or lowered as required. The depth of the immersion in the size solution and the speed of the machine govern the actual time the yarn takes

to pass through the size box. The longer the yarn is in contact with the size solution, the more size it will absorb. In general, the greater the speed of the machine, the higher will be the take-up of size paste.

The size paste is kept at a desired temperature by means of steam passing through the perforated steam pipes. Usually, the higher the temperature of the size paste, the greater the degree of size penetration into the yarn structure. The warp loaded with size paste is then passed through the nip of the size and squeeze rollers.

In a size box, there may be either one pair of squeezing rollers or a double squeezing roller. In the double squeezing process, the yarn is immersed twice. Some modern sizing machines are equipped with several size boxes. The purpose of extra immersion and squeezing is to facilitate as full a penetration of the warp sheet as possible. The squeeze rollers on modern machines are covered with rubber of shore hardness 45°. Rubber rollers on modern machines often have a basic weight of 230–320 kg with extra loading facilities to increase the effective weight well beyond 450 kg [5].

The squeeze roller exerts a defined amount of pressure on the warp sheet so that most of the excess size is squeezed off the surface of the yarn and a certain amount of penetration into the yarn also takes place (Fig. 4.10B) [5]. Thus, a sized yarn has a coating of size film and penetration of adhesive into the yarn structures. The amount may vary. Penetration of the adhesive into the yarn structure prevents disintegration

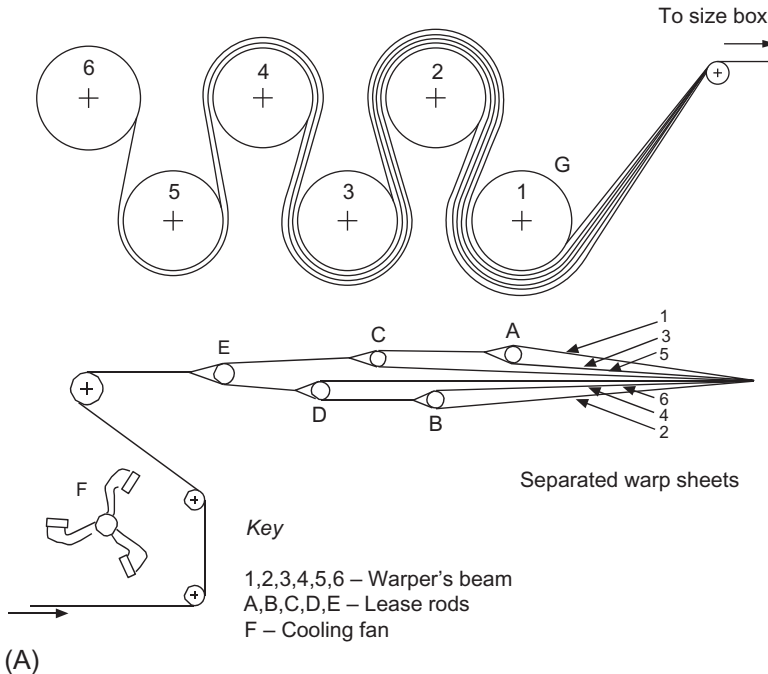


Fig. 4.9 (A) Over and under (zigzag) creel and

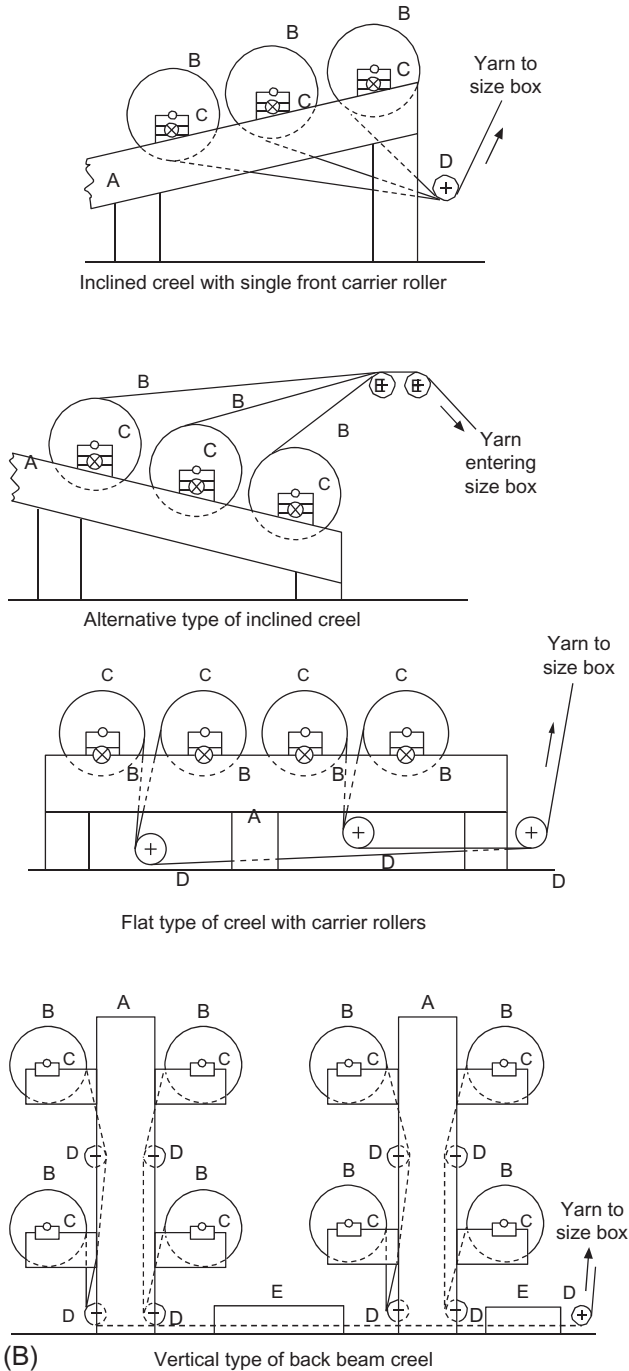


Fig. 4.9, cont'd (B) different creel designs.

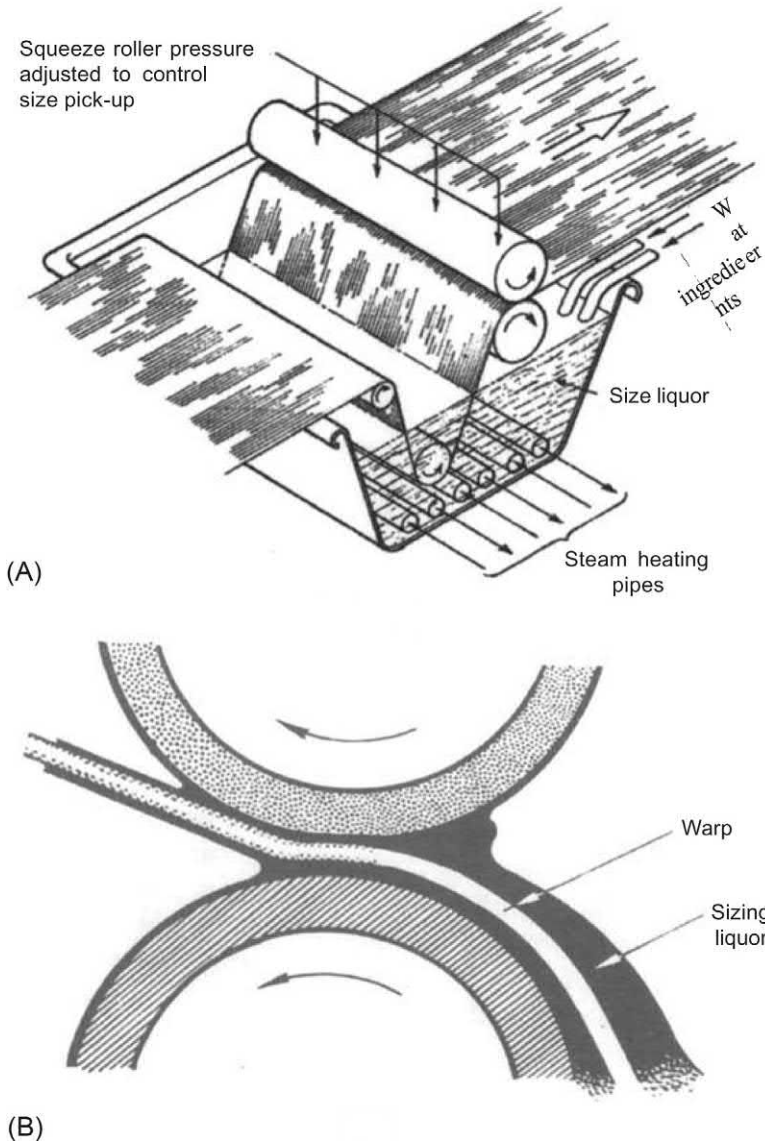


Fig. 4.10 (A) Size box of a sizing machine and (B) schematic representation of squeezing roller action.

on occasions when the outer coating fails to withstand the forces of abrasion. It also binds the fibres and prevents them being pulled out. Coating helps to lay the fibres, reducing the hairiness of the yarn and affording initial protection against abrasion.

The pressure exerted by the squeeze roller has a direct effect on the amount of size picked up by the yarn. The heavier the pressure, the lower the pickup. A slight increase in penetration is more than counterbalanced by the extra size removed from the surface of the sheet of threads by the higher pressure. Increasing the weight or pressure of the squeezing roller tends to decrease the amount of size added to the yarn. By using a higher concentration of size and a heavier roller, the same percentage of size can be applied to the yarn as with a lower concentration of size and a lighter roller. Less water will be picked up by the yarn so it will require less drying and the machine speed can be increased accordingly. An increase in roller weight from 90 to 227 kg reduces the percentage of size required in pure sizing by about one-fifth [6].

4.6.3 Assessing size box performance: Size concentration, pickup, and percentage of size on yarn

There are a number of variables to consider in assessing size box performance:

- *Size concentration* is defined as the percentage of oven-dry sizing material in a given quantity of size or paste.
- *Pickup of paste* is the number of kilograms of size paste on 100kg of oven-dry yarn as it leaves the squeeze rollers. The most accurate way to find the pickup is through laboratory determinations of concentration and percentage of size. Then,

$$\text{Pickup} = \frac{\text{Size percentage on yarn}}{\text{Size concentration in box}} \times 100$$

- *Percentage of size on yarn* is a product of (a) concentration of the sizing paste and (b) take-up of paste as the yarn leaves the squeezing rollers. The percentage of size on yarn can be calculated as follows:

$$\% \text{ of size on yarn} = \frac{\text{Size box concentration of size (per cent solids)}}{1} \times \frac{\text{Pick - up of paste}}{100}$$

If the size concentration is 9.0% and after squeezing, 110kg of paste is left on 100kg of unsized yarn from the beams, the percentage of size applied to the yarn would be: $9 \times 110/100 = 9.9\%$. If the amount of size paste picked up by the yarn is 150kg, then the percentage of size on the yarn will now be $9 \times 150/100 = 13.5\%$. This shows how important it is to keep the desired percentage of paste pickup by the yarn if the right percentage of size on the yarn is to be achieved.

The amount of paste picked up by the warp and the final percentage of size on the yarn depend on many factors. These are given in Fig. 4.11 [7]. Fig. 4.12A and B shows the cross sections of sized yarns, the penetration of size into the yarn structure, and the varying amount of coating around the yarn [3].

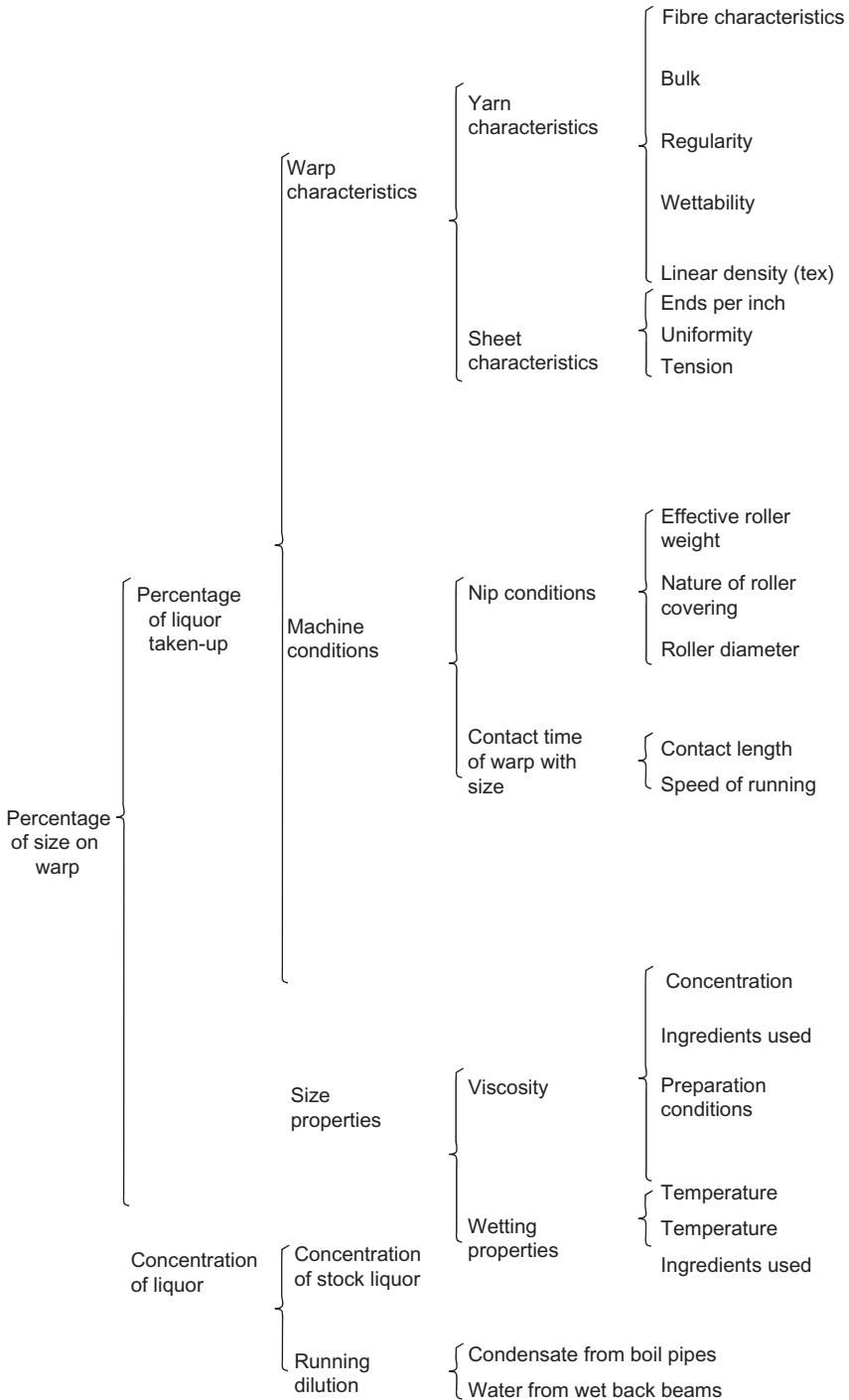
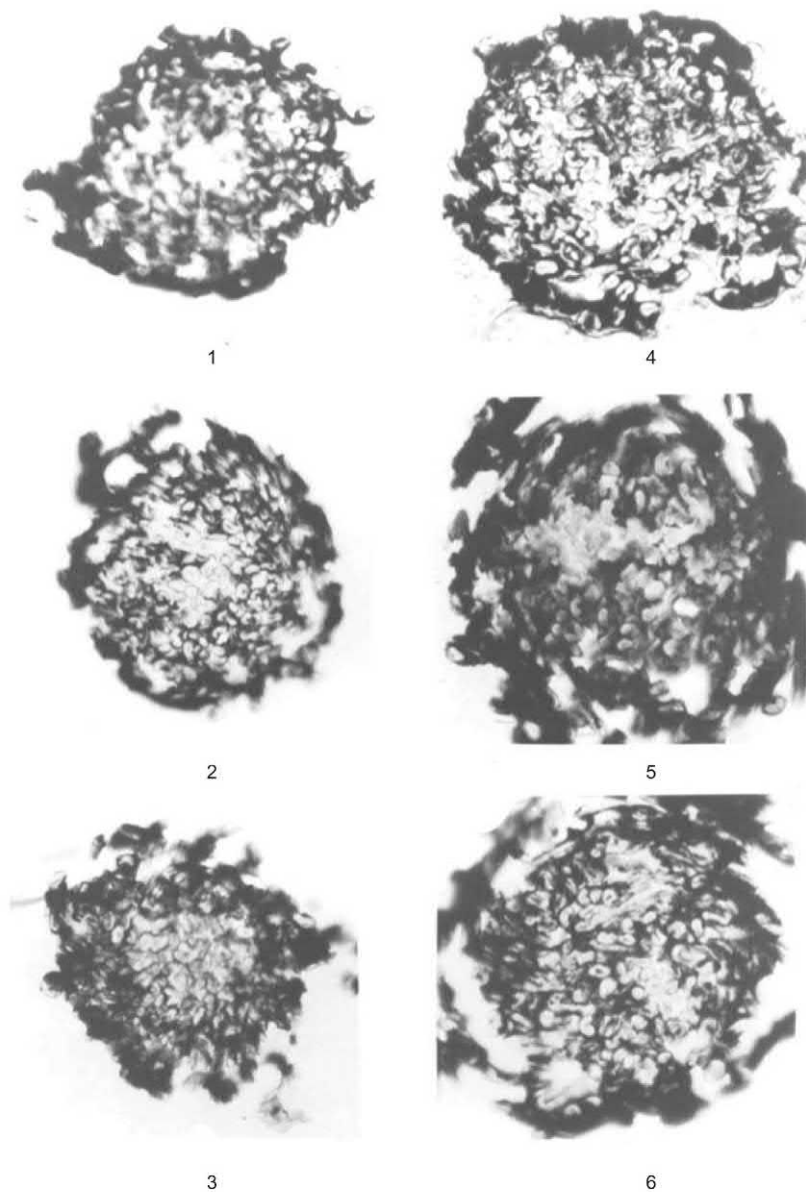


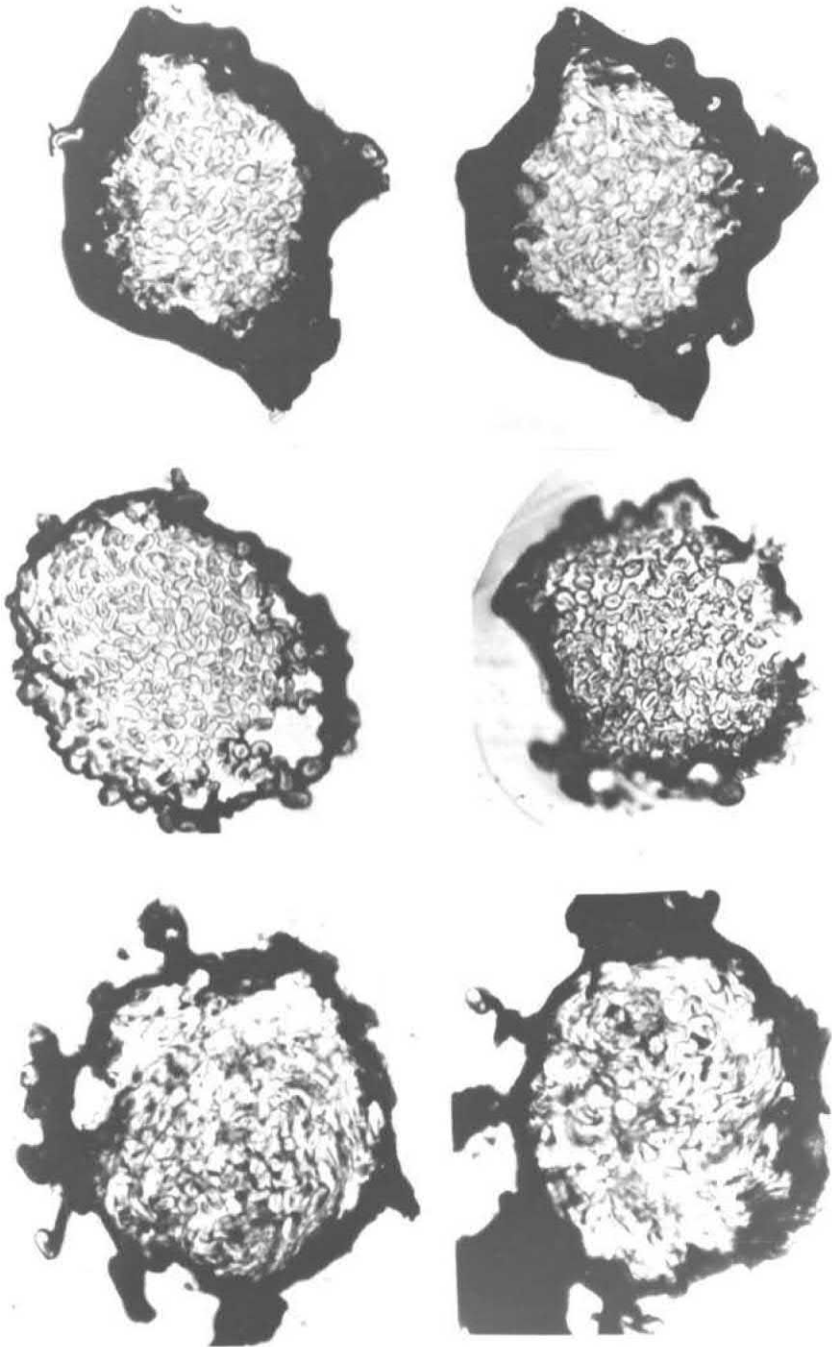
Fig. 4.11 Factors affecting the percentage of size applied to a warp.



Key:
1,2,3 – Ring-spun yarns
4,5,6 – Open-end yarns

(A)

Fig. 4.12 (A) Cross sections of sized yarns. Size paste cases have penetrated the yarn structure



(B)

Fig. 4.12, cont'd (B) cross sections of sized yarns with varying degree of coating (*in black*) of size film rather than penetration of size into the yarn structure.

4.6.4 Drying section

Sizing machines are usually defined by the method by which the yarn is dried. Two techniques for drying the wet warp are normally available:

- *Hot-air drying*: in hot-air sizing machines, the wet warp is dried using hot air in an enclosed chamber through which the warp sheet is passed. The yarn is dried on all sides at the same time rather than on one side as in the case of a cylinder drying machine. The air is heated either by electric coil or steam. One drawback of the hot-air sizing machine is its lack of heat efficiency. It is claimed that the fuel costs for hot-air drying are at least 40% higher than for equivalent drying by heated cylinders. Also, hot-air drying takes up more space and takes longer to cooldown. Therefore, the conduction method using cylinder drying is most commonly used [15].
- *Cylinder drying*: as the wet warp sheet leaves the size box, it is passed around the drying cylinders (Fig. 4.8A and B) which are heated with steam. The warp is pressed against the surface of the heated cylinder under pressure which is controlled largely by the tension in the warp sheet. The drying capacity of the sizing machine is defined as the weight of water which the machine is capable of evaporating in a given time. A nine-cylinder sizing machine, working at 2.8 kg cm^2 steam pressure would be expected to have a capacity to evaporate 570 kg of water per hour. About 75%–80% of the total energy used in the sizing process is consumed in drying the wet warp sheet loaded with size paste. The number of cylinders on a cylinder drying machine can vary from two to 32 cylinders, with four or more size boxes to facilitate the application of multiple layers of sizing material to the warp yarn [5, 11].

The following factors affect the rate of drying of a warp passing over steam-heated cylinders [15]:

- number of cylinders and their dimensions
- pressure of the steam in cylinders
- pressure of air in the steam
- thermal conductivity of the cylinder wall
- warp tension (pressure of warp on cylinders): the higher the tension, the greater the rate of drying
- degree of drying of the warp
- size concentration
- number of ends in the warp and the material

The drying process governs the properties of the size film – its elasticity, plasticity, and flexibility. Drying the warp needs careful attention as an over-dried warp would tend to become brittle and harsh, whereas under-drying would produce a sticky warp and increase the number of warp breaks during weaving. Some multicylinder machines are provided with individual temperature controls for each cylinder. In others, temperature control over the whole range of cylinders is obtained by fitting a special type of pressure regulating valve. A moisture regain of nearly 7% is recommended in the sized yarn. All modern warp sizing machines are installed with moisture measuring equipment. Typical cylinder temperature figures for a seven-cylinder filament and spun yarn sizing machine are shown in Table 4.3 [10].

Table 4.3 Cylinder temperatures for filaments and spun yarn sizing (°C).

Yarn type	Material	Cylinder number							Mean temp. (°C)	Max. temp. (°C)
		1	2	3	4	5	6	7		
Filament	Polyester	75	95	115	115	115	95	75	98	115
	Viscose	80	90	115	110	110	90	80	96	110
	Acetate	70	80	100	100	100	80	70	86	100
	Nylon	85	95	100	110	110	100	90	99	110
Spun		Group 1		Group 2		Group 3				
	Cotton	140	140	140	140	140	140	140	140	140
	Viscose	120	120	120	120	120	100	100	114	120
	P/Cotton	110	110	120	120	120	100	100	111	120
	P/Viscose	110	110	110	110	110	100	90	106	110

Note: Cylinder no. 1 situated next to size box.

4.6.5 Leasing section (splitting)

As the warp sheet is dried, there may be adhesion between individual yarns. It is of the utmost importance to separate each sized end of yarn before the warp can be used in weaving. This is done in the leasing section, using a series of rods of varying diameter. The number of lease rods is generally one less than the total number of warp beams in the creel. The arrangement is shown in Fig. 4.9a where the back beams are numbered 1–6, respectively. The sheets of yarn from each beam, after being divided by the lease or splitting rods A, B, C, D, and E, are numbered 1, 3, 5, 6, 4, 2 to indicate their positions at the headstock [6]. The splitting rods extend the full width of the machine and are housed in brackets for easy removal. The separated yarns are passed through an expandable comb to maintain the division of the sheet into separate ends and to position them for winding.

4.6.6 Headstock

The final section of the machine is the headstock. This consists of two small guide rollers and the main draw (drag) roller as well as a unit to support weaver's beams of varying widths (Fig. 4.8B). The warp sheet is guided around the draw roller as it emerges from the comb. It is then wound onto the weaver's beam, the surface speed of which is kept constant so the yarn can be wound at a consistent tension from start to end of the beam. When the required length of warp has been wound, the warp is cut and a new empty weaver's beam is positioned in its place to continue the process until the desired number of beams has been produced. The warp yarn wound on the weaver's beam is then ready for the drawing-in process. This consists of drawing the yarns from drop wires, healds, and reed, after which they are taken to the back of the loom, ready for weaving.

4.7 Yarn stretch during sizing

During sizing, the yarns are kept under tension, even on a positively driven sizing machine. This results in a slight permanent stretch in the yarn with a resultant decrease in the extensibility or elongation at the breaking point of sized yarns. A useful conception of stretch is that of the amount of elongation which occurs in, or is imposed upon, a given length of warp as it passes through the various zones in a sizing machine [15].

Stretch is usually expressed as a percentage and the quantity can be either positive or negative. A negative value of stretch implies the opposite of an elongation, that is, a shrinkage. The greater the yarn stretch, the higher the loss in extensibility of the yarn. This causes a higher rate of end breakage during weaving. The extensibility of the sized yarn is controlled by ensuring that the stretch during sizing is 2% or less. Loom performance deteriorates significantly if this is exceeded.

There are five main zones where stretch is applied:

- creel zone – between the last warper's beam and the first guide roll in the size box
- size box and first drying cylinder – wet stretch
- drying zone
- splitting zone – from the last drying cylinder to the drag roll
- winding zone – between the draw roller and the weaver's beam

Stretch in the creel zone should be no more than 0.5%. Wet stretch should be as low as possible and up to 1.5% in the drying and splitting zone. Tension control in the drying area is very important since it governs the elastic properties of the sized warp. There should be no stretch in the winding zone.

4.8 Automation controls of sizing machines

A modern sizing machine may supply sized warps for 300–500 looms and just 1 h of substandard work in sizing may produce hundreds of metres of poorly sized warp. This may result in weeks of poor work, loss of production, waste of material during weaving, and consequent dissatisfaction for both labour and management. Therefore, on grounds of economics alone, the preparation of efficiently sized warps is essential.

To meet this objective, most modern sizing machines are equipped with the following automatic controls [10]:

- pneumatic creel loading to control tension
- temperature of size box
- size box level
- squeeze roller pressure and stretch control
- speed of drying cylinders relative to draw roll
- temperature of drying cylinders
- moisture content of sized yarn
- beam tension between beam and draw roll
- beam pressure – roll loading

4.9 Developments in warp sizing

‘Well sized is half woven’ is true in every sense. In the days when the microprocessors and electronics technology were not available, quite often sized warps of poor quality were produced. Significant developments in shuttle less weaving have imposed the strongest demands on the quality of sized warps, especially for air jet weaving, which require even-sized warps and even moisture percentage and elongation, with least hairiness and yarn breakage.

The production of quality sized warp is, therefore, of paramount importance. To meet the needs of shuttleless looms and improve the quality of sizing on the whole, sizing machine manufacturers have over the years concentrated on using and incorporating microprocessors and electronics technology in the design of their sizing machines. Significant interesting developments have taken place in the last two decade in the structure and design of different sections of the sizing machines leading to incorporation of many automatic functions as integral part of the machine. These functions control the following factors which significantly affect the quality of sized warps:

- tension in the creel zone
- stretch between all zones
- size temperature

- size level
- squeeze roll pressure as a function of the machine
- size added on to the yarn
- size viscosity and concentration
- drying temperature
- moisture
- tension in the wet and dry zones
- beam winding tension
- wet splitting
- uniform hardness of the beam produced

Apart from the different levels of automatic functions that are incorporated in a modern sizing machine, most of the leading sizing machine manufacturers also tend to design the machine which offers:

Documentation of all the sizing processing values by the computer in a line chart. The software used by the individual machine manufacturers enables all the vital machine processing parameters to be set and displayed, saved, and recalled at any time. However, the degree and level of automation of various functions varies from one manufacturer to another.

At Itma 2015, with the exception of few manufacturers who exhibited some sections of their sizing machines, others were only marketing the machines through brochures. In this section, the author has presented his views on the incremental developments in sizing on the basis of information that he gained from the representatives of the manufacturers and the brochures handed over to the author.

In the following sections are covered the incremental developments incorporated in the different sizing machines that are available from the respective manufacturers.

4.10 Karl Mayer sizing machine PROSIZE

Karl Mayer from Germany were marketing a breakthrough innovation in their sizing machine PROSIZE (Fig. 4.13) [16] by developing unique new size boxes type VSB with patented size application system and feeding unit and type HSB with patented size application system prewetting unit. These integrate the patented size application system. The PROSIZE allows the highest process quality, using the minimum size liquor volume.

4.10.1 Newly designed size boxes VSB and HSB

The innovative size boxes operate with no immersion whatsoever. It consists of three highly turbulent, uniform application zones with patented application/squeeze rollers and a spray bar technology (Figs 4.14 and 4.15) [16]. Applying the size from the spray nozzle under pressure results in an extremely uniform application. This is due to uniform concentrations, temperatures, and viscosities as a result of the high size circulation rate. The uniform liquor application also enables the double size box to be converted to a single size box – a switch that makes further processing even more



Fig. 4.13 Sizing machine PROSIZE.

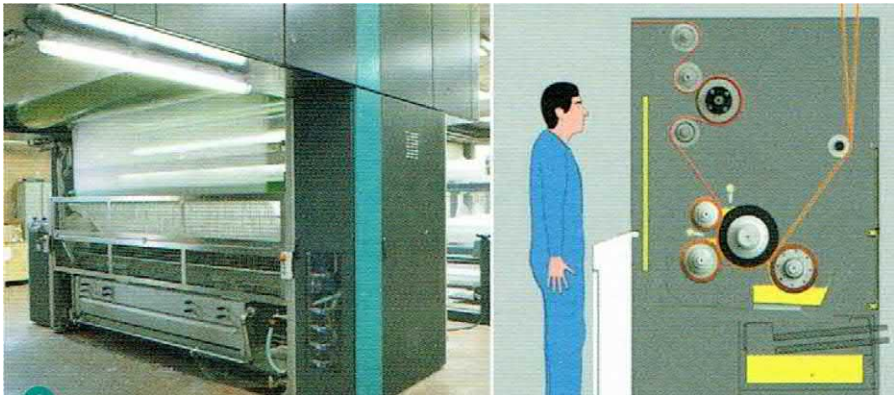


Fig. 4.14 Size box VSB.

economical. The net result is achieving the following advantages compared to the immersion bath technique:

- Up to a 10% fewer sizing additives are needed.
- Energy consumption is reduced during desizing.
- Less effluent is produced.

4.10.2 Size circulation system

Extremely efficient size circulation system is provided and only filtered size is applied on the yarn with a drastically dust reduction in weaving (Fig. 4.16) [16].



Fig. 4.15 Size box HSB.

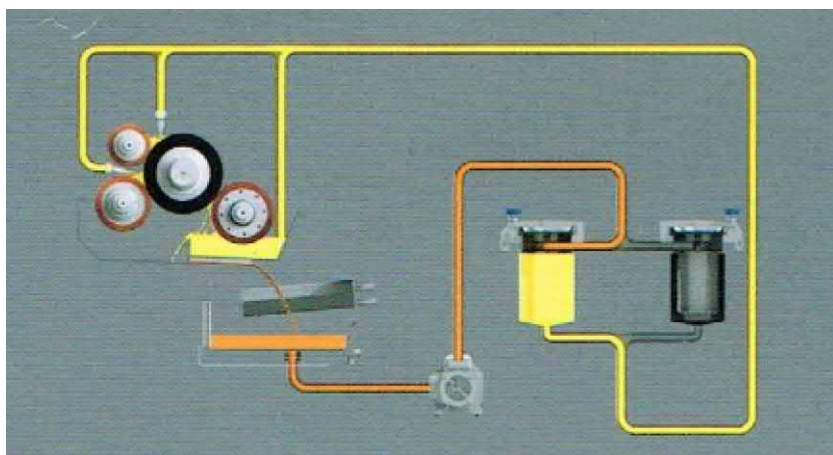


Fig. 4.16 Extremely efficient size circulation system.

4.10.3 Working range of size box

The VSB size box is extremely flexible. Its working which depend on the number of yarn ends and the yarn count, may be as much as 20% higher than conventional systems (Fig. 4.17) [16].

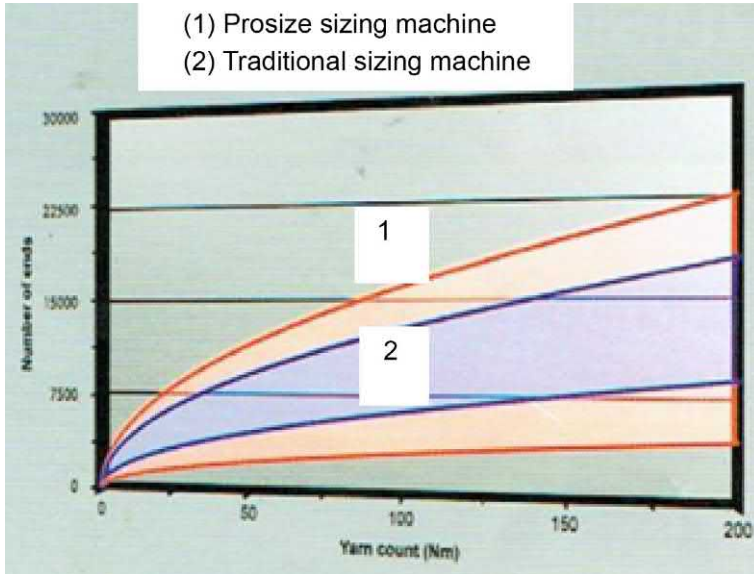


Fig. 4.17 Working range of size box.

4.10.4 Ergonomics layout of size box

The VSB size box also offers advantages in terms of its ergonomics and clear layout. The unique design enables the warp sheet to be operated vertically during delivery, which provides enough space for the easy access to the machine. The operator has a unrestricted view of the entire processing sequence.

4.11 Karl Mayer sizing machine ISOSIZE for staple fibres

Karl Mayer also offer their well-equipped sizing machine ISOSIZE. The machine is designed to provide a constant let-off tension beam creel with a triple drip and double nip size box, dryer frame for geometric and guidance warp sheet, easy, and intuitive software. The features include:

4.11.1 Special size boxes

The machine has specially designed size boxes CSB and CSB-PW type with prewetting unit (Fig. 4.18) [17] and can attain a speed of 125 m/min with working width of 1800–2400 mm and beam diameter of 800–1400 mm, with drying cylinders from 4 to 20 and loom beam width of 2100–3800 mm.

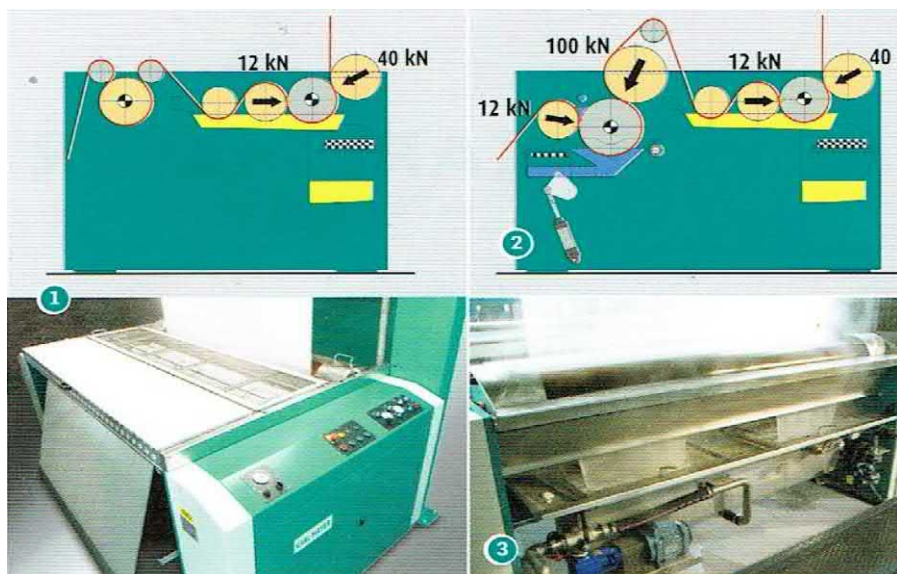


Fig. 4.18 (1) Size box type CSB, (2) size box type CSB-PW with prewetting unit, and (3) large sizing filters easy to inspect and clean.

4.11.2 Dryer configurations

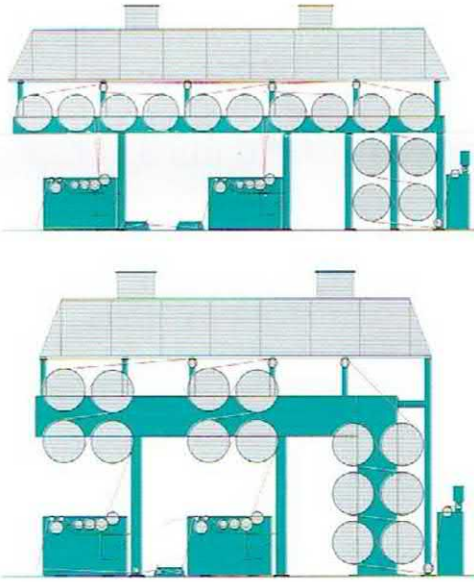
Different dryer configurations for every kind of application are available. (Fig. 4.19A and B) [17].

4.12 Sizing machine TTS10S

T-Tech Japan Corp. breaks tradition in warp sizing in developing their innovative spun sizing machine TTS10S (Fig. 4.20) [18] with new structure and control for the two size boxes and drying cylinders along with technical improvements incorporated in other sections of the sizing machine as listed below. The size liquid in two size boxes circulates through the cavity box and is mixed so the size concentration and viscosity are even in both boxes.



(A)



(B)

Fig. 4.19 (A) and (B) Different dryer configurations for every kind of application.



Fig. 4.20 Sizing machine TTS10S.

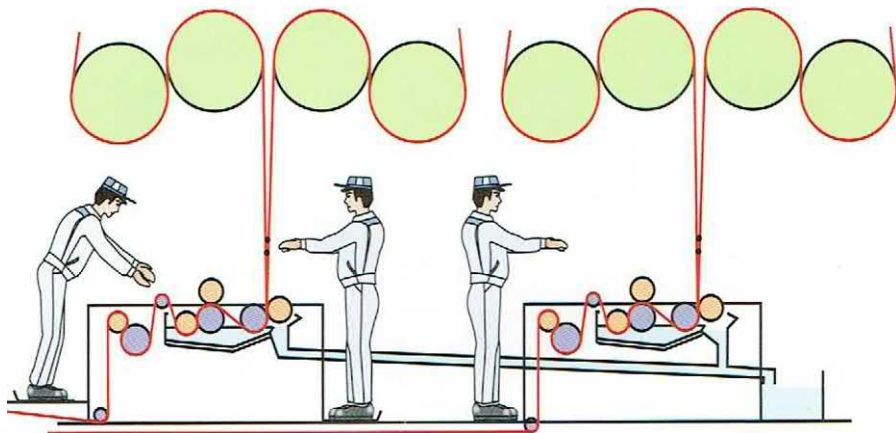


Fig. 4.21 Easy access to size box.

The size box can be accessed from any direction, access to rolls is easy and the safety and operation are noticeable improved (Fig. 4.21) [18]. The amount of size pickup on the yarn sheets that pass through the boxes is even. The stretch can be independently controlled for the first and second sizing sections by the multi-section drive system. The yarn sheet is pulled out of the size boxes to the pre-cylinders vertically without using a guide roller. Nothing touches the yarn sheet and this ‘touch free’ system reduces fluff and yarn breakage. The size liquid gently touches the yarns without causing yarn sheet disturbance. Other interesting features of the machine include:

The sizing machine offers the following technical features.

4.12.1 Beam stand

- The yarn sheet tension is measured in front of the size box for feedback control.
- Adding the noncontact diameter detector can control the tension uniformly even during acceleration and deceleration.
- The computer precisely controls the braking of the combined pneumatic cylinder and band brake.

4.12.2 Even sizing

- The double-jacket size box together with the size liquid mixing and recirculation system for the first and the second size boxes produces size with an even concentration and viscosity.
- The roll for uniform squeeze produces width wise even squeezing pressure and even size pickup amount.
- The SQ squeezing pressure control automatically controls the squeezing pressure for stop, low speed, high speed, acceleration, and deceleration.

4.12.3 Multisection drive

- AC vector motors individually drive each section offering accurate and repeatable control.
- Stretch can be individually set for the first and second size boxes.
- Using one or both size boxes is possible with the flip of a switch.
- Because there is no mechanical frictional drive as such maintenance is easy.
- One direct current power supply controls the AC vector motors hence there is no wastage of power consumption.

4.12.4 Take-up

- Beam lifting and width adjustment with the turn of a switch.
- With the three-roller system, the comb is installed near the operator and the yarn break repair is easy.
- Tension is controlled by an AC vector motor to assure accurate control of take-up tension in a wide-range power consumption.

4.12.5 Drying

- Drying cylinders are located over the size boxes which offer even drying and drying efficiency.
- Driving system designed to maintain the residual elongation of the sized yarns.
- Positively moving the precylinders prevents elongation loss during acceleration and deceleration.
- Semipositive drive of the main cylinders absorbs heat contraction during drying thus maintaining the yarn elongation.

4.12.6 Nip and twin squeeze (40 kN high-pressure squeeze)

An indirect heating system due to the double-jacket structured size box reduces dilution of size liquid caused by the low temperature of size liquid which results in a more even size concentration and viscosity (Fig. 4.22) [18]. With a high-pressure feeding device, the stretch of yarn sheet is properly controlled while the yarn sheet is wetted in the sizing process. Less size gathers around the contact area of the second squeeze roll and stops marks are reduced. The size on the roll surface does not dry out quickly which reduces size film on the roll surface.

4.12.7 Dip and twin squeeze (20 kN squeeze)

The immersion roll of the dipping type produces a yarn sheet with little disarrangement. Since the second sizing roll and the contact roll are eccentrically arranged, the size liquid brought up by the contact roll gently touches the yarn sheet. This enables the yarn sheet to run smoothly without disturbance as well as reduces doubled or taped yarn.

*TTS10S nip and twin squeeze system
(40 kN high-pressure squeeze)*

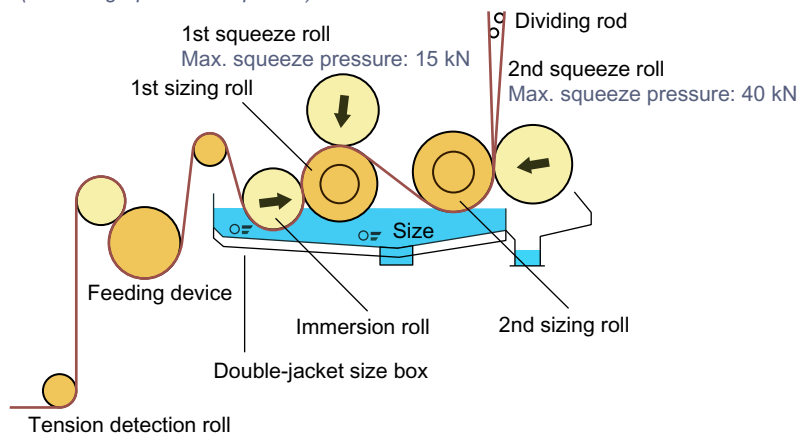


Fig. 4.22 Nip and twin high-pressure squeeze system.

*TTS10S dip and twin squeeze system
(8 and 20 kN low • medium-pressure squeeze)*

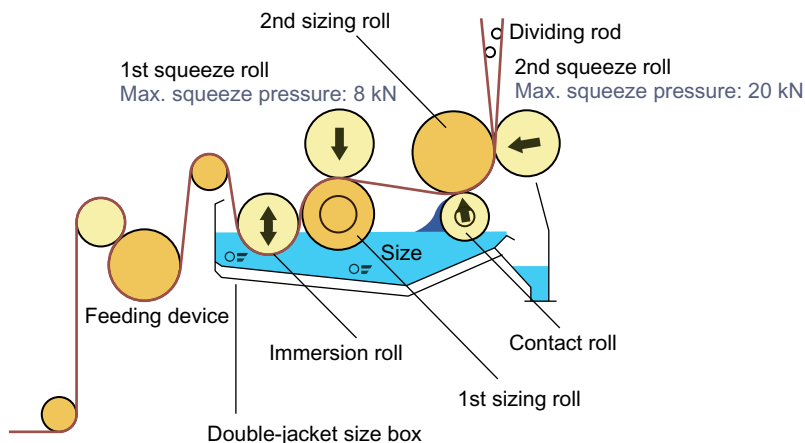


Fig. 4.23 Dip and twin, low-medium squeeze pressure system.

After the contact roll penetrates the yarns with size and removes extra size, the final squeeze is done without supplying size. This obtains a squeezing effect that is as large as a high-pressure squeeze (max. 40 kN) though it is only medium pressure (max. 20 kN). The medium-pressure squeeze produces soft sized yarns with sufficient penetration (Fig. 4.23) [18].

4.12.8 Even sizing and perfect fluff lay down

The machine uses the indirect size heating system by the double-jacket size box together with a size liquid mixing and circulation system where the size liquid flows from two size boxes to a single cavity box to make the size concentration and viscosity even. Lint and size residue are easily removed by the large exchangeable filter.

The precylinders have sufficient contact length with the yarns and prevent rapid drying of the sized yarns. This makes four sheets drying possible. Combined with water-cooled dividing rods, perfect fluff lay down is obtained. The short distance between the second squeeze roll and the cylinder prevents yarns from snarling. Even weak yarns or additionally twisted yarns can be easily sized by using two size boxes.

4.12.9 Even drying

The drying cylinders are arranged horizontally to make drying conditions uniform for each sheet, while also keeping the length of each yarn sheet of each size box the same from sizing section to the take-up which results in an excellent warp yarn with even drying.

4.12.10 Size concentration control

The size concentration is automatically controlled according to the set value. Differences in the size concentration – which greatly influence the size pickup amount – are reduced to achieve quality sizing (Fig. 4.24) [18].

4.12.11 SPM size pickup monitor

The SPM size pickup monitor uses air pressure to detect the amount of size liquid consumed in real time. As the size pickup amount is detected and displayed without delay, abnormalities are avoided, making the control accurate, simple, and productive (Fig. 4.25) [18].

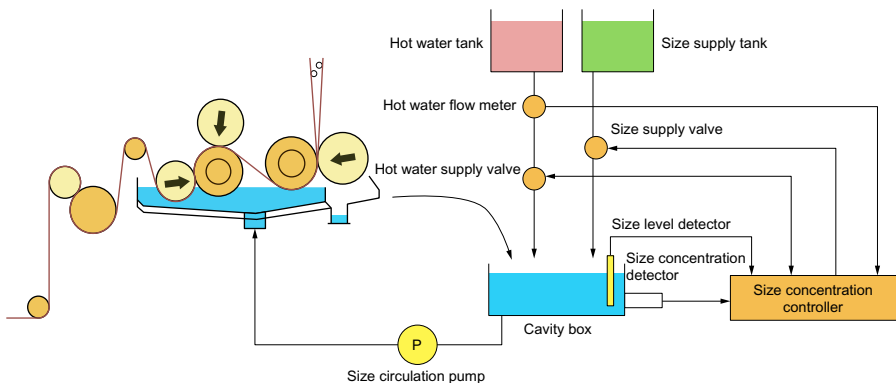


Fig. 4.24 Size concentration control.

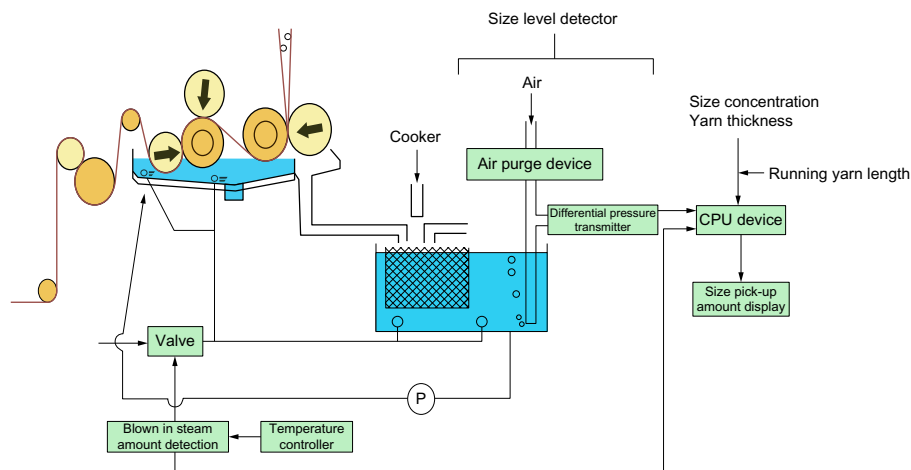


Fig. 4.25 SPM size pickup monitor.

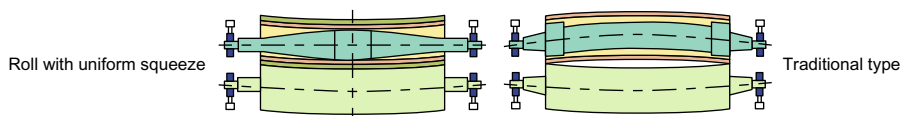


Fig. 4.26 Squeeze roll with a structure for uniform squeezing.

4.12.12 Squeeze roll with a structure for uniform squeezing

The squeeze roll is designed to apply width-wise uniform squeezing pressure and to pick up even amount of size pickup (Fig. 4.26) [18]. Squeezing pressure for ‘HIGH SPEED’ is automatically adjusted according to the yarn speed.

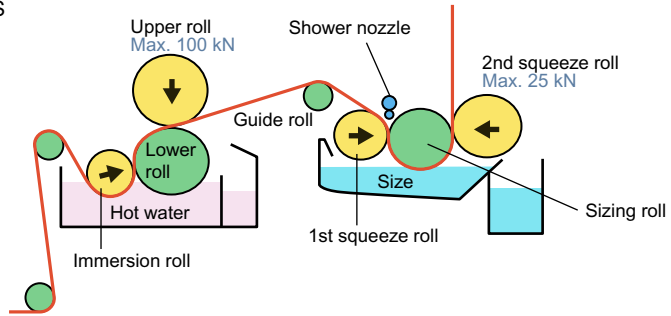
4.12.13 Reducing running costs with prewet sizing

Prewet sizing technology helps in 20%–40% reduction in the size pickup amount. Prewetting the yarns makes it easy to penetrate then with size and the size evenly and efficiently adheres to the yarn surface, which reduces the size pickup amount. The sized yarns are soft and have less decrease of elongation. Preventing the dilution of size by the moisture brought by the wet yarns is an important technique.

4.12.13.1 Prewet sizing type S and W

The type S prewet sizing system is especially efficient for yarns thicker than 30s whereas type W is a multifunction sizing system that can size thin yarns for high-density fabrics are not suitable for prewet sizing. This system can be used as the nip and twin squeeze sizing system with a feeding device by letting water out of the prewet tank (Fig. 4.27) [18].

■ Prewet sizing Type S



■ Prewet sizing Type W

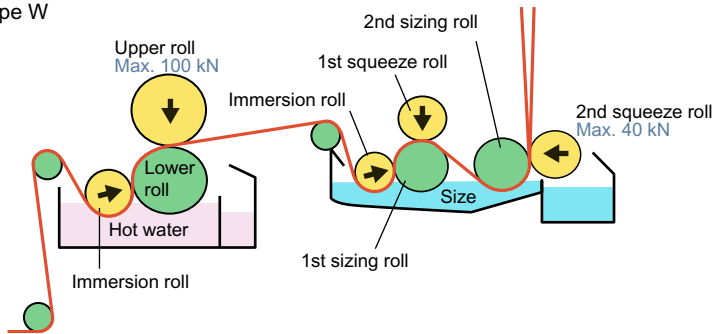
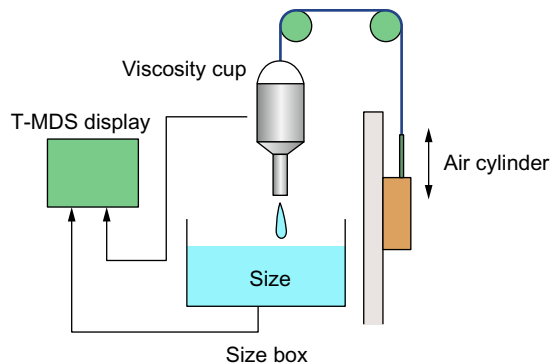


Fig. 4.27 Prewet sizing Type S and W.

4.12.14 Automatic size viscosity measuring device

Size dripping from the viscosity cup is detected with a minute electric current and the size viscosity is automatically measured and displayed. It is indispensable for quality sizing to ensure accurately measure and control the size viscosity (Fig. 4.28) [18].

Fig. 4.28 Viscosity measuring device.



4.12.15 T-MDS machine data station

The above station integrates control of the TTS10S and provides the following salient features [18]:

- Individual indication and setting of the temperature, the tension, the stretch, and the squeezing pressure.
- Monitoring the operating status to find the checkpoints for troubleshooting.
- The operating conditions are automatically set, controlled, and monitored. Changing the condition during running is also possible.
- Recommended sizing conditions are displayed by entering the yarn kind, the thickness, the beam stand number, and the total ends/size box.
- Up to 300 operating conditions can be registered.

4.13 Filament sizing machine TSE30F

T-Tech Japan Corp. offer their filament sizing machine TSE30F (Fig. 4.29) [19] with the following newly developed technical features [19] incorporated in the machine.

4.13.1 Multisection drive system

Filament yarns are widely classified depending on their kind, texture, and fineness. Thus, the stretch setting has to be changed often when changing the production style. The multisection drive system employs technology that synchronously operates



Fig. 4.29 Filament sizing machine TSE30F.

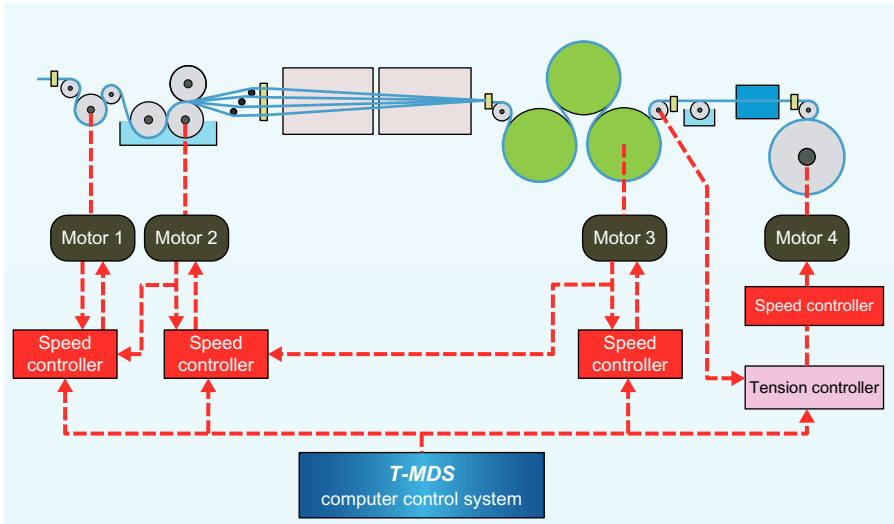


Fig. 4.30 Multisection drive system.

multiple motors according to a retain ratio (Fig. 4.30) [19]. Stretch is adjusted even during operation according to the yarn types and speed. The adjustments can be easily done while the sizing machine is in operation. Motors 1–3 control the stretch for the feeding section, the sizing section, and the cylinder section, respectively, in 0.01%–0.001% increments.

4.13.2 Uniform squeeze for quality

The newly designed squeeze roll has an iron core with a special shape which has no space at the centre when both ends of the roll are pressed with air cylinders thus width-wise uniform pressure is achieved. A high-pressure squeeze system of 15 kN is employed (Fig. 4.31) [19].

The pressure is automatically controlled sleeplessly taking into account yarn speeds. By entering the respective target squeeze pressure for stop, low speed and high speed, width-wise uniform squeeze can be achieved. The ideal roll arrangement and a large 180-L cavity box prevent size from splashing and foaming.

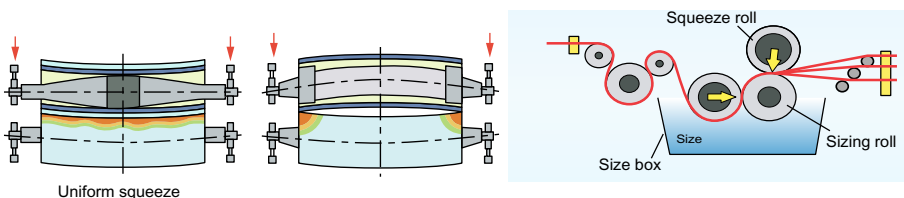


Fig. 4.31 Squeeze roll with a structure for uniform squeeze and the size box.

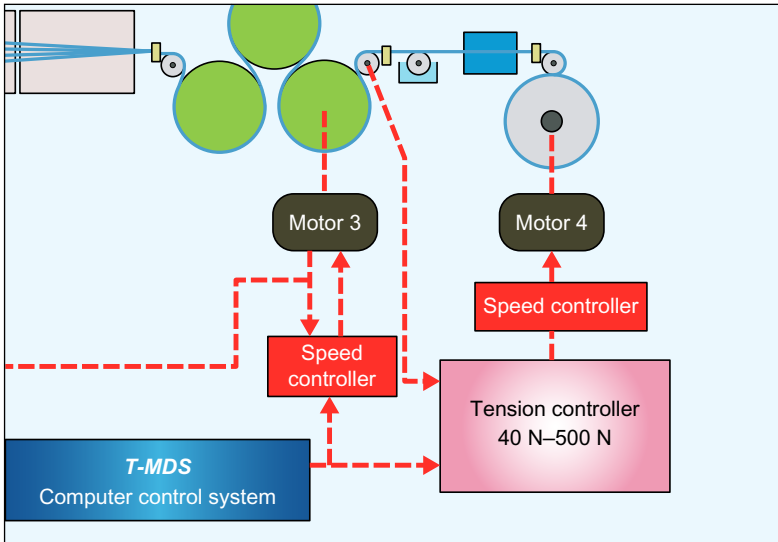


Fig. 4.32 Low tension control.

4.13.3 Low tension control

As the winding diameter increases, the change gear ratio between the cylinders and the take-up beam is adjusted so that the take-up tension maintains the target value. This function stably controls the tension from the lowest 40 N and to the highest 500 N (Fig. 4.32) [19]. Low tension control is especially efficient for delicate yarns like fine yarns. The machine operates with stable tension during acceleration and deceleration.

4.13.4 Beam cooling device

When concentrated size liquid is used, sized yarns end to adhere to each other on the beam. By cooling the sized beams, the adhesion is prevented (Fig. 4.33) [19].

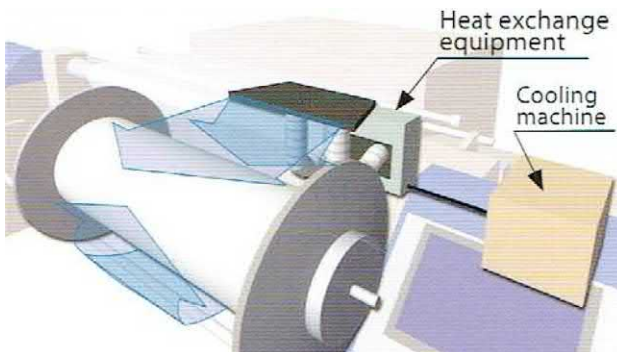


Fig. 4.33 Beam cooling device.

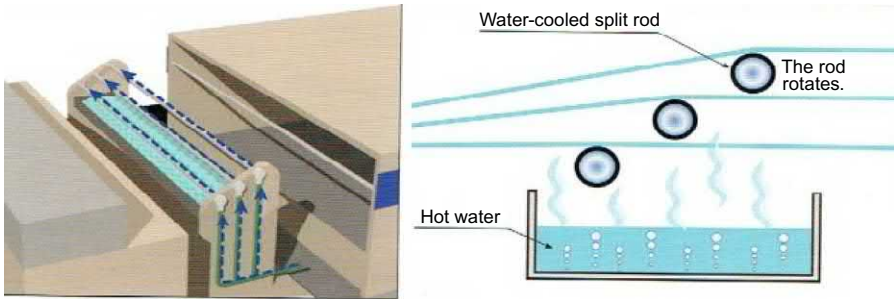


Fig. 4.34 Humidifying system in the split section of the sizing machine.

4.13.5 Humidifying system in the split section

This prevents size residue from adhering to the rods in the event of condensation building up on the water-cooled split rods (Fig. 4.34) [19]. The split rods rotate at the appropriate speed in order to keep rod contact to the yarns unchanged. This makes size pickup amount uniform since no excess water is contained by the yarns even while the machine stops or operates at the slow speed.

4.13.6 Advanced roll structure

Coupled with the tension control range from 20 to 250N, the roll structure is also advanced to adjust the tension suitable for the yarn fineness. This also supports ultra-low tension control (Fig. 4.35) [19].



Fig. 4.35 Advanced roll structure.



Fig. 4.36 Flocked roll.

4.13.7 Flocked roll (optional)

Nylon chips are contained in the synthetic rubber wound around the squeeze roll (Fig. 4.36) [19]. This roll wipes excess size on the yarn and contributes to more effective squeezing preventing size beads on yarns, and enhancing weaving performance.

4.13.8 Gas burner-type drying chamber (optional)

The model TSE30F is efficient for yarns that require drying at temperatures of 200°C for more such as glass yarns. High to low temperature is easy and potential application for this specification is high. Because air is directly heated by gas combustion, thermal efficiency is high, and energy is saved (Fig. 4.37) [19].

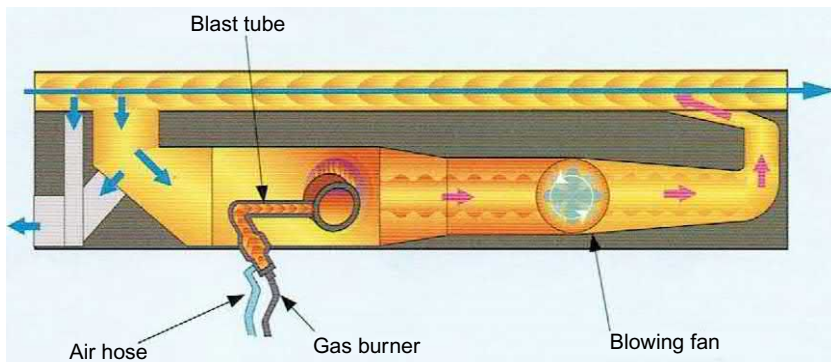


Fig. 4.37 Gas burner drying chamber.

4.13.9 Fluorine resin-coated tension roll in the cylinder section

When sized yarns are not sufficiently dried in the hot-air drying chambers or the cylinder section, size drips from the yarns and accumulates on the tension roll, resulting in easy yarn breakage. In order to prevent size accumulation, a fluorine resin-coated guide roll is employed which reduces the yarn breakage.

4.13.10 Stretch/tension control changeable device

Control of the yarn tension in the hot-air drying chambers can be switched between the stretch control and then tension control as needed. For yarns that have different proper stretch depending on the yarn speed, selecting the tension control holds the tension in the hot-air drying chamber constant.

4.13.11 Alarm for size level control in the size box

Size box level is constantly monitored and should the size level lowers than required, the machine is stopped by an alarm in order to prevent uneven size pickup amount.

4.13.12 Automatic size supply

The size level in the cavity box is monitored and should the level lowers, the size supply valve opens to allow the size enter the cavity box and closes when the size level is sufficiently high.

4.13.13 Multipoint taper control for take-up tension

This is efficient when there is a possibility that sized warp yarns adhere to each other on the beam when concentrated size is used. As the weaving diameter increases, the take-up tension is lowered to lighten up tight winding.

4.13.14 Size pump inverter (centrifugal pump)

Concentrated size foams easily and this can be reduced to keep size conditions constant even by controlling the feed rate of size by the inverter.

4.13.15 Yarn speed following rotation of the water-cooled split rods

The split rods rotate at the appropriate speed in order to keep rod contact to the yarns unchanged. This makes size pickup amount uniform since no excess water is contained by the yarn even while machine stops or operates at low speed.

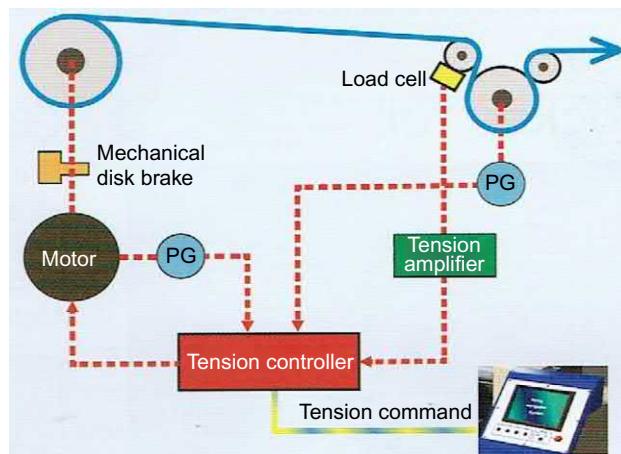


Fig. 4.38 Stable tension control.

4.13.16 Supply stand TSD30F – Tension control

The supply stand offers the following developments.

4.13.16.1 Tension setting and control in increments of 1 N

Tension setting and control in increments of 1 N is now possible instead of 10 N in the previous models of the machine. Setting in increments of 1 N allows finely tuned setting and control. Tension suitable for yarn fineness can be set and yarns can be sized while retaining their rate of elongation.

4.13.16.2 Stable tension control

There are no dance rolls between the supply stand and the sizing machine, resulting in no snarling problem. In case of a power failure, power supply to the motor stops. To prevent yarns from overrunning due to the inertia of the beam, a mechanical brake works (Fig. 4.38) [19]. The low tension control for the lowest tension 20 N is also available as an option.

4.13.16.3 Pulling-out direction switchable function

The direction to pull out the yarn sheet is switchable between ‘from above’ and ‘from underneath’ Adjusting the direction reduces warp streaks.

References

- [1] A. Barella, Hairiness of yarn—review of literature, JTI (1966) 477–478.
- [2] W.E. Morton, JTI, (1952) 60.

- [3] K.L. Gandhi, *A Comparison Between Break-Spun and Ring-Spun Yarns With Particular Reference to Sizing and Weaving*, (PhD thesis) University of Manchester, 1975.
- [4] P.V. Seydel, J.R. Hunt, *Textile Warp Sizing*, Long & Clopton, Atlanta, GA, 1972.
- [5] H. Hacking, *The Sizing of Spun Yarns*, Scientific Era Publications, Stamford, 1980.
- [6] T. Ramsbottom, *Warp Sizing Mechanisms*, Columbine Press, Manchester, 1964.
- [7] J.B. Smith (Ed.), *Technology of Warp Sizing*, Columbine Press, Manchester, 1964.
- [8] V. Heap, *Sizing Material for Continuous Filament Yarns*, Textile Institute & Industry, 1973, 172 July.
- [9] D.M. Hall, S. Adanur (Ed.), *Wellington Sears Handbook of Industrial Textiles*, Technomic Publishing, Lancaster, PA, 1995.
- [10] A. Ormerod, W.S. Sondhelm, *Weaving – Technology & Operations*, The Textile Institute, Manchester, 1995.
- [11] B.C. Goswami, R.D. Anandjiwala, D.M. Hall, *Textile Sizing*, Marcel Dekker, New York, 2004.
- [12] J.E. Booth, *Textile Mathematics*, vol. 3, The Textile Institute, Manchester, 1977.
- [13] A.L. Landau, *Warping and Slashing, Sizing Part 1*, International Text Book, Scranton, PA, 1941.
- [14] P.R. Lord, M.H. Mohamed, *Weaving: Conversion of Yarn to Fabric*, Merrow Technical Library, Watford, 1973.
- [15] E.H. Jones, J.B. Smith (Ed.), *Technology of Warp Sizing*, Columbine Press, Manchester, 1964.
- [16] Karl Mayer Textilmaschinenfabrik GmbH, Germany, Technical Leaflet Warp Preparation PROSIZE® We-A-1126/1/11/15 and information sheet Innovations for Warp Preparation / Karl Mayer p 1–2.
- [17] Karl Mayer Textilmaschinenfabrik GmbH, Technical Leaflet Warp Preparation, ISOSIZE, We-A-1124/1/11/15.
- [18] T-Tech Japan Corp. (ttj), Tsudakoma Corp – Technical Catalogue TTJ-050805-E, TTS10S Spun Sizing Machine.
- [19] T-Tech Japan Corp. (ttj), Tsudakoma Corp Technical Catalogue TTJ-041505E-Single-End-Sizing System Filament Sizing Machine.

The fundamentals of weaving technology

5

K.L. Gandhi

The Textile Institute, Manchester, United Kingdom

5.1 Introduction

Whether carried out on a simple hand loom or a power loom, weaving consists of interlacing two sets of yarns at right angles to each other. The yarns that run the length of the woven fabric are called warp yarns, and the yarns that run across from side to side are called weft yarns (also known as filling). Warp yarns are generally stronger than weft yarns because warp yarns experience a lot of stress and strain during weaving as a result of the different loom motions during the weaving cycle. The manner in which the warp and weft threads interlace with each other is known as the weave. Broadly speaking woven fabrics can be categorized into the following three types:

1. Fabrics in which warp yarns (also referred to as ends) and weft yarns (also referred to as picks) intersect one another at right angles.
2. Fabrics in which some warp yarns interweave to the right and left of the adjacent warp. Such fabrics are called gauze and leno fabrics.
3. Fabrics in which warp or weft yarns project outwards from the foundation of the cloth and form a loop or pile on the surface of the fabrics. These fabrics are called pile fabrics (examples are carpet, terry towel, velvet, and corduroy).

Fig. 5.1 [1,2] shows the passage of warp yarns through a loom that is basically the same whether it is a table loom (Fig. 5.1A), a hand loom (Fig. 5.1B), or a power loom. All the warp ends are drawn through the eyes of the heald shafts, which are raised or lowered as one unit. A minimum number of two heald shafts are required to weave a fabric. The need for more than two shafts depends on the weave structure of the fabric. All the warp ends are then passed through the dents of the reed. The reed is primarily composed of parallel strips of steel wires with gaps (or dents) between them. The reed keeps the warp yarns evenly separated and held parallel as they pass through the dents of the reed. The operation of drawing each warp yarn through its appropriate heald eye and through the dents of the reed is known as drawing-in, before the weaver's beam is positioned at the back of the loom.

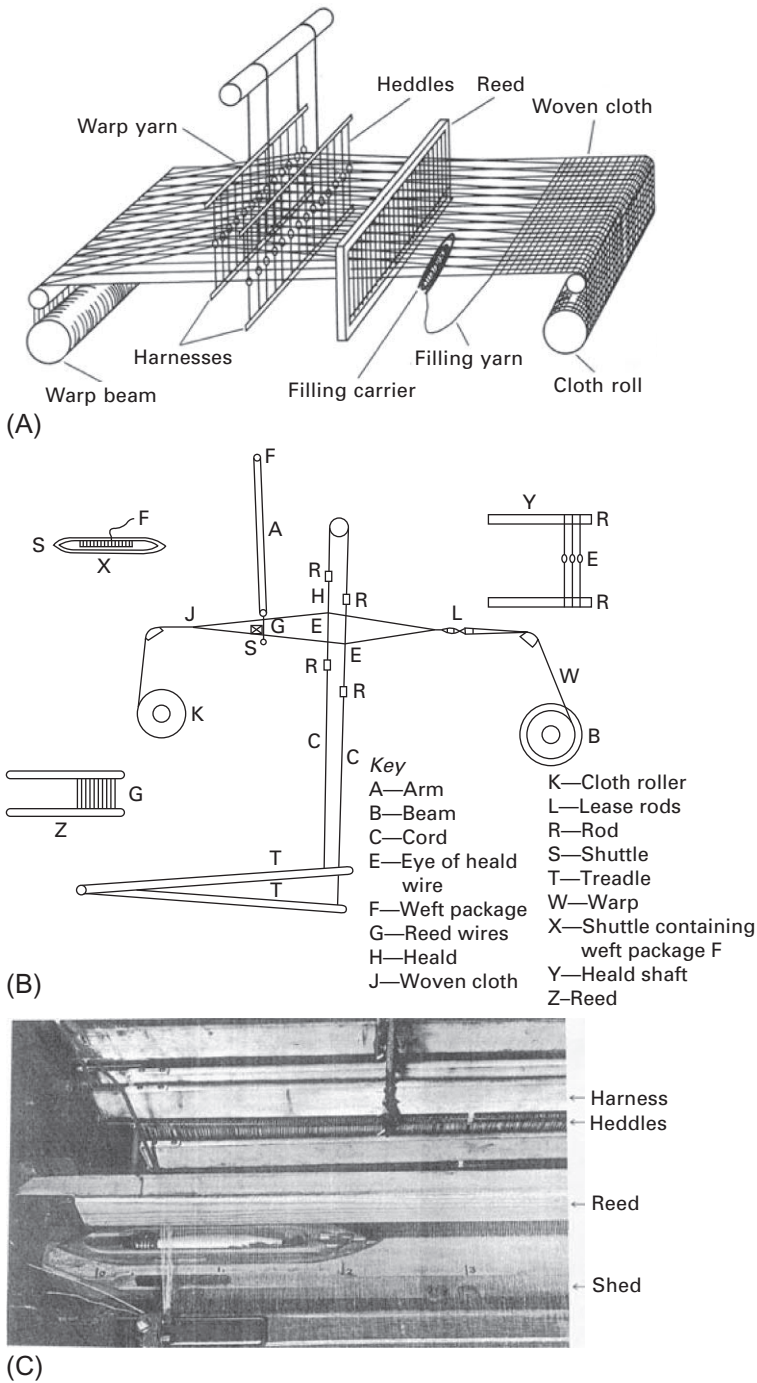


Fig. 5.1 (A) Passage of warp through basic loom parts, (B) passage of warp yarn from a basic hand loom with treadles, and (C) shuttle entering the shed.

5.2 Primary loom mechanisms

In order to interlace the warp yarn with the weft yarn, three primary mechanisms have to take place, completing one loom cycle or one complete revolution of the loom. The three primary mechanisms are shedding, picking, and beat-up, and these are discussed later. Without any of these mechanisms, weaving cannot take place.

5.2.1 *Shedding*

The shedding mechanism separates the warp threads into two sheets (layers) by lifting some of the heald shafts up whilst lowering others. Since each warp yarn from the weaver's beam passes through an eye of the heald shaft when some of the heald shafts are lifted and lowered by a shedding mechanism, the corresponding warp ends are raised or lowered, thus forming an opening. When this happens, we say a shed is formed, and the next primary mechanism, 'picking', can commence. A shed can be formed by different types of shedding mechanisms such as tappet, cam, dobby, and jacquard. The minimum number of heald shafts required to form a shed is two. When the number of heald shafts being used is more than two, whether a shaft is lifted or lowered is decided by the weave structure of the fabric being woven on the particular loom. On a table loom, the shed is made by lifting the heald shafts manually by hand, whilst on a simple hand loom, it is generally made by depressing the treadle levers (Fig. 5.1B).

5.2.2 *Picking*

On a shuttle loom, when the warp sheet has been divided into two parts and a shed is formed, a shuttle carrying the weft yarn in a package (called a cop or pirn) is thrown through the shed [1] by a picking mechanism (Fig. 5.1C). When the shuttle has almost reached the other side of the loom, the shed begins to close as the direction of the heald shafts is changed. On a shuttle-less loom, the weft is thrown through the shed by a projectile (a projectile loom), a rapier (a rapier loom), by air (on an air-jet loom), or by water (on a water-jet loom).

5.2.3 *Beat-up*

As soon as the weft has been inserted through the shed, beat-up (the last primary motion of the loom) can take place. With the help of the reed, the inserted weft is pushed into the edge of the already woven cloth at a point called the 'fell of the cloth' [3] (Fig. 5.2). The reed gets its forward and backward movement from a crank shaft.

Thus in one revolution (one cycle) of the loom, all three primary mechanisms take place and are then continuously repeated as weaving continues.

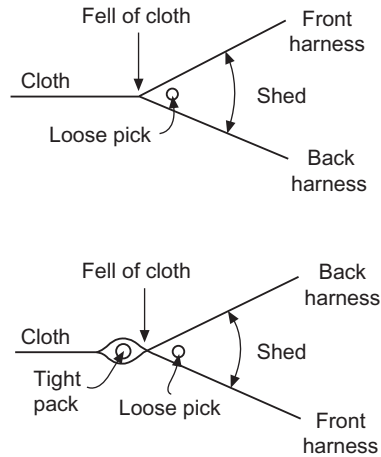


Fig. 5.2 Fell of the cloth.

5.3 Secondary loom mechanisms

Although not essential for weaving a fabric, i.e., to interlace warp and weft yarns, there are other mechanisms which assist in the continuous weaving of a cloth on a power loom. These secondary mechanisms are carried out simultaneously.

5.3.1 Let-off

On a power loom, let-off is the delivery of the warp yarn from the weaver's beam at a constant rate, and at a constant suitable tension, by unwinding it from the beam as weaving continues. On a power loom, the position of the fell of the cloth always remains in the same place, whereas on a traditional hand loom, the fell of the cloth position keeps on changing as each loom cycle completes.

5.3.2 Take-up

Take-up is the automatic withdrawing or winding of the fabric as weaving continues, at a constant rate, onto a cloth roller. Take-up motion controls the weft density, i.e., the number of picks/cm in the fabric.

5.4 Auxiliary loom mechanisms

In addition to the primary and secondary mechanisms discussed, there are other auxiliary mechanisms on almost all power looms, whether with or without shuttle. These auxiliary mechanisms are warp stop motion and weft stop motion and, although not

absolutely essential, they are nevertheless critical for controlling fabric quality and production on a power loom. Their primary function is to stop the loom when either a weft yarn or warp yarn breaks during the weaving process. The absence or malfunctioning of these mechanisms can lead to a lot of problems, causing serious defects in a fabric.

5.4.1 Warp stop motion

Warp stop motion can be either mechanical or electrical, both of which are widely used. In both types of systems, each warp yarn from the weaver's beam is drawn through the eye of a special drop wire. These drop wires can vary in dimension and weight depending on the quality of yarn. (In general, the coarser the yarn, the heavier the drop wire should be.) If the warp yarns are to be drawn through the eye of the drop wire at a point away from the loom, the base of the drop wire is closed (Fig. 5.3B) [4], but if the drop wires are to be inserted onto a warp at the loom, the drop wires (C) are open from the base as shown in Fig. 5.3.

One of the most common mechanical warp stop motions has the drop wires suspended over three slotted or serrated bars, the outer pair of which are fixed whilst the middle bar moves between them [5] (Fig. 5.3). When a warp yarn breaks, the drop pin falls and interrupts the movement of the oscillating serrated bar. This action (in one way or another) pushes the starting handle from its position and stops the loom. Electrical warp stop motions basically use the same principle, except that there are no serrated oscillating bars and each warp yarn is passed through special drop wires which can make contact across a pair of electrodes. When a yarn breaks, the drop

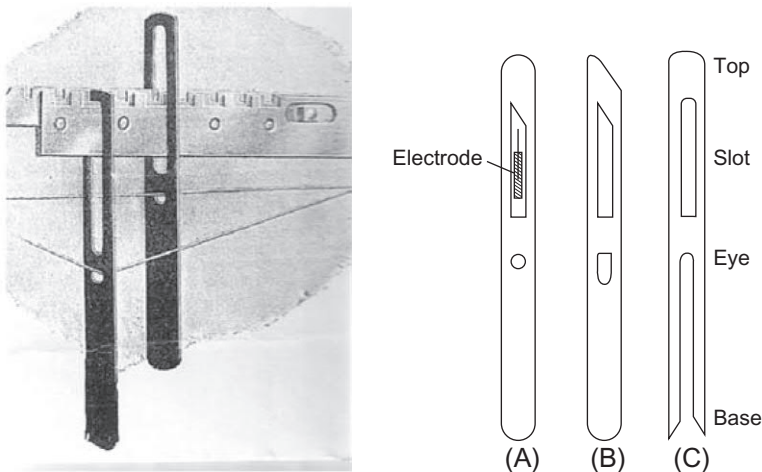


Fig. 5.3 Warp stop motion.

pin falls, thus making contact with the bar and completing a circuit which, through a relay medium, stops the loom.

5.4.2 Weft stop motion

The main function of weft stop motion is to stop the loom when the weft yarn either breaks or when the supply package is completely used and needs replacing. If the loom does not stop immediately when this happens, a fabric defect called a broken pick is created and, if the loom continues running without weft for a number of picks, a far more serious fabric defect is created. In either case, the weaver has to spend some time correcting the fault, resulting in increased workload as well as reducing productivity. On shuttle looms, the weft stop motion is commonly known as the weft fork mechanism and is either located at the side of the loom (between the selvedge and the entrance to the shuttle box) or in a cut-out space.

5.5 Temples

Every power loom is equipped with temples on both the right and left side of the loom in front of the reed and near the fell of the cloth. A few centimetres of fabric near the selvedge on both sides pass through these temples (Fig. 5.4). The function of the temples is to [6, 7]:

- control contraction of the fabric due to the interlacing of warp and weft
- keep the fell of the cloth at the same width as the warp in the reed; if this width is not maintained, the reed will abrade against the selvedge ends on both sides and cause breakages during the beat-up cycle
- overcome the drag on the selvedge when the shuttle passes from one box to the other

There are various kinds of temple:

- *Ring temples* are rings with spikes which are mounted on a shaft. The number of spikes varies, as does the number of rings. Ring temples are used for light, medium, and heavy fabrics. If not maintained properly, they can damage the fabric edge.
- *Rubber temples* are temples without spikes and are used for delicate fabrics and on water-jet looms.
- *Steel roller temples* do not have rings but are covered with short spikes. Suitable for light and medium fabrics, they are mostly used in pairs and are covered with a cap.
- *Full-width temples* are usually used for fabrics that should be free from temple marks, such as nylon, etc. These temples do not have spikes and consist of a steel rod running across the full width of the loom. The fabric passes around it as shown in Fig. 5.4. The temple controls the fabric close to the fell of the fabric.

For medium and heavy fabrics, the following distinct types of temples are normally used [7]: tapered rings and tapered cap with all the rings inclined; inclined rings, all the same size, with an semicircular oblong cap; inclined and straight rings on the same shaft, with a semicircular oblong cap; or roller temples, the rollers being covered with short spikes, and the two rollers being covered with a convenient cap.

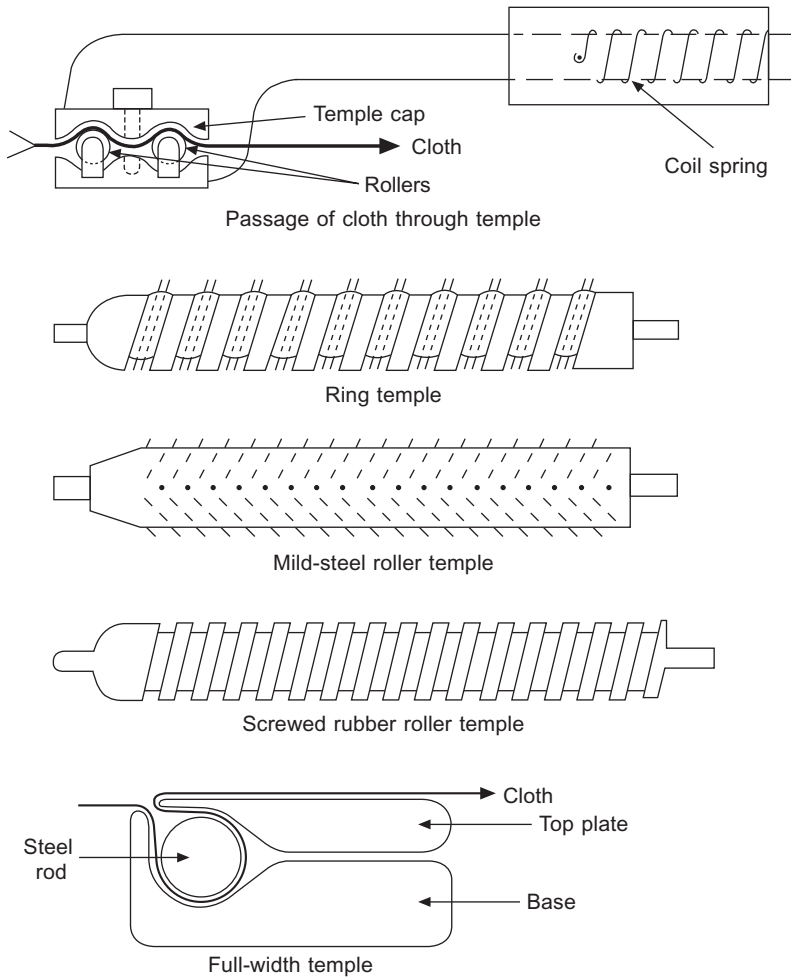


Fig. 5.4 Types of temples.

5.6 Shedding mechanisms

Shedding is the first primary mechanism that takes place during the weaving operation and is the division of the warp threads into two parts by the lifting and lowering of selected sets of warp threads on each new loom cycle. Which of the warp threads should be raised and lowered is dependent on the weave structure.

The lifting or lowering of the heald shafts is achieved by using different shedding mechanisms which can be positive or negative. In positive shedding, the heald shafts are both raised and lowered by crank cams or tappets or by a lever system within the shedding mechanism. In negative shedding, the healds are either raised or lowered by

Table 5.1 Summary of main shedding motion characteristics for cam (tappet), crank, dobby, and Jacquard shedding

Shedding mechanism	Main characteristics
Cam (tappet) shedding	(a) Simple to maintain and operate (b) Loom speed is relatively fast (c) Limited to designs repeating on 8–10 heald shafts (d) Complicated for frequent change of designs and therefore more economical for mass production of the same patterns (e) Fewer fabric faults occur during weaving (f) Design repeat in the weft direction is limited
Crank shedding	(a) Most characteristics are the same as for cam shedding (b) Mainly used on high-speed air-jet and water-jet looms for weaving plain and basic weaves only
Dobby shedding	(a) Can be built to control up to 48 heald shafts but commonly made with 32 levers. Each lever controls one heald shaft (b) Offers unlimited picks per repeat in the design (in weft direction) (c) Easy to change the design. Requires only that the new design be punched on the plastic paper or on to lags with pegs (d) Higher initial costs and maintenance costs (e) Slightly prone to produce fabric faults
Jacquard shedding	(a) Can produce virtually unlimited designs both in warp and weft directions (b) Most jacquard shedding mechanisms, except the most advanced, tend to limit loom speeds compared to cam and dobby shedding weaving machines (c) Costly to install and maintain

the shedding mechanism but then returned by the action of an external device, such as a spring or reversing roller mechanism. Different shedding mechanisms are discussed below, and a summary of the main shedding motion characteristics are presented in [Table 5.1](#).

5.6.1 Negative cam (tappet) shedding

[Fig. 5.5B](#) shows the passage of warp yarn through various parts of a loom fitted with a negative tappet shedding mechanism [7]. The shedding cams (tappets) get their rotary motion through the bottom shaft on which they are fitted. When the tappets rotate, they depress ‘followers’ (called antifrictional bowls), which are fitted to the treadle levers, fulcrummed towards the back of the loom. The lower ends of the heald shafts are connected to the treadle levers, whilst the tops are connected through cords to a reversing roller device consisting of two rollers of different diameters. [Fig. 5.5A](#) shows the shape of the tappets and cam [8]. When the cams rotate, they push the bowls down,

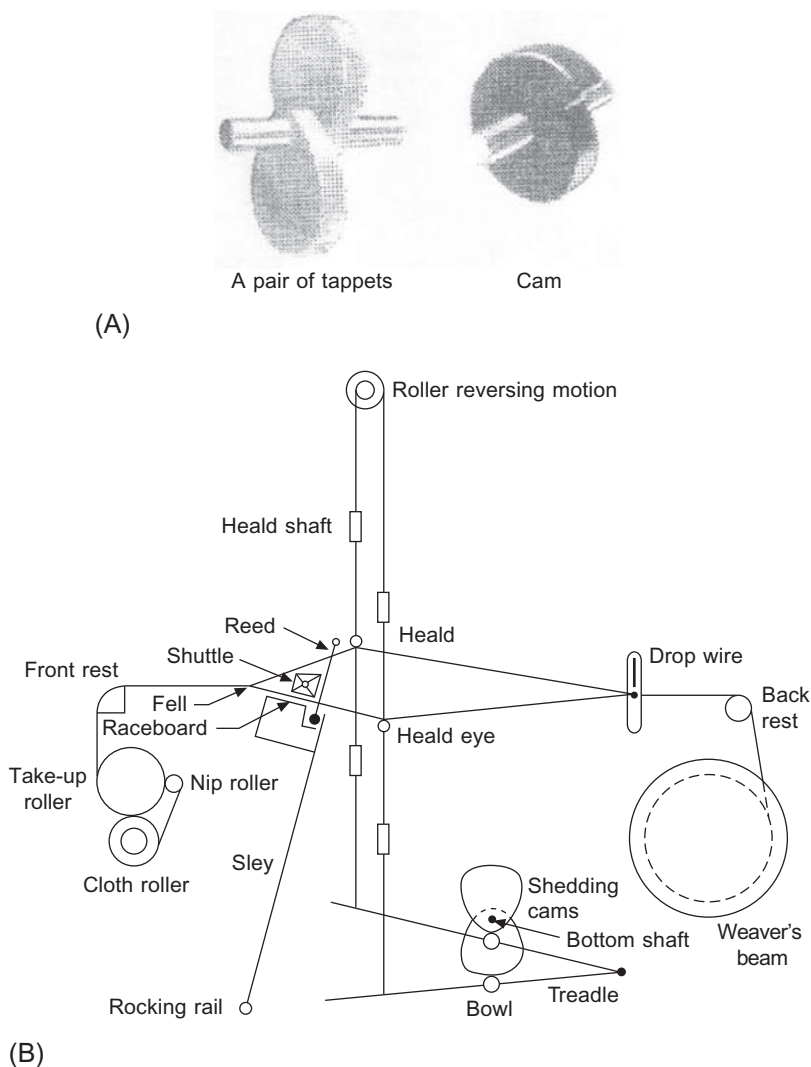


Fig. 5.5 (A) Shape of tappet and cam, (B) passage of yarn from the loom parts.

thus depressing the treadle levers and the corresponding heald shafts. Positive action is achieved because the downward drive given to one heald is used to generate an upward action for the other heald shaft via the roller reversing action fitted at the top.

Fig. 5.6C shows a negative cam shedding from Toyota [9] which can realize speeds of operation up to 1000 rpm. Fig. 5.6D shows one of the Stäubli cam shedding motions [10] designed for precision high-performance machines and ideally suited for all plain weaves, heavy fabrics, and technical fabrics.

5.6.2 Positive cam (tappet) shedding

Fig. 5.6A shows a positive cam shedding mechanism [8]. The cam (B) with a groove (C) is fitted on the cam shaft. A bowl (D) fits in the groove. The heald shafts are connected with appropriate connecting rods to one end of the cam lever (E), which is fulcrummed at (F). When the cam gets its rotary motion from the cam shaft, the bowl moves and follows the path of the groove, transmitting the motion to the link rods (G and J) which then pass on the upward or downward movement to the heald shafts, depending on the position of the bowls in the grooved cam.

As the upward and downward movement of the heald shafts is controlled by the cam, this type of shedding is classified as positive shedding. There are as many cam units as there are working heald shafts. The tappet or cam shedding mechanism can be located inside or outside the loom [5]. Fig. 5.7A shows an inside tappet shedding mechanism for up to eight shafts on a Picanol loom. The action is positive in

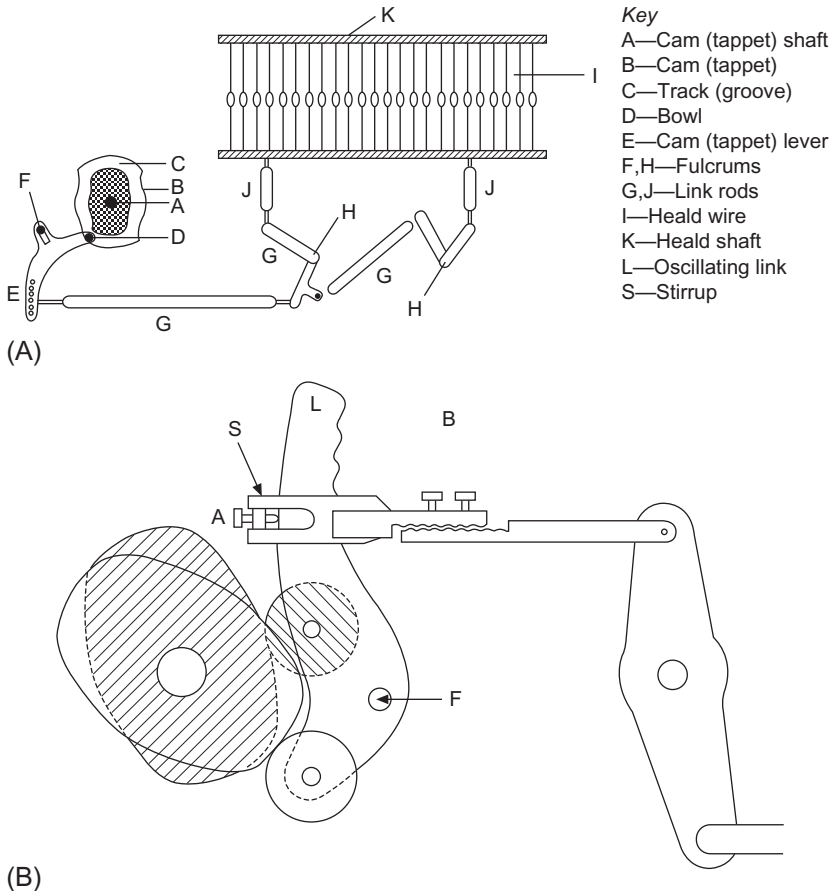
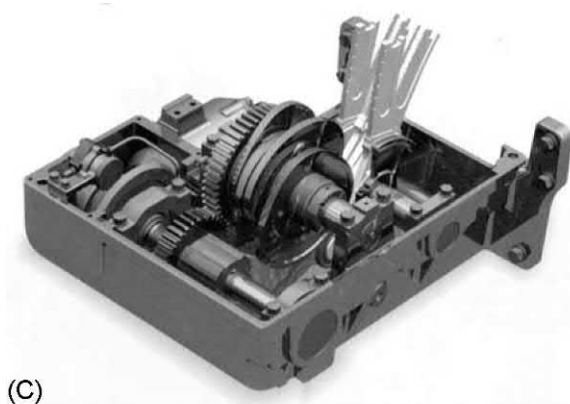


Fig. 5.6 (A) Positive cam shedding mechanism, (B) positive cam shedding,



(C)



(D)

Fig. 5.6, cont'd (C) Toyota negative cam shedding, (D) Stäubli cam motion.

lowering the heald frames, which are then returned by a clock spring motion. [Fig. 5.7B](#) shows a typical example of an outside positive tappet shedding mechanism on a Saurer loom. The heald shafts are driven positively from below by means of angle levers and connecting rods, ensuring smooth and accurate shedding.

Another type of positive cam shedding, on a Sulzer loom, is shown in [Fig. 5.6B](#). Such double cam shedding consists of a pair of matched cams mounted on a shaft, with an oscillating link (L) fulcrummed (at F) by two antifriction rollers, one of which is in contact with each cam face [\[7\]](#). There are as many double shedding

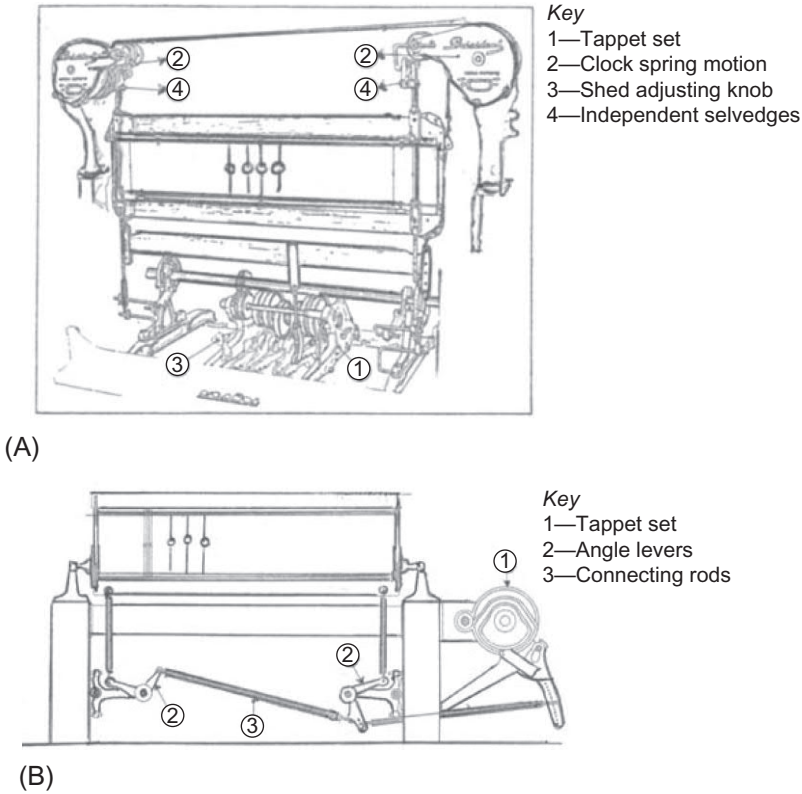


Fig. 5.7 (A) Inside tappet mechanism, (B) outside tappet mechanism.

cams and motion transmission mechanisms as there are heald shafts, with each double cam having its own antifrictional roller. When a cam continuously rotates in a clockwise direction, the oscillating lever swings in clockwise and counter-clockwise directions, and dwells at the end positions when necessary. The oscillating levers are connected through a series of links to the heald shafts, and, finally, their clockwise and counter-clockwise movement is transmitted in upward and downward movements to the heald shafts. Adjustment for the depth of the shed is made by moving the stirrup (S) up or down, which does not affect the height of the shed. This is adjusted at B.

5.6.3 Crank shedding

Fig. 5.8 shows a schematic view of a crank shedding mechanism [11], which consists of a crank rocker mechanism ($Ao A BB_o$) and a slider crank mechanism ($B_o CD$). The crank link (2) rotates at half of the loom's speed. The crank's continuous rotation is transmitted to link (4) by link (3). During one revolution of the crank, link (4) swings between its foremost and rearmost positions. The slider crank mechanism converts the angular displacement of link (4) to the linear displacement of the heald frame. The

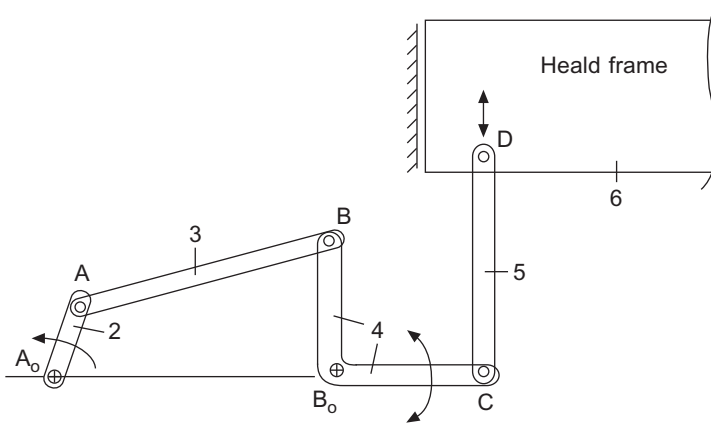


Fig. 5.8 Crank shedding.

foremost position of link (4) corresponds to the bottom position, whilst the rearmost position corresponds to the upper position of the heald frame. Heald frames change position in each loom revolution and, consequently, this mechanism is suitable only for plain weave.

5.6.4 Dobby shedding

Dobby shedding mechanisms have been in use for well over 150 years and, over the years, there have been significant improvements in their design to meet the requirements of modern high speed weaving machines.

Dobby shedding offers a considerably greater scope than most other mechanisms and is used in the production of simple figured fabrics. Modern dobbie mechanisms are basically divided into single lift and double lift, or positive and negative types. The single-lift dobbie provides a bottom-closed shed whilst the double-lift dobbie creates either an open or semiopen shed. Positive dobbies are commonly used to weave medium to heavy weight fabrics, whilst negative dobbies (which tend to be simpler) are used for light to medium weight fabrics. In negative dobbie shedding, the heald shafts to be raised are lifted by a cam by the dobbie mechanism but are normally lowered by the action of springs (Fig. 5.9A) [12]. In positive dobbie shedding, the shafts are raised and lowered by the dobbie mechanism (Fig. 5.9B) [12].

In early versions of dobbie shedding mechanisms, despite their different designs, the principle of selecting and lifting the heald shafts for positive or negative dobbie is more or less the same [2] (see Fig. 5.10A). The dobbie is moved by a rod (R) worked from the crank. The hook D is given backwards and forwards ('to and fro') motion through the lever (L). The actual selection of the heald shafts to be lifted on each pick is made by the presence or absence of pegs in the lags. The selection of the heald shafts to be lifted on each pick is pegged in the lags [12] (Fig. 5.10B). These pegs are joined in the form of a chain, which is put on a barrel (B) that in turn

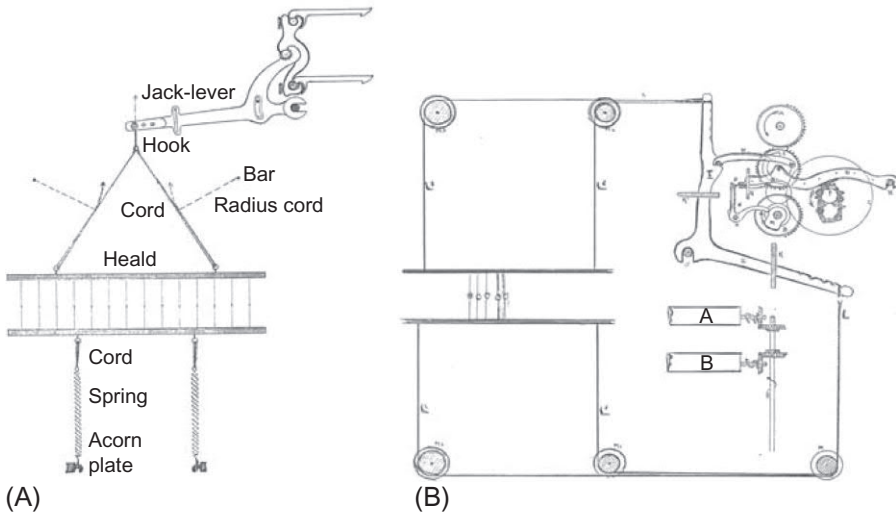


Fig. 5.9 (A) Negative dobby, (B) positive dobby.

moves into a new position on every revolution of the loom. A series of feelers, or levers (A), are located above the pegs. One end of each lever (a) supports another hook (C). The presence of a peg lifts the filler which, through the leverage mechanism, lowers a hook (C) (as indicated by broken lines in the figure). The hooks (C and D) are engaged and the resulting movement of the hooks through the levers raises the heald shaft (h). For each heald shaft, there is one feeler, one hook, and a lever, and their total number indicates the capacity of the dobby, i.e., the maximum number of shafts that can be used for a given design. Fig. 5.11 represents a modern version [13] of a dobby attachment on a loom, using a plastic punched tape instead of the pegs on lags as described above.

5.6.5 Jacquard shedding

Jacquard fabric is a fabric in which a large number of warp threads, in excess of the capacity of a dobby, weave differently and therefore require a jacquard mechanism [14]. In tappet and dobby shedding, heald wires are not operated singly but are attached to heald frames, or heald shafts, and each wire on a given shaft conforms to the movement of the shaft, rising or falling with it. Both types of shedding systems are used to control shedding where, due to the simplicity of the interlacing, only a few heald shafts are required. Both methods have limitations if the design repeat is more than 32 shafts.

In Jacquard shedding, heald wires are manipulated individually by means of cords (or a harness) and not collectively through the agency of a heald frame. The shedding mechanism is mostly mounted on top of the loom on a gantry. Fig. 5.12 shows a modern Stäubli jacquard on a Vaupel weaving machine with the harnesses attached to the

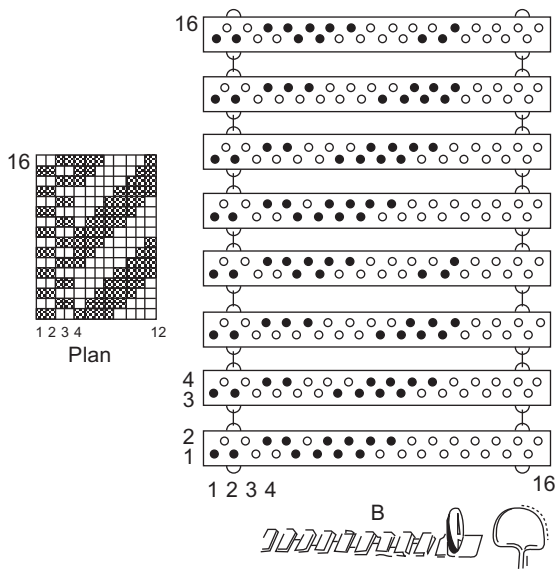
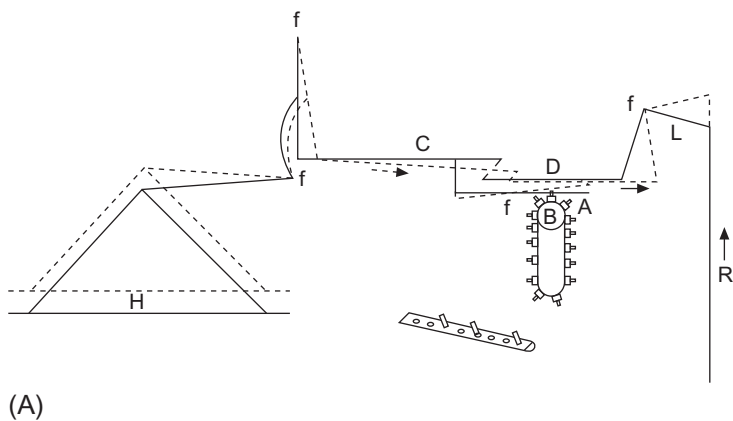


Fig. 5.10 (A) Working principle of dobby, (B) pegged lags joined in chain form.

top of the jacquard. Jacquard shedding is divided into two categories: single cylinder single-lift and double cylinder double-lift and is used for high speed weaving machines.

Fig. 5.13 shows a schematic diagram of a single cylinder single-lift jacquard [7]. The essential elements of a traditional jacquard are hooks, needles, perforated squared cylinder, and a griffe with knives. On a single-lift jacquard, there is one needle for each hook, with one end of the needle resting in a spring box, the coiled spring of which presses the needle toward the right and out of the needle board. All the needles

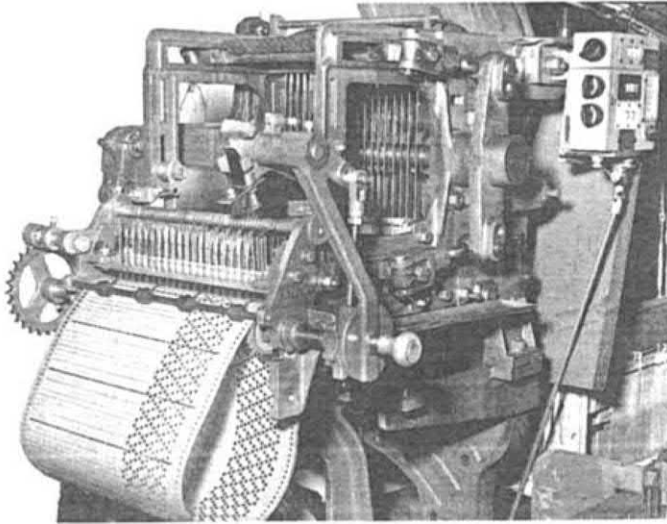


Fig. 5.11 Plastic punched tape that controls the warp shedding.

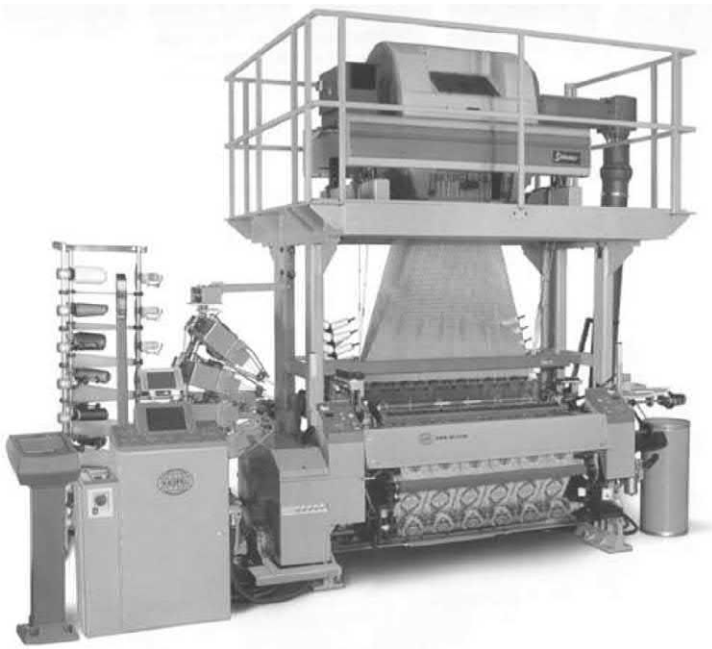


Fig. 5.12 Stäubli jacquard on top of the Vaupel loom.

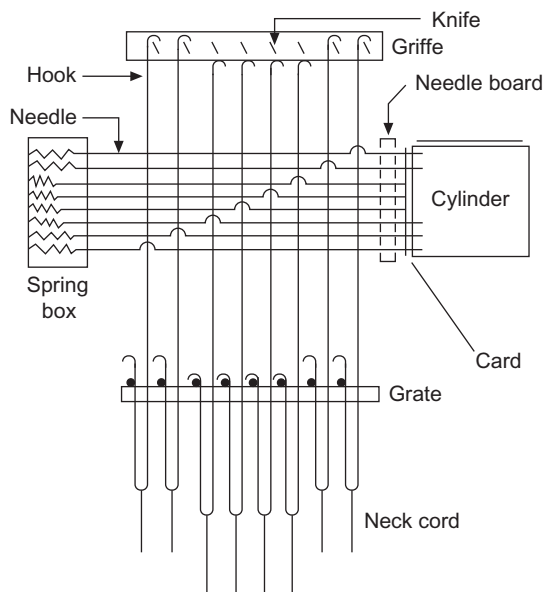


Fig. 5.13 Single cylinder single-lift jacquard.

face the holes on the squared cylinder, each needle corresponding to a hole. Each needle has a small bent kink into which the vertical hook is positioned.

A Jacquard design is punched onto strips of card, with one card for each pick. When all the cards have been punched, they are laced together in the form of a chain and placed around the squared perforated cylinder. The holes in the card match the holes in the cylinder, whilst blanks in the card cover holes in the cylinder. For each loom cycle, the cylinder has two movements – away from the needles as well as turning once to bring the next punched card into place and pressed against the needles. If there is a hole in the card opposite the particular needle, the needle can enter the hole in the cylinder beneath, and the position of the corresponding hook will not be disturbed.

As this is happening, the griffe on the top with knives fixed into it reciprocates vertically once every pick. If the hook has not been disturbed from its position, the knife gets engaged with the hook, and, while moving up, takes the hook with it. At the bottom of the hook, the harness cord is attached by a mail through which the warp end has been passed. Thus, when the hook goes up, the warp is raised with it.

If there is a blank in the card, as the cylinder moves inward and the card is presented against the needle, the card pushes the needle to the left. Thus, the hook controlled by this needle is moved out of the path of the knife as it goes up and the hook is not engaged; the hook and the warp ends tied to it are therefore not lifted. Each hook controls a number of harnesses depending on the number of repeats of the design in the given width of the warp. This type of jacquard forms a bottom-closed shed and limits the loom speed. The figuring capacity of the jacquard is limited by the number of hooks it has. On a single-lift jacquard, there is one needle for each hook.

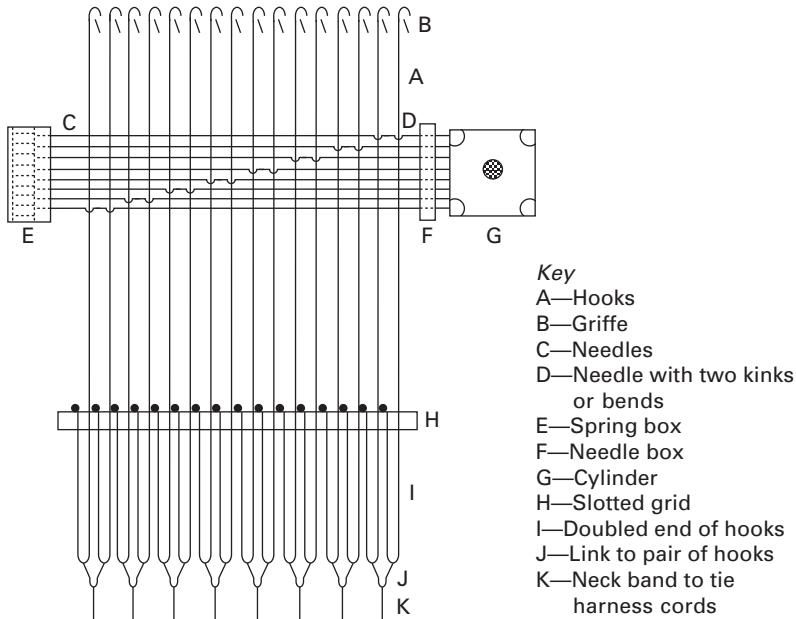


Fig. 5.14 Single cylinder double-lift jacquard.

5.6.5.1 Single cylinder double-lift jacquard

[Fig. 5.14](#) presents an outline of a single cylinder double-lift jacquard [6]. In this type of jacquard, each needle is made with two kinks to control the movement of two hooks. It has two sets of knives mounted in two griffes that move up and down in opposition over a two-pick cycle. The cylinder reciprocates and turns every two picks. The principle of selecting the ends to be raised is almost identical to the single-lift jacquard. The mechanism offers the advantage that if an end is required to remain up for more than two or more consecutive picks, it is lowered half way between the picks and raised again. This reduces the strain on the particular warp ends and the breakage rate also; it produces a semiopen shed.

5.6.5.2 Double cylinder double-lift jacquard

In a double cylinder double-lift jacquard ([Fig. 5.15](#)), there are two sets of needles and hooks as well as two cylinders (one of which carries the even-numbered cards and the other, the odd-numbered cards) [6]. Each needle controls one hook. Since the cylinder speed is half that of the single cylinder jacquard, the double cylinder double-lift jacquard is capable of running at higher speeds. Apart from that, it works on the same principle as the single cylinder double-lift jacquard and produces a semiopen shed. One advantage of this mechanism is that, if an end needs to remain up for more than two or more consecutive picks, it is lowered just half way between the picks before being raised again. This reduces the strain on the warp ends concerned and, consequently, reduces the breakage rate.

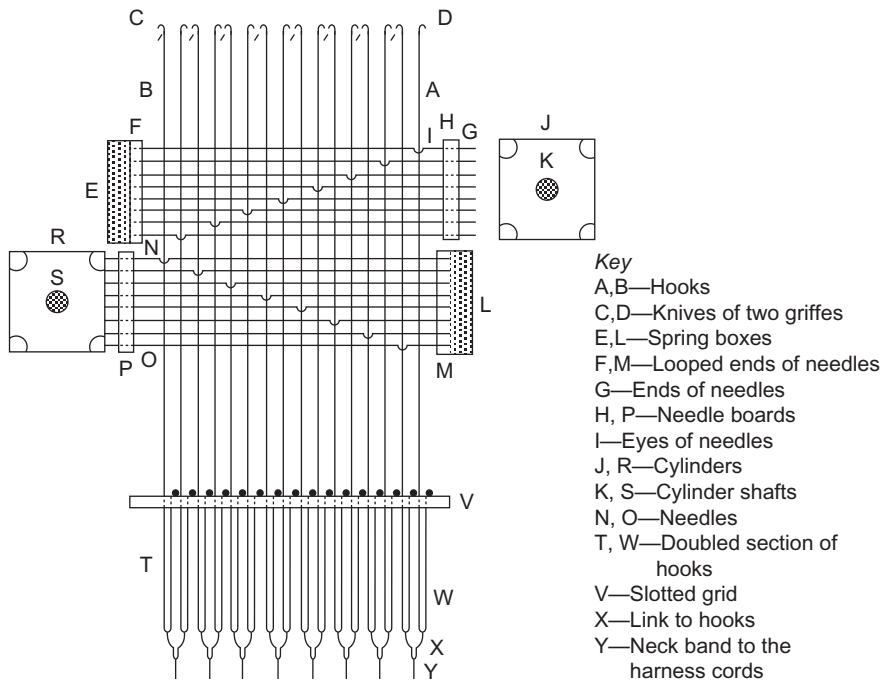


Fig. 5.15 Double cylinder double-lift jacquard.

Over the years, various electronically controlled jacquards have appeared on the market and have become very popular, with Stäubli being the leading manufacturer. Although the fundamental principles of jacquard shedding have not changed much, the methods of selecting the warp ends to be raised have been revolutionized. Fig. 5.16A demonstrates some of the operating phases of the functional principle of Stäubli CX 860 type jacquard with electronic control. The double rollers 'a' move the harness cord to the upper and lower shed positions. Fig. 5.16B shows a jacquard machine with a hook-selection device [2,15].

5.7 Different types of shed

During the process of forming a shed (see Fig. 5.17), cam, crank, dobby, and jacquard shedding mechanisms all give different types of motion to the heald shafts which, in turn, produce different types of shed, that can be divided into two main groups: open and closed [2,7].

5.7.1 Bottom closed shed

The mechanism used to form a bottom closed shed is very simple and reliable. After every pick, all the yarns return to the bottom line from their top position, and the shed closes, even if some of them are required to be raised again on the next pick. As such,

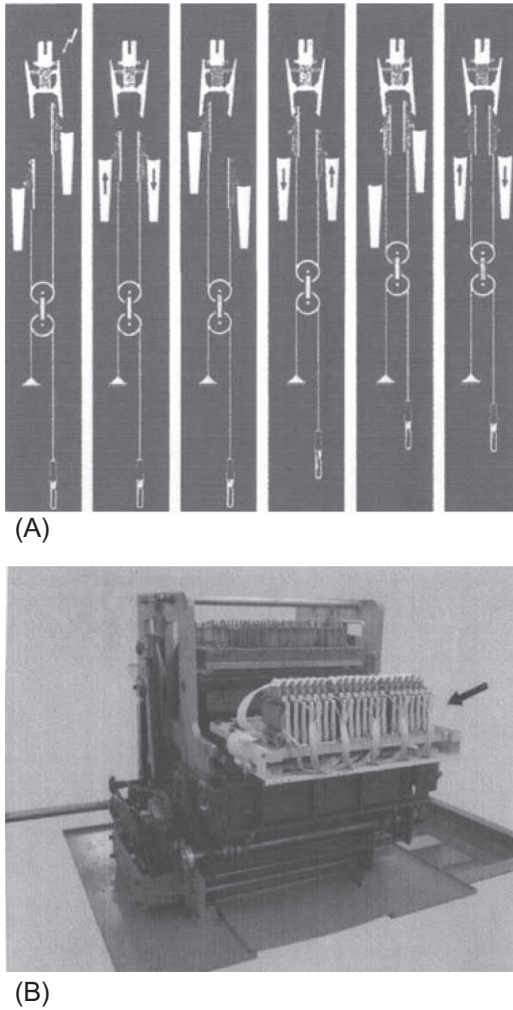


Fig. 5.16 (A) Electronically controlled hook-selection system:

1 – (lower shed position) hook *b* in its upper-most position has placed ratchet *d* against electromagnet *h*. This magnet is activated according to the pattern, briefly retains ratchet *d*, and prevents hook *b* from hooking onto ratchet; 2 – (lower shed position) hooks *b* and *c* follow the knives *g* and *f* moving up or down. Double rollers *a* compensate the motions of hooks *b* and *c*; 3 – (lower shed position) by the rising motion of knife *g*; hook *c* has placed ratchet *e* against electromagnet *h*. According to the pattern, the magnet is not activated, which causes hook *c* to hook onto the ratchet; 4 – (shed motion) hook *c* is hooked onto ratchet *e*, hook *b* follows the rising knife *f* and thereby lifts the harness cord; 5 – (upper shed position) hook *c* remains hooked onto ratchet *e*. Hook *b* has placed ratchet *d* against electromagnet *h* by the rising motion of knife *f*. According to the pattern, the magnet is not activated, which causes hook *b* to hook onto ratchet; 6 – (upper shed formation): hooks *b* and *c* remain hooked onto ratchets *d* and *e*. Knives *g* and *f* are in rising and descending motion, respectively. Jaquard machine with hook-selection device (indicated by *arrow*).

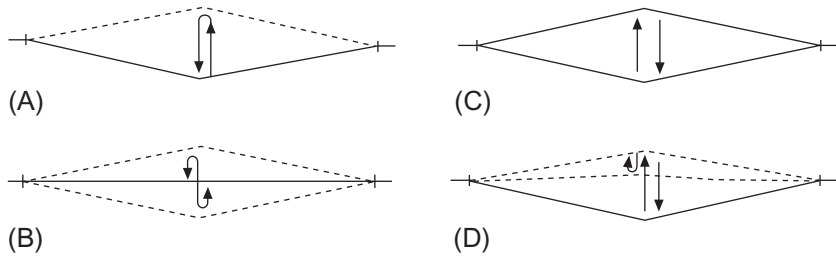


Fig. 5.17 Types of shed (A) bottom closed (B) centre closed (C) open and (D) semiopen.

some warp yarns move a distance equal to twice the depth of the shed each time. Hence, there is a great deal of wasted movement, and it takes a long time to produce a shed. Consequently, this type of shed is not suitable for high-speed looms. Wear and tear of the loom, and power consumption, are also high.

5.7.2 Centre closed shed

In a centre closed shed, all the yarns return to the middle position (centre line) to form a closed shed after every pick. For the next pick, yarns which are to form the top and bottom line are raised and lowered respectively from the centre line. After inserting a pick, both the lines meet at the centre. Whatever the weave, every end is either raised or lowered at every pick, resulting in wasted movement. Centre closed shed tend to place a little more strain on the warp than open shed, but are employed widely in plain tappet, dobby, and jacquard looms.

5.7.3 Open shed

With an open shed, the warp threads form two stationary lines, one at the top and the other at the bottom, and the shed never closes. After the insertion of the pick, changes are made by only some yarns from one fixed line to the other, i.e., some threads are lowered from the top line, and some are raised from the bottom line, simultaneously. Since there is no wasted movement, the shed is formed relatively quickly. Open sheds offer advantages such as low strain on the warp, low power consumption, less wear and tear of the loom, and can be used on high-speed looms. However, because the warp is not levelled, it is difficult for the weaver to repair any broken ends, and a levelling mechanism is provided on most looms to overcome this problem. As the shed is always open, the yarn is subjected to strain and, with weak yarns, increased breakages may result.

5.7.4 Semiopen shed

The semiopen shed combines elements of both the closed and open shed systems; a stationary bottom line is retained. Warp yarns from the top line, which are not required to be raised in the next pick, are lowered to the bottom line. Yarns which are required to stay up for two or more picks in succession are lowered but stopped in the centre position between picks (i.e., not fully lowered to the bottom line) before being raised again to the top position. At the same time, ends from the bottom line which are

required to be at the top line are raised. The shed is thus never fully closed or open: hence the name 'semiopen shed'. In this type of shed, there is less wasted movement by the warp, and higher loom speeds can be offered. However, the strain upon the warp is not so equally distributed as in the open shed type. Double-lift dobbies and jacquard normally use this type of shedding.

5.8 Classifications of plain and automatic shuttle looms

5.8.1 Plain nonautomatic shuttle loom

In a plain nonautomatic shuttle loom, a weft package called a cop is inserted onto the spindle in the shuttle [6] (Fig. 5.18) and the yarn is drawn from the eye of the shuttle. When the supply package is exhausted, the loom stops and the weaver takes out the empty package, inserts a new one in the shuttle, draws the yarn from the shuttle eye, and re-starts the loom. This procedure puts a serious limitation on the number of looms a weaver can oversee.

5.8.2 Pirn changing automatic loom

A pirn changing automatic loom requires a specially designed shuttle without a spindle, as well as a weft package (Fig. 5.19). When the supply package is finished, the exhausted pirn is ejected from the shuttle, and a new one is fed automatically, whilst the yarn is self-threaded from the thread guide. Automatic pirn changing mechanisms can be fitted to tappet (cam) looms, dobby looms, and jacquards. Fig. 5.20A shows a Northrop pirn changing loom [16]. The weft, in the form of ring pirns with three metal rings at the base (Fig. 5.19), is placed in a circular magazine (sometimes called a battery), which can hold 24 packages (Fig. 5.20B). The supply is kept topped up by battery filler. The shuttle used on this type of loom is specially designed with a pair of grooved spring jaws to hold the pirn with the three rings (Fig. 5.19). The circular magazine is mounted on one side of the loom. When the running weft supply package is

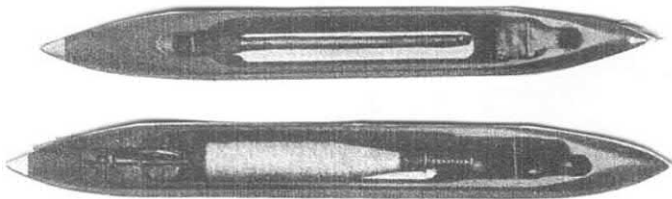


Fig. 5.18 Shuttle for nonautomatic loom.

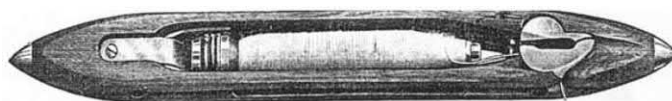
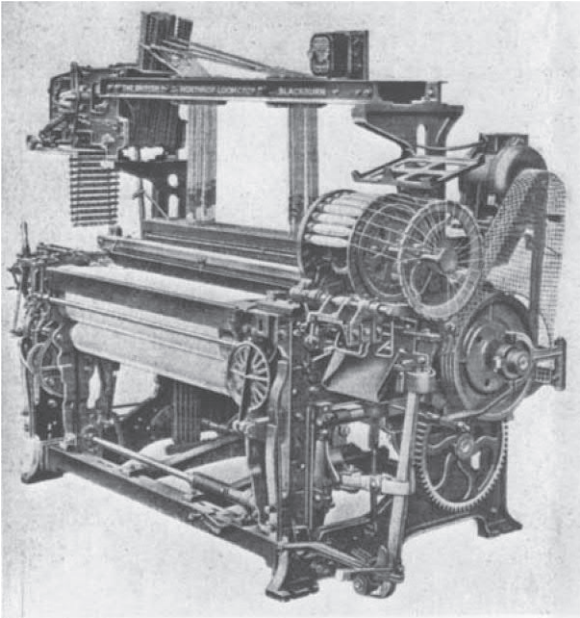
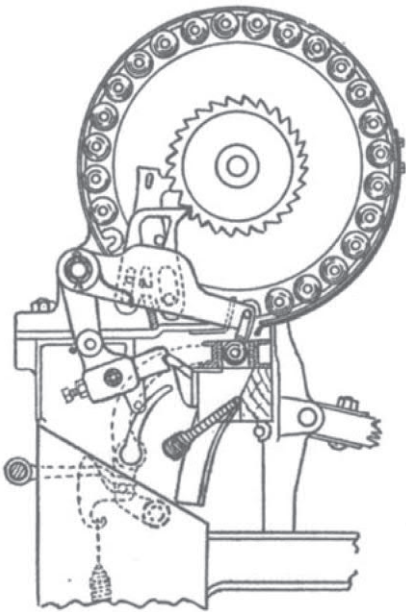


Fig. 5.19 Shuttle for automatic pirn changing loom.



(A)

Fig. 5.20 (A) Northrop pirm changing loom with dobby on the top left-hand side of the loom and underpick motion on the right-hand side, (B) pirm changing mechanism showing the battery in the transfer position.



(B)

finished, a weft feeler mechanism senses the absence of weft and triggers a mechanism which in turn raises a change lever. When the sley moves forward to the beat-up position, the change lever is then pressed back by a striker fixed to the sley. As a result of this action, a transfer hammer is depressed, forcing a new pirn from the magazine into the two grooved spring jaws in the shuttle and, at the same time, ejecting the empty one (Fig. 5.20B) [6].

5.8.3 Automatic shuttle changing looms

Automatic shuttle changing looms still use conventional nonautomatic shuttles, and the weft package (provided in the form of either cops or pirns) is therefore interchangeable with those used for nonautomatic looms. This is an advantage when, as is often the case, both automatic and nonautomatic looms are used in the same factory, since no change in the spinning equipment is called for (as is the case, for example, for a pirn changing loom). Shuttle changing looms are well suited to the use of weft of a fine or delicate nature.

Shuttles are changed by a number of different methods, though the most successful looms appear to be those which are automatically stopped for the change and then automatically re-started when the change has been made. Fig. 5.21 shows an automatic shuttle-changing loom [16]. A vertical stationary magazine, with the capacity to hold about 9 or 10 shuttles, is located on the opposite side of the loom to the weft fork and weft feeler, either of which can be used to set the shuttle change mechanism in motion. When a change of shuttle is required, the loom is automatically stopped and the changing mechanism controls the various movements. The shuttle box front is

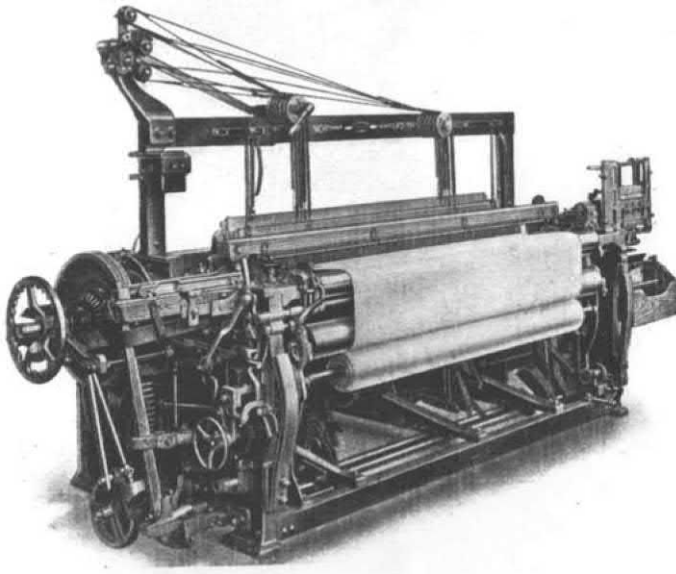


Fig. 5.21 Northrop shuttle changing loom.

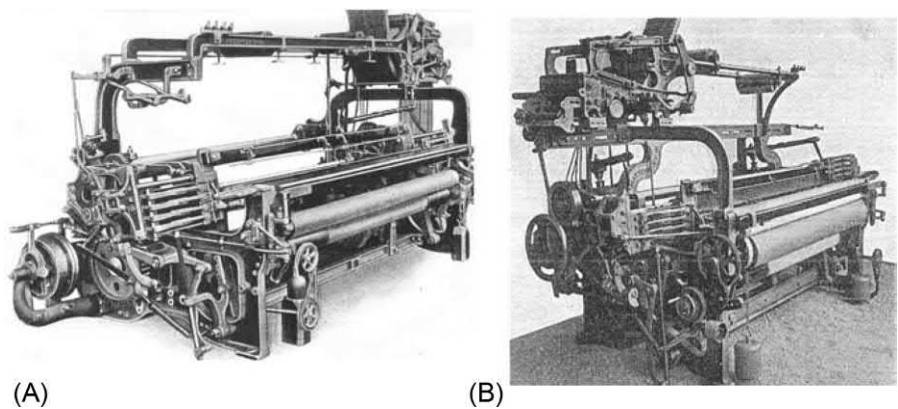


Fig. 5.22 (A) Hattersley 4 ¥ 1 drop box loom, (B) Hattersley 4 ¥ 4 drop box loom with dobby on top of the loom.

lifted and the spent shuttle pushed out of the box; the bottom shuttle in the magazine is lowered onto a conveyer which places it in the box, afterwards returning to its position below the magazine. The box front is lowered and the loom is automatically re-started. The whole operation takes 3–4 seconds.

5.9 Drop box looms

Drop box looms are used for weaving fancy fabrics requiring different colours or kinds of weft yarn in any sequence; the boxes are moved up and down to bring the correct shuttles into position, as required. There are basically two types: (a) pick-and-pick and (b) pick-at-will (Fig. 5.22A and B) [6]. In the case of pick-and-pick looms, an even number of picks of any colour or kind of weft yarn can be inserted as desired, whilst on pick-at-will looms, either an odd or even number of picks can be inserted as desired. To achieve this, there must be the desired number of shuttle boxes on either side of the loom. Drop box looms are generally classified as shown in Table 5.2.

Table 5.2 Classification of drop box looms

No. boxes			
Left side	Right side	Maximum shuttles that can be used	Category of the drop box loom
2	1	2	Pick and pick
2	2	3	Pick at will
4	1	4	Pick and pick
4	3	6	Pick at will
4	4	7	Pick at will
6	6	11	Pick at will

5.10 Weft insertion on shuttle looms

Weft insertion involves throwing the weft yarn (the pick) through the shed formed by the shedding mechanism. On a shuttle loom, the weft package is inserted in the shuttle, and the shuttle is then thrown through the shed with the help of the picking mechanism. On each side of the shuttle loom, there is a box called a shuttle box in which the shuttle rests after being thrown from one box to the other by the picking mechanism. The picking mechanism located at each side of the loom propels the shuttle from the box, through the shed to the other shuttle box. In the next revolution of the loom, the picking cycle throws the shuttle back to the other side; this process is then repeated, as required.

Usually, there are two types of picking mechanisms: (a) overpicking; and (b) underpicking. (See Fig. 5.23 for a schematic representation.) [7] In both cases, the rotary motion of the bottom shaft is converted into rectilinear motion to project the shuttle through the shed.

5.10.1 Overpicking mechanism

With an overpicking mechanism, a so-called picking-tappet, is fitted on the bottom shaft (Fig. 5.23A) which, during its rotation, hits a cone fitted on a vertical rod (called a picking shaft). On top of the shaft is a picking stick on the free end of which a leather band is wrapped. The other (free) end of the leather band is fastened to another part, called a picker, which slides freely on a spindle. As it revolves, the picking tappet hits the cone, which turns the vertical picking shaft sharply. This energy through the

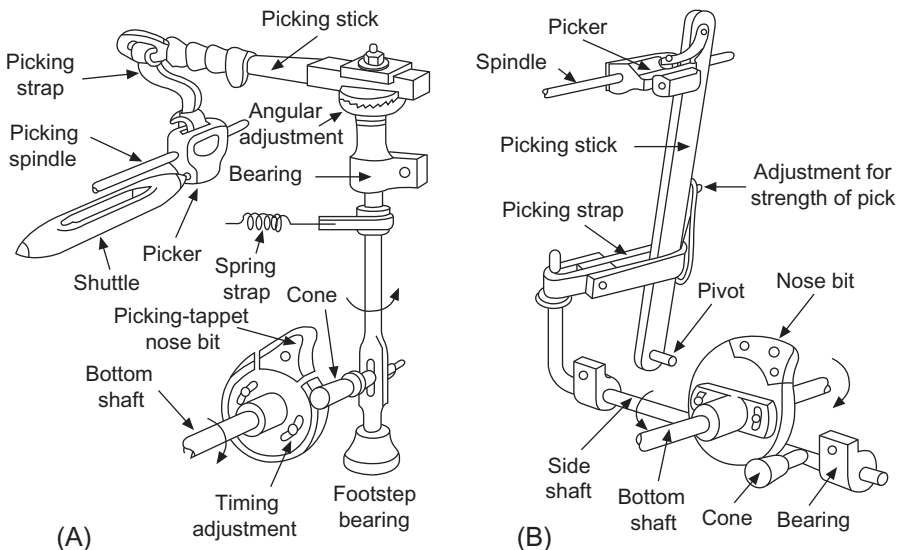


Fig. 5.23 Over- and underpicking mechanisms: (A) cone-overpick, (B) cone-underpick.

picking stick and leather band is transferred to the picker which hits the shuttle tip and throws it out of the shuttle box. The shuttle passes through the shed and is received in the shuttle box on the other side of the loom. In the next loom cycle, picking then takes place from this box, and the process alternates from side to side.

5.10.2 Underpicking mechanism

The principle of operation for an underpicking mechanism is almost the same as for an overpicking mechanism, except that the picking mechanisms are located on the sides of the loom; the parts of the mechanism are almost the same, i.e., a picking cam fitted onto the bottom shaft (Fig. 5.23B), a cone, picking stick, and the picker which slides on a spindle. The picking stick hits the picker directly which throws the shuttle from the box on one side of the loom to the box on the other side.

5.11 Weft insertion on shuttle-less looms

The principle of weaving for both shuttle and shuttle-less looms is exactly the same, i.e. the primary motions – shedding, picking, and beat-up – take place in one cycle for both types of loom. The main difference between shuttle and shuttle-less looms is the method of weft insertion: on a shuttle loom, the picking (i.e., weft insertion) unit is located on both sides, whilst on shuttle-less looms, the picking always takes place from the left side of the loom.

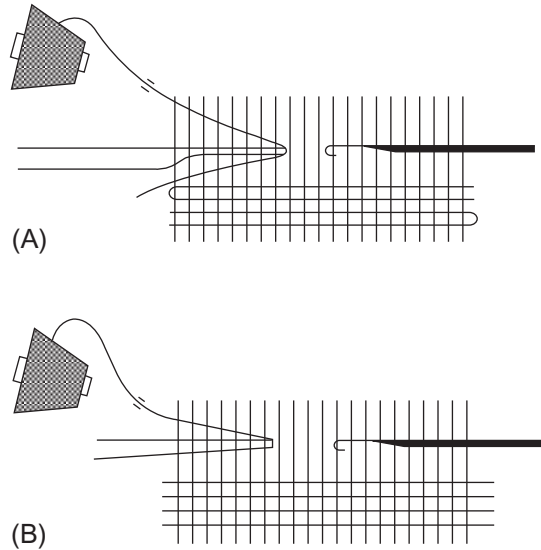
The revolutionary difference between a shuttle and a shuttle-less loom is the method of weft insertion across the shed. In the case of a shuttle loom, the shuttle (itself weighing around 500 g or even more) is thrown across to insert one pick length of yarn, weighing just 4–5 g (depending on the yarn quality), which clearly consumes a lot of energy. In the case of shuttle-less looms, the yarn is thrown not by a shuttle but by any of four different methods: by rapier, projectile, or by a jet of air or water.

5.11.1 Rapier looms

Rapier looms are considered to be the most flexible weaving machines and produce a huge variety of fabric styles and designs. There are basically two types of rapier looms: (a) single rapier and (b) double rapier looms. With single rapier looms, a single rigid bar (a ‘rapier’), of circular cross section equal to the width of the reed, enters the shed from one side, picks up the tip of the weft yarn on the other side, and then passes it across the width of the warp as it retracts. Consequently, the rapier only carries the yarn in one direction, and half of the rapier movement is wasted, limiting the loom speed significantly; as such, this type is not very popular (though they are suitable for yarns that are difficult to control).

In a double rapier loom, two rapiers are used: a ‘giver’ and a ‘taker’. The giver takes the yarn from the supply package on the left of the machine and takes it to the middle of the shed where it is met by the taker, which retracts and transfers the weft yarn to the other side of the warp. Double rapier looms can be either rigid or flexible. In both

Fig. 5.24 (A) Gabler and (B) Dewas system of weft insertion.

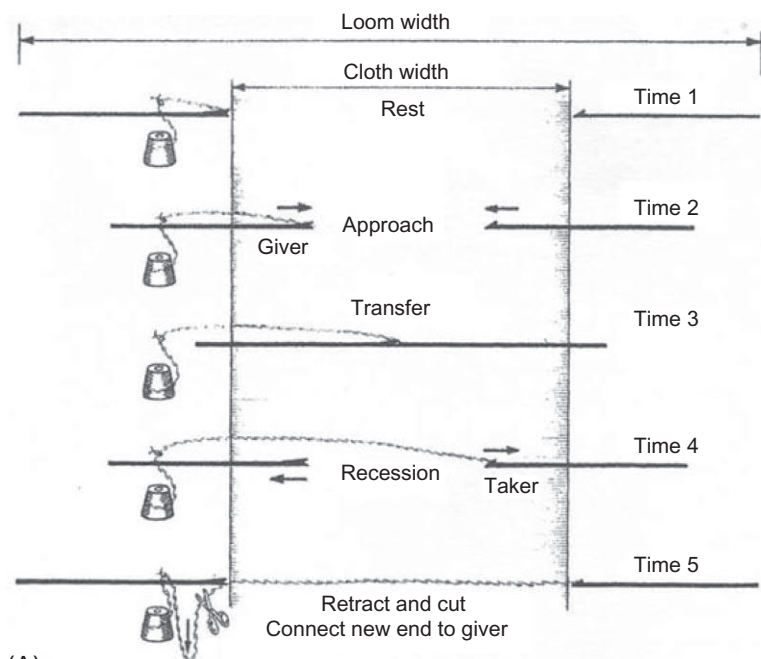


cases, the second rapier, i.e., the taker, completes the weft insertion.) These two types are considered below:

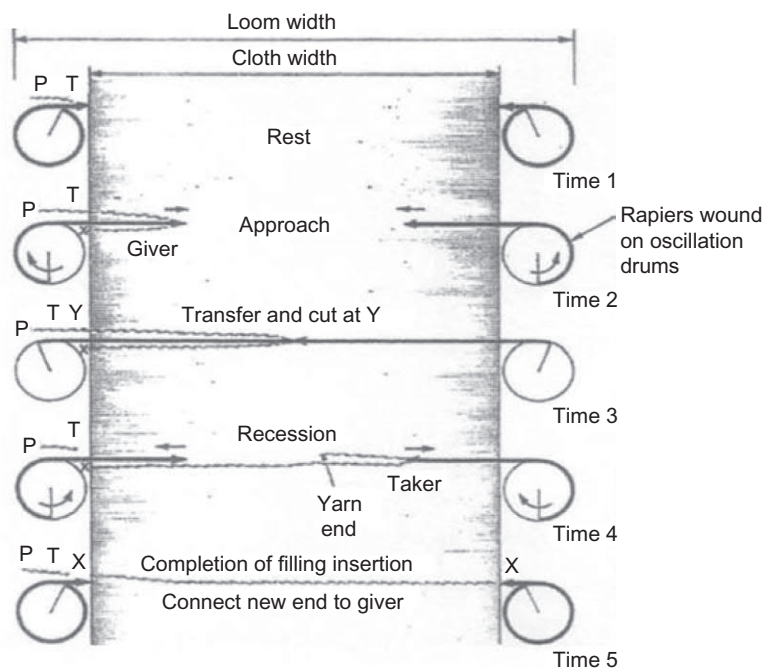
- *Double rigid rapier looms.* Here, the weft yarn is transferred in one of two ways (Fig. 5.24): either by tip-to-tip transfer or loop transfer [17]. In tip-to-tip transfer (the dewas system), the giver grips the tip of the yarn and takes it to the middle of the warp where it transfers to the other rapier head (the taker), which retracts and carries the weft to the other side of the warp. This method inserts each pick separately, and both edges of the fabric are identical. In loop transfer (the Gabler system), the yarn is not gripped from the tip. Instead, the weft yarn is hooked by the giver (i.e., the rapier which extends the yarn in the form of a 'U' shaped loop to the middle of the warp). The yarn is then transferred to the taker which takes it to the other side of the warp by straightening it. The yarn for each full pick is withdrawn from the supply package in the first half of the pick cycle. This puts tension on the yarn and sometimes restricts the range of weft yarns (i.e., fine or delicate yarns) that can be woven using this method. This method of weft insertion is not currently very common. However, the method allows for convenient selvedge formed at one side of the fabric. Fig. 5.25A shows a rigid rapier sequence [18].
- *Flexible rapier looms* [18]. Here the principle of weft insertion is almost the same as on a rigid rapier dewas system, except that the rapiers have a tape-like structure that can be wound on a drum as shown in Fig. 5.25B. This design saves space, and, consequently, flexible rapier looms are more common than rigid rapiers. The yarn is gripped by both the giver and the taker.

5.11.2 Two-phase weaving machines

Many years ago, Saurer introduced their Saurer 500 two-phase rapier machine [17] in which the rigid rapier is centrally driven (as shown in Fig. 5.26) and the weft is inserted from the centre from weft packages adjacent to the inside selvedges of the



(A)



NB Yarn package or storage system situated at P
Filling tension control situated at T

(B)

Fig. 5.25 (A) Schematic diagram of a rigid rapier sequence, (B) schematic diagram of flexible rapier sequence.

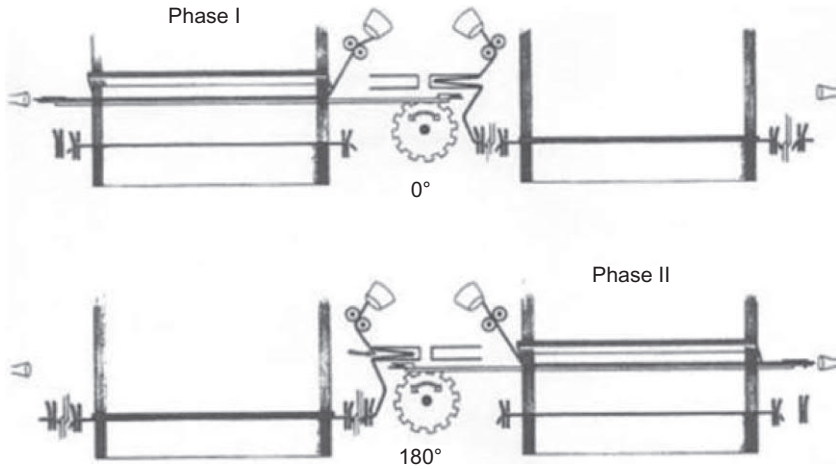


Fig. 5.26 Saurer 500 two-phase rapier loom.

two fabrics. (The Saurer 500 produces two fabrics simultaneously.) The rapier inserts picks alternately in the left-hand and right-hand fabrics: with the left-hand reed on back centre, the rapier first inserts a pick from the left-hand rapier gripper; as the rapier is withdrawn, the right-hand reed recedes to the picking position and the right-hand rapier gripper picks up the weft end from the other weft package and inserts it into the right-hand fabric. At the same time, the left-hand reed forces the previous pick to the cloth fell where it is severed very close to the two selvages.

5.11.3 Projectile looms

The manufacturer Sulzer first introduced the projectile method of weft insertion to the market in 1952, and then exhibited it at International Textile Machinery show (ITMA) in Brussels in 1955. Over the decades, significant developments have gone into its design, and the company continues to totally monopolize the market because of the following advantage offered by this method of weft insertion [19]:

- flexibility to weave more than one width of fabric at a time, i.e., 33–540 cm
- low-power consumption
- reduced waste of weft yarn due to its unique, clean tucked-in selvedge
- its ability to weave multicolour weft for any sequence of up to six different weft yarns
- low spare parts consumption and easy maintenance

For projectile looms, the principle of weft insertion [2,17,20,21] is such that the weft yarn is inserted in the shed by means of a projectile [21] weighing only 40–60 g (Fig. 5.27). The gripper (projectile) carrying the weft is thrown from the picking side to the receiving side across the machine. The energy used to throw the gripper holding the weft yarn is derived from the shear strain energy stored in a torsion bar which is twisted a predetermined amount and triggered off to provide the means of propulsion.

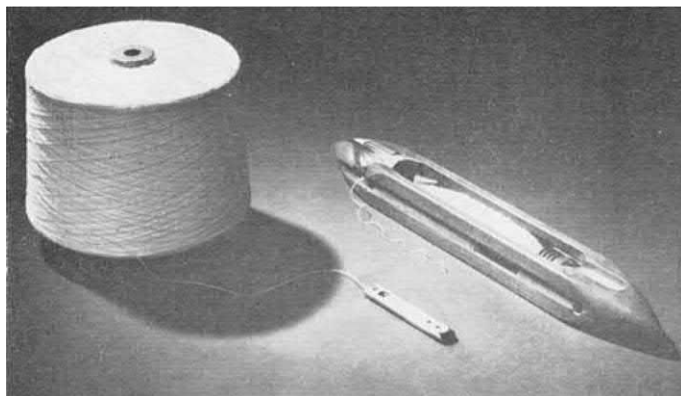


Fig. 5.27 Sulzer package and gripper shown for comparison with a conventional shuttle and pirm.

During this journey, the gripper projectile glides through the shed in guides and draws the weft yarn into the shed.

The picking action is illustrated [20] in Fig. 5.28. The projectile (missile) (1) is about to be picked by a metal picker (2) joined by a short connecting rod to the picking arm (3). This arm is attached to the rotatable end of a steel torsion rod (11), which has its other end fixed at (12); the rod is twisted by the anticlockwise rotation of the arm (13) attached to the sleeve (10). This arm is turned when the toggle formed by the arms (8 and 9) is straightened out by the action of the cam (4) which, rotating in a clockwise direction, moves the lever (8) to the right. The diagram illustrates the situation immediately following the straining of the torsion rod: the rod is being held at its position of maximum torsion, and cam (4) has ceased to operate on the cam follower mounted on the arm (8). The cam (4) is itself provided with a cam follower (5) which, in the next phase of the operation, initiates picking by pressing on an extension of arm (8), which moves the arm to the left and abruptly nullifies the holding action of the toggle. The torsion rod is now free to untwist, and the pent-up energy in it is released, causing the picking arm to rotate and launch the projectile at high speed, typically at about 30 m/s. The residual energy in the picking system is absorbed in the hydraulic buffer (7).

The energy available for picking depends on the angular displacement of the free end for a particular design of torsion bar; the strength of pick is completely independent of the speed of the machine. At the receiving side, the weft-end gripper is positioned to grip the weft after reception. It is braked in the receiving unit and is then transported by a conveyor belt (situated under the shed) to its original position on the picking side. It is thought that the gripper projection energy is about one-third to one-half of that normally needed in conventional shuttle picking.

The weft package is situated outside the machine on the picking side, all the picks being delivered from the same side. The weft is withdrawn from the package through a tension device, a weft tensioner, a feeder, scissors, and the weft-end gripper. Fig. 5.29A shows the weft insertion system in detail on a Sulzer projectile weaving machine, whilst Fig. 5.29B shows a projectile with weft yarn entering a shed [1].

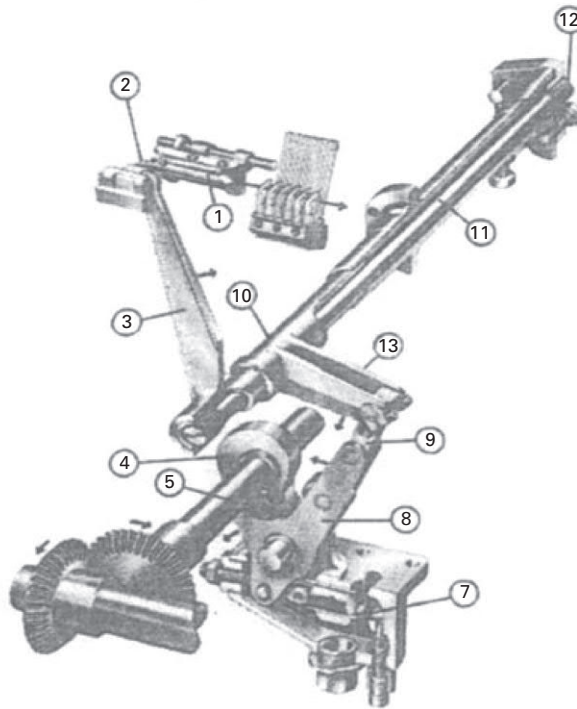


Fig. 5.28 Picking mechanism of Sulzer weaving machine. The strain energy in the torsion rod (11) is about to be released by further movement of the cam follower (5), causing parts (8), (13), (3) and the missile (1) to move in the directions shown by the arrows.
Courtesy of Sulzer Bros Inc.

A description of the weft insertion system corresponding to the seven stages in Fig. 5.29A is as follows:

- (i) The projectile (1) moves into the picking position.
- (ii) The projectile feeder (2) opens after the projectile has gripped the end of the weft thread presented to it.
- (iii) The projectile has drawn the thread through the shed during which time the weft tensioner (3) and the adjustable weft brake (4) act to minimize the stress on the thread at the moment of picking.
- (iv) The projectile (1) is stopped by the brake (8) and pushed back inside the receiving unit housing. Feeder (2) moves close to the edge of the cloth.
- (v) The feeder (2) grips the thread, while the selvedge grippers (5) hold the weft at both sides of the cloth.
- (vi) The thread is severed by the scissors (6) on the picking side and released by projectile (1) on the receiving side. The ejected projectile (1) is then placed on the conveyor belt which carries it outside the shed back to the picking position.
- (vii) The weft has now been beaten up by the reed. The needles (7) tuck the weft ends into the next shed (a tuck-in selvedge).

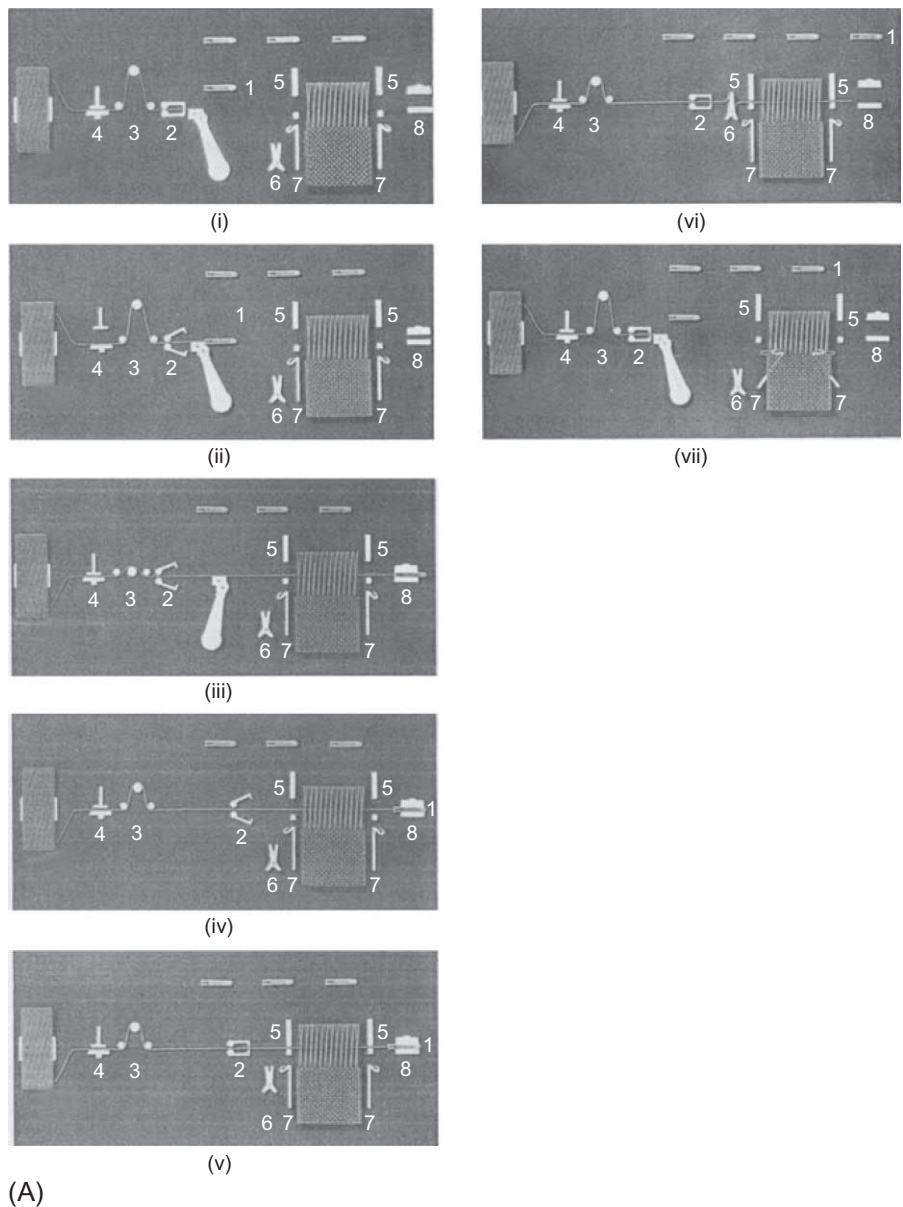
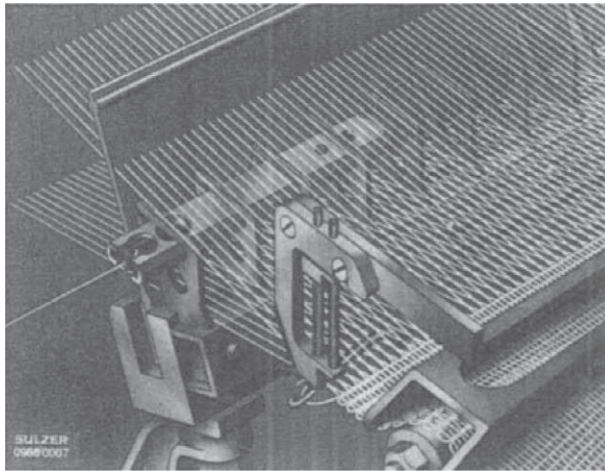


Fig. 5.29 (A) Schematic of the weft insertion system of a projectile loom.

(Continued)



(B)

Fig. 5.29, cont'd (B) Sulzer projectile entering the shed. Every pick is cut off after complete insertion. The ends are then tucked in the shed and woven in with the next pick.
Courtesy of Sulzer Bros Inc.

5.11.4 Weft insertion on jet-looms

On a jet loom, the weft is inserted by means of a nozzle and carried across the shed by a jet of a working substance, i.e. a fluid. The relative velocity between the jet and the weft thread produces a force on the weft which results in its insertion in the shed. As the tractive force applied to the weft is not very high, the weft thread cannot be unwound directly from a cross-wound package but must be prepared for picking by a metering device.

In the majority of jet weaving machines, the picking system is fitted only on one side of the machine. In all types of jet weaving machines, the picking system is fixed firmly to the machine frame so that the beat-up mechanism carries only the reed or the air duct. Hence, the moment of inertia of the beat-up mechanism is small, and, therefore, the operation of the jet weaving machine is smooth and uniform.

Air-jet weaving machines are supplied with compressed air from a central source or equipped with individual built-in compression units. Water-jet weaving machines are equipped with individual injection pumps, and water is supplied to them from the water main; waste water is discharged into a drain.

Fig. 5.30 shows the working principle of jet looms in the following stages [22]:

- (a) The weft (2) is unwound from the cross-wound cone (1) and passed through the guide eye and tensioner (3). The metering device (4) measures the necessary pick length of the weft yarn and the holders (5) serve to retain the weft thread after picking. The water or air is supplied to nozzle (6) through tube (7).

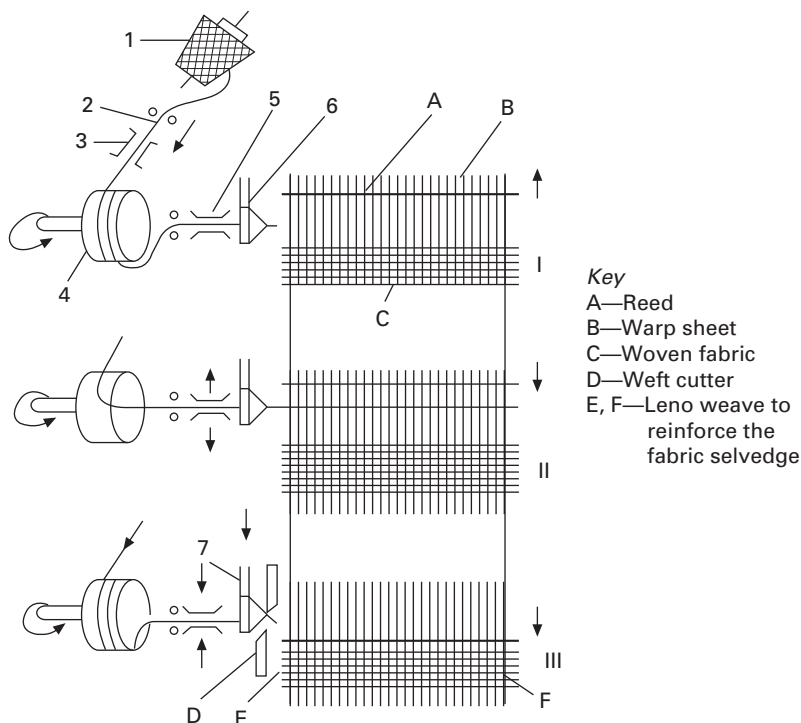


Fig. 5.30 Principle of sequence of operation of jet weaving machines.

- (b) The reed (A) moves backwards. The metering device (4) completes the preparation of the necessary pick length of the weft thread.
- (c) Holders (5) open and, simultaneously, water or air is released into the nozzle (6) to take the weft yarn across the shed.
- (d) When the weft insertion is completed, holders (5) clamp the weft thread.

The reed (A) beats up the inserted weft to the fabric fell, and the cutter (D) cuts it off near the nozzle. Simultaneously the weft thread is secured by the leno weave (E, F). Before each weft is beaten up, the metering device (7) starts preparing the next pick length.

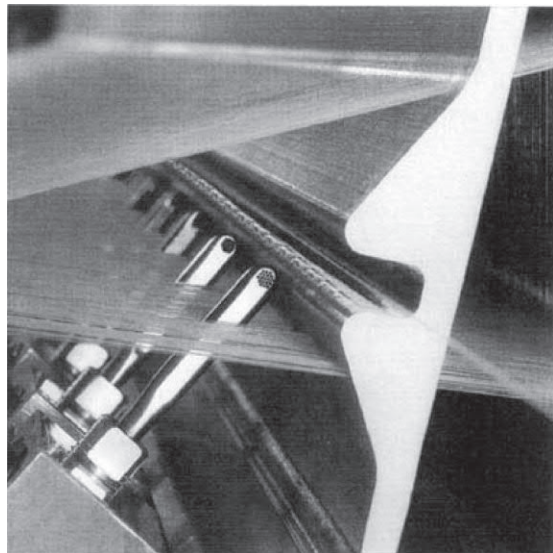
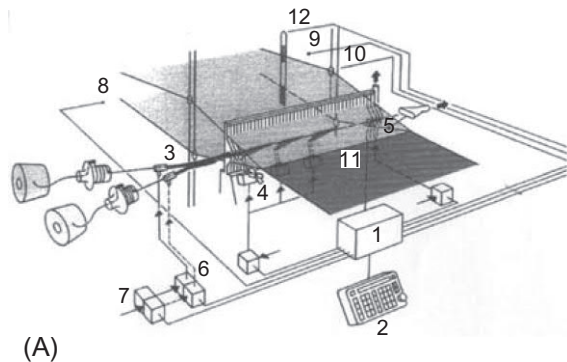
5.11.5 Air-jet looms

Air-jet weaving is considered the most efficient and productive way of inserting the weft across the shed for the production of light to medium weight fabrics, terry towels, furnishing fabrics and denims, etc. Compared to the rapier and projectile methods of weft insertion, the mass of the insertion medium in air-jet weaving is very small. This novel feature allows high weft insertion rates to be achieved. Although the first commercial single-nozzle air-jet loom was exhibited at ITMA in 1958, the real

breakthrough came in 1967–68 when a 165 cm wide loom with relay nozzles running at a weft insertion rate of 530 m/min was exhibited. Over the last few decades, there have been further technological advances in air-jet weaving. As a result, weft insertion rates from 2000 to 2900 m/min have been achieved, weaving fabric widths from 190 to 340 cm.

The principle of weft insertion [17] is shown in Fig. 5.31A. The weft is withdrawn from the weft package(s) by the constant-speed weft feeder units prior to delivering to the two main jet nozzles (3), whilst air is delivered from the pressure regulating valve (7) to the two control valves (6). The velocity of the weft is maintained by the relay nozzles (4) which are integral to the sley and located at intervals across the reed space. The main nozzles provide the initial acceleration, whilst the relay nozzles provide high air velocity to carry the weft across the width of the warp. The relay nozzles

Fig. 5.31 (A) Sulzer Rütli L 5100 (air-jet) weft insertion system and (B) tunnel reed and relay jets in picking position on Sulzer Rütli L 5100.



(B)

are controlled along with the main nozzles from the central processor (1), which is controlled from the operator's terminal (2). The warp let-off (8), the warp tension sensor (9), the shed formation control (10), the weft detector (11), and the warp detector (12) are all controlled through the central processor (1). The stretching nozzle (5) is shown outside the receiving side selvedge. The weft is projected into a tunnel [17] profiled in the reed (shown in Fig. 5.31B) by relay jets in the picking position. The profiled reed provides guidance for the air and separates the weft yarn from the warp. A cutter is used to cut the weft yarn when the insertion is complete.

5.11.6 Water-jet looms

For nearly two decades in the 1970s and 1980s, water-jet looms were regarded as superior due to their impressive weft insertion rates of up to 2700 m/min [23]. However, they are confined to handling only 100% hydrophobic yarns and, from the 1980s onwards, dramatic improvements in the productivity of air-jet and rapier weaving machines started to overshadow their popularity. At ITMA 2003, not a single water-jet loom was exhibited. However, at ITMA 2007, one manufacturer (VUTS from Liberec) exhibited their Camel W water-jet machine, weaving a reinforced fabric 178.6 cm wide at a speed of 600 ppm and with a weft insertion rate of only 1071 m/min. The trend has continued though, and air-jet and rapier machines have taken a major share of the fabric production previously undertaken by water-jet looms. Water-jet looms, although still in commercial use in some parts of the world (and running with weft insertion rates higher than 1200 m/min), are now decreasing in popularity.

Although similar in principle to an air-jet loom (i.e., it uses water as a fluid, instead of air), water-jet looms differ in construction and operating conditions in a number of ways. Each loom has its own miniature pump to feed water under pressure to the nozzle and, to get the best results, the water must be filtered, of a specified hardness, and supplied to the loom at a constant temperature.

Fig. 5.32A shows the working principles of a water-jet loom [24]. Weft yarn, from the cone package (7) is drawn off by a measuring device (2) and passed through a tension regulator (3) and the weft clamp (4). When the pick has to be inserted, the weft clamp (4) loosens its hold and the weft, inserted inside the nozzle (1), is struck by a jet of pressurized water and launched through the shed. The weft is held flat by the leno threads near the entry and exit points of the shed on both sides near the selvedges. The thermal knives (14) enter into action on the launch side to cut the weft, and on the opposite side to trim the fabric. A yarn clamping device (13) holds the weft waste which is cut off by the right-handed thermal knife (14). The water from the container (9) is conveyed by a pump (8) controlled by a cam (10) and a device that controls the pressure (18). A drying device removes the humidity absorbed by the fabric, sucking it through grooves produced in the front beam (6). The loom completes its one cycle, and then additional cycles are completed. Fig. 5.32B shows the water jet outlet along with the weft yarn from the nozzle [22].

Water-jet looms are normally compact, mechanically simple, and require much lower energy than air-jet picking systems. They are best suited for weaving fabrics made from water-insensitive continuous filament yarns, flat polyolefin, and glass.

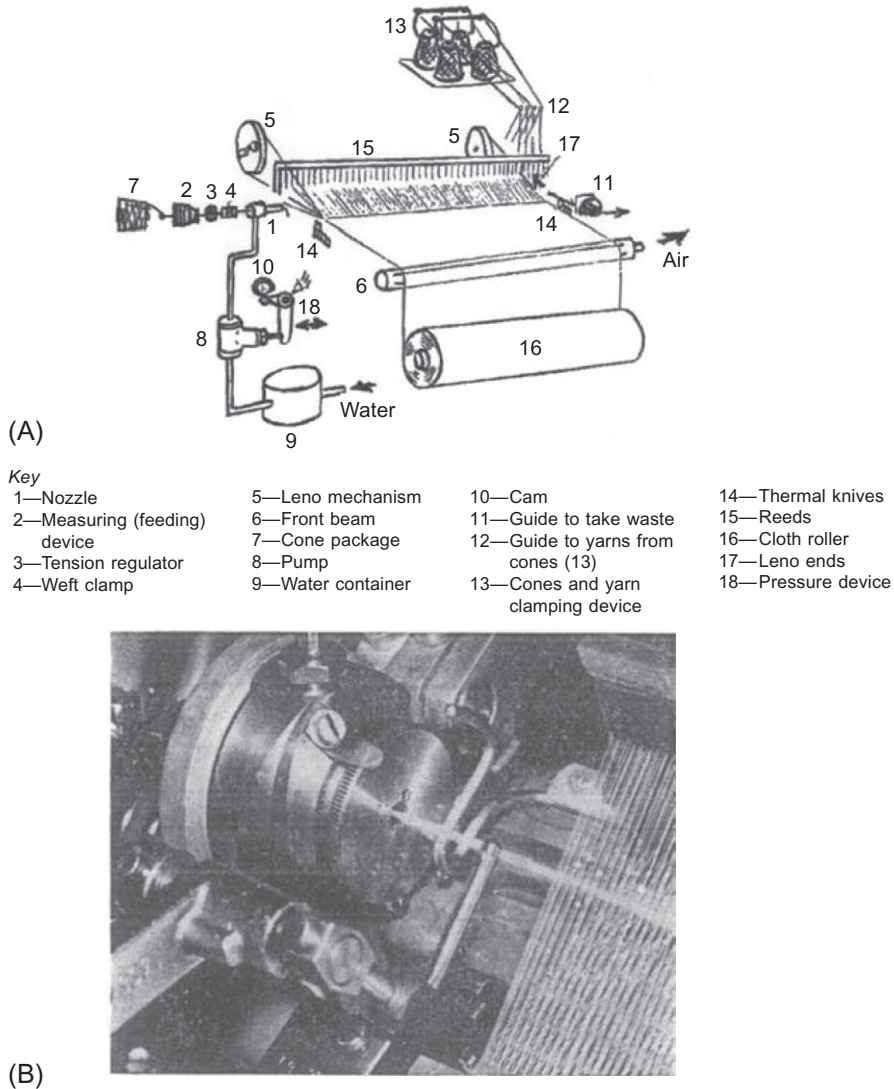


Fig. 5.32 (A) Principle of weft insertion on water-jet loom, (B) water-jet outlet with weft from the nozzle.

One of their drawbacks is their limitation on fabric width. The jet of water which is used to propel the weft yarn disintegrates increasingly into droplets the further it is from the nozzle, and this characteristic (together with the effect of gravity) limits the loom width appreciably compared to air-jet looms. Another limitation is that water-jet looms are not readily adaptable to deal with multicoloured or multiple types of weft. Currently, Toyota offers a model which can be equipped with three-colour

pick-at-will and w-FIS that allows the insertion of fine or coarse and heavy yarns without changing the pump and nozzle, thereby offering high versatility.

5.12 Multiphase weaving

Weaving machines are classified into two groups: single-phase and multiphase. In a single-phase loom, a single insertion of weft yarn is made in one revolution of the loom; the shed is fully opened across the whole width of warp, and the pick is inserted. In a multiphase loom, not just one, but several sheds are formed, and at the same time, several weft insertion elements enter the entire width of the warp.

Single-phase shuttle-less looms, such as rapier, projectile, air-jet, and water-jet are considered to be the second generation of weaving machines in which the primary mechanisms of weaving (i.e., shedding, picking, and beat-up) take place in one loom cycle, thereby inserting one pick in a single phase. Only one shed is formed across the width of the warp.

In multiphase weaving, several sheds are formed across the width of warp at the same time (see Fig. 5.33B) [2]. Multiphase looms are considered to be the third generation of weaving machines. Multiphase weaving can be achieved by employing two different principles, either: (a) in which shedding, picking, and beat-up occur across the width of the warp, i.e., in the weft direction, or (b) in which these actions take place along the length of the warp (in the warp direction).

5.12.1 Principle of weft insertion in multiphase weaving

Several weft carriers, one behind the other, traverse the reed space and insert one pick length of weft yarn (stored inside them) at a time [17]. Weft yarn is continuously drawn from weft packages and wound onto the weft carriers one pick length at a time. Their phase number and velocity determine the weft insertion rates. The shed and reed clearance open and close around each carrier as it traverses the reed space with the movement of the upper extremities of the shedding elements giving the impression

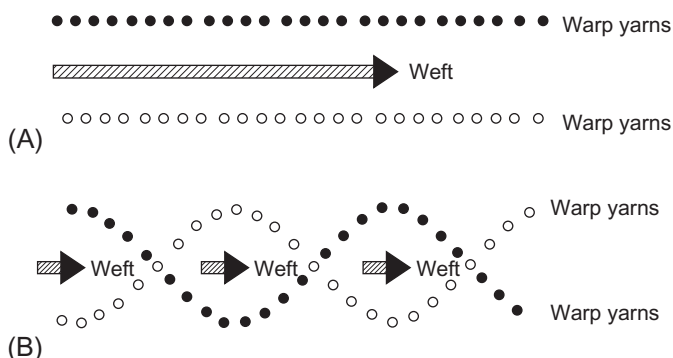


Fig. 5.33 Principle of (A) single-phase and (B) multiphase weaving.

of a wave motion travelling from picking to receiving side. The special reed motion impels the weft carrier through the shed, each of which inserts weft length as it goes. At their reversal point, the mobile reed dents beat the weft yarn emerging from the weft carriers against the fell of the cloth. Upon reaching the receiving end, the carriers then return under the fabric to the picking side for recharging, the weft from the package is transferred to the carriers, and the process continues.

5.12.2 Sulzer Textil multiphase loom M8300

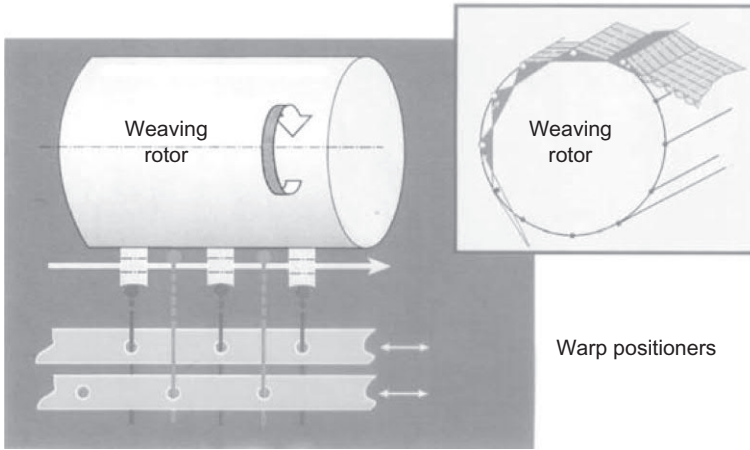
Sulzer *Textil* introduced their revolutionary multiphase loom M8300 [25] at ITMA 1995, with a working width of 190 cm running at 2050 ppm with weft insertion rates of 3894 m/min. The machine has no healds and a nonreciprocating beat-up. The weft is inserted with the aid of compressed air at low pressure and at a uniform speed, with low weft loading. Shedding is based on the multilinker shed principle: sheds are formed positively by shed-forming elements which deflect the warp threads into the upper shed position. The curvature and rotation of the rotor shown in Fig. 5.34A and B cause the shed-forming elements to open the sheds consecutively. A single movement of the warp positioners positions the warp threads so that they are either picked up and lifted by the shed-forming elements, thus forming the upper shed, or remain in the lower position. As many as 2800 sheds are formed consecutively per minute. Each warp thread is inserted individually into the eye of a positioned warp.

A number of sheds are arranged in parallel, one behind the other in the direction of the warp, and are opened simultaneously. Four weft yarns are inserted at the same time, though staggered as in a relay race, into the open sheds on the rotor. To open a number of sheds one after another in the warp direction, the warp is led over a 12-channel continuously rotating drum (the weaving rotor), which is provided with combs consisting of numerous individual elements. The combs form the shed as well as a guide channel for the insertion of the weft as soon as the shed is opened.

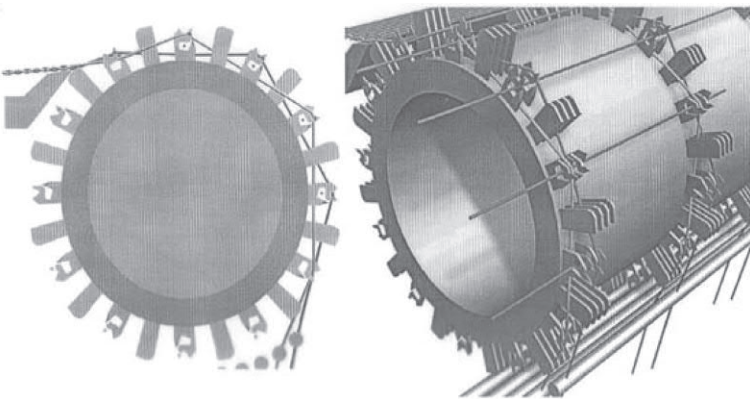
The rotating movement of the weaving rotor lifts the threads off the shoulders of the shed forming elements and lays them over the weft channel, while the remaining threads come to rest below the weft channel. Warp positioners determine the threads that are to be raised. Once the shed is formed completely, low-pressure air carries the weft yarn through a weft insertion channel. During this insertion, further weft yarns start to enter the combs that follow. As soon as the weft has been inserted completely, it is clamped and cut on the feed side. The weft yarn is beaten up by the special beat-up reed that follows each shed forming comb.

This innovative technology offers the following immense advantages:

- a reduction in weaving cost by 30%–40%
- three to four times the productivity
- up to 30%–40% lower energy consumption
- 60% lower space requirement than a single-phase air-jet weaving machine
- noise levels around 10 db (a), lower than that of a single-phase weaving machine
- reduced yarn residues and dust



(A)



(B)

Fig. 5.34 (A) Sulzer Multiphase loom M8300, (B) weaving rotor.

However, multiphase weaving machines have serious limitations from the point of view of fabric design and their narrow field of application. This has, of course, resulted in the demise of multiphase weaving.

5.13 Developments in shuttle-less weaving machines

The truth is that in the last 2/3 decades there has not been any significant revolutionary innovation or developments in the weaving sector on the basis of a new weft insertion system. However, over the same period, there have been incredible incremental

developments in the weaving machines which has created a highly significant excitement and interest to the fabric manufacturers. These developments have been basically in terms of:

- Engineering excellence.
- Ergonomics.
- Machine design.
- Automation as a result of dramatic growth of high-technology electronics as well as micro-processors and their incorporation in the looms to automate wide-ranging aspects of fabric production.

Developments of electronics and their incorporation in the design of the weaving machines have played an extremely important part in improving the automation levels leading to:

- Reducing the work load of the personnel.
- Maximizing energy consumption.
- Ensuring higher safety requirements.
- Providing the flexibility to adopt to new demands.
- Guaranteed reliability.
- Providing remote support.
- Reduced cost of maintenance.

Although from the weaving point of view, the performance of the loom in terms of weft-insertion rate is quite realistic; however, from the engineering point of view, speed carries more importance, and this aspect has been clearly demonstrated at each Itma.

The key elements at recent ITMA's in respect of weaving technology have been the versatility, improved reliability, less noise, simplicity in setting up, adjusting high production speeds, high productivity, ease of operation, lower energy consumption, and the production of high quality of fabrics for a vast variety of end uses including technical textiles and the loom's structural design. It is anticipated that the loom's structural design and the components, including shedding mechanisms (i.e., tappets, dobbies, and jacquards) sooner or later might be designed from new materials/alloys. A typical example is the Composite Material Sley used in one of the air-jet looms from VUTS-Liberec. The sley offers high rigidity, is well balanced, and offers a lower weight. Noise-damping, energy-reducing materials such as Carbon, fibre-based resins, might be used. The number of components, along with overall dimensions and weight of weaving machines, might be reduced.

However, the degree to which the developments in the above key elements that are shown at ITMA varies from one manufacturer to the next.

The author of this chapter has attended all the Itma's since 1983. A great deal of information provided in the following sections has been included from the technical brochures, catalogues, information from loose sheets, and personal basis, provided at ITMA's by the courtesy of respective loom manufacturers as well as information collected from their websites. The author is extremely grateful for their help in providing the technical information without which it would not have been possible to write this chapter.

5.14 Developments in rapier looms

Rapier technology dates back to 1870 or even earlier, and the flexible rapier involving loop transfer was patented in 1925. From 1930 to 1940, a good number of rapier looms were in commercial production. In 1939, R. Dewas proposed the idea of grasping the weft at its tips by the giver or a carrier rapier and then transferring it to the taker or receiver rapier in the middle of the shed. In the period up to the beginning of the war, many manufacturers applied for patents. Further developments continued in the field, and as time progressed and with the availability of modern techniques, new materials, new forms of gearing, etc., a *newly designed rapier loom* eventually appeared on the market with weft insertion rates far in excess of the original speed.

Since then, it has gone through significant radical and incremental developments in its overall design and constitutes the largest group of shuttle less weaving machines offering tremendous flexibility in fabric design and an almost unlimited range of size and novelty yarns that can be woven.

5.14.1 Picanol rapier loom OptiMax-i

Picanol offers their latest innovatively designed rapier loom OptiMax-i and claim this new model to be the fastest, most versatile, and user-friendly rapier machine with the lowest energy consumption on the market. It provides weavers with a great deal of flexibility in meeting the demands of the market and offers the following salient features. Not all of these are provided as the standard features on the loom as some are optional.

5.14.2 Guided gripper system (GC)

Ideal for spun yarns, the rapier tape on the light-weight guided gripper system is perfectly guided by one-piece hooks (patented). Together with a small shed and a small rapier head, Picanol claims that industrial speeds are reached that were never attained before (Fig. 5.35) [26].

5.14.3 OptiMax-i with guided positive grippers (GPG)

The innovative design of the grippers stands out from older technology because of its dry insertion, avoiding the oil stains often found on lubricated projectiles. This enables it to be used for lamination or knife coating without further cleaning. The machine is available in widths ranging from 190 to 540 cm. and can reach weft insertion rates of 1500 m/min (Fig. 5.36) [27].

OptiMax GPG rapier system makes it possible to mix completely different types of wefts, such as monofil and multifilament, or course spun with a fine texturized yarn. It is even possible to double insert certain types of yarns, such as two 1100 dTex PES yarns, as often seen in geotextiles, conveyor belting, and coating fabrics, something almost impossible to achieve on projectiles.

GPG OptiMax machines can even handle stiff yarns such as polypropylene tapes up to 3 mm and monofil yarns up to 0.7 mm, opening up many possibilities in agrotextiles and the carpet-backing business.

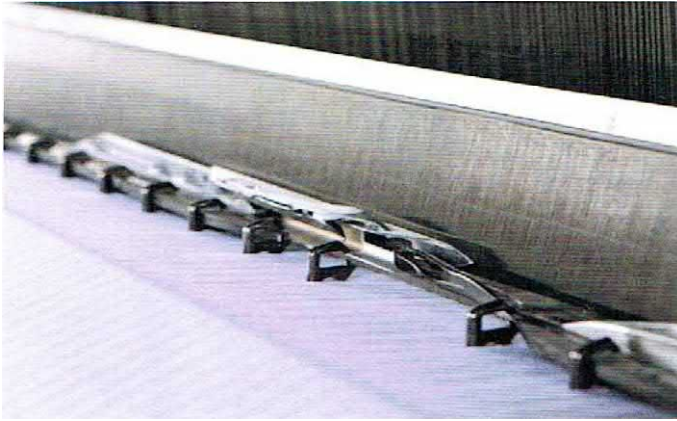


Fig. 5.35 Guided gripper system.



Fig. 5.36 Guided positive gripper system (GPG).

Multi- and monofilaments covered with PVC such as found in outdoor furniture and sunscreens, Fibrillated yarns and even bulky BCF yarns can also be woven successfully, at highest competitive speeds.

5.14.4 Free flight system (FF)

The free flight system specially designed for weaving delicate fabrics is covered by race board for gentle treatment of filament warp yarns or guided by supporting hooks (Fig. 5.37) [26].



Fig. 5.37 Free flight system (FF).



Fig. 5.38 Active filling tensioners.

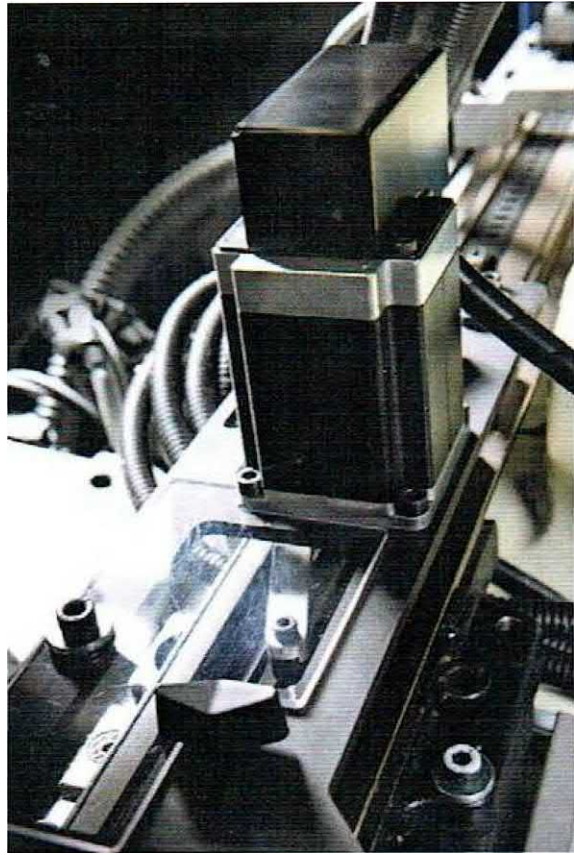
5.14.5 Active filling tensioners

Each prewinder can be equipped with a Programmable TEC Filling Tensioner (patented). Tension control makes it possible to weave weak yarns at even higher speeds (Fig. 5.38) [26].

5.14.6 Electronic right hand gripper opener (ERGO)

This feature offers improved control of weft insertion and is assured by positive opening of the right-hand side gripper with the Electronic Gripper Opener system. This allows individual setting of the moment of opening according to each type of weft inserted, to manage the length of the weft waste (Fig. 5.39) [26].

Fig. 5.39 Electronic right hand gripper opener.



5.14.7 Rigid construction

The redesigned and extra reinforced machine structure, combined with an optimized rapier drive, brings a new step forward in performance. Two redesigned cast-iron side frames are connected by sturdy cross-members. The sley is driven by conjugated cams with cam followers below the fabric. The sley with its reed holder is perfectly balanced by counterweights and provides powerful beat-up.

With the dedicated backrest, adapted take-up, and clamping arrangement for cloth support (patented), the OptiMax-*i* is capable of producing fabrics with high cover factors, such as heavy canvas or heavy filter fabric.

5.14.8 OptiLeno

OptiLeno offers the possibility to produce leno fabrics without superstructure or leno heddles. With the OptiLeno module (patented), it is not only possible to obtain fabrics with S-crossing or Z-crossing of leno ends, but also to obtain alternating S- and Z-crossing in the same fabric (Fig. 5.40) [26].



Fig. 5.40 OptiLeno.

5.14.9 Tuckers

The OptiMax-*i* can be equipped either with versatile mechanical tucker or with air tucker. Changing from leno selvedge to tucked selvedge or vice-versa is easy and quick with repeatable settings (Fig. 5.41) [26].

5.14.10 Width adjustment

The OptiMax-*i* has many unique features to keep machine down times ultra-short: all components to be moved on the left and on the right are mounted on a single support that allows easy position changes. Software-assisted procedures are available in case transfer position of rapiers is to be modified (Fig. 5.42) [26].

5.14.11 Electronic selvedge system (ELSY)

The unique full leno selvedge motions are electronically driven by individual stepper motors. They are mounted in front of the harnesses, so that all harnesses remain available for fabric pattern formation. The selvedge crossing and pattern are programmed on the microprocessor independently of the shed crossing, even while the machine is in operation, allowing an immediate check of the result of a resetting (Fig. 5.43) [26].

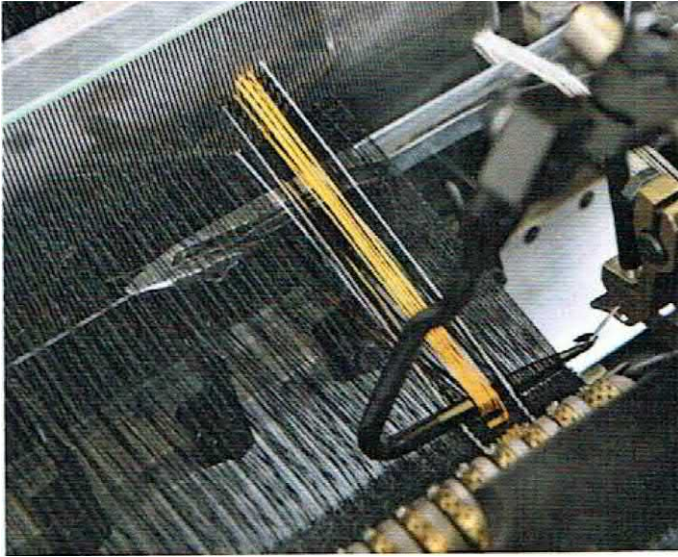


Fig. 5.41 Tuckers.



Fig. 5.42 Width adjustment.

5.14.12 Shed geometry

The short stroke of the sley and the frames and the redesigned rapier heads allow the OptiMax-*i* to weave with a small shed opening. The optimized shed geometry leads to uniform fabric characteristics over the whole width. The location of the sley cams below the fabric allows heavier beat-up forces, so fabrics with very high cover factor can be woven with ease.



Fig. 5.43 Electronic selvedge system.

5.14.13 *Optimized harness frames and connection*

Connecting the harness frames to drive the system is done in a single movement. The unique harness height adjustment is done entirely top of the harness frames (Fig. 5.44) [26].

5.14.14 *Electronic setting of shed crossing (AKM)*

The crossing timing of the shedding motion can be set from the machine display – no tools required! A unique Picanol feature that allows the weaver to easily control the aspect and feel of the fabric (Fig. 5.45) [26].



Fig. 5.44 Optimized harness frames and connections.



Fig. 5.45 Electronic setting of shed crossing (AKM).

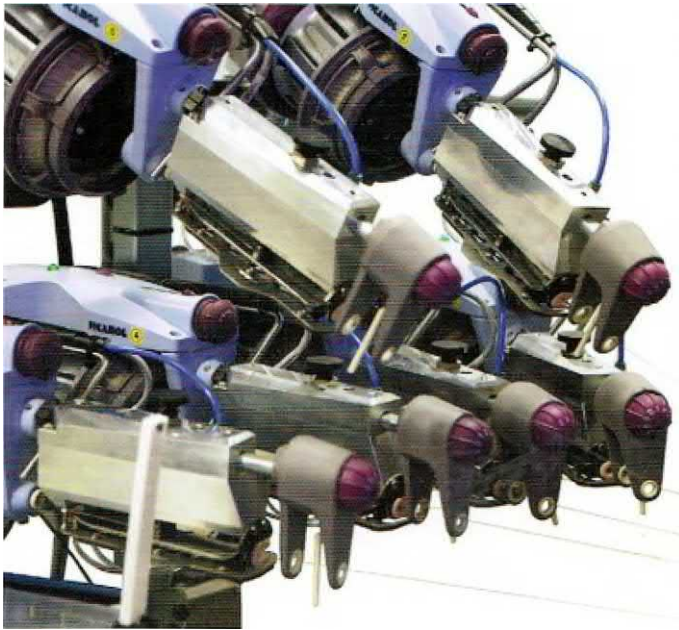


Fig. 5.46 Electronic filling tensioner.

5.14.15 Electronic filling tensioner (EFT) (rapier)

The newly designed tensioner ensures minimum filling tension during the complete insertion cycle and is ideal for weaving weak yarns that don't tolerate additional forces; this controls the widest possible of filling yarns, such as wool, chenille, bouclette, monofilament, flax, and filling for blankets (Fig. 5.46) [27].

EFT is an electronically controlled brake using very long yet extremely light lamellas together with damping elements. By using these long lamellas, the braking force is distributed over a long filling length. In this way, the filling tension during insertion of the irregular filling yarns, such as bouclette or flax, is kept well under control.

5.14.16 SmartCut

The SmartCut is the latest and most advanced cutter available on the market.

The newly designed system has its independent drive which allows the cutting moment to be controlled individually. As a result, the clamping in the gripper and the length of filling tail can be fully adjusted. This allows every filling combination – coarse as chenille, subtle as Lurex, or weak as wool in single or multiple pick – to be cut and clamped at the exact moment required, ensuring faultless insertion with minimum waste. The cutter mechanism itself consists of a conjugated cam-pair in oil bath driven by a high-performance motor, ensuring maintenance-free, durable operation (Fig. 5.47) [27].

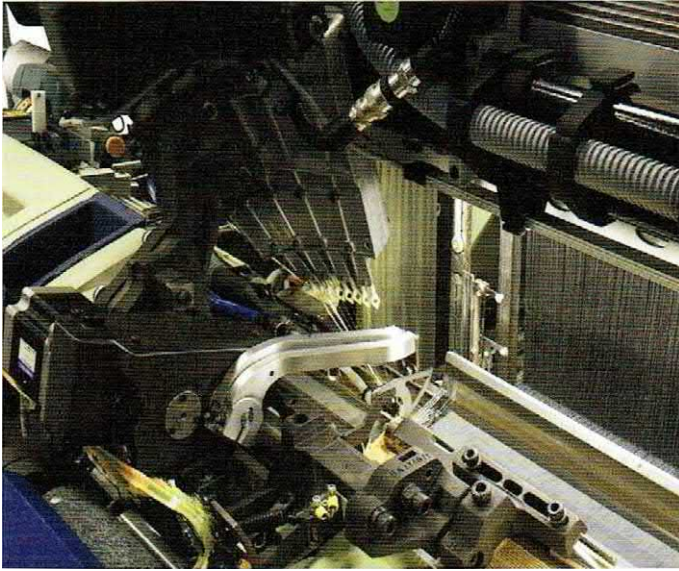


Fig. 5.47 SmartCut.

5.15 Developments in Dornier rapier weaving machine P1

Dornier offers their latest newly designed rapier weaving machine model P1 that is capable of running 16 colours and is able to produce a wide variety of fabrics, i.e., technical textiles, home textiles, and geotextiles with flexibility and precision, whether in combination with Jacquard machine with up to more than 30,000 lifting hooks and a 28-shaft dobby, a cam motion, or the Dornier Easy Leno unit. It can handle coarsest yarn counts in warp and weft between 7 den and 4500 tex and weft densities of 0.5 ends/cm or even lower. The interesting newly designed salient features of P1, some of which are offered as optional, follow:

5.15.1 DORNIER – Specific filling insertion system

Filling insertion with positively controlled centre transfer is the novel feature of the P1 rapier weaving machine. The filling is picked up and transferred precisely and reliably through the open shed and held securely until bound in.

Filling transfer from left-hand to right-hand rapier is effected positively in the centre under full control. The shed remains open throughout the entire insertion phase. The filling is released by the controlled rapier clamp only when it is firmly secured by the catch selvedge.

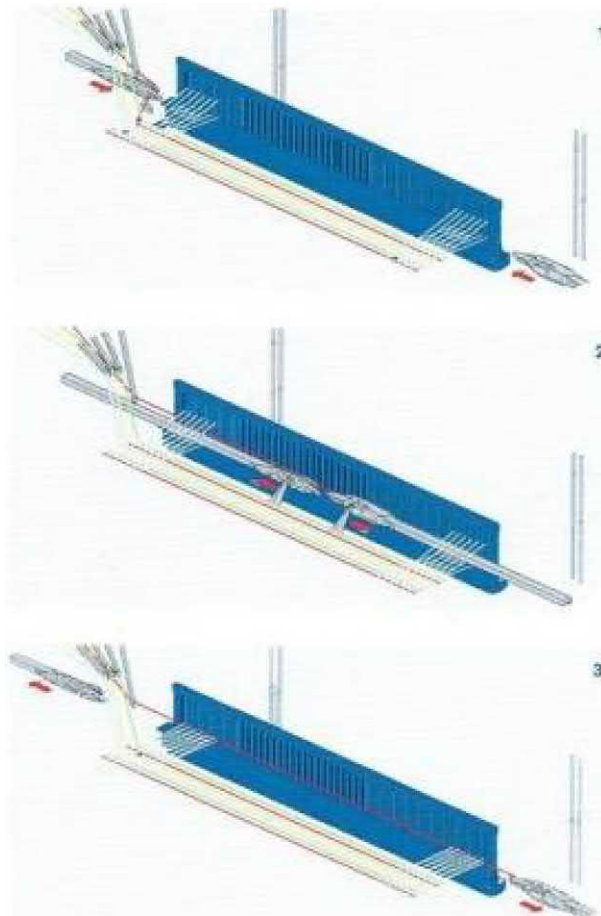


Fig. 5.48 Dornier specific filling insertion.

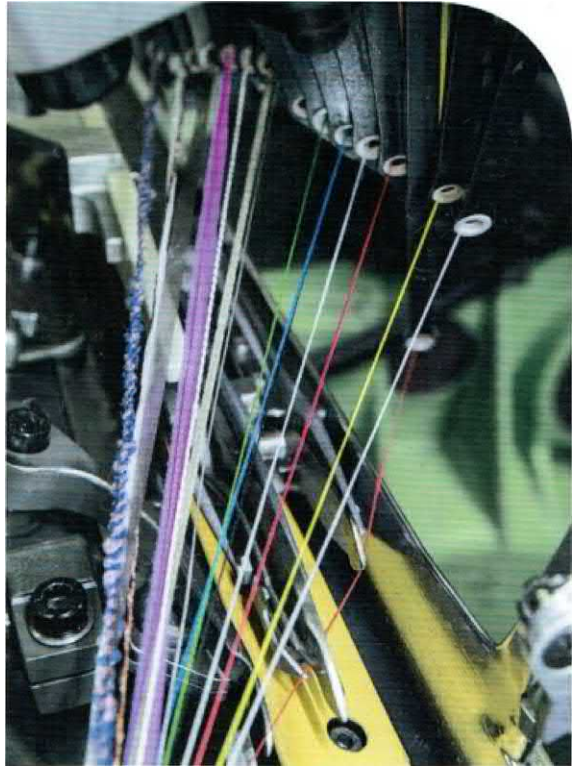
The DORNIER specific filling insertion system includes (Fig. 5.48) [28a]:

1. Yarn pick-up by the left-hand rapier before entry into the shed.
2. Filling yarn transfer in the fabric centre.
3. Release of the inserted filling by the right-hand rapier only after being secured by the catch sledge.

5.15.2 Wide application yarn range

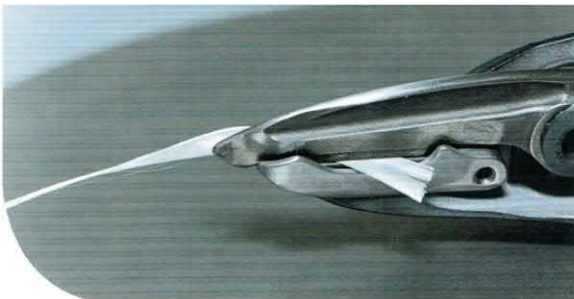
The controlled weft insertion at every stage on the P1 machine enables processing of an extraordinary range of yarn types and counts. It runs from fine silk yarns and mono-filaments via glass rovings through to the coarsest fancy yarns. Yarn count ranges between 7 den and 4500 tex (Fig. 5.49) [28a].

Fig. 5.49 Wide application yarn range.



5.15.3 Precision control transfer

With the specially designed soft clamps with a hard metal insert and precision controlled transfer – even coarse 2200 dtex filaments with 450 individual capillaries are securely clamped and inserted (Fig. 5.50A and B) [28a].



(A)



(B)

Fig. 5.50 (A) and (B) Precision control transfer.

5.15.4 Newly designed electronic colour selector

The new electronic selector motor (ECS) yarn presentation is effected in micro step resolution with an automatic yarn needle motion monitoring and correcting function. This allows gentle yarn presentation with reduced yarn tension peaks. Low tensile strength yarns and also heavy yarns with high yarn tension, like 2400 tex glass, can be processed without difficulty (Fig. 5.51) [28a].

5.15.5 DORNIER MotoEco for perfect selvages (option)

The newly modularly designed, patented DORNIER MotoEco double-disk leno consisting of two full-turn lenos with system-related rotation reversal, which operate side by side for fabric selvedge; catch selvedge can be available with no additional shafts or catch selvedge bobbins required. The double-disk leno provides for intensive binding with very short yarn ends and also operates from standard king bobbins. Waste-saving and material recycling are thus optimized with this Dornier Moto Eco (Fig. 5.52) [28a].

5.15.6 Weft yarn tension level

The manufacturer claims that the yarn tension level of the DORNIER P1 rapier weaving machine is lowest. Dornier claims that compared to all existing negative rapier weaving machines, the DORNIER positive rapier system remains superior in terms



Fig. 5.51 Newly designed colour selector.



Fig. 5.52 Dornier Moto Eco.

of basic tension level, thus offering the best possible filling yarn breakage figures attainable (Fig. 5.53) [28a].

5.15.7 Dornier open reed weave technology (ORW)

For the first time, Dornier exhibited a new concept of weaving and embroidery running at the same time on their specially designed rapier loom (Fig. 5.54A and B) [28b].

ORW technology allows integrating additional threads into the weaving process by using special thread guides arranged between the reed and weaving shafts. Linear drives shift the thread guides horizontally on a profile depending on the pattern. The additional pattern threads create a filling effect on the fabric surface that can be controlled as desired. This filling effect is similar to embroidery and Scherli patterns. ORW technology therefore offers more flexibility and pattern options such as domestic textile applications (e.g., curtains, tablecloths) and clothing materials. ORW technology also can be seen as a process for creating multiaxial fabrics for technical textiles.

Arranging two axes driven independently allows weaving additional threads into the plain weave in any diagonal direction as 3rd or 4th thread systems. This adapts the position of the diagonal threads to the direction of active forces.

Apart from the option of integrating additional thread systems in the plain weave across the complete fabric width, ORW technology is especially suitable to do this partially in order to integrate reinforcements required for specific fabric areas.

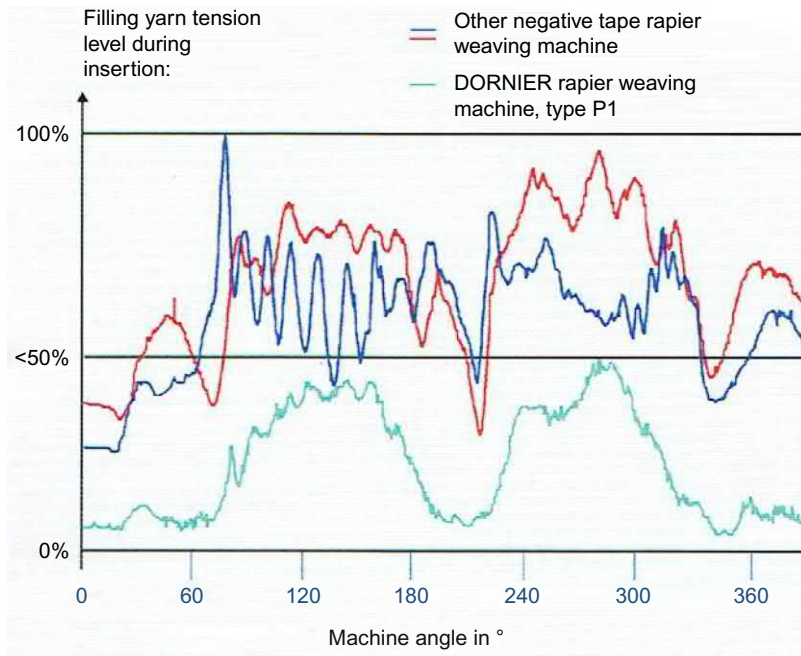


Fig. 5.53 Filling yarn tension level.

Modular integration of the ORW unit retains the full productivity and unrestricted application spectrum of the weaving machine.

5.15.8 Unique torsion-free double filling insertion

The machine offers a unique facility to offer filling (weft) insertion of up to 5 fillings in one pick, particularly in the production of screen fabrics and panama or rep weave. A significant production increase without additional energy consumption is achieved (Fig. 5.55) [28a].

5.16 Smit Textiles – Newly developed single rapier loom – ONE

At Itma 2015, Smit Textile, Italy, leader in design and manufacturing of dynamically controlled flexible ribbons rapier looms, presented their new loom SMIT ONE, offering the highest versatility and ergonomics in style changing and flexibility with the widest range of fabrics that the loom can weave.

SMIT ONE offers a ‘dynamically controlled’ flexible tape rapiers system combined with the development of advanced ‘mechatronic’ solutions enhancing the weft insertion. The results obtained with SMIT ONE offer decisive competitive

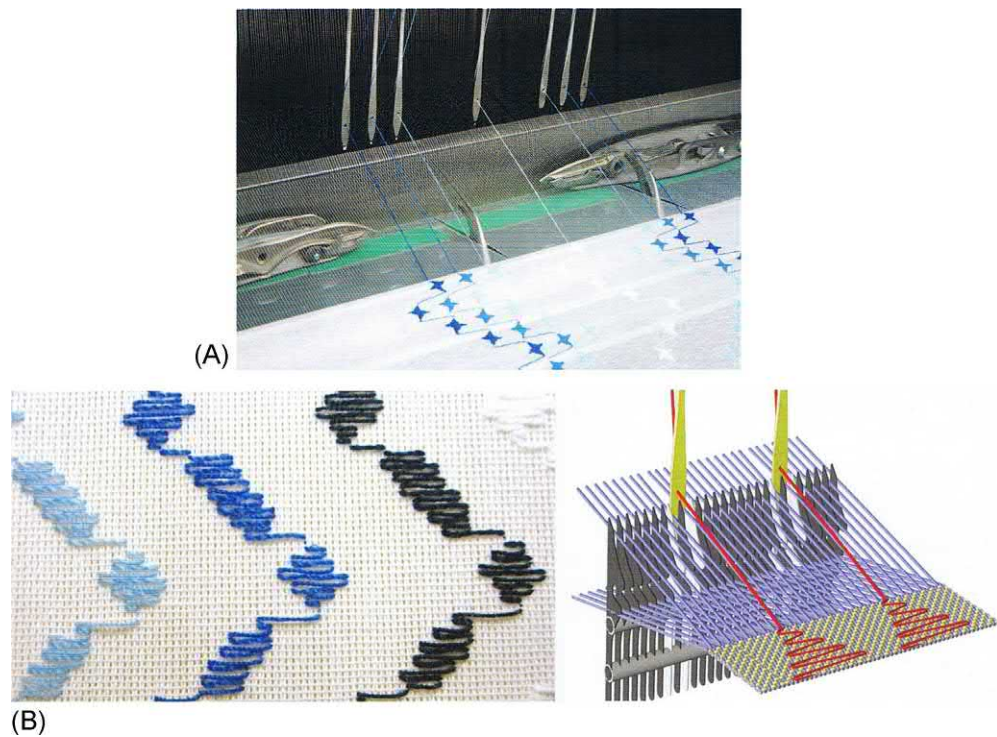


Fig. 5.54 (A) Open reed weave technology. (B) Open reed weave technology: weaving and embroidery to at the same time.



Fig. 5.55 Unique double insertion system.

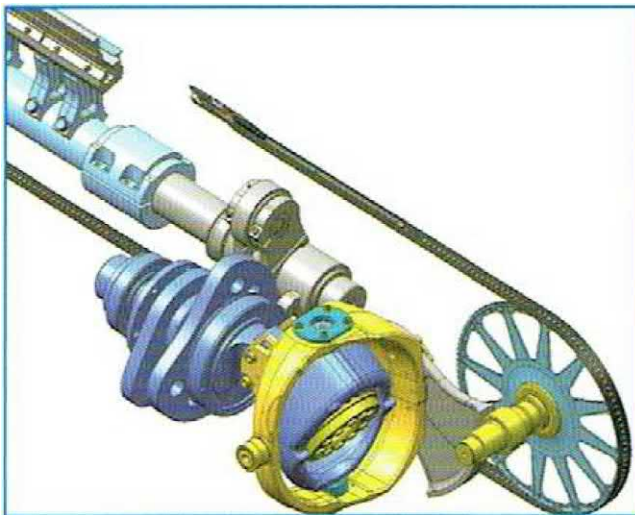


Fig. 5.56 Rapier motion control.

advantages, not only in the most sophisticated clothing and furnishing sectors, but also in fields such as those of technical fabrics for safety applications, glass fabrics for electronics, fabrics for filters and for sportswear in which complicated yarn are used requiring extreme regularity in the insertion process.

The adoption of an insertion system based on only one rapier allows the use of the widest range of yarns, an unparalleled simplicity in the article change, and minimum maintenance costs. The rapier motion ([Fig. 5.56](#)) [29] control is carried out with spherical crankshaft characterized by:

- Optimum acceleration and speed profiles.
- Minimum rapier extra-stroke.

- Minimum weft cutting, changing, and release speed.
- Highest regularity in weft insertion and maximum efficiency.

A patented system performs the presentation of the weft always in the same position. The lack of weft transfer in the middle allows to work with very low-weft tensions, thus increasing the insertion efficiency.

Other features the SMIT *ONE* offers are

- Reduction of the warp shed amplitude
- Significant reduction in energy consumption
- Easier adjustments at article change, drastically reducing the machine downtime
- Capability of working with very low weft tensions, thus increasing the insertion efficiency
- Minimum maintenance costs
- Widest range of yarn selection

5.17 Trinca rapier loom for weaving wide technical fabrics

At ITMA 2015, Trinca, Italy were offering their unique rapier weaving machine T.20.10E-PS 11750 (Fig. 5.57A and B) [30] for the production of technical textiles in weaving widths from 3000 mm up to 11,750 mm at a weaving speed adjustable from 5 up to 90rpm, eight colours weft Position Change, driven by Servomotors.

The complete loom control, all data settings, and operating function adjustments are carried out by the TRINCA electronic control device and the specially developed TRINCA loom managing. All electronically controlled devices are installed inside the main switchboard, and all data, as well as loom driving and control functions, are developed by an industrial PC with software window CE.

5.18 Developments in air-jet looms

The history of air-jet technology began in 1914 when the first patent was lodged by Brooks of America, and a 61 cm wide prototype was demonstrated in 1917. A single nozzle Air-jet loom first appeared at ITMA Milan in 1959, and in 1967–68, a real



(A)



(B)

Fig. 5.57 Trinca—Flexible rapier machine for weaving technical fabrics.

breakthrough came when looms with relay nozzles 165 cm wide running at 530 m/min were available. By 1971, weft insertion rates had gone up to 720 m/min.

The most significant breakthrough started in 1975 aimed to achieve (a) increased width and speed (b) greater patterning possibilities and (c) the incorporation of more electronics/microprocessors in the machine design. Two looms were exhibited by Investa and Rüti-te Strake. By 1979, loom widths had gone up to 350 cm and weft insertion rates had increased to 1200 m/min. Just after a decade in 1991, weft insertion rates of 2300 m/min were exhibited at Itma. The prospects for air jet weaving soon became so bright that just 8 years later at ITMA 83, the number of exhibitors had gone up to 11, and this number went up to 12 in 1991.

One of the fastest air jet looms shown at Itma 1995 was Tsudakoma ZAX-390 weaving bed sheet plus pillowcases 371 cm wide at weft insertion rates of 2600 m/min using positive cam shedding, running with six colours. Of the 41 air-jet looms shown at ITMA 1995, 26 featured 190 cm reed width running speeds from 1000 to 1500 ppm.

Picanol showed their Omni 2P 380 cm loom weaving bed sheeting fabric 368 cm wide at weft insertion rates of 2281 m/min. Whereas most of the machines were running with 2-colour weft, Tsudakoma, Toyota, and Picanol showed some looms with six weft colours. Maximum of eight colours was exhibited on a Dornier loom LWV8/J weaving high quality upholstery fabric 294 cm wide at weft insertion rates of 1560 m/min.

5.18.1 Picanol air-jet loom OMNIplus Summum

At ITMA 2015, Picanol exhibited their latest model Omniplus Summum with the new revolutionary insertion system, with fully electronic pressure regulators, a separate and integrated air tank for each weaving channel, and a unique triple air tank set-up for the relay nozzles, offering many advantages in terms of user-friendliness and flexibility.

The integrated BlueBox concept, translates all the available data into optimal settings for maximum performance at lowest possible air consumption. BlueBox allows all this without making compromises when it comes to performance, flexibility, and energy. The unique features offer modularity, flexibility, versatility, and efficiency.

The manufacturer claims that the loom's new platform is superior to any existing system on the market. It features superior microprocessor performance and memory capacity to meet the hardest working conditions. The LoomGate remote monitoring solution allows customers to check the performance of the entire weaving mill at any-time, anywhere they like. Performance data such as production, efficiency, average speeds, number of stoppages, and much more can be exported for reporting and optimisation purposes.

Picanol OMNIplus Summum offers the following salient features/incremental developments in the new model. Not all of these are provided as standard features on the loom as some are optional.

5.18.2 Picanol BlueBox system

The uniquely designed Picanol BlueBox is the electronic platform to keep up with increasing requirements for modern weaving mills and to be ready for future developments. It offers optimal microprocessor speeds, increased memory capacity, and modular circuit board setup. The network connectivity allows for remote monitoring and service (Fig. 5.58) [31].

5.18.3 Separate air design tank per weaving channel

Air tanks built into the machine side frame enables optimal setting by means of an electronic pressure regulator for each individual weaving channel.

5.18.4 Dedicated sley cam

Dedicated newly designed sley cam versions make it possible to weave the most demanding fabrics and yarns. It is also available for larger-width applications.

5.18.5 New robust structure

Two solid side frames are connected by large-section cross bars with the sley driven at both sides by conjugated cams. This configuration offers the required machine stability and the highest beat-up force, making it possible to weave any kind of fabric successfully.



Fig. 5.58 Picanol Bluebox.

5.18.6 Fixed and movable main channel

The model is equipped with the most efficient nozzles for all yarn types, is adaptable with nozzle clamps for heavy stretching yarns as also has Jet funnel for guiding multiple channels into the reed tunnel.

5.18.7 Electronic pressure regulators

Because of the new configuration of air preparation, there is significant improved pressure build-off time in the main nozzles. This reduces the impact on the filling yarn, thus bringing a real advantage when handling delicate or weak yarns. There is full control over pressure settings for main and relay nozzles. All settings can be optimized from the machine terminal.

5.18.8 Pressure for main and relay nozzles set from display

Because of the unique configuration of the pressure regulators, air pressure is displayed in Bars – a direct and easily understandable reading (Fig. 5.59) [31]. Pressure for the main and relay nozzles is managed completely digitally from the machine's terminal. The pressure settings can easily be monitored by a central system or transferred to another machine weaving the same style.

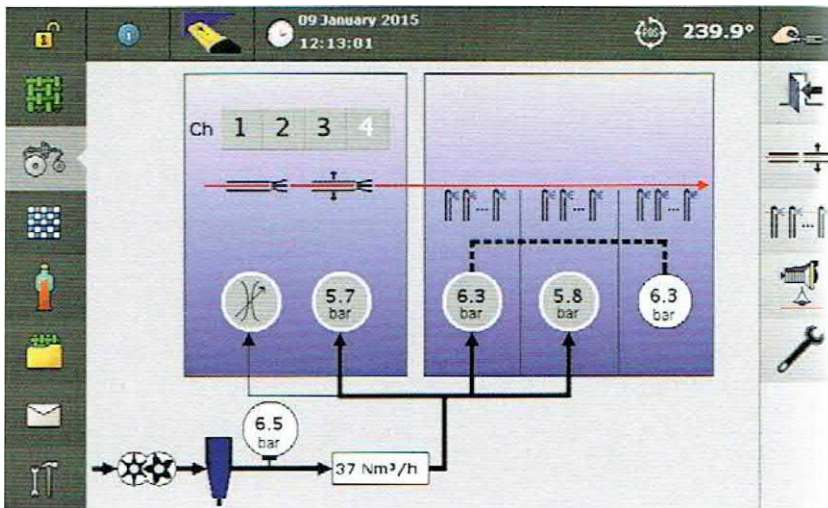


Fig. 5.59 Display of air pressure.

5.18.9 Unique triple air tank configuration

Lower air pressure on centre air tank minimizes impact from the relay nozzles on the fabric. It enables the user to set the machine with the lowest possible pressure and to reduce air consumption by up to 15% without compromising on fabric quality.

5.18.10 Unique Picanol relay nozzle design

Picanol has developed relay nozzles that offer an optimal performance/consumption ratio as a result of which air consumption is fully under control on the OMNI*plus* Summum (Fig. 5.60) [31]. Different types of nozzles are available for a wide range of yarns:

Multihole: offers the highest traction force and is the choice when no compromises can be made on the weaving speed.

EcoOne: designed to achieve the best balance between speed, air consumption, and maintenance, capable of weaving even under the most dusty and fluffy conditions.

5.18.11 Twin stretch nozzle

Their provision adds that extra stretch to prevent flip-backs throughout the fabric and to increase productivity with kinky fabrics. A simple but universal mounting solution for a wide range of products.

5.18.12 Adoptive relay valve drive – ARVD II PLUS

The ARVD technology automatically adapts the closing time of the relay nozzle valves according to the behaviour and air-friendliness of the filling yarn. It is possible to select one of three levels of automatic adjustment – low, medium, or high – to suit the type of filling yarn. When activated from the machine terminal, ARVD continuously monitors the main insertion parameters, such as the winding timings and filling arrival

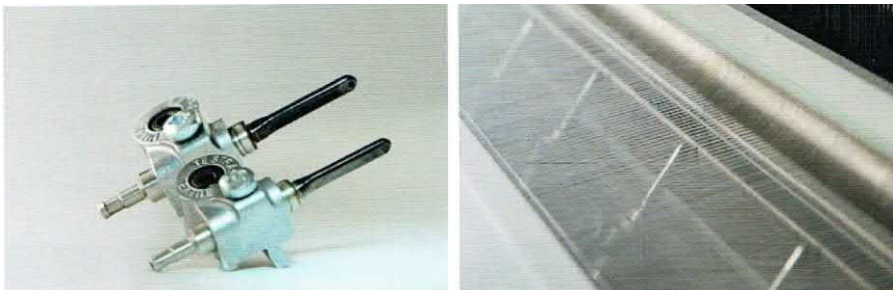


Fig. 5.60 Relay nozzle design.

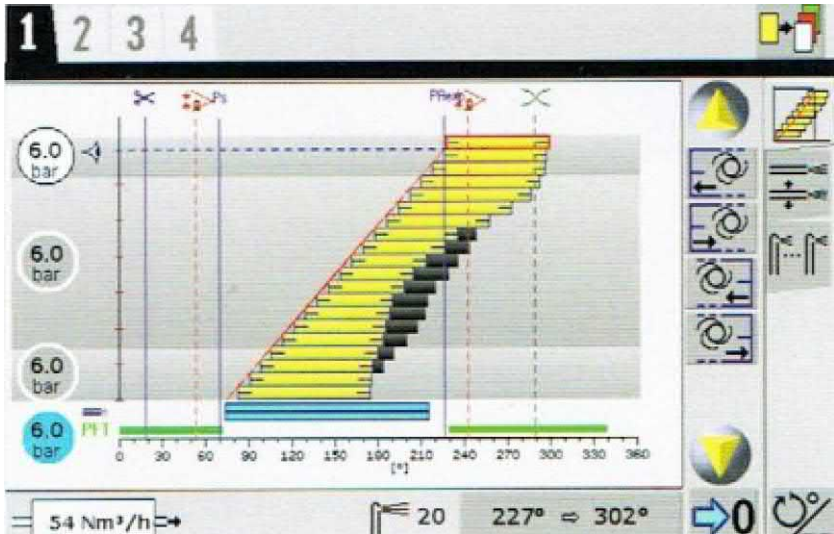


Fig. 5.61 Adoptive relay valve drive.

time. These results are processed, and the blowing timings of the relay nozzles valves are then adapted automatically.

Since the relay nozzles are responsible for 75% of total air consumption, optimizing the valve timings significantly impacts the overall air consumption without comprising on fabric quality.

With the new ARVD II Plus, the machine also optimises the opening time of the relay nozzle valves, which in turn gives a reduction in air consumption of up to 20%.

The technology is effective in a broad range of yarns and gives optimal results with both spun and filament yarns(Fig. 5.61) [31].

5.18.13 AIRMASTER

The device monitors and manages air consumption. It automatically checks the consumption of each individual insertion component by means of an automated diagnostic procedure (Fig. 5.62) [31].

5.18.14 Auto speed and speed adjustment

The machine adapts its speed to the behaviour of the filling yarn. Information from the filling detector is centrally processed, and if conditions allow it, the microprocessor changes the machine speed and adapts the other machine settings to this new situation, all fully automated. Meanwhile, the machine stop level is constantly monitored to make sure that limits set by the user are not exceeded.

Fig. 5.62 AIRMASTER.

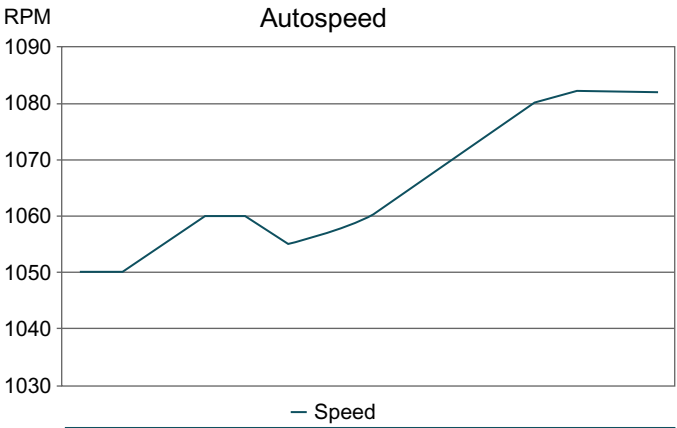
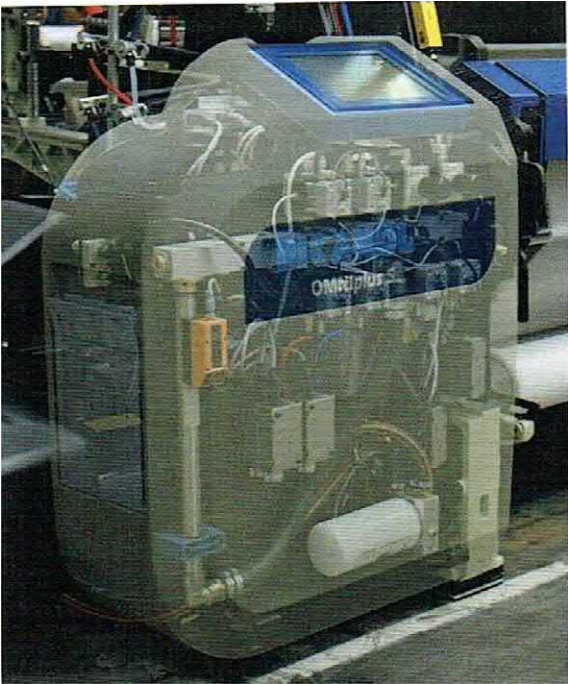


Fig. 5.63 Auto speed adjustment.

Machine speeds can be set and adjusted on the machine display. Changing the speed can be done in real time using multispeed or automatically following a preprogrammed speed pattern, for which opt speed is needed. This makes it very easy to set the best speed for a given style on a running machine and to make sure that speed is not exceeded. Auto speed can result in an average speed increase up to 5% (Fig. 5.63) [31].



Fig. 5.64 New pick repair automation.

5.18.15 The new pick repair automation (PRA II Plus)

In case of a machine stop (filling stop), the new PRA II Plus system automatically removes the filling from the shed and starts the machine again if conditions allow. The new PRA II Plus system combines pneumatic and mechanical actions for removing the yarn, making it unique in its kind. After successful removal of the filling, the machine is automatically restarted. Fine-tuning of the PRA settings can be done for each insertion channel individually so that the benefits of the salient feature are obtained even when using different types of filling yarn (Fig. 5.64) [31].

5.18.16 Sumo main motor

The specially designed motor offers the fastest and most stable machine start-up and reduced power consumption because of the drive train with fewer gears and less friction.

The integrated machine concept is fully synchronized with all the other electrically driven motors: Electronic Take-Up (ETU) and Let-Off (ELO). The common power supply features real-time speed adjustment and recuperation of braking energy (Fig. 5.65) [31].

5.18.17 New filling detector

A new version of the filling detector in front of the reed has been designed by eliminating the connector on the cable (detector side), thus further increasing the reliability of this critical component. The new design eliminates connectors giving more space just next to the filling detector, which allows better positioning of relay and stretching nozzles (Fig. 5.66) [31].

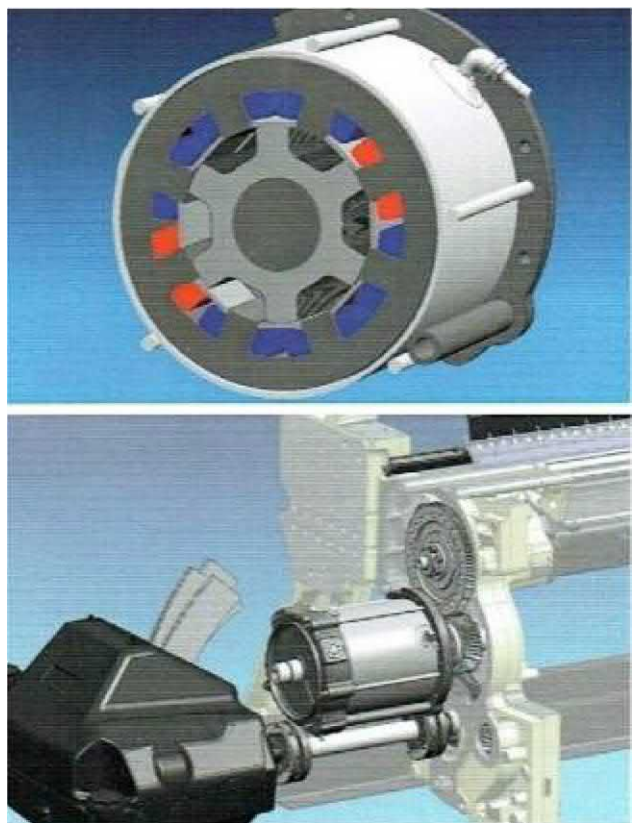


Fig. 5.65 Sumo main motor.

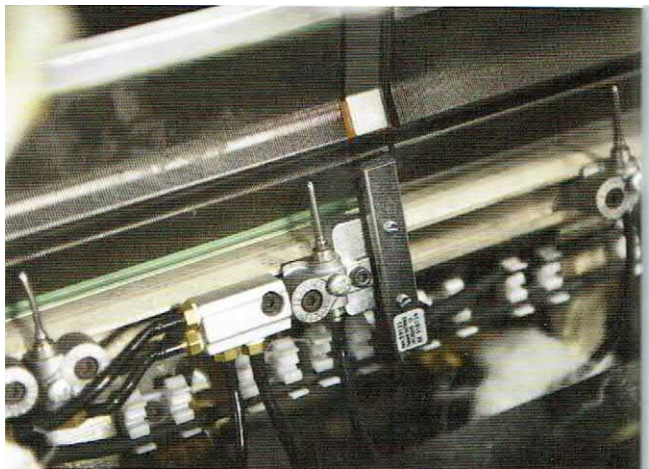


Fig. 5.66 New filling detector.

5.19 Developments in Dornier air-jet loom – A1

At Itma 2015, Dornier (Germany) presented their new air-jet loom A1 with significant incremental developments/features incorporated in the loom.

The new patented drive concept DORNIER SyncroDrive with energy class EFF1 motors increases speeds by up to 10% with minimum heat development and the same energy requirement. The quick-reacting, automatic pressure control DORNIER ServoControl-2, the option with two relay nozzles per valve, a pneumatic filling thread clamp that runs without any holding air at all, not only reduces air consumption but also brings a decisive reduction in air pressure.

The new DORNIER air-jet weaving machine A1 offers innovative solutions for all challenges of weaving with a completely new electronic control system and an application-oriented main drive concept based on three different systems.

The extremely wide insertion range of the A1 covers spun and filament yarns made of natural and man-made fibres as well as mixtures of both. The fineness for spun yarns ranges from Nm 4 to Nm 160 and from 10 to 2200 dtex for filament yarns.

The application spectrum of the A1 ranges from technical textiles such as lightest spinnaker silk, tightly woven airbags, or conveyor belting to car- and airline seating upholstery. Fabrics for garments of fine worsted or Jacquard damask tissues of Egyptian cotton, function and sportswear fabrics, home textiles for decoration, and table cloths with matching napkins in multiple widths, and sheer window drapery as well as many more can be reliably produced on the A1 with excellent quality in machine widths ranging from 150 cm up to 540 cm.

DORNIER's weave-by-wire replaces the existing mechanical connections (between weaving machine and shedding device) with electronic data transfers which allow optimum execution of complex processes. The A1 convinces with a completely new electronic control system and an application-oriented main drive concept based on three different systems whether operating with a simple cam motion in combination with a Jacquard head of 12,000 hooks, a dobby with up to 16 heald frames, or with the DORNIER EasyLeno motion.

A multitude of patented components, e.g., the DORNIER PIC system with DORNIER ServoControl-2 or the DORNIER PneumaTucker guarantee a process security which is unparalleled in air-jet weaving.

Some of these developments have been summarized and mentioned in the following sections. New innovations on their air-jet weaving A1 have improved the sustainability and hence made fabric production processes more efficient and more compatible for the environment. Some of the features covered are available as optional.

5.19.1 DORNIER PIC

The patented Permanent Insertion Control (PIC) recognizes imprecise function of magnet valves right from the start and thus guarantees the highest process reliability. The permanent control of the function timing of the relay nozzles with continuous comparison of set to actual values of the sequential nozzle group timing

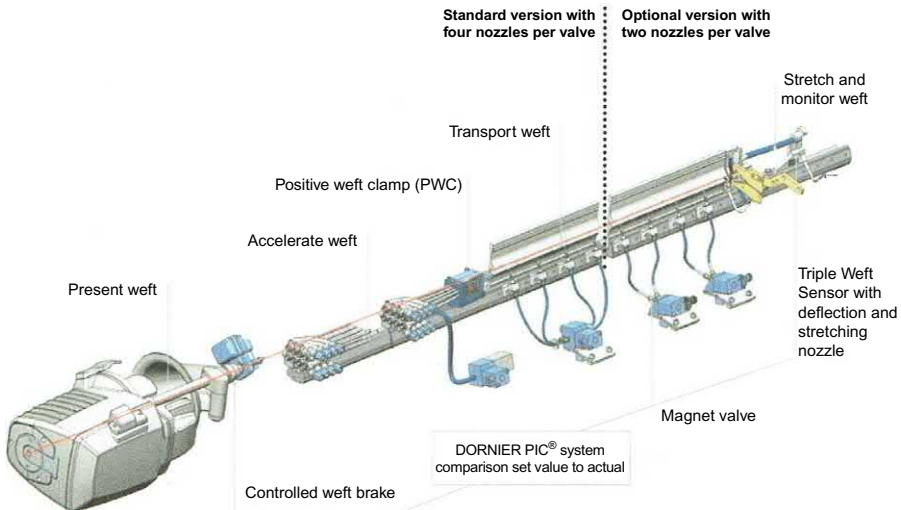


Fig. 5.67 Dornier PIC system.

(‘on-condition monitoring’) guarantees high quality of weaving and eliminates unnecessary stops for maintenance (Fig. 5.67) [32].

5.19.2 The compact throttle block with DORNIER ServoControl-2

The patented DORNIER ServoControl-2 system with integrated entry-pressure monitoring controls the air pressure in one common closed circuit for main and tandem nozzles in accordance with the predetermined thread arrival times for each individual colour. The pressure values are displayed digitally in absolute figures which increases the degree of automation and simplifies the reproducibility of article data (Fig. 5.68) [32].

5.19.3 Efficient: The new single-hole relay nozzles

Important performance improvements have been realized through the refinement of details in design and manufacturing which result in a reduction of air consumption. The strength of the DORNIER single-hole nozzle is its uncomplicated usage, free of any maintenance procedures. A sectional view (numeric simulation) shows the iconicity of the air hole opening and the optimum air flow it creates (Fig. 5.69) [32].

5.19.4 The new valve technology

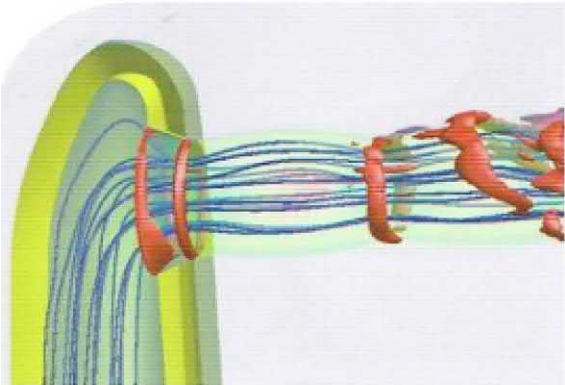
Faster reaction times and smaller dead volume considerably decrease the air consumption of main, relay, and stretching nozzles. With an optional two nozzles per valve, the air consumption of relay nozzles is additionally reduced and allows a more precise



Fig. 5.68 Compact throttle block.



Fig. 5.69 New single hole relay nozzle.



adjustment of the sequential nozzle group firing, resulting in a wider insertion window with a more gentle treatment of the filling thread.

5.19.5 Gentle filling yarn handling, improved fabric appearance

The weft feeders with layer separation and advanced electronics are developed further to be able to precisely measure the length of even more complex yarn necessary for one insertion across the shed. The optimized airflow of main and relay nozzles exerts a gentle acceleration to the filling thread at lowest tension levels, thus permitting higher machine speeds with lower filling stop levels. Ultimately, this results in less hairiness of yarn and a better final fabric quality.

5.19.6 Simple fabric width changes

A newly designed temple profile allows an even faster width adjustment. The throttle block is easily shiftable which permits simple symmetrical settings of fabric widths and substantially reduces set-up times.

5.19.7 Efficient nozzle and valve technology

The mobile tandem nozzle attached to the reed bar allows extra prolonged insertion times – an undisputable requirement for maximum machine speeds and multiple width weaving. In combination with the optional Tandem Plus nozzle and the PWC-clamp, the range of insertable filling yarn types is substantially increased.

5.19.8 The performance boosters – Tandem plus and TRIM

Optionally, a third prenozzle of fixed position and up to eight colours can be installed for the high speed insertion of slick or subtle yarns – the Tandem Plus feature. On extra wide machines with up to four colours, optionally a third mobile prenozzle can be installed on the reed bar – the TRIM feature. Both of these technologies reduce the necessary air pressure of the main nozzles, thus minimizing the impact of power transmission on the surface of delicate yarns. Higher efficiencies and overall performance improvements are the consequence.

5.19.9 For complex yarns: The PWC-clamp

The patented, positively acting filling thread clamp PWC works reliably, preventing the use of any holding air pressure. The clamp is positioned at the exit of the main nozzle tubes which is unique for air-jet weaving machines. Thus the application spectrum of insertable filling yarns can be widened out to core yarns, Elasthan, fancy yarns such as flammées, ratinées, and slub yarns, up to low twist materials, etc., always maintaining the eight colour capability. Fancy styles with exceptionally long pattern repeats, as are sometimes used for home textiles and garments, can now be produced for the first time without problems using air-jet technology.

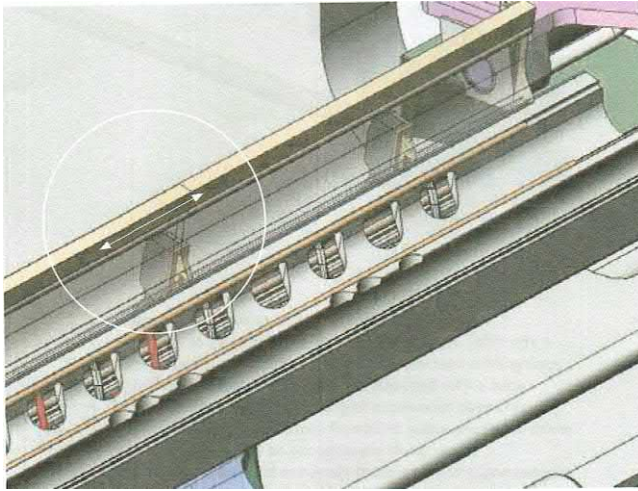


Fig. 5.70 The new filling stop sensor, STS.

5.19.10 Slim throughlight sensor (STS)

The new filling stop sensor DORNIER STS (Slim Throughlight Sensor) is based on the throughlight principle (Fig. 5.70) [32]. It also provides highest functional and quality reliability for dark filling colours and finest threads down to 10 den. It can be easily positioned anywhere on the reed with a clip-on attachment according to filling insertion width.

5.19.11 Robust construction, solid reed drive

Reliability in the production of high-value fabrics starts with a sturdy machine frame, equipped with a solid reed drive system. The bilateral reed drive of the A1 is equipped with a large dimensioned main shaft, rotating at accelerated speed which connects the two gear boxes. Combined with a shortened drive train section, it forms an exceptionally sturdy unit (Fig. 5.71) [32].

The mass-reduced but extremely stable reed bar guarantees an exact and well-balanced reed beat-up. The vibration behaviour is significantly improved, and start marks are positively eliminated.

5.19.12 DORNIER Ergo Weave

ErgoWeave provides extensive functions for a quick and perfect fabric quality result to the weaver. Start-mark correction can be limited to one setting, or ideally adjusted whenever necessary. One of the DORNIER ErgoWeave's special strengths is the simple production of the statistical evaluations of all weaving functions plus the recording and correction of stoppage causes by means of a system diagnosis tool. Standard articles, automatic settings, and high product setting reproducibility reduces personnel workload.

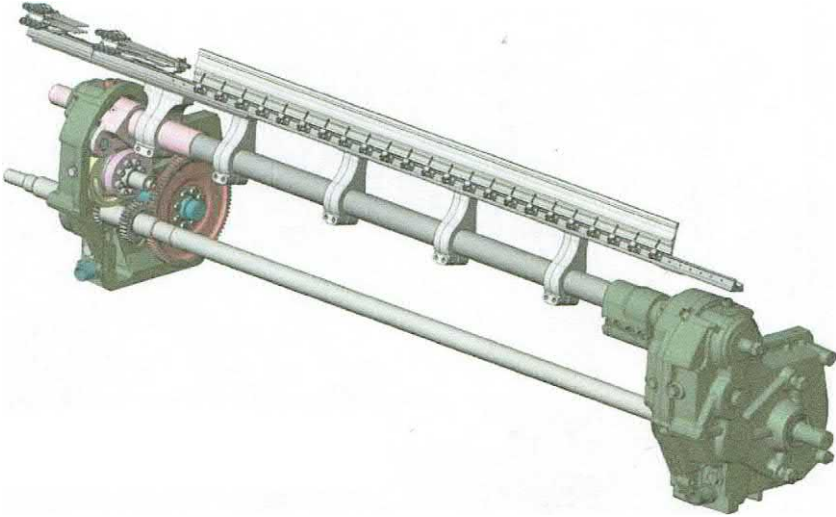


Fig. 5.71 Slim thoroughlight sensor.

5.19.13 USB and Ethernet interface

The recording of pattern and product data, as well as the loading of new configurations and software, is effected simply and conveniently via USB-Stick (Fig. 5.72) [32]. The weaving machine can be linked with all customary operating data systems, or connected to a network, via an integrated mass-produced Ethernet interface.



Fig. 5.72 USB & Ethernet interface.



Fig. 5.73 Dynamic warp guide unit (DWG).

The DORNIER ErgoWeave's pattern storage volume records up to 1 million pick repeats and can be further extended.

5.19.14 *Sturdy designed machine frame work*

The machine side frames connected with a specially designed robust profile traverse and its sturdy basic framework guarantees low vibration operation even at high speeds and in double width version. Therefore it is not necessary to bolt or cement the machine to the floor.

5.19.15 *Dynamic warp guide (DWG)*

The highly dynamic warp guide unit (DWG) (Fig. 5.73) [32] enables it to weave with the lowest possible warp tension level leading to a significant warp end break reduction. Through its synchronous movement with the shed motion, this patented, roller-free unit guarantees an ideal tension balance between open and closed shed motion even at maximum machine speed.

5.19.16 *Dornier MotoEco for perfect selvages*

Based on the DORNIER MotoLeno, the modularly designed, patented DORNIER MotoEco double-disk leno is available as an alternative (Fig. 5.74) [32]. The double-disk leno provides for intensive binding with very short yarn ends and also operates from standard king bobbins. Waste-saving and material recycling are thus optimized with the DORNIER MotoEco.

It consists of two full-turn lenos with system-related rotation reversal which operate side by side for fabric selvedge and catch selvedge. No additional shafts and catch selvedge bobbins are required for the leno.

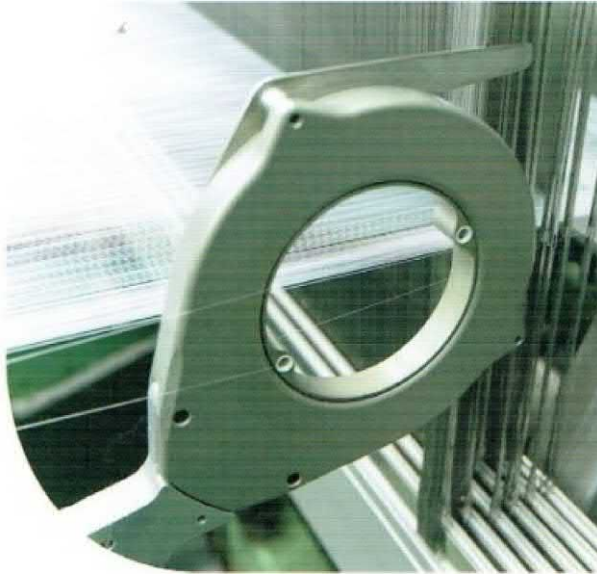


Fig. 5.74 Moto Eco double-disk leno.

5.19.17 Dornier EcoValveControl

The newly developed EcoValveControl detects the arrival of the weft end in the area of the respective relay nozzle group. The magnet valves of the nozzles open therefore only when the weft end enters the zone of the air-jet leading to saving in air consumption (Fig. 5.75) [32].

5.19.18 The new A1 temple profile (Fig. 5.76) [32]

- The newly designed temple profile with its new supports can be sleeplessly positioned laterally only by turning a few screws.
- Width changes are possible very simply and without time-consuming adjustments.
- Optionally, the temple cylinder can be easily adjusted in depth position.

5.19.19 Areas of developments

Overall, the Dornier A1 Air jet machine has significantly offered incremental developments in the areas of:

Reduced maintenance cost:

- Compact Drive with reduced maintenance times
- Direct drive and Dornier SyncroDrive drive system without dutch brake system
- Maintenance-free single-hole relay nozzles and
- Compact throttle block with stable arrangement of air-hose connections

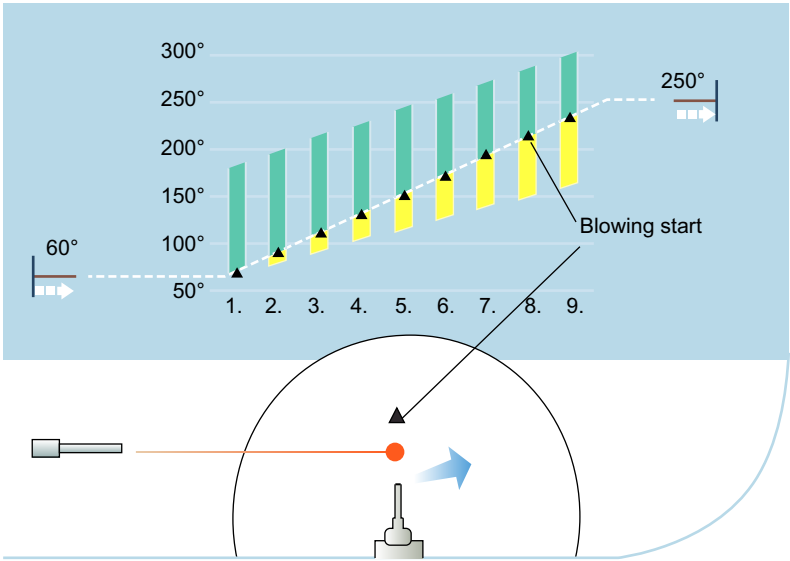


Fig. 5.75 Eco valve control.

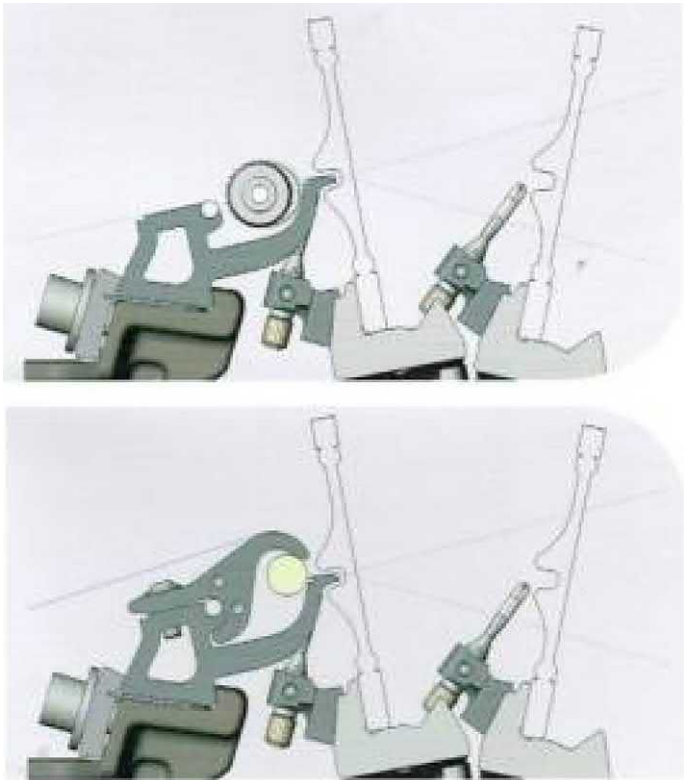


Fig. 5.76 The new temple profile.

Reduced set-up times

- Faster width changes
- Integrated speed control
- Effective reproducibility of electronic article data on settings
- Electronic adjustment of shed-closing during operation with DORNIER SyncroDrive

Reduced air consumption

- New valve technology with faster reaction times and reduced dead volumes
- New, faster DORNIER ServoControl-2 with integrated monitoring of entry air pressure
- Optional 2 instead of 4 relay nozzles installed per magnet valve

Efficient and secure production

- Reduced manual time on filling stop repairs through compact throttle block
- Gentle insertion of delicate yarns and low tensile strength material
- Potential for high speed on weaving with up to 16 harness frames with DORNIER SyncroDrive
- Dornier PIC permanent monitoring of electronic filling insertion components

5.20 Developments in Tsudakoma air-jet loom

At ITMA 2015, Tsudakoma from Japan exhibited their latest upgraded air jet loom *MASTER ZAX 9200 i* including many incremental developments/features offering savings in resources, energy, and manpower, wider versatility and harmony with the environment including the upgraded electric components. It can run with various shedding motions and can weave a wide range of high-density and high-tension fabrics along with eight colours.

The newly designed version of the loom offers the following outstanding features. Not all of these are provided as the standard features on the loom as some are optional.

5.20.1 *Soft weft insertion at high speed – Stable weft insertion*

A 4-link beating motion works excellently at ultra-high speed for narrow looms whereas a 6-link beating motion with more time allowance for weft insertion is used for wider looms, thus achieving more stable weft insertion.

5.20.2 *Reduced floor vibration*

A new robust frame structure has been designed. By employing the offset rocking shaft with fewer moments of inertia and a hollow reed holder, beating is well balanced, and floor vibration is reduced and aimed to harmonize with the environment.

5.20.3 *Clear shedding*

The beating stroke is shortened and the driving parts that are the most essential for the weaving machine to run at high speed are additionally reinforced. The healds are placed as close to the cloth fell as possible. While keeping the shedding amount,

the shedding angle is increased, and defective shedding is reduced. It ultimately offers stable operation at high speed compared with the conventional model.

5.20.4 6-Link crank shedding

By increasing the number of links from four to six, a dwell angle is given for lower shedding as a result of which there is a tension difference between the upper and lower warp sheets at beating. Higher pick density is realized compared to the four link crank shedding, and the weaving range is expanded from poplin to broad cloth (Fig. 5.77) [33].

5.20.5 Needle-less tuck-in device

Wefts are tucked in the edge by air instead of tuck-in needle, and it is possible to make adjustments without interference between the reed and a tuck-in needle. The tuck-in device can be adjusted by entering values on the Navi-board, and the fine tucked in selvedge can be formed easily (Fig. 5.78) [33].

5.20.6 Electronic independent selvedge motion – EIS

It uses fewer consumable parts than the conventional mechanical motion, and high speed is available. The shedding amount, shedding time, and the shedding pattern can be set on the Navi-board. It is user friendly and increases the versatility (Fig. 5.79) [33].

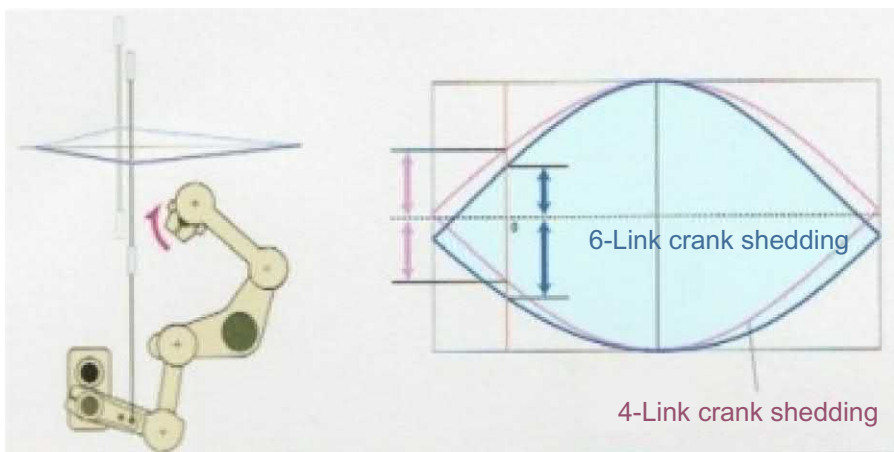


Fig. 5.77 6-Link crank shedding.



Fig. 5.78 Needle-less tuck-in device.

5.20.7 Wider versatility – Eight colour weft selection

The ZAX9200i can run with various shedding motion and can weave high-density and high-tension fabrics with up to eight colours and in a wide range of fabrics. The FDP-AIII free drum pooling system is superior in responding to high speeds. Its advancing reel system separates weft yarns positively and is useful in weaving even long hair yarns such as worsted easily. It stabilizes insertion with less yarn breakage even at high-speed weaving or extra-wide weaving (Fig. 5.80) [33].

5.20.8 i-WBS weft brake system

By adjusting the breaking force to the weft according to weft insertion conditions, energy saving is attained and broken picks are reduced. Stable weft insertion contributes to high efficiency and good fabric quality. The weft brake sharply reduces the peak tension that occurs at the end of the weft insertion in order to prevent weft



Fig. 5.79 Electronic independent selvage motion.



Fig. 5.80 Eight colour weft selection.

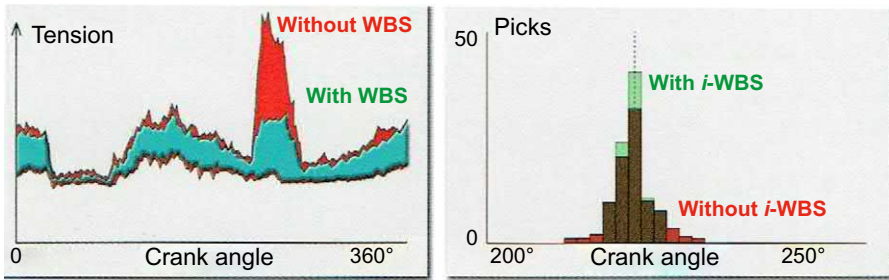


Fig. 5.81 Weft brake system and i-Weft brake system.

breakage and looseness. It is ideal for extra-wide weaving which invites higher peak tension and for yarns which may cause broken picks (Fig. 5.81) [33].

5.20.9 Catch cord-less (CCL)

The weft entered in the stretch nozzles is caught and held by an ejector mouth and is cut by a selvage cutter for several picks. Catch cords are not required, thus reducing consumption and resources (Fig. 5.82) [33].

5.20.10 Programmable speed control (PSC)

It is possible to set up to 32 kinds of loom rpm independently. The PSC automatically adjusts the rpm to the optimum for each yarn kind thereby increasing the productivity dramatically. The loom rpm is changed within one pick (Fig. 5.83) [33].

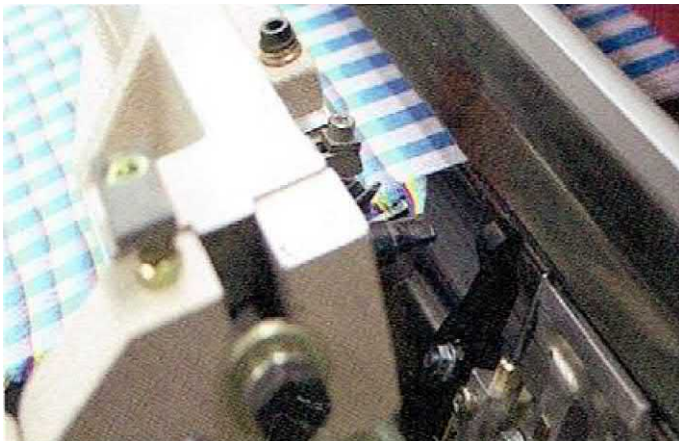


Fig. 5.82 Catch cord-less – CCL.

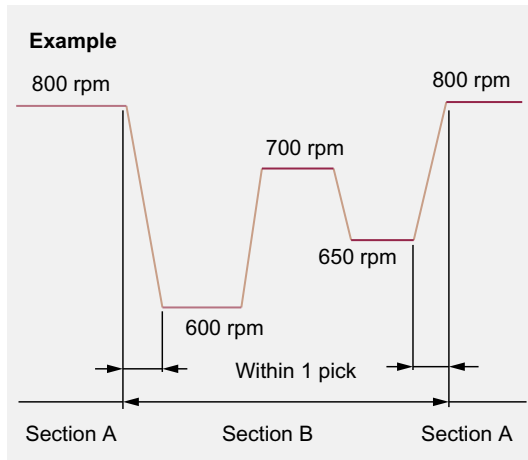


Fig. 5.83 Programmable speed control – PSC.

5.20.11 Automatic defective pick remover (APR-III)

When using coloured yarns, adoption of a mechanical sensor enhances accuracy to detect a defective pick. The removed defective yarn is discharged to the trash box which is easily collected later on (Fig. 5.84) [33].

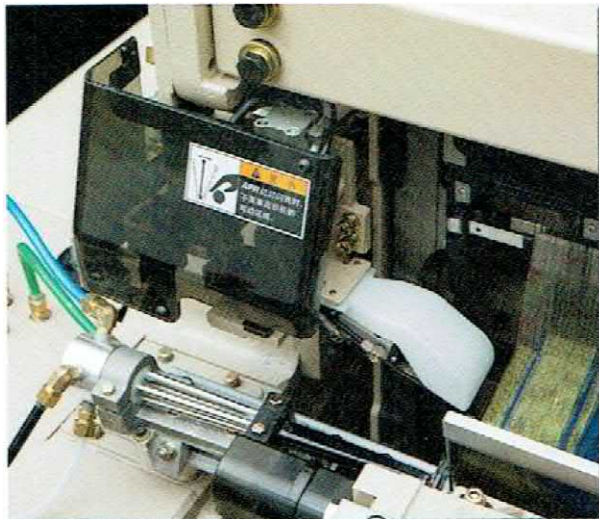


Fig. 5.84 Automatic defective pick remover.

5.20.12 i-weave

The 'i-Weave' is provided as standard on the ZAX9200i loom, and it cleverly optimizes the three basics of weft insertion for air jet loom: nozzle, valve, and control technology, providing high speed performance accompanied with energy saving.

5.20.13 Switchable subnozzle block

By placing the subnozzles close to the weft, lower air pressure for weft insertion can be used, hence air consumption is reduced. The lower air pressure also reduces damage to the weft (Fig. 5.85) [33].

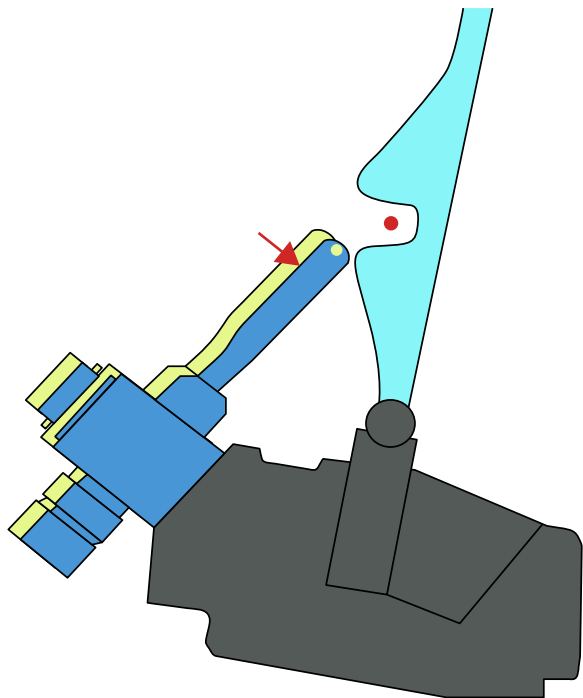
5.20.14 Direct subnozzle system DSS II

By employing an efficient new valve and optimizing the piping from the manifold, low setting pressure is accomplished while saving air (Fig. 5.86) [33].

5.20.15 i-start

In addition to the conventional kickback function that controls the cloth fell just before the loom starts, compensating the let-off and take-up speeds just after the loom starts makes stop marks less prominent.

Fig. 5.85 Switchable subnozzle block.



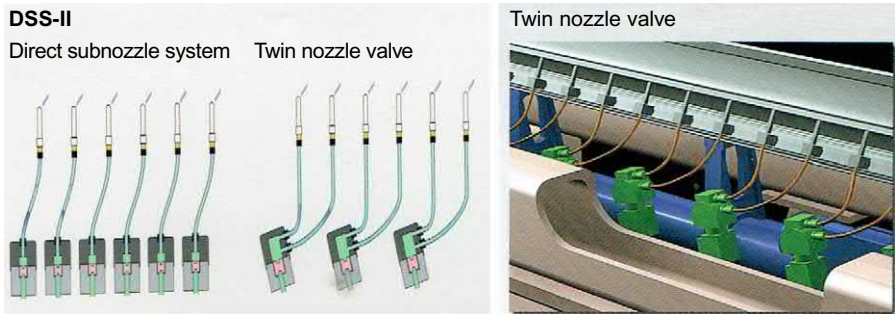


Fig. 5.86 Direct subnozzle system.

A new function is added: By changing the warp tension that was decreased during loom stop back to the tension just before the loom starts, stop marks caused by a decrease in warp tension can be eliminated.

5.20.16 Air consumption indicator (ACI)

By indicating air consumption per loom, abnormal settings can be easily found on the Navi-board.

5.20.17 Weave Navigation System-II

Tsudakoma have developed a unique weaving support system: Weave Navigation System-II. It leads the loom itself to the optimum weaving conditions for a wide variety of fabrics. The system employs a 15-in. display – the largest in the weaving machine field, which reduces the hierarchy levels of the menu and number of button operations for user friendliness. Due to the optimum weaving conditions, high quality fabrics are produced while saving energy at a high level. Weave Navigation monitors loom operation while the loom is in operation. It gives advice to improve the operation in various situations, thus navigating to the best weaving possible.

5.20.18 Tune navigation

The best setting values are automatically entered for the desired fabric and loom specifications. Optimum mechanical settings are recommended for the tension roll position, easing the amount and various pressure settings according to the fabrics to be woven.

5.20.19 Self-navigation

Excellent self-diagnosis and maintenance information help maintenance work such as the position and parts for periodic replacement. Weft insertion adjustment does not need measuring equipment.

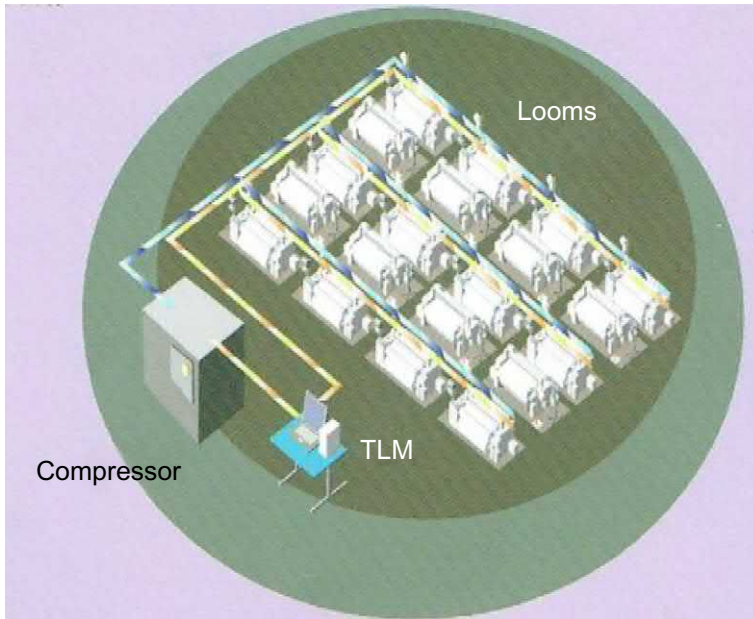


Fig. 5.87 Smart air grid.

5.20.20 Auto cruise

It provides automatic adjustments for the loom's setting according to the ever changing weft insertion status. Thus, it provides an excellent auto cruise in weaving.

5.20.21 Tsudakoma loom monitoring system (TLM)

As well as monitoring operation of the looms, bidirectional communication supports loom-to-loom setting data transfer and dobby pattern transfer. The loom adjustment data and mechanical settings are controlled by the host computer according to the fabric.

5.20.22 Smart air grid

Smart air grid is a new concept designed by Tsudakoma to reduce the air consumption. Information about the air pressure and air consumption is sent to the compressor through the TLM. The new Smart Air Grid function combined with an air compressor can reduce the total energy costs of the factory (Fig. 5.87) [33].

5.21 Developments in TOYOTA air-jet loom – JAT810

Toyota Industries Corporation (TICO) – Japan presented the latest model of their air jet loom JAT 810, which was comprehensively designed for energy savings, higher productivity, and improved ease of use.

JAT810 boasts a diverse range of features, including an Air-Saving System that reduces energy consumption and the new 'E-shed' electronic shedding motion, JAT e-Reed. In addition, a newly developed function panel and a factory management system dramatically improve operability.

Interesting developments/features incorporated in JAT810 are included in the following sections. Not all of these are provided as standard features on the loom as some are optional.

5.21.1 Reduction of power consumption

The new weft insertion system which has produced a 20% reduction in air consumption compared to the previous model. With the new subnozzle, weft insertion with less air usage is achieved by the optimization of the air stream angle and nozzle aperture configuration (Fig. 5.88A–C) [34].

5.21.2 Jat e-REED

The optimized shape of the newly designed proprietary Air-saving 'JAT e-REEDs' tunnel allows the sub nozzle to be located closer to the reed. This thereby prevents the air stream from scattering and allows weft insertion at low pressure. This enables air consumption for the weft insertion to be reduced (Fig. 5.89A and B) [34].

5.21.3 ALPIN – New air saving technology

In collaboration, Uster and Toyota have developed a new air-saving technology. A newly designed sensor is installed between the feed and the feeder that allows for the system to monitor the characteristics of the weft yarn. Processing this information, the system can optimize the valve timing to reduce overall air consumption. The system provides key operational conditions based on the variations of the weft yarn (Fig. 5.90) [34].

5.21.4 Development of the 'E-shed' electronic shedding device

The independently-driven shedding technology developed by TICO enables faster weaving of complex fabrics, thus achieving both high-speed and versatility that surpass any electronic dobby and positive cam shedding.

5.21.5 Automatic brake system (ABS) – Optional

ABS prevents yarn breakage by controlling peak weft tension and is also effective in saving air (Fig. 5.91) [34].

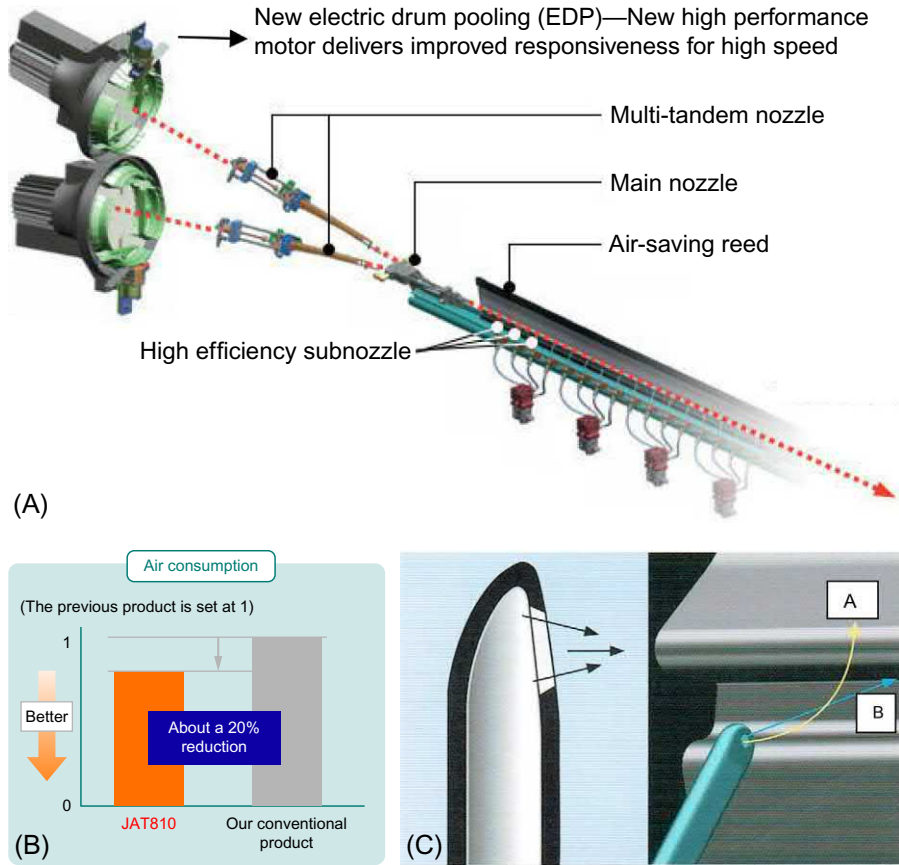


Fig. 5.88 (A) New weft insertion system. (B) Air consumption on JAT 810 previous model. (C) A – Air jetting at low pressure with another’s company nozzle. B – Air jetting at low pressure with the JAT 810 nozzle.

5.21.6 Toyota automatic pick operator (TAPO)

If a mispick occurs, the feature automatically removes the mispick and restarts the loom. A specially designed variable-speed motor makes it possible to adjust the speed of mispick removal (Fig. 5.92) [34].

5.21.7 Air gripper system (AGS) – Optional

The system eliminates dropped picks of stretched yarn, while preventing damage to covered yarns.

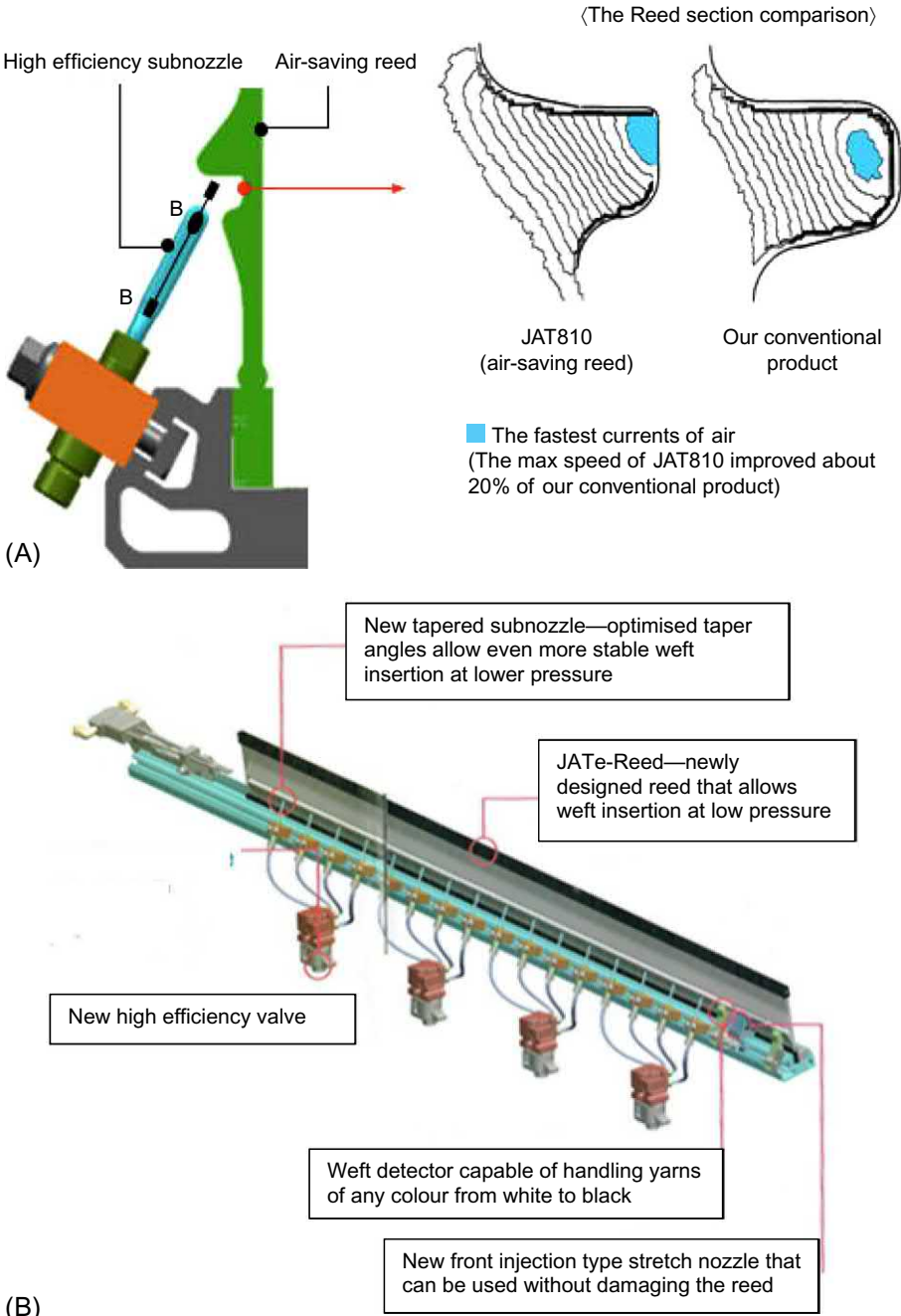


Fig. 5.89 (A) Jat e-Reed. (B) Jat e-Reed, Weft detector, New High efficiency valve, and new stretch nozzle.

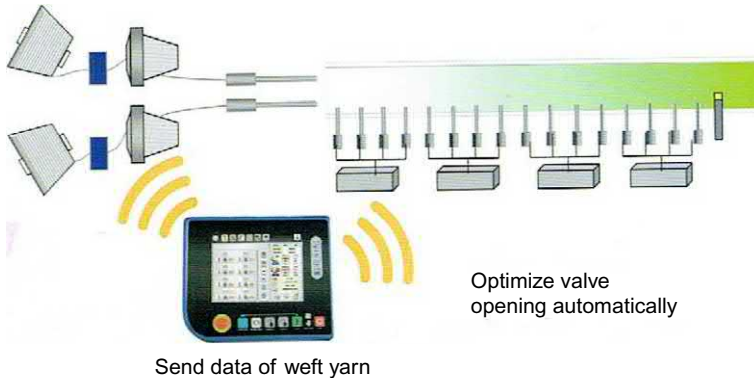


Fig. 5.90 ALPIN – new air-saving technology.



Fig. 5.91 Automatic braking system.

5.21.8 Automatic insertion system (FIS) – Optional

When a yarn supply fault occurs, AIC continues weft insertion by automatically switching to another drum without stopping the loom.

5.21.9 Flexible insertion system (FIS) – Optional

The main nozzle pressure can be set independently for each pick according to the weft insertion pattern. Also, the sub nozzles' pressure can be switched between high and low pressure for each pick. It can handle a maximum of 75 – times the difference in weft yarn count (e.g., channelled yarn 1500 d, 20 d).

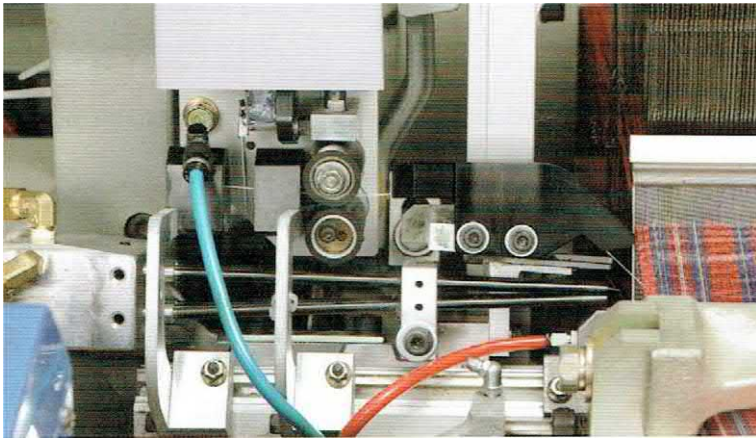


Fig. 5.92 Toyota automatic mispick operator.

5.21.10 Weave assist system (WAS)

The new weave assist system automatically makes optimal settings, enabling the machine to perform the role of a skilled worker. Optimal weaving conditions and settings are automatically determined by the 'New WAS' simply by selecting the basic conditions (type of yarn, density, pattern) corresponding to a wide variety of textiles.

5.21.11 Factory management system 'FACT'

The 'FACT' system can display a wide range of operational parameters and production information for each machine including air consumption according the actual factory layout, thus achieving enhanced productivity through centralized management of the entire factory.

5.22 New concept – Air-jet loom for the production of leno fabrics

At Itma 2015, VUTS from Liberec exhibited their new air-jet loom CAM EL (Fig. 5.93A and B) [35] running at 550 r.p.m., designed to produce leno weave fabrics (Fig. 5.94) [35] which primarily are produced on conventional weaving machines. VUTS offers a comprehensive solution to this problem with a sophisticated and efficient special purpose weaving machine for the production of fabrics in the leno weave with the maximum width of 220 cm.

The loom is equipped with a direct drive by means of the synchronized servomotor with an electronic control. An electronic cam is included at the beginning of the drive, and a crank mechanism is located on its shaft.

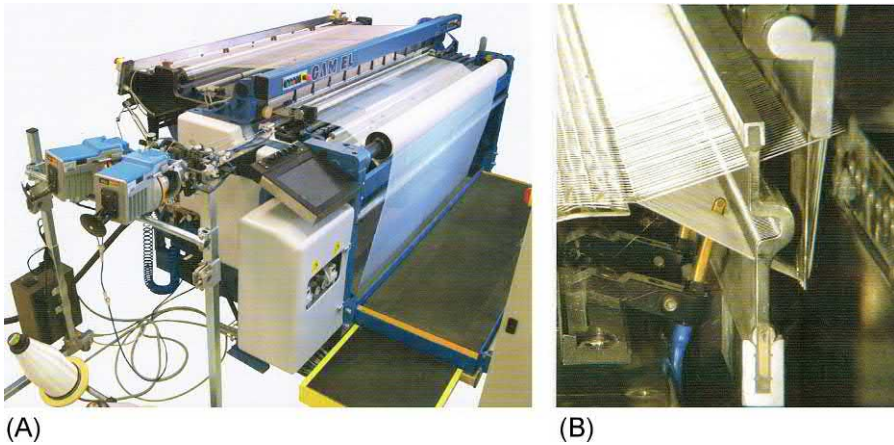


Fig. 5.93 (A) Air jet loom CAM EL for leno fabric weaving. (B) Air jet loom CAM EL weft insertion.

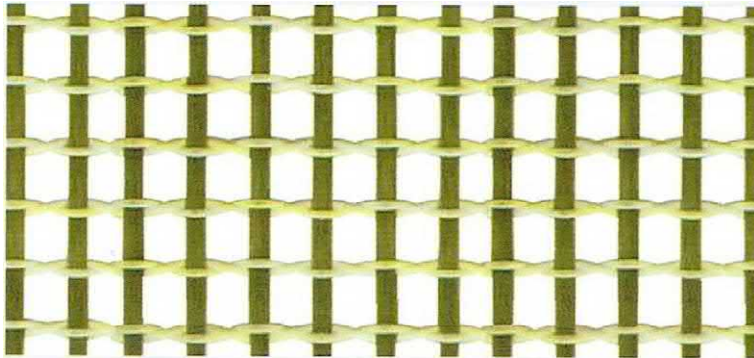


Fig. 5.94 Leno weave fabric on air-jet loom.

5.22.1 First heald-less system for leno weaving

Heald systems permit the speed of weaving to be up to 200–250 picks per minute.

It is a novelty to use a system of leno weave creation without heald. This heald-less system for weaving the leno weave was the first that allowed overcoming all the deficiencies of existing heald systems and increasing the speed of the loom more than twice with increased fabric quality.

5.22.2 Shed creation (Fig. 5.95A and B) [35]

The loom design offers an original solution not only for the loom drive, but also for weaving the leno weave. The concept of two systems of warp threads that do not cross in the area between the half shaft and back rail brings new qualitative viewpoints into the production on leno fabrics.

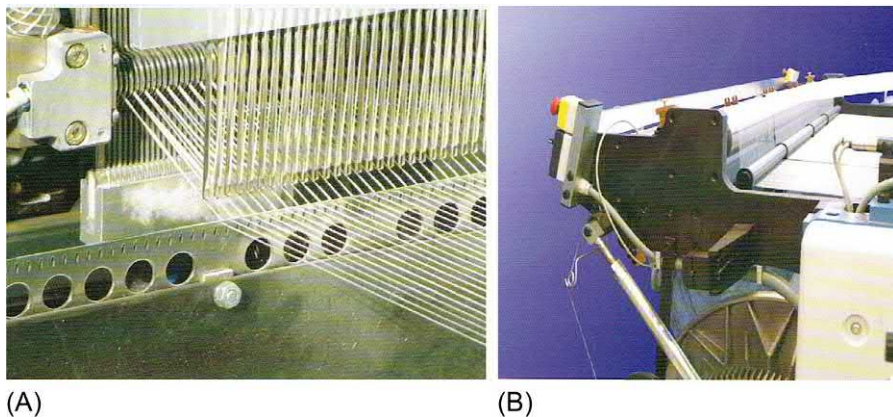


Fig. 5.95 (A) Shed creation. (B) Shed creation.

- Vertical movement – The shed is created by the movement of the first system of warp threads guided in the eyes of heald half shaft.
- Horizontal Movement – The second system of warp threads is guided into the needles and it creates the leno weave by interlinking. The block of needles is mounted just like the batten by leaf springs, and its movement is derived from another electronic cam.

5.23 Developments in Tsudakoma water-jet loom

Tsudakoma exhibited their latest water jet loom Model Professional ZW8100 offering some newly designed technical features/developments incorporated in the loom design. The new features offer higher productivity, best quality, higher operability, wider versatility, and environmental measures. The model ZW8100-190-3C-J integrated with a positive electronic jacquard machine was exhibited running at a weft insertion rate of 1425 m/min weaving a fabric with 39 end/cm and 38 picks/cm with 470 dtex warp and weft, fabric width of 190 cm with three colours in the weft direction (Fig. 5.96) [36].

The newly designed frame structure, beating and shedding increased weft insertion performance. The pitch-shortened nozzle helped to increase the operation speed by 10% when compared with the existing machine. The Programmable Start System (PSS-W) is designed to efficiently reduce stop marks. The warp line height is 40 mm lower than the existing model for easy access. It automatically conducts pick finding after recovering from a loom stoppage and restarts, thus demonstrating outstanding operability.

The weft insertion technology allows the ability to weave a wide range of fabrics: from extra-fine to thick yarns, from narrow to wide widths and unbalanced constructions such as double weave. All this is achieved by using a combination of electronic dobby machine, pitch-shortened nozzle, a twin pump, and four colour weft selection.

With the redesigned mechanism of weft insertion, shedding, beating the 'ZW8100' requires 5% less electric power. The robust designed frame structure and the optimized beating mechanism reduce vibration by 25% compared with the existing model.



Fig. 5.96 Water jet loom Professional ZW8100 with jacquard.

Professional ZW8100 offers the following incremental developments/salient features. Not all these are provided as standard features on the loom as some are offered as optional.

5.23.1 Robust frame structure

The front, bottom, and the back top stay are completely strengthened for stable operation at high speed. The transverse rail is employed for special fabrics such as air bag and double weave, controlling vibration efficiently (Fig. 5.97) [36].

5.23.2 Low warp line

The machine's dimensions have been redesigned to effect the warp line. A 40mm lower warp line compared with the existing model significantly enhances workability such as warp repair, as well as contributing to a reduction in vibration (Fig. 5.98) [36].

5.23.3 Short stroke beating

By redesigning the beating stroke and making the position of the 1st heald frame closer to the cloth fell compared with the existing model, the high-speed operation is attained while maintaining fabric quality. For three-colour or more weft selection, a 6-link beating motion is used (Fig. 5.99) [36].

5.23.4 New offset rocking shaft

In order to reduce the vibrations further compared with the existing models, a newly designed pipe-type offset rocking shaft is provided for the standard specifications with a reed space of 190cm or less (Fig. 5.100) [36].

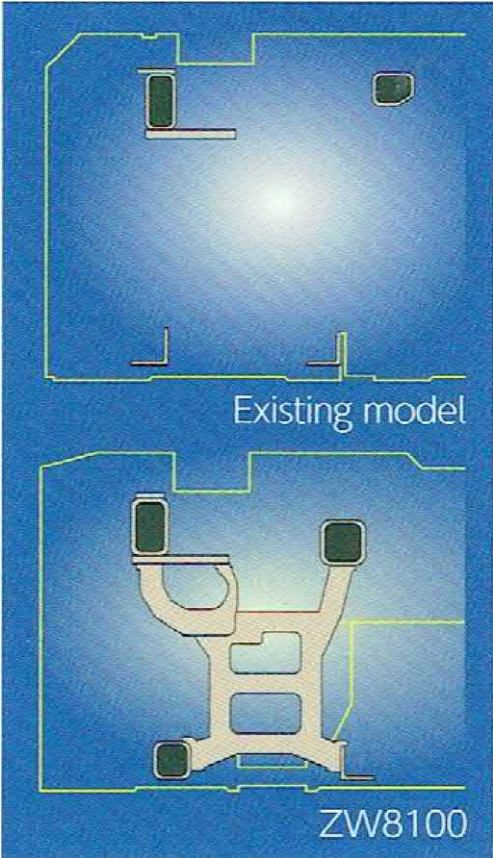


Fig. 5.97 Robust frame of water jet loom.

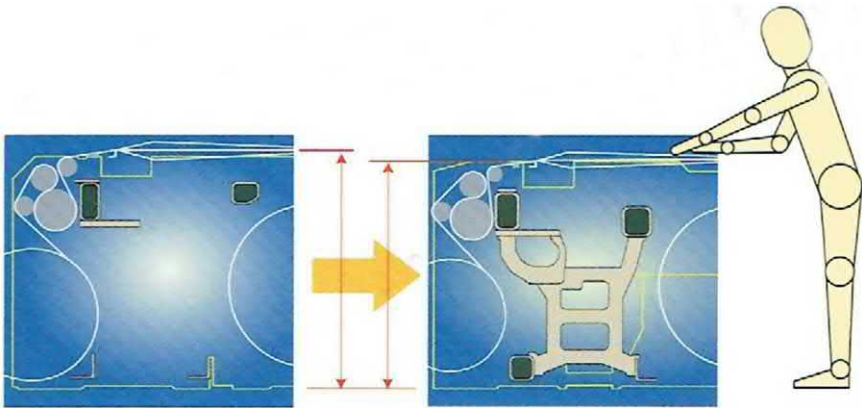


Fig. 5.98 Low warp line structure of ZX8100 loom.

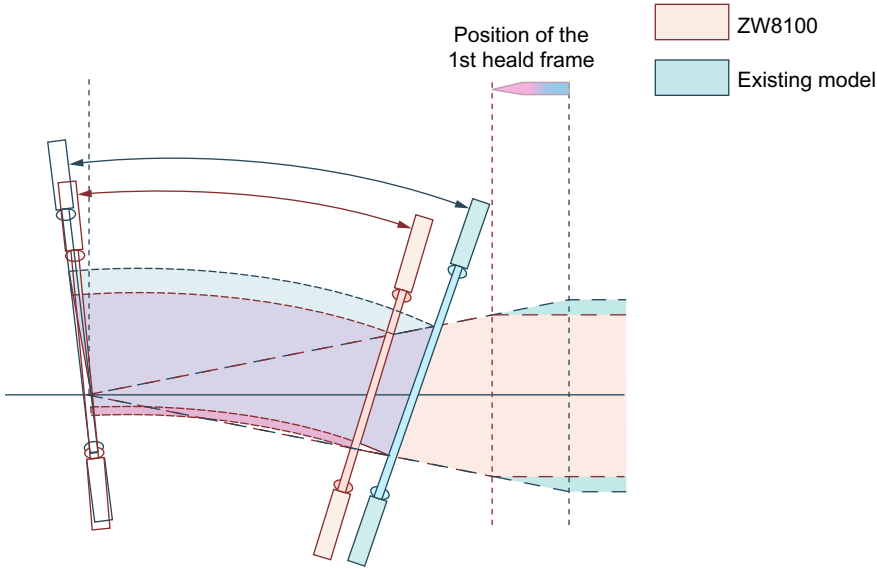


Fig. 5.99 Short stroke beating.

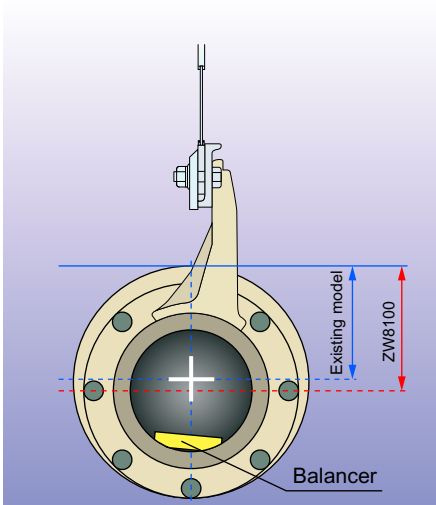


Fig. 5.100 Offset rocking shaft.

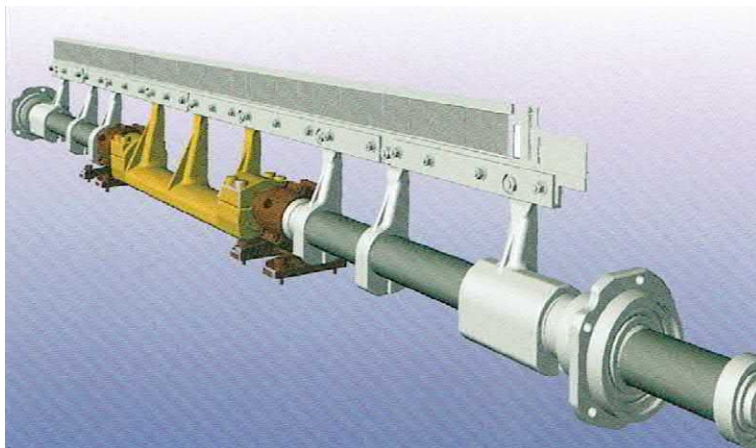


Fig. 5.101 Offset rocking shaft (intermediate support type).

5.23.5 Offset rocking shaft (intermediate support type)

The weight is reduced by separating the main shaft section and the balancing section of the rocking shaft, achieving high speed and balancing beat up (Fig.5.101) [36].

5.23.6 Electric weft pull-back device

For some fabrics, the weft tip that protrudes from the nozzle is pulled back to give it a good posture in order to prevent the weft yarns from being entangled. This stabilizes weft insertion (Fig. 5.102) [36].



Fig. 5.102 Electric weft pull-back device.

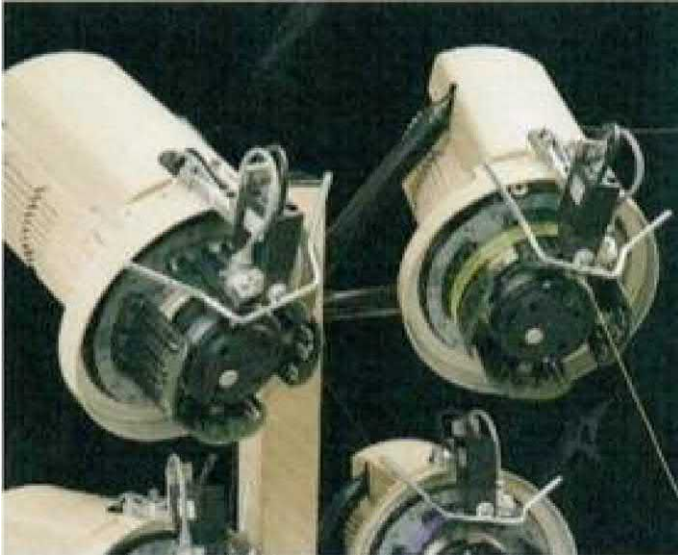


Fig. 5.103 Weft break system WBS.

5.23.7 Weft break system (WBS)

The weft brake system effectively reduces peak tension at the end of weft insertion. This makes the crimping effect of high-twist yarn fabric while at the same time also prevents tight or loose pick of textured fabrics (Fig. 5.103) [36].

5.23.8 Rotary drum pooling device (RDP)

The device assures quality fabric weaving even at high speeds with the single-nozzle use. In addition to regular yarn fabrics, those added value fabrics such as twisted, taslan, nep, or loop yarn are easily woven. With the inverter control (OP), airflow amount is controlled properly for energy saving (Fig. 5.104) [36].

5.23.9 Stationary drum pool (SDP)

The SDP does not require a storage blower. Great energy saving is expected. The tension given to the weft is small, so the difference in measuring pick length is minimized (Fig. 5.105) [36].

5.23.10 AllIW free drum pooling device (FDP)

The newly designed device supports various types of weft. The advancing mechanism that is excellent at high-speed and positively separates yarn, even a thick yarn, is easily stored and released.

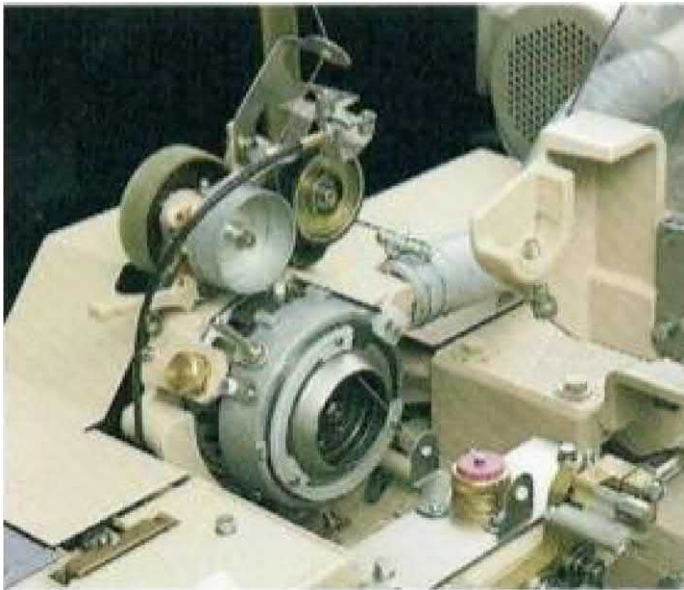


Fig. 5.104 Rotary drum pooling device – RDP.



Fig. 5.105 Stationary drum pooling device – SDP.

5.23.11 Twin pump

Layout is redesigned and a special shaft for cam driving is attached, achieving high-speed operation. Stable high-speed operation for value-added fabrics that use weft yarns of different characteristics is achieved (Fig. 5.106) [36].

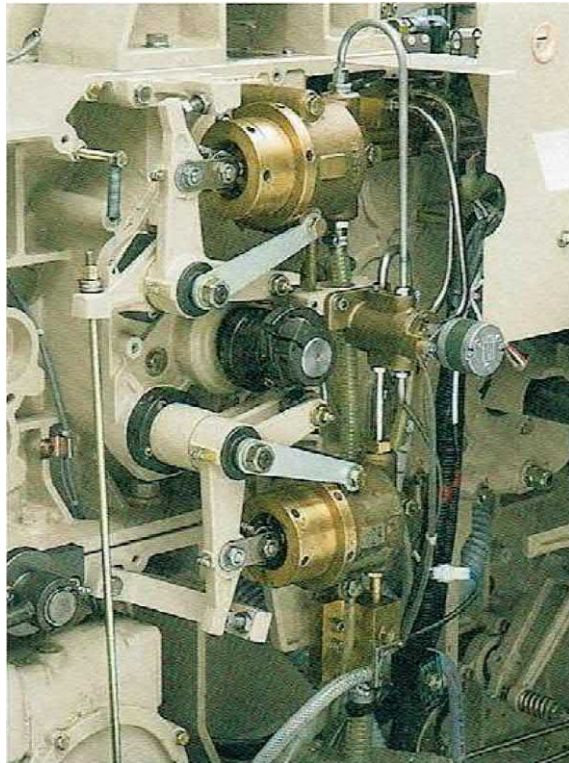
5.23.12 Exclusive positive cam shedding for plain weave (ECS)

Tsudakoma ECS uses less power because no cables or wire guides are provided, offering easy maintenance. Also, it is ideal and suitable for high-density fabrics such as air bags (Fig. 5.107) [36].

5.23.13 Rush start motor

The rush start motor provides an ultra-high torque start and effectively prevents stop marks and first pick looseness. Large capacity electromagnetic brakes directly connected to the crankshaft accurately stop the loom at the programmed position (Fig. 5.108) [37].

Fig. 5.106 Twin pump.



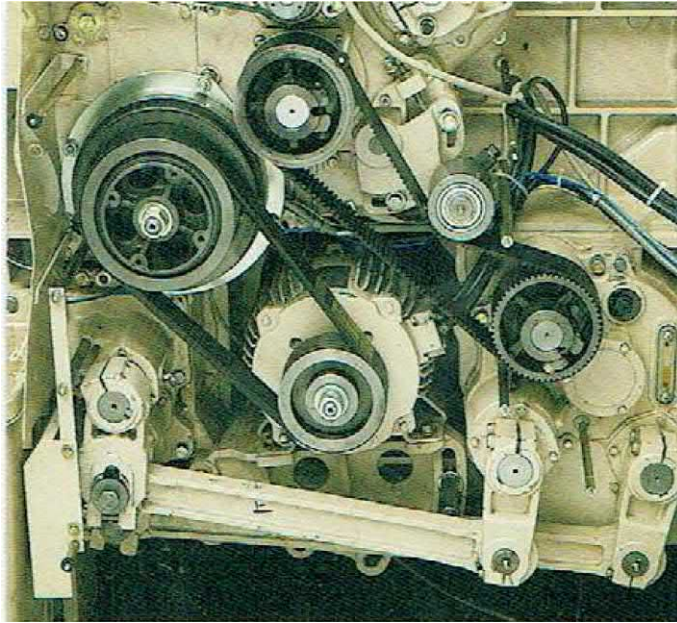


Fig. 5.107 Exclusive positive cam shedding.

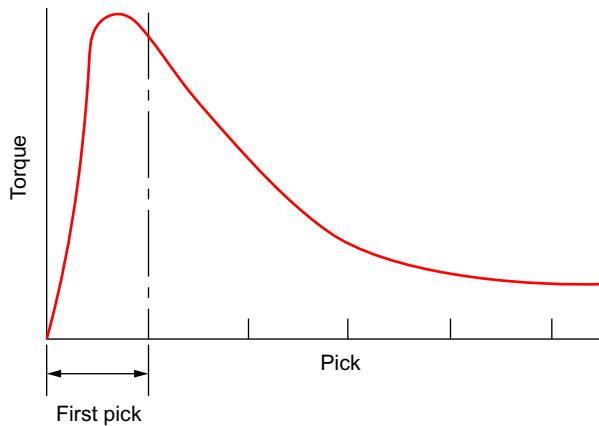


Fig. 5.108 Rush start motor.

5.23.14 Electronic let-off (ELO) and electronic take-up (ETU) redesigned (Fig. 5.109) [36]

5.23.14.1 Higher pick density

Shortening the cloth passage allows stable weaving of higher density fabrics.

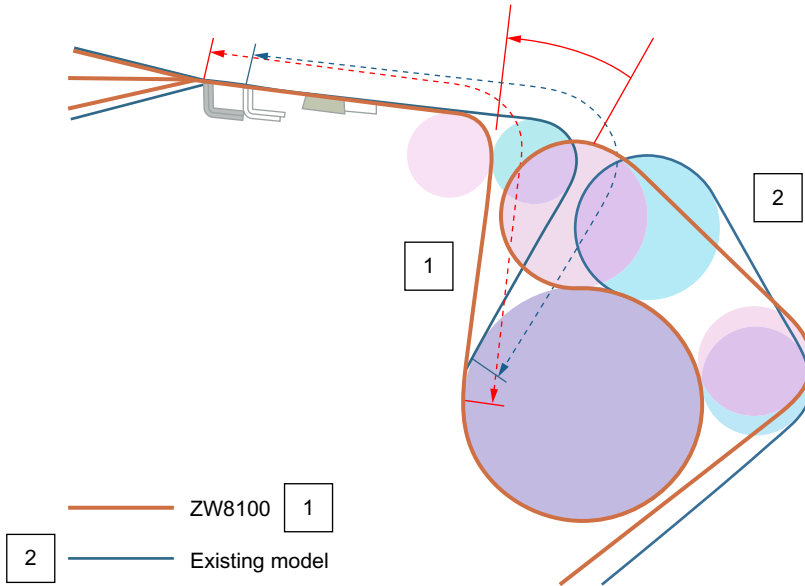


Fig. 5.109 Cloth passage.

5.23.14.2 Inclined cloth passage

By inclining the cloth passage from the cloth fell, the stable operation to produce unbalanced fabric constructions, such as double weave, is achieved without causing vertical movement at the cloth fell.

5.23.15 PSS-W programmable start system

In addition to the cloth fell control just before the re-start, the PSS-W compensates for speeds immediately after re-start to reduce stop marks after the cloth fell, by the linked operation of the ELO and the ETU. The warp tension that was changed during loom stoppage is also compensated. The PSS-W controls speed changes of the ELO immediately after the restart.

5.24 Maximum loom speeds and weft insertion rates exhibited at ITMA's

Although from the weaving point of view, the performance of the loom in terms of weft-insertion rate is quite realistic; however, from the engineering point of view, speed carries more importance, and this aspect has been clearly demonstrated in the past ITMAs. [Table 5.3](#) summarizes the maximum loom speeds and weft insertion rates that were actually demonstrated at each ITMA on the different methods of weft insertion. WIR indicates the amount of weft that is converted into fabric, or inserted, in

Table 5.3 Maximum loom speeds and weft insertion rates (WIR) for different methods of weft insertion exhibited at Itmas 1991–2015

ITMA year	1991	1995	1999	2003	2007	2011	2015
Maximum loom speeds (ppm) exhibited at ITMAS 1991–2015							
Rapier	550	550	820	720	750	810	800
Air jet	1500	1500	1800	1025	1800	2011	1800
Water jet	1700	2000	1600	x	x	750	750
Projectile	350	400	360	370	400	240	x
Multiphase	x	2050	2430	2824	x	x	x
Maximum weft insertion rates (m/min) exhibited at ITMAS 1991–2015							
Rapier	1242	1452	1505	1684	1628	1490	1521
Air jet	2550	2600	3222	2500	2900	3034	2700
Water jet	2600	2500	2700	x	x	1420	1425
Projectile	1200	1430	1400	1300	1400	1260	x
Multiphase	x	3894	4118–6088	4775	x	x	x

one minute during weaving. This is a product of loom speed and width of warp in the reed.

It appears that the loom speeds and weft insertion rates have, over the years, now come to their saturation limits, and it may not now be feasible to look forward to further significant increases in the speeds/weft insertion rates in any of the following methods of weft insertion. Rightly so, the manufacturers over the last 10–15 years or so have concentrated in significantly improving the loom design, etc. to achieve other useful technical features which have been elaborated in the previous sections. All of this has been achieved as a result of developments of electronics/microprocessors and their incorporation in the design of the different weaving machines.

References

- [1] B.P. Corbman, *Textiles – Fibre to Fabric*, McGraw-Hill, New York, 1983.
- [2] T. Ishida, *Innovations in Weaving Machinery*, Osaka Senken Ltd, Japan, 1994.
- [3] B.H. Crawford, *Draper Loom Fixing*, A.J. Showalter Co., Dalton, GA, 1947.
- [4] R. Marks, P.J. Lawton, D.A. Holmes, *An Introduction to Textiles vol. III*, Comett Eurotex School of Textiles, Bolton University, UK.
- [5] W.A. Hanton, *Automatic Weaving*, Ernest Benn Ltd, Manchester, 1929.
- [6] J.W. Hutchinson, *The Practical Management of Looms and Yarns*, Mr.Hutchinson, Bradford, UK, 1949.
- [7] R. Marks, A.T.C. Robinson, *Principles of Weaving*, The Textile Institute, Manchester, 1976.
- [8] Woven Fabric Production – Shedding, NCUTE. <http://www.pdexcil.org/news/51N1203/weaving1.htm>.
- [9] Toyota Brochure for loom LWT 710.

- [10] Stäubli brochure – shedding solutions for modern frame weaving.
- [11] Recep Eren, G. Ozkan, M. Karahan, Comparison of heald frame motion generated by rotary dobby and crank and cam shedding motions, *Fibre & Textiles in Eastern Europe* 13 (4) (2005) 52. October/December.
- [12] W. Wilkinson, *Practical Weaving*, Coulton & Co., Nelson, 1915.
- [13] N. Hollen, J. Saddler, A. Langford, *Textiles*, Macmillan, New York, 1979.
- [14] *Textile Terms and Definitions*, The Textile Institute, Manchester, 1995.
- [15] The 4 of Horgen, Bulletin no. 86, 1988.
- [16] G.A. Bennett, *Introduction to Automatic Weaving*, Harlequin Press Co. Ltd, Manchester, 1948.
- [17] A. Ormerod, W.S. Sondhelm, *Weaving – Technology and Operations*, The Textile Institute, Manchester, 1995.
- [18] P.R. Lord, M.H. Mohamed, *Weaving: Conversion of Yarn to Fabric*, Merrow Publishing Co. Ltd, Watford, UK, 1973.
- [19] S. Adanur, Chapter 9 – Projectile weaving, in: *Handbook of Weaving*, CRC Press, Boca Raton, FL, 2000.
- [20] J.J. Vincent, *Shuttle-less Looms*, The Textile Institute, Manchester, 1980.
- [21] V. Duxbury, G. Wray, *Modern Developments in Weaving Machinery*, Columbine Press, Buxton, UK, 1962.
- [22] O. Talavasek, V. Svaty, *Shuttle-Less Weaving Machines*, Elsevier Science, Oxford, 1981.
- [23] K. Gandhi, ITMA fruits of the loom, *Textile Month* (6) (2007) 8.
- [24] www.textile.school.com/school/weaving/waterjetweavingmachines.aspx.
- [25] Sulzer *Textil* M8300, Brochure – the reinvention of weaving.
- [26] Picanol Brochure – Let us grow together, Rapier loom – OptiMax-i, EN 08.10.201.
- [27] Picanol News Brochure, *Let us grow together*, (2015).
- [28] (a) Dornier Weaving, Brochure Brochure—Rapier Weaving Machine, Quality Creates Value-P1. (b) <http://www.lindauerdornier.com/en/weaving-machine/open-reed-weave-orw-technology>.
- [29] Santax Rimar Group—Technical leaflet, SMIT ONE—Rapier loom.
- [30] Trinca—Italy—Catalogue Weaving machines for the production of technical fabrics.
- [31] Picanol Brochure—Let us grow together, Air jet loom OMNIplus Summum, EN
- [32] Dornier Weaving Brochure—Air-Jet Weaving Machine A1, Quality Creates Value.
- [33] Tsudakoma Corp, Japan, Catalogue Air jet loom ZAX9200 i (A02ZVB02TE).
- [34] Toyota Industries Corporation, Japan, Catalogue, Air-Jet Loom JAT810.
- [35] VUTS, a.s LIBEREC VERA/CAMEL Air Weaving Loom—Technical Leaflet Non-traditional Concept of Air weaving looms.
- [36] Tsudakoma Corp, Japan, Brochure, Water Jet Loom ZW8100 Professional (W15ZVG15HE)
- [37] Tsudakoma Corp, Japan, Brochure, Water Jet Loom, ZW 408 (WO2QY101TE).

Part Two

Woven structures

CAD/CAM in the woven textiles industry

6

Pammi Sinha

University of Leeds, Leeds, United Kingdom

6.1 Introduction

Weaving is one of the oldest crafts known to man. Fragments of woven cloth have been dated to the Neolithic/Eneolithic period [1]. The woven fabric has been regarded as possessing mystical qualities: woven rags are offered as part of the prayers in some Buddhist shrines, form the requisite set of ceremonial accoutrements for many different religions' prayer settings, and as observed by Kramrisch [1a] "in the Rig Veda and the Upanishads, the universe is envisioned as a fabric woven by the gods. The cosmos, the ordered universe, is one continuous fabric; the uncut fabric is a symbol of totality and integrity" [1a, pp. 67–68]. Knowledge and mastery of the skill has long been a matter of intellectual pride – as illustrated by the Greek myth of the weaving competition between the goddess Athena and the human Arachnida. Arachnida won the competition but her demonstration of pride in winning was punished by Athena who turned Arachnida into a spider and cursed her to forever spin and weave. To understand and be knowledgeable about woven design is a matter of mastering weaving techniques and mathematics and the competitive environment within which the textiles industry operates requires computer-aided design and manufacture (CAD/CAM) skills to develop new products and new textiles applications.

This chapter introduces the reader to some of the key issues regarding the use of CAD/CAM within woven textile design. The chapter will begin with an overview of the scope and standing of the textiles industry within the global trading environment and the role that CAD/CAM plays. The chapter then discusses key management issues when using CAD/CAM within the woven design process such as: cost, expertise and skills training, impact on the supply chain, and development of new products and new market areas. The chapter will conclude by discussing some of the current research being undertaken with CAD/CAM applications for woven textiles with a view towards future trends and sources of useful information for readers wishing to explore the issues raised in greater depth.

6.2 The textiles industry and innovation

6.2.1 Scope and size of the textile industry

The textiles sector is wide and diverse with applications as diverse as clothing, geology, architecture, auto industries, civil engineering, medicine, aerospace, etc. [1b].

According to the latest available COMTRADE figures, textiles (not including apparel) are one of the top 25 globally traded goods; it is 17th of 25 goods valued at about \$0.35 trillion of the total goods traded globally valued at \$25 trillion [2].

The textiles industry has traditionally been regarded as consisting of three main production areas: fibres (natural or synthetic), fabrics, and the finished product (consumer goods, e.g., clothing, domestic interiors). Production of fabric (the first two main production areas of the textiles industry) is capital intensive, requiring technology and automation to produce requisite volumes of fabric. Although more labour intensive, the third production area, which is the consumer facing end of the chain (import, distribution, and retail) has become increasingly competitive and significant in the industry's value chain [2a, 2b] and new applications of textiles have led to expanding market potentials for technical textiles. Indeed, it has been noted that there are four specific areas where value could be incorporated or improved through product or process: flexibility, quality, environmental performance, and innovation [3].

New technology, research, and development activities are regarded as essential factors to compete within the capital-intensive countries (such as those within the OECD) as it helps to develop products that are differentiated from competing companies and are able to be traded within the saturated market conditions. CAD/CAM applications play significant roles in developing differentiated products and reacting to the changing nature of the supply chain. An area of innovation in textiles where CAD/CAM is essential is technical textiles and three-dimensional (3D) weaving, because of its complex weave structures and interdisciplinary nature of working.

6.2.2 3D weave and technical textiles

Technical textiles may be knitted or woven fabric structures [4]. Defining technical textiles has proven difficult as it was originally coined as a term in the 1980s to follow on from the term 'industrial' textiles (which is still used in the United States), as it was regarded as too narrow in scope of applications (<https://technitex.org/>). The term in its original use became too narrow because it was initially regarded as "textile materials and products manufactured primarily for their technical and performance properties rather than their aesthetic or decorative characteristics" but the rising use of technical textiles within sportswear apparel and the increasing use of design to attract sales has rendered this approach somewhat narrow (Byrne, in Ref. [5]). Byrne [6] provides some common features of technical textile products: they are the results of understanding and know how about combinations of the techniques of manipulating fibres, fabrics, and finishing and how they perform in different combinations and environments.

Woven technical textiles tend to be developed using 3D weave structures. Woven fabrics may be single layer or multiple layers and the weave structure may be as simple as plain weaves through to complex weave structures, depending on the final product requirements. Multilayer woven fabrics are also known as 3D weaves, as they have several layers of warp and weft yarns woven together in an almost infinite number of possible ways, but broadly categorized as orthogonal, through-thickness angle interlock and angle interlock (also known as layer to layer). Braided fabrics (created

by interweaving three or more yarns in a diagonally overlapping pattern) are also commonly used to develop technical textiles. Two types of braided fabrics are widely available, biaxial (two sets of aligned yarns) and triaxial (three sets of aligned yarns). As with woven fabrics, multilayered (3D) braided fabrics are also manufactured. Three-dimensional weaving may result from specific loom technologies such as 3Tex and Bitem or through a conventional weaving loom which has the advantages of readily available technology, flexibility in the types of 3D structures to be produced and lowered costs, however, it can be complicated to design and manufacture 3D fabrics in this way [7].

Technical textiles are interdisciplinary in nature; “cross-discipline collaboration between textiles and engineering” were noted to be increasingly commonplace within research and industry by woven textile designer and academic Soden [8]. She also noted that although these types of projects resulted in mutually beneficial outcomes, there were challenges regarding “deep rooted prejudices of both disciplines” and ensuing communication problems regarding “terminology, basic understanding of... specific technical requirements and limitations.”

To design technical textiles, the designer needs to have a very good understanding of the yarn and its properties, in particular because much of the 3D woven fabrics are used for the applications such as textiles reinforced composite materials (TRCM) – where both the materials used as the matrix and the reinforcing material (such as textiles) retain their individual properties at microscopic level. Textile composites may be textile structures within polymers, ceramics, or metals [9]. Building upon this knowledge, the ability to conduct mechanical or geometrical modelling of the textiles is paramount.

CAD software becomes essential in this field as geometric modelling of yarn is necessary; “solid volumes representing the approximate bounds of the fibres contained within them” [4, p. 5] for the application in composite textiles is important because it enables:

- determination of the mechanical properties of the fabric forming behaviour,
- prediction of the permeability of fabrics for processing of composites, and
- modelling of the mechanical properties of composite parts and their damage behaviour for use in engineering applications.

6.3 Some basic principles of CAD/CAM in the woven textile industry

According to Price et al. [10], CAD came to be used in the large textile manufacturing firms in the United States since the 1980s. According to Collier and Collier [11], CAD/CAM is a term often used to cover three areas of activity controlled by a linked computerized system: design, analysis, and manufacture. CAD helps in design and product development and CAM helps in controlling the operations steps of production and equipment. The analysis of design and their translation for the manufacturing system is carried out by equipment that is part of computer-aided engineering (CAE). It is

the combination of CAD, CAE, and CAM that make up computer-integrated manufacture (CIM) – otherwise referred to as CAD/CAM [11].

A fully integrated CAD/CAM system implies that the graphic designs developed in the CAD system are translated into numerical information that is analysed by a numerical control (NC) element which enables production controls through computer-generated instructions to computer-controlled looms (Ref. [12] in Ref. [11]). Electronic looms are controlled by a control panel with features that enable the user to save important setting parameters for different fabrics for ease of recall should the operation need to be repeated or amended, thus saving time. Instructions may be printed out and entered manually or sent digitally through USB, floppy disks, or email to the manufacturing loom. ScotWeave (a UK-based textile design CAD system) states that the following elements are necessary for a CAD to CAM system to be fully functional [13]:

- accurate printouts with a colour printer,
- obtain printed production data (loom card) with weaving instructions,
- create data to interface with electronic textile machinery, and
- send design by email easily to other sites.

A CAD/CAM system may also link the production stages to orders, sales, production planning and scheduling and sales analysis, etc., via a secure server through an electronic data interchange (EDI) system. EDI is computer to computer communication between trading partners for business documents such as sales invoices or purchase orders in a standard electronic format typically ANSI (for the United States) or EDIFACT (for Europe and Asia) which are further tailored to meet particular industry needs [e.g., for the textiles industry it is the Textile/Apparel Manufacturing Communications (TAMCS)] [14]. As information is exchanged between computers, there is no human handling of information beyond the initial identification of required documents to be exchanged. The process is, therefore, paperless, takes very little time and is error free (e.g., keying in data incorrectly, etc.); this raises efficiencies in the business process in terms of time, cost, and length of the business cycle (i.e., time taken for the business transaction to be communicated) [15]. CAD/CAM systems may also link their EDI to an enterprise resource planning (ERP) system which moves the business information communicated via EDI through the various stages of production and the manufacturing pipeline to enable timely decision making about the product and production stage to optimize resource and materials efficiencies. The following section provides exemplars of CAD/CAM systems currently in use within the textiles industry.

6.4 CAD/CAM systems in the woven textiles industry

As noted earlier, the textile industry may be regarded as having domestic and commercial applications (such as apparel or interiors) to industrial and technical (such as geo-engineering, medicine, and heavy industry). There are some nonspecialist software applications that enable a woven design to be created on the CAD system.

LECTRA have developed CAD/CAM systems such as for apparel industry that can also develop knit and weave designs within the CAD function. However, as there is no link to a manufacturing element, the design is saved or printed out (with technical information) to undergo the necessary procedures to make the design manufacturable. The intention, therefore, in this type of approach is to enable apparel designers to express their creative vision or amend/reinterpret a current design that a specialist textile designer may then develop. The following sections introduce and explain some of the features of the specialist textile CAD/CAM systems. In general, weave software is built up as a series of modules: CAD, CAM, and server systems.

6.4.1 CAD features

6.4.1.1 Domestic and commercial textiles

Commonly used weave CAD packages are: AVA, ScotWeave, Textronic, Arahne, NedGraphics, and EAT. Windows is the most common operating platform for the software but Apple Mac and Linux are also used. The designs can generally be read across different platforms, circumventing, as far as possible, technology ‘lock in’. In general, weave software may be able to design for dobby, jacquard, and for carpet designs. CAD systems should provide the following functionalities:

- printout loom cards with all production instructions that may be linked to peripherals such as printers or send instructions directly to looms for manufacture [i.e., links to computer-assisted manufacturing (CAM) processes, most often Bonas or Staubli for jacquard weaving],
- calculating yarn consumption and cost implications as part of the design functions,
- archiving system for data storage, retrieval, sharing and management systems, and presentation methods,
- presentation – such as texture mapping, story boarding, and
- draping functions (to visualize the woven fabric design applied to a product) [16].

Most software packages will provide dobby or jacquard weaving features. Differentiating features tend to be around specialisms such technical textile weaving, colour matching specialisms, or links with retail, examples of which are:

- ScotWeave software has a package for face-to-face velvet and technical textiles, ScotCad (e.g., for the automotive industries, geotextiles, medical textiles, antiballistics, etc.) and has a cross-sectional and 3D visualization feature which enables the weave structure to be viewed from any angle desired to identify any defects in the weave structure.
- AVA is highly regarded within the printed textiles industry and so has sophisticated functions regarding colour matching of yarns to ensure that colour specifications for the designs are maintained throughout the production process.
- Arahne presents its software as the most cost-effective package to be used by industry and educational institutes; it offers the dobby and jacquard together on one software package.
- Textronic, NedGraphics, and EAT software along with dobby and jacquard have a carpet weaving software package which is also capable of being linked to CAM operating looms such as Staubli.
- Textronic features a retail solution (Tailor-I, Try-on, Style me, and 3D showroom) which are mechanisms to show as realistically as possible what the end products may look like for clients and retail consumers.

6.4.1.2 *Heavy industrial/technical textiles*

CAD has propelled the technical textiles sector of the industry into prominence. CAD has been developed for the technical textiles sector on a commercial basis by software development companies such as ScotWeave's Technical Weaver or The Designscope Company's EAT (3D Weave and 3DWeave Composite) software. However, as research continues and develops, academic institutes have also been developing software applications from within textiles related or materials departments. The following discussion, therefore, is merely an overview of the key features; it is difficult to provide an in-depth analysis of each of the types of software applications available because each application has been developed in response to a particular product requirement and is outside the scope of this chapter.

The way that CAD is used for technical textiles differs from how it is used within the domestic markets. Many of the functions in the ScotWeave package (yarn costing data, scanning feature, image edit tools, library of over 700 weaves, float checking, auto-drape, fabric finishing, import/export weave data, output instructions directly to the looms, etc.) are of limited value to the technical textile researcher [4]. ScotWeave's Technical Weaver module (ScotWeave Technical Weaver), however, models technical textiles at the mesoscopic scale providing some of the requirements of the technical textiles designer. The different scales of examining textiles have described as: "microscopic scale of the yarn, the macroscopic scale of the woven structure, and an intermediate (mesoscopic) scale of a few intertwined yarns, which defines the unit cell reproducing the whole structure by a periodic translation" [17]. A unit cell has been defined as "... the smallest unit of textile that, when tiled, will recreate the full scale textile" [4, p. 5]. The unit cell needs to be geometrically modelled in order to determine how the yarns are arranged, what the strains on them are and therefore, develop predictions regarding their behaviour (shape forming, porosity, breaking, impact damage, etc.). In ScotWeave's Technical Weaver yarn cross-sectional shape and weave pattern can be specified to create a 3D geometrical model.

Various commercial software packages have been produced for designers within textiles composites industries. However, depending on their uses, there may be limitations placed upon the commercially available packages requiring more bespoke software packages, for example, according to Sherburn [4], ScotWeave's Technical Weaver as bought did not enable calculation of mechanical properties and was limited to modelling orthogonal woven fabrics. The necessity to be able to mechanically or geometrically calculate and model yarns have led companies and universities to develop software systems of their own, such as TexGen, WiseTex and TexEng Software Ltd. TexGen [4, 18, 19] and WiseTex [20] were CAD modelling systems to provide predictive functions for fabric permeability and composite mechanical properties. TexGen is a free and open source licenced software (General Public Licensing) and operates on Windows and Linux. WiseTex differs from TexGen in that it models based on the physical properties of fabrics, thus enables the modelling of gaps created when designing the fabric [4]. TexEng Software Ltd. is developed from research at the University of Manchester on technical textiles. It developed and now markets Weave Engineer, Hollow CAD, GeoModeller, UniverWeave, and Structra.

The programmes have been developed as user friendly with commercial applications in mind. Weave Engineer supports speedy and accurate design and manufacture of 3D solid fabric of multi as well as single layer, Hollow CAD, supports design of 3D hollow woven architectures with uneven or flat surfaces when opened up, and can be used in the investigation of lightweight textile composites [7].

6.4.2 CAM features

6.4.2.1 Transfer of designs from CAD to the loom

The transfer of the design from the CAD system to the loom for manufacture is of obvious importance and this can take place in several ways. Essentially, the CAM of woven textiles requires three events to take place: (i) the CAD design to be developed, (ii) translation of the design so that the loom can understand the instructions, and (iii) a means of inputting the instructions to the loom to create the textile in the required design.

In its simplest form, a design can be exported (or imported) as a standard image file (such as TIFF, BMP, etc.) and a production ticket (loom card) with full production details can be printed out to be input into mechanical looms. Where electronic looms are used, the loom card can be output as HTML for direct input into the loom via a control panel on the loom as described in Section 6.3. Jacquard weave designs tend to require programmes that will translate the design into the relevant instructions for the loom. For example, ScotWeave's Jacquard Designer programme is a CAD facility for creating jacquard designs, the designs are then sent to Jacquard Looms (the CAM facility in ScotWeave) which translates the design into the appropriate instructions for correct loom settings and parameters for the jacquard loom [13, 16].

6.4.2.2 Design archive and product data management

All CAD/CAM systems can create, save, store, retrieve, amend, and correct designs created on the CAD system used. Some software systems have developed in-house (intranet) server systems for (i) storage of designs and (ii) production planning. The system operates as in Fig. 6.1.

A server-based design archive incorporates 3D texture mapping, for draping and product simulation, decoding of weave designs, and produces technical report cards. As the archive is stored within a server, it enables remote working. A designer may be working on a laptop or tablet with their client at a client's premises or perhaps at a trade exhibition, they will be able to create, or, amend designs stored in the archives,

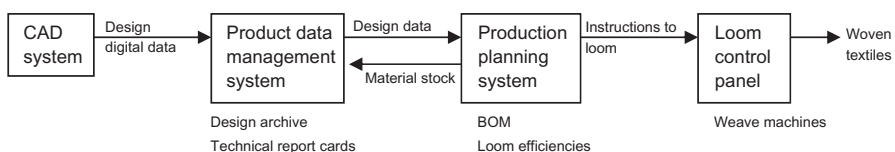


Fig. 6.1 A generalized server system for design archive and production planning.

create simulations of the end product, develop bespoke catalogues as well as produce more technical information. In addition, customers may be given access to the archive so that they may have greater flexibility and choice over design of products, without the need to download any software. The server-based design archive is, therefore, a product data management (PDM) system allowing a company greater transparency and control over the product specification. In NedGraphics, the design archive is called 'PDM' system and in Textronic the archive is called Design Integra [21].

The design archive transfers design data and instructions to a production planning server system to which it may be linked. As the production planning system is based on a server, it can connect with several looms and so its role is to transfer data to the right loom at the right time. NedGraphics and Textronic have developed their own systems. At Textronic, the system is called 'production planning and control' (PPC) while NedGraphics system is called 'loom connection'. Both systems have very similar functions and the following is taken from NedGraphics webpage describing the functionalities of loom connection [22]. Loom connection manages and controls electronic jacquard looms and links it with the design archive. The loom connection also has the following functions:

- tracks status of jobs,
- version management,
- monitors loom efficiency,
- captures, stores, transfers loom parameters,
- adds information to weave jobs, and
- automatically rearranges harness layout.

The system also enables loom operators to retrieve jobs from the server and modify production information. Design management capabilities ensure that, although the adjusted pattern can be merged directly with the original, it cannot be overwritten without notification. Amendments made on the loom controller can be stored directly in the original database and any corrections are automatically incorporated into the production data the next time it is sent over the network. Email notifications can be issued to anticipate production flaws or controller availability [22].

The combination of the PDM (which manages product data information) with the production planning system brings to the company the capability to manage products and processes – that is, product lifecycle management (PLM) within the company. The production planning systems can be linked with any existing planning system. When integrated with an efficiency resource planning system (ERP), the company is connected across the supply chain. Real-time information is available across the whole business with visuals of the product in process to enable quick decision making about efficient and timely deployment of resources or materials.

Internet web-based server technology has been used by EAT (the designscope company, 2018). The design archiving system, 'Designbase Victor' is linked to the 'LoomNet Victor' and offers remote access as well as remote working capabilities. Looms can be controlled remotely, and several manufacturing plants can be controlled simultaneously. As with other server-based systems, there is multiuser access and multilevel authorization facilities but, since the framework is Internet web based, it is accessible via a web browser providing faster communications across supply chain partners.

6.5 The role of CAD/CAM within the woven textile industry

The most obvious benefit of using CAD/CAM is the speeding up of the process of product development and in some areas of weaving CAD/CAM is essential (e.g., in jacquard weaving to avoid mistakes in the complex process of design). There are issues raised through the use of CAD and CAM in product development, manufacture, and supply chain.

6.5.1 *Product development*

The weave design process would often take weeks or months to complete as the weave design was first conceived of and drawn onto graph or point paper by the fabric designer and then copied onto board by a painter to the exact and precise colours of the design. This board would be sent to the mill for a sample to be woven for approval by the client. Any amendments would be noted and fed back to the studio by the mill. With the advent of CAD/CAM, the designer can design or decide which yarns will be employed, draw out the weave design in the computer, either print or email (as JPEG or another file) to the customer and make any amendments as required. Computer screen and printer calibration technology has enabled a 'real-life/virtual' sampling technique, although further approvals may still be required before final production commences. [Fig. 6.2](#) illustrates the changes in timing and the closer relationship between customer/client and designer enabling quicker communications and more creative decision making regarding the final product.

CAD/CAM enables the following: quicker and shorter production cycles, reduction of mistakes, value-added merchandize, and direct communication between buyer and designer. As CAD/CAM systems commonly now have draping and texture mapping functions, it is also possible to visualize the end products as the consumer might see them (be they interiors, garments, etc.), thus enabling quicker alterations of designs and decision making throughout the supply chain.

6.5.2 *Manufacture and the supply chain*

The use of CAD/CAM is of increasing strategic importance in the supply chain [\[22a\]](#). The nature of the textiles supply chain has changed from a linear sequential or serial system to a network system. Globalization and its effects have profoundly changed sourcing and manufacturing as well as trading and the market place. To compete, a company needs to have greater flexibility and quicker response. As supply chains have dispersed geographically they have become increasingly dynamic in nature, requiring ever greater communication and networking. Intraorganizational networking has been common place as communication within a company is vital for it to progress. Information technology (IT) has made interorganizational networking increasingly common as different companies begin to form virtually integrated operations to cope with competitive pressures.

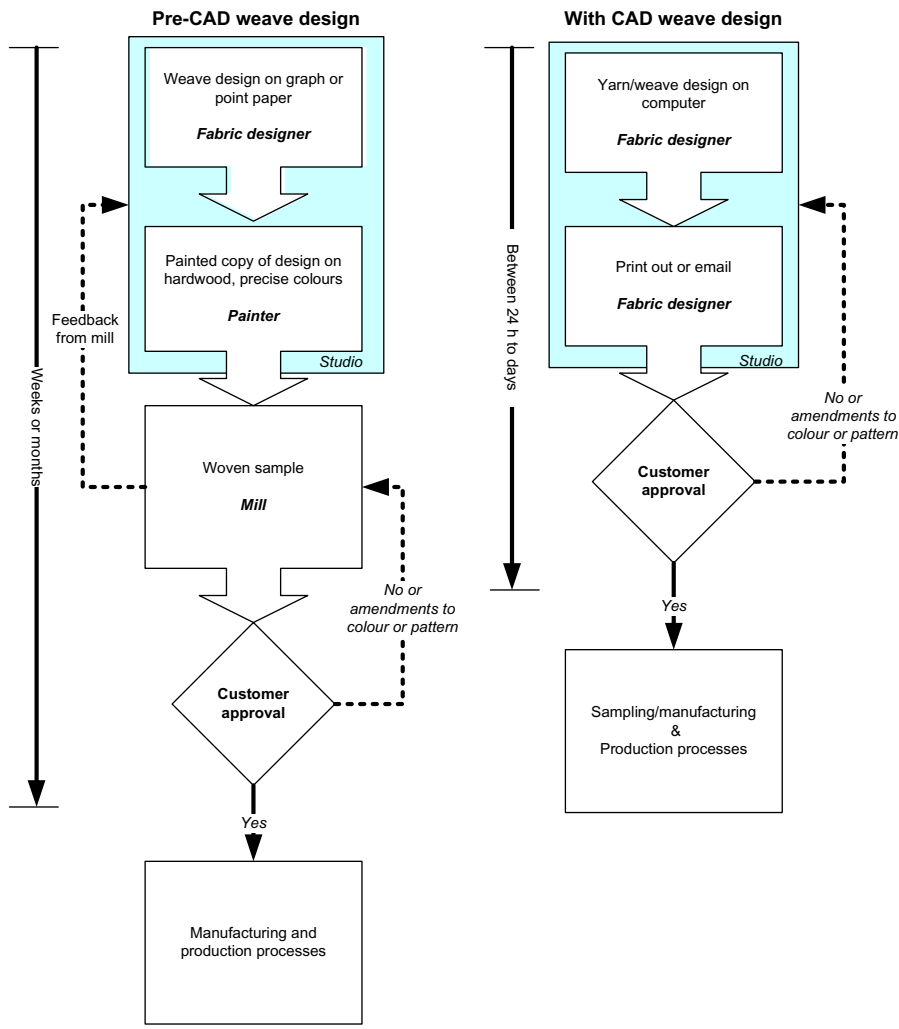


Fig. 6.2 Weave design before and after introduction of CAD technology.
After A. Price, A.C. Cohen, I. Johnson (Eds.), J. J. Pizzuto's *Fabric Science*, seventh ed., Fairchild Publications, 1999.

Virtual integration differs from vertical integration. Where vertical integration is based upon a single organizations range of capabilities, virtual integration is based upon the most competitive capabilities of several organizations working together in a network as it enables flexibility and responsiveness (Wang and Chan, 2010). CAD/CAM, coupled to enterprise resource and planning (ERP) and, or, systems applications and products (in data processing) (SAP) systems has helped partnering companies in product development across a supply chain to achieve greater and more effective cooperation, communication, and higher productivity with lower costs.

6.6 Key issues in the use of CAD/CAM for the woven textile industry

6.6.1 Design

It is possible to scan in a design and reinterpret through the software into a weave design for the client. This can raise issues about the line between interpretation and ownership, which, although too complex for a discussion within this chapter, nevertheless have a significant impact on companies from the legal, financial, and brand reputation perspectives.

6.6.2 Communication

CAD/CAM, a form of IT, has helped partnering companies in product development through a supply chain to achieve greater and more effective cooperation, communication, and higher productivity with lower costs. Therefore, use of the same IT and CAD/CAM systems helps companies to understand each other better (e.g., product specifications are in the same 'language') but raises issues that have to be addressed in order for the network to continue to flourish: trust, shared resources and competencies, agreement on size of network (for the market size and its constraints), optimization of the global supply chain and, in some cases, possible technology 'lock in' whereby the use of a particular platform is necessary to enter the virtually integrated network.

6.6.3 Expertise and skills required for woven textile CAD/CAM

Weave designers need to be multiskilled and understand both the supply and cost issues, the technicalities of the production such as fabric analysis, drafting the pattern, tensions and yarn lengths required as well as CAD packages. Skillfast UK (<http://www.skillfast-uk.org/>) conducted a survey of skillsets that the fashion and textiles industry felt were necessary for a variety of roles within the industry and itemized those required of the weave designer (Table 6.1). Most textiles companies require new employees to be have a working knowledge of CAD/CAM, even though they may provide some in-house training from the software providers. Most new textile designers will learn their skills from universities or colleges of textiles. To become adept in the use of CAD/CAM, one must understand the principles of weaving by hand, this will often take a year or so before the application of CAD/CAM can be used to develop woven designs from. To develop skills in CAD/CAM for technical textiles markets requires further study as this requires not only fundamental understanding of fibre properties and CAD/CAM but skills in mathematical modelling techniques that be applied to leverage the fibre and fabric properties. The level of specialist knowledge and expertise that a technical textiles CAD/CAM weaver would require could be approximated to a Master level of study or PhD, that is, this is a highly

Table 6.1 National Database of Accredited Qualifications: woven fabric design (reference no. R/502/2281)

Learning outcome		Assessment criteria	
1	Understand the process of woven fabric design and development from initial idea to finished product	1.1	Analyse the factors impacting on design development
		1.2	Describe the different types of repeat and their application
		1.3	Explain the processes of design from initial idea to finished product to include: • Research • Interpretation of design brief • Customer requirements • Costings • Design specification, • Sample requirements • Sample production • Production Specification
2	Understand the principles of technical drafting	2.1	Explain the principles of technical drafting for each of the following: plain fabric, twill, stain and sateen weaves
		2.2	Draw a technical draught for two designs to be woven on two different types of machine
3	Be able to use CAD techniques in woven fabric design processes	3.1	Describe CAD – computer-aided design techniques and processes
		3.2	Produce a design for a woven fabric using CAD – computer-aided design
4	Understand fabric analysis techniques	4.1	Describe sample analysis techniques for: fibre type, yarn type and count and type of fabric
		4.2	Analyse two woven fabrics of different construction and for each of the following: produce fabric notations, measure fabric parameters and carry out calculations
5	Understand the principles and processes of weaving	5.1	Describe the primary motions of weaving
		5.2	Explain the manufacturing processes and production cycle of woven fabrics
		5.3	Explain factors influencing handling characteristics of materials during processing

specialized area that is to be found in the R&D areas of companies or universities. There are several weave CAD/CAM software packages available to both industry and education, and to be a credible weave designer, especially to enter the larger companies, a working knowledge, if not some degree of expertise, in using CAD/CAM has become a necessity.

6.6.4 *Costs incurred in using CAD/CAM*

A term most often associated with CAD/CAM is ‘investment’ and it is often the larger companies who are suppliers or part of a global network that spend the most and benefit from this. The costs of software are varied and cannot be estimated in a simple manner. The costs of buying in CAD/CAM may vary between about £1000’s to multiples of £10,000’s. Factors that influence the actual and final cost include the following:

- The licence to use the software (and numbers of each person requiring the use would need to have the licence).
- If ‘floating’ licences and ‘keys’ are required (to use in situ or on lap top away from the office).
- Training to use the software:
 - trainer’s daily rate,
 - travel for the trainer to come to the studio, and
 - any stay and sustenance.
- Computer platforms to support the use of the software (and what are they compatible with).
- Peripherals (e.g., printers, links to CAD/CAM at other sites, links to factories, etc.).
- Servers to store or access the information.
- If there is an annual subscription or payment for annual software update.

6.7 **New products/markets and future trends through CAD/CAM**

While the textiles industry has gradually become ever more mechanized and reliant on the use of CAD/CAM architecture of its production plants, the area of technical textiles has been growing and is now a means of competitive advantage for saturated textiles producing economies. This sector has been described as a growth area, and, indeed, a report in 2006 stated that the technical textiles sector was a dynamic and buoyant one with an annual growth of 5% [23, 24], however, because of the problems in defining the sector, measuring the size of the market is a difficult one. Kowalski and Molnar [25] described some of the efforts to try to estimate the size of this sector which include dividing the market into (i) traditional, (ii) technical, and (iii) technical and mixed textile product categories.

- Traditional textiles being: silk, cotton, wool, and other vegetable textile fibres.
- Technical textiles: man-made filaments made of or containing nylon, polyamide, polyester, polypropylene, viscose; man-made staple fibres and impregnated, coated, or laminated textile fabric (e.g., various man-made tyre cord fabrics).
- Technical and mixed textiles products: products manufactured from both traditional and man-made fibres such as: wadding, felt, nonwovens, yarns, twine, cordage, carpets, knitted, or crocheted fabric.

Despite these problems of categorization, they noted that exports from China and India are increasingly technical textiles. According to Byrne [6] major, influential

textiles industrial exhibition, Techtextil, was launched in 1985 which provided a taxonomy that has been used to describe the various industry and market sectors that technical textiles are applied in:

- **Agrotech** – agriculture, horticulture, forestry, and aquaculture textiles.
- **Buildtech** – building and construction textiles.
- **Clothtech** – technical components of shoes and clothing, for example, linings.
- **Geotech** – geotextiles and civil engineering materials.
- **Hometech** – technical components of furniture, household textiles, and floorcoverings.
- **Indutech** – textiles for industrial applications, for example, filtration, conveying, cleaning, etc.
- **Medtech** – hygiene and medical products.
- **Mobiltech** – automobiles, shipping, railways, and aerospace.
- **Oekotech** – environmental protection.
- **Packtech** – packaging materials.
- **Protech** – personal and property protection.
- **Sportech** – sport and leisure.

Notwithstanding the actual size and share of the textiles market, CAD/CAM knowledge and expertise has had a powerful influence on the technical textiles sector. Of increasing interest is the composite textiles (textile-reinforced composite materials) which have been described as “multiphase materials within which the phase distribution and geometry have been deliberately tailored to optimize one or more properties” [9, p. 264] and as “such that they do not dissolve or merge completely into each other” [26, p. 1]. Ogin [9] continues to describe how textile composites are formed of a matrix (which may be polymers – such as epoxide, polyester, nylon – metals) reinforced by a fibrous material – such as carbon fibres, glass fibres, boron, ceramic, aramid, or textiles. Textiles have been used in industrial composites for over a century [26] and therefore, it is a mature application. However, the use of CAD/CAM, advances in computational modelling and mathematical analysis techniques have seen an increasing replacement of other fibres with textiles. Textiles have the advantage of cost, enhanced by its affinity to being processed with other materials for adequate or improved mechanical properties. Woven textile composites have been used very successfully in aerospace because they are light, have good drapeability, allow complex shapes to be formed without gaps and costs are lowered as biaxial fabrics have replaced two layers of nonwoven fabrics. The ease of handling of the textiles has enabled automation. Woven textiles also have the advantage of increased resistance to damage from impact and compression strength. The disadvantage of using woven textiles is their lower stiffness and strength than nonwoven textiles.

Technical textiles require high input of R&D efforts as well as new technology and has been advanced through the development of user-friendly software system for designing woven structures based on the mechanical and geometrical modelling with the aim of creating close-to-reality geometrical models for analysing mechanical, fluid, and thermal properties, essential in systems such as predicting fluid filtration performance through filtration textiles, 3D hollow composites for energy absorption, shock absorption or antiballistics performance, etc. [7, 23].

Efforts in textiles woven CAD/CAM applications are continuing in the areas of colour, drape, yarn modelling which can have applications in either the commercial or technical areas. Linked up with other digital applications, there are possibilities for visualizing, characterizing, modelling, and predicting textiles properties with a view towards manufacture. Traditional jacquard designing, reliant on the skills of craftsmanship of freehand design for copying through the mechanical weave loom, is assisted through the application of CAD/CAM systems. Digital jacquard technology incorporates CAD and digital production technology (electronic jacquard machine and new-generation weaving looms). This enables total digital control of design and production, and all data from design to weaving are processed, controlled, and transmitted via the computer. This has enabled jacquard fabrics with photo-realistic effects with a mega-level colour number on the face of the fabric, raising the potential for security applications of this research [27]. Advances in modelling dry drape of textiles have their applications in the development of predictive modelling for 3D woven technical textiles (composites), garment design and manufacture and reverse engineering of weave structures from samples of fabric, useful in security applications [28].

6.8 Sources of further information and advice

The reader is directed to visit the following websites for further information and advice:

<https://www.ucas.com> an organization that manages applications to higher education courses in the United Kingdom, to help students make informed choices about their applications, there is a database of courses at all universities around the United Kingdom. This website will provide the initial information regarding any details about courses at universities to attend regarding textiles and CAD.

<https://www.ukft.org/skills-and-training/sector-skills-body/> UKFT, an industry body which supports skills and training for people and businesses in the United Kingdom fashion and textile industries: they provide news and information about fashion and textiles.

<https://ktn.innovateuk.org> set up by the government and in collaboration with industry, the Technology Strategy Board have developed a Knowledge Transfer Network which is a tool to help collaborate, disseminate and share knowledge, and seek funding for projects. There are a number of groups: environmental sustainability, materials, technical textiles, creative industries, etc.

Further information regarding the software programmes reviewed is available at the following websites:

www.ScotWeave.com

<https://www.arahne.si/>

<https://www.textronic.com/>

www.avacadcam.com

<https://www.nedgraphics.com/>

EAT GmbH at www.designscopecompany.com/

References

- [1] O. Soffer, Recovering perishable technologies through use wear on tools: preliminary evidence for upper paleolithic weaving and net making, *Curr. Anthropol.* 45 (3) (2004) 407–425.
- [1a] S. Kramrisch, *Unknown India: Ritual Art in Tribe and Village*, Falcon Press, 1968.
- [1b] J.M. Allwood, S.E. Laursen, S.N. Russell, C. Malvido de Rodríguez, N.M.P. Bocken, An approach to scenario analysis of the sustainability of an industrial sector applied to clothing and textiles in the UK. *J. Clean. Prod.* 16 (2008) 1234–1246, <https://doi.org/10.1016/j.jclepro.2007.06.014>.
- [2] UNCTAD, Key Statistics and Trends in International Trade 2017, The Status of World Trade, United Nations, New York and Geneva, 2018. Accessed from, <http://unctad.org/en/Pages/Publications/Handbook-of-Statistics.aspx>.
- [2a] Atlas on Regional Integration in West Africa, economy series: Cotton, ECOWAS — SWAC/OECD. (2006) Available at, <http://www.oecd.org/regional/atlas-on-regional-integration-in-west-africa.htm>.
- [2b] H.K. Nordas, The global textile and clothing industry post the agreement on textiles and clothing, Discussion Paper No. 5, World Trade Organization, Geneva, Switzerland, 2005. Available at https://www.wto.org/english/res_e/booksp_e/discussion_papers5_e.pdf.
- [3] M. Criettee, Dialogue on supply chain is critical, in: *Machinery Compendium*, second ed., Fibre2Fashion, 2015, , pp. 34–38.
- [4] M. Sherburn, *Geometric and Mechanical Modelling of Textiles*, (PhD, Unpublished Thesis), University of Nottingham, Nottingham, 2007.
- [5] A.R. Horrocks, S. Anand, *Handbook of Technical Textiles*, Textile Institute, Manchester, 2000.
- [6] C. Byrne, Technical textiles market – an overview, in: A.R. Horrocks, S. Anand (Eds.), *Handbook of Technical Textiles*, Textile Institute, Manchester, 2000, pp. 1–23.
- [7] X. Chen, Mathematical modelling of 3D woven fabrics for CAD/CAM software, *Text. Res. J.* 81 (1) (2010) 42–50. sagepub.co.uk.
- [8] J.A. Soden, Design and CAD Innovation in Woven Textile Research, Point, 2001, p.9. <http://www.point.ac.uk/articles/jsoden.htm>.
- [9] S.L. Ogin, Textile reinforced composite materials, in: A.R. Horrocks, S. Anand (Eds.), *Handbook of Technical Textiles*, Textile Institute, Manchester, 2000.
- [10] A. Price, A.C. Cohen, I. Johnson (Eds.), J. J. Pizzuto's *Fabric Science*, seventh ed., Fairchild Publications, 1999.
- [11] B.J. Collier, J.R. Collier, CAD/CAM in the textile and apparel industry, *Cloth. Text. Res. J.* 8 (3) (1990) 7–13.
- [12] M.F. Hordeski, *CAD/CAM Techniques*, Reston, Reston, VA, 1986.
- [13] ScotWeave, Jacquard Looms, <http://scotweave.com/products/product/jacquard-loom>s, 2018.
- [14] Oracle Docs, EDI Standards, https://docs.oracle.com/cd/E51433_01/fscm92pbr2/eng/fscm/sedi/task_EDISTandards-9f1203.html, 2018.
- [15] OpenText, EDI Basics. How Successful Businesses Connect, Communicate, and Collaborate Around the World, http://www.gxs.com/assets/uploads/pdfs/eBooks/EDI_Basics_GXS_eBook.pdf, 2017.
- [16] ScotWeave, Dobby Designer, <http://scotweave.com/products/product/dobby-designer>, 2018.
- [17] B.B. Boubaker, M. Assidi, J.F. Ganghoffer, Evaluation of Poisson's ratio of textiles from mesoscopic models, *Int. J. Mater. Form.* 3 (1) (2010) 81–84, SpringerLink.

- [18] F. Robitaille, R. Gauvin, Compaction of textile reinforcements for composites manufacturing. ii: compaction and relaxation of dry and H₂O-saturated woven reinforcements, *Polym. Compos.* 19 (5) (1998) 543–557.
- [19] F. Robitaille, A. Long, M. Sherburn, C. Wong, C. Rudd, Predictive modelling and performance properties of textile composite unit cells: current status and perspectives, in: 11-European Conference on Composite Materials, Spn, May, ESCM: European Society for Composite Materials, Rhodes, 2004.
- [20] S., V. Lomov, I. Verpoest, Compression of woven reinforcements: a mathematical model, *J. Reinf. Plast. Compos.* 19 (16) (2000) 1329–1350.
- [21] NedGraphics, Product Data Management, <https://www.nedgraphics.com/product-data-management/>, 2018.
- [22] NedGraphics, Loom Connection, <https://www.nedgraphics.com/woven-and-knits/loom-connection/>, 2018.
- [22a] W.Y.C. Wang, H.K. Chan, Virtual organization for supply chain integration: two cases in the textile and fashion retailing industry, *Int. J. Prod. Econ.* 127 (2010) 333–342.
- [23] X. Chen, C.A. Lawrence, G.K. Stylios, Engineering the performance and functional properties of technical textiles, (2006)(EPSRC Final Report, GR/S09227/01, GR/S09210/01 and GR/S09203/01).
- [24] M. Miozzo, P. Dewick, K. Green, Globalisation and the environment: the long-term effects of technology on the international division of labour and energy demand, *Futures* 37 (2005) (2005) 521–546 (Elsevier).
- [25] P. Kowalski, M. Molnar, Economic Impacts of the Phase-Out in 2005 of Quantitative Restrictions Under the Agreement on Textiles and Clothing, OECD Trade Policy Working Paper No. 90, TAD/TC/WP(2007)14/FINAL <http://www.oecd.org/trade>, 2009.
- [26] J. Wiggers, Analysis of Textile Deformation during Preforming for Liquid Composite Moulding, (Unpublished Thesis)University of Nottingham, Nottingham, 2007.
- [27] M.C.F. Ng, J. Zhou, Innovative layered-combination mode for digital jacquard fabric design, *Text. Res. J.* 79 (8) (2009) 737–743 Sage Publications.
- [28] B. Xin, J. Hu, G. Baciú, X. Yu, Investigation on the classification of weave pattern based on an active grid model, *Text. Res. J.* 79 (2009) 1123–1134. www.sagepub.com.

Further reading

- [29] American Textiles Manufacturers Institute (ATMI), The U.S. Textile Industry, Scope and Importance, Office of the Chief Economist, Washington, DC, 1996.
- [30] B.P. Corbman, *Textiles: Fiber to Fabric*, fifth ed., McGraw-Hill, Inc, New York, 1975.
- [31] EAT, LoomNet victor, www.designscopecompany.com/loomnet-victor/, 2018.
- [32] EPA, EPA Office of compliance sector notebook project: profile of the textile industry, U.S. Environmental Protection Agency, Washington, DC, 1997 20460, EPA/310-R-97-009.
- [33] EURATEX, European Technology Platform for the Future of Textiles and Clothing, A Vision for 2020, The European Apparel and Textile Organisation, 2004.http://www.fp7.org.tr/tubitak_content_files/270/ETP/Euratex/AVisionfor2020December2004.pdf.
- [34] J. Gillow, B. Sentence, *World Textiles: A Visual Guide to Traditional Techniques*, Thames and Hudson, London, 2004.
- [35] Z.J. Grosicki, *Watson's Textile Design and Colour*, Newnes-Butterworths, London, 1975.
- [36] I.B. Wingate, *Fairchild's Dictionary of Textiles*, sixth ed., Fairchild Publications, New York, 1979.

Modelling the structure of woven fabrics

7

B.K. Behera^a, Pramod Kumar Hari^a, Ahmad Rashed Labanieh^b

^aIndian Institute of Technology Delhi, New Delhi, India, ^bENSAIT Textile engineering School, Roubaix, France

7.1 Introduction: Fundamentals of woven structure

A woven fabric is produced by interlacing two sets of yarns called the warp and the weft at right angles to each other in the plane of the fabric. The warp is along the length and the weft along the width of the fabric. Individual warp-and-weft yarns are called ends and picks. The interlacement of ends and picks with each other produces a coherent and stable structure. The yarns are held in place due to the inter yarn friction [1,2]. The repeating unit of interlacement is called the weave. In this fabric formation process, there is a great scope in choosing fibres with particular properties, arranging fibres in the yarn in several ways and organizing in multiple ways interlaced yarns within the fabric. This gives the textile designer great freedom and variation for controlling and modifying the fabric structure. Fig. 7.1 shows plain weave in plan view and in cross section along warp and weft. The weave representation is shown by a grid in which vertical lines represent warp and horizontal lines represent weft. Each square represents the crossing of an end and a pick. A mark in a square indicates that the end is over the pick at the corresponding place in the fabric that is warp up. A blank square indicates that the pick is over the end that is weft up. One repeat of the weave is indicated by filled squares and the rest by crosses.

The properties of the fabric depend on the fabric structure. The formal structure of a woven fabric is defined by weave, thread density, crimp, and yarn count. The interrelation between fabric parameters can be obtained by considering a geometrical model of the fabric. The geometrical model is concerned mainly with the shape taken up by the yarn in the warp-or-weft cross section of the fabric. Mathematical deductions obtained from simple geometrical form and physical characteristics of yarn combined together help in understanding various phenomena in fabrics. The basic model of Peirce's [3] analysis is shown in Fig. 7.2. It represents a unit cell interlacement in which the yarns are considered inextensible and flexible. The yarns have circular cross section and consist of straight and curved segments. The main advantages in considering this simple geometrical are:

- It helps to establish the relationship between various geometrical parameters.
- It enables calculation of the resistance of the cloth to mechanical deformation such as initial extension, bending, and shear in terms of the resistance to deformation of individual fibres.

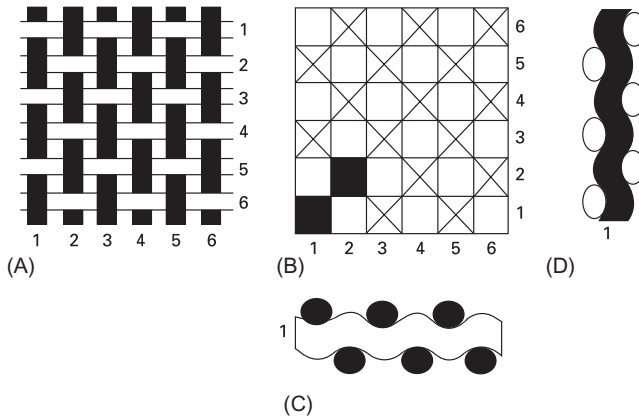


Fig. 7.1 Plan (A), weave representation (B), cross-sectional view along weft (C), and cross-sectional view along warp (D) of a plain woven structure.

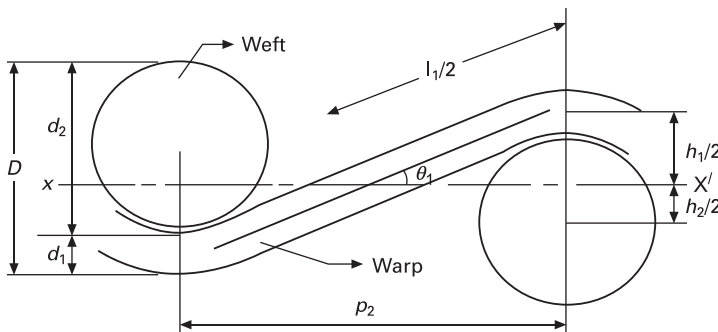


Fig. 7.2 Peirce model of plain weave.

- It provides information on the relative resistance of the cloth to the passage of air, water, or light.
- It provides a guide to the maximum density of yarn packing possible in the cloth.

From the two-dimensional (2D) unit cell of a plain woven fabric, geometrical parameters such as thread spacing, weave angle, crimp, and fabric thickness are related by deriving a set of equations. The symbols used to denote these parameters are:

d = diameter of thread

p = thread spacing

h = maximum displacement of thread axis normal to the plane of cloth (crimp height)

θ = angle of thread axis to the plane of cloth (weave angle in radians)

l = length of thread axis between the planes through the axes of consecutive cross-threads (modular length)

c = crimp (fractional)

$D = d_1 + d_2$

Suffixes 1 and 2 to the above parameters represent warp-and-weft threads, respectively, in Fig. 7.2. The projection of yarn axis parallel and normal to the cloth plane gives the following equations:

$$c_1 = \frac{l_1}{p_2} - 1 \quad (7.1)$$

$$p_2 = (l_2 - D\theta_1) \cos \theta_1 + D \sin \theta_1 \quad (7.2)$$

$$h_1 = (l_1 - D\theta_1) \sin \theta_1 + D(1 - \cos \theta_1) \quad (7.3)$$

Three similar equations are obtained for the weft direction by interchanging suffixes 1 and 2 or vice versa as follows:

$$c_2 = \frac{l_2}{p_1} - 1 \quad (7.4)$$

$$p_1 = (l_2 - D\theta_2) \cos \theta_2 + D \sin \theta_2 \quad (7.5)$$

$$h_2 = (l_2 - D\theta_2) \sin \theta_2 + D(1 - \cos \theta_2) \quad (7.6)$$

$$\text{Also, } d_1 + d_2 = h_1 + h_2 = D \quad (7.7)$$

In all, there are seven equations connecting 11 variables. If any four variables are known, then the equations can be solved and the remaining variables can be determined. Unfortunately, these equations are difficult to solve. Researchers have tried to solve these equations using various mathematical means to find new relationships and also some useful simplified equations.

7.2 Fundamentals of design engineering

Designing is the process of delineating a product to meet the functional and the aesthetic performance criteria with efficient use of resources. Engineering is an applied science dealing with relationships between the raw material, the fabric, and the finished product. Therefore, the design engineer has to engineer fabric construction for predetermined properties that fit specific applications with quick response. Designing of textile-related products has been carried out for thousands of years in a traditional and intuitive way. However, in the last few decades, the importance of design has increased due to the growing needs of the industry and the consumer for complex and specific requirement of functionality. This has called for a system of engineered manufacturing of textile product in place of traditional experience-oriented manufacturing. The design process itself may be subjected to certain restrictions such as time, manpower, cost, etc. Nevertheless, no standard procedure or logic is available or followed as far as textile product design is concerned. The design is usually carried out manually, based on the experience and trial and error. In the recent years, inexpensive computers have made the design of textile products more popular.

Also, simulation and other technologies are brought into use to design and develop numerous quality products.

7.2.1 Traditional designing

In the traditional designing method [4], as shown in Fig. 7.3, the market expert formulates the rough concept of fabric requirements; thereafter, the fabric designer, in consultation with the experts from various departments such as marketing, production, quality assurance, costing, and others, prepares a detailed description of the fabric design. With this derived design, a sample fabric is woven, tested, and undergoes the whole process until the customer is satisfied; then the fabric is taken for the mass production. This fabric design cycle is the result of experience, heuristic reasoning, and intuition. The basic problem here is the amount of expert knowledge available and its consistency, and also the fact that no single expert is usually available for a group of domains. A further development introduced in the fabric design process is known as manual design. A typical manual design procedure [5] for industrial fabrics is illustrated in Fig. 7.4. This is a rough procedure for synthesizing a fabric structure through several subtasks from top-down resolution of the overall design task. At first, for a set of property constraints, the designer chooses the fibre type for interlacing yarns governed by its cost, physical properties, etc., along with the type of yarn and its strength. The yarn linear density with strength of individual yarn components is then determined. At this point, the fabric tensile strength is specified, and fine adjustment of yarn properties is made using yarn twist followed by consideration

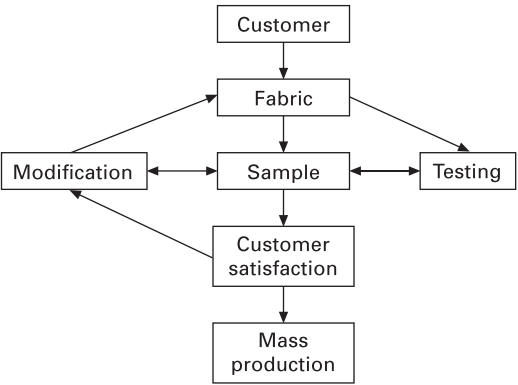


Fig. 7.3 Traditional fabric design cycle.

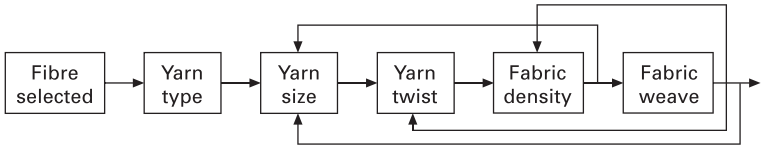


Fig. 7.4 Manual design procedure for industrial fabrics.

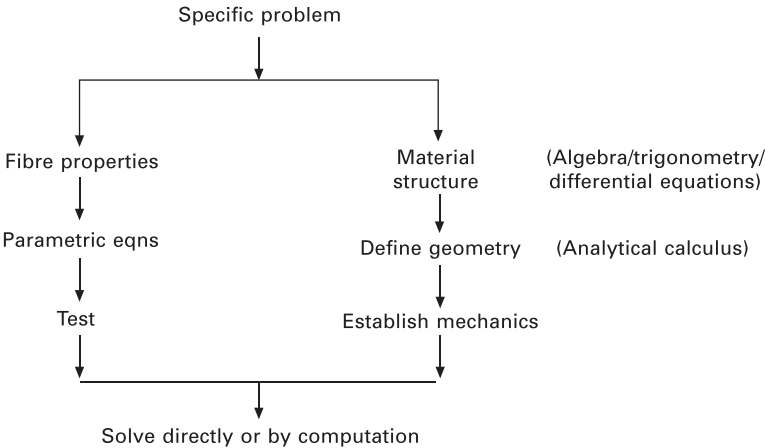


Fig. 7.5 Mechanics of textile structure: traditional route.

of yarn density. The fabric weave structure is then selected, depending on the tearing strength, thickness, fluid permeability, etc. The manual design procedure for other types of textile materials, such as technical textiles, is almost the same with the only difference in properties requirement dependent on end-use applications.

7.2.2 Traditional designing with structural mechanics approach

The stages of the traditional approach based on the mathematical and physical principle are shown in Fig. 7.5 [6]. It is strongly mathematical with computations brought on at the end in order to solve equations. Fibre properties are specified by the parameters of the linear or nonlinear equations. Geometry can be defined by algebraic and trigonometric equations. Mechanics can be analysed by differential or integral calculus.

7.3 Designing of textile products

Overall, the major areas of designing textile products can be broadly classified into colour or pattern and material design. Table 7.1 presents the difference between an artistic and engineering design approach. The colour or pattern design deals with the visual

Table 7.1 Artistic design versus engineering design

CAD for artistic design	CAD for engineering design
• Colour • Pattern • Weave • Motif	• Thread count • Thread density • Weave • Areal density, etc.

appearance and fashion of the products that includes the motif [7–10], colour [11–17], patterns preparation [18–30], etc. This involves creating infinite combinations of motifs and arriving at an arrangement that may be aesthetically pleasing to the consumer.

In artistic design, traditionally the logic and main process is achieved through ‘pencil-paper’ sketching. To begin with, the creative idea is expressed by freehand sketching. If the design is thought to have a commercial potential, it is then processed by the designer or design technicians from the sketch onto a special design paper. At this stage, the design is modified according to the process for which it is intended, that is, knitting, weaving, or printing, etc. [31–33]. Then, this design paper becomes an enhanced sketch with additional information. With the advent of the computer, the creative idea of designers is translated to the computer environment for design purposes. A large amount of innovative work has been carried out in the area of colour and pattern designing [34] by using computer-aided design (CAD). In fact, the application of colour graphics technology for colour pattern designing is becoming ever more popular because of its effectiveness.

Material design can be defined broadly as design that deals with the structural, aesthetic, and functional behaviour of the material based on the product type [35]. The logic of material designing involves mapping a specified function onto a realizable structure [36]. A correct material design is one whose basic structure correctly sets up the specified function or effect. In this system, material behaviour mediates function and structure. On the other hand, the colour or pattern and material design has a common region that is the surface or texture appearance caused by the material effect. Both will overlap effectively in producing a product. Although a considerable amount of research has been carried out on colour or pattern designing related to the fabric appearance and fashion, the material design technology for textile products is still at the development stage. Compared to other fields of engineering, textiles may have taken the longest to realize the potential of CAD [37] for innovation and creativity in product design. This is primarily attributed to the constraint of material characteristics.

7.4 Design engineering using theoretical modelling

7.4.1 Model

A model is a description or an analogy which helps to visualize something that cannot be directly observed. It can be a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs. Modelling is an activity about which we think and make models to describe how the objects of interest behave. There are several ways in which objects and their behaviour can be described. We can use words, drawings, physical models, computer programs, or mathematical formula. In designing an engineered product, normally, mathematical equations and/or logical concepts are used to simulate and predict real events and processes while making models. Mathematical models represent the behaviour of objects in mathematical terms. In modelling, it is important to know how to generate and validate mathematical representations (equations). It is also important to know how model equations are

used and their limitations. Before analysing these issues, it is worthwhile to understand why we do mathematical modelling.

7.4.2 Theoretical modelling

Theoretical models describe a type of object or system by attributing to it what might be called an internal structure, a composition or mechanism that, when taken as a reference, will explain various properties of that object or system. A theoretical model, therefore, analyses a phenomenon that exhibits certain known regularities by reducing it to more basic components, and not simply by expressing those regularities in quantitative terms or by relating the known properties to those of different objects or systems. A theoretical model is considered as an approximation that is useful for certain purposes. Models can be used for the purpose of explanation, prediction, calculation, systematization, derivation of principles, etc. The most important characteristic of a theoretical model is that it consists of a set of assumptions about the concept or system. The models provide explanations; but these explanations are based on the assumptions that may be simplified, and this condition must be borne in mind when one compares them with theories. It is also important that a theoretical model is often formulated and developed and sometimes even named on the basis of an analogy between the object or system that it describes. The model simulates the behaviour or activity of systems, processes, or phenomena. They include the use of mathematical equations, computers, and other electronic equipment.

7.4.3 The need for theoretical modelling

Modelling methodologies for predicting fabric properties are essential to design fabrics according to the specifications desired by the customer. If the relationships between different parameters that determine the specific fabric property are known, they can be handled to optimize that particular property for different end-use applications. Predictive modelling methodologies can also be used to identify different levels of combinations of process parameters and material variables that yield the desired fabric property. From this, a specific combination of process and material variables resulting in maximum savings in cost and time can be selected.

7.4.4 Mathematical modelling and the scientific method

Scientific methods help to identify the real world and the conceptual world. In the real world, we observe various phenomena and behaviours which could either be natural or produced by artefacts. The conceptual world is the world of the mind. The conceptual world has three stages: observation, modelling, and prediction. In the observation part of the scientific method, we measure what is happening in the real world. Here we gather empirical evidence and facts on the ground. Modelling is concerned with analysing the above observations for at least one of the three reasons. The model describes the behaviour or results observed and allows us to predict future behaviours that are yet unseen or unmeasured. In the prediction of a scientific method, we use models to

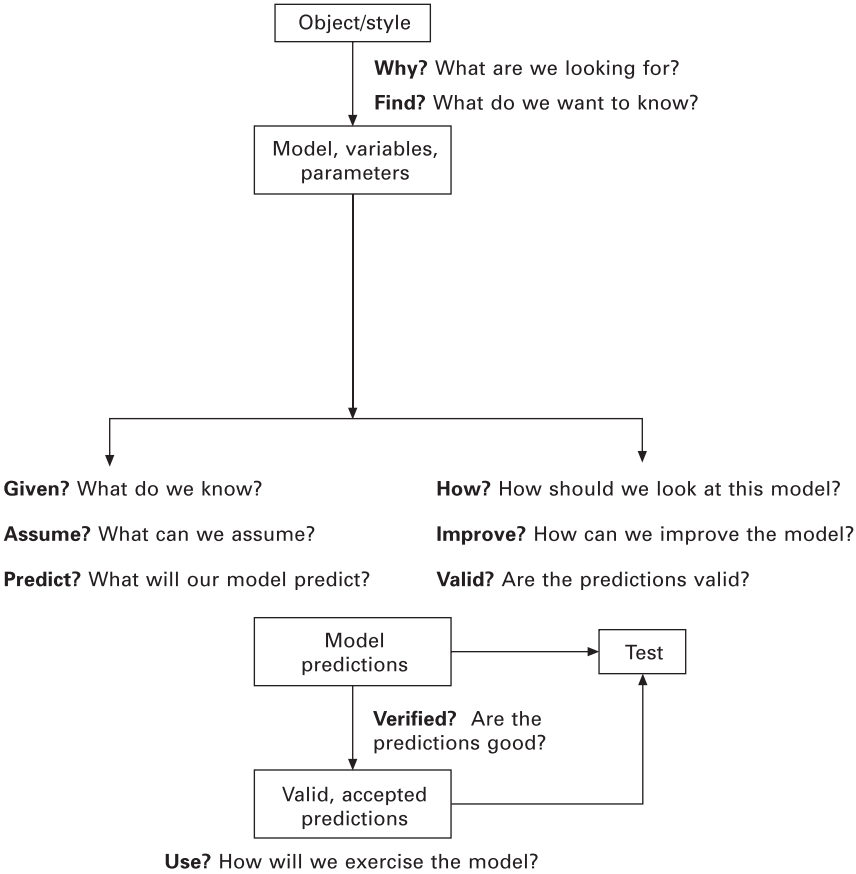


Fig. 7.6 The philosophy of mathematical modelling.

tell us what will happen in a future experiment or in an anticipated set of events in the real world. These predictions are followed by observations that serve either to validate the model or to suggest reasons for an inadequate model. The scientific method and engineering design have much in common, but there are differences in motivation and approach. In the practices of science and engineering design, models are often applied to predict what will happen in a future situation. Mathematical modelling is formulated using certain principles. The basic philosophical approach to formulate a model is shown in [Fig. 7.6](#).

7.5 Modelling methodologies: Deterministic models

Over the years, many attempts have been made to develop predictive models for textile properties using different modelling methodologies. These are essentially of two kinds: deterministic and nondeterministic. Mathematical models, empirical models,

and computer simulation models such as finite element analysis are deterministic models, whereas models based on the genetic methods, neural networks (NNs), chaos theory, and soft logic are nondeterministic. Each method has its own merits and demerits. Nowadays, more and more processes and systems are modelled and optimized using nondeterministic approaches. This is due to the high degree of complexity of systems, and consequently, the inability to study them efficiently with conventional methods only. In nondeterministic approaches, there are no precise, strict mathematical rules. No assumptions regarding the form, size, and complexity of models are made in advance. Hence this approach offers a flexible means to provide solutions to a wide variety of textile problems with reasonable prediction accuracy [38]. A brief overview of various computing tools is given in this chapter. For a detailed explanation on these modelling methodologies and other soft computing tools, one can refer to the standard texts available [39–41].

7.5.1 Pure geometrical model

Fabric properties are greatly affected by the choice of fabric parameters. The choice of fabric parameters influences the structure. The behaviour and relationship between the fabric parameters are a precursor to the optimal solution for fabric engineering problems. Many features of the cloth are essentially dependent on the geometrical relationships. The geometrical model of fabric provides some simplified formulae to facilitate calculations and specific constants which are of value for fabric engineering, problems of structure, and mechanical properties [38]. These fabric parameters are a tool for an innovative fabric designer in creating fabrics for diverse applications. The theoretical relationship between the fabric parameters enables the fabric designer to play with different fibres, yarn linear density, thread density and weave to vary texture and fabric properties.

It is possible to predict the fabric parameters and their effect on the fabric properties by simple computing. This information is helpful in taking a decision regarding specific buyers' need. A simplified algorithm is used to solve fabric geometry equations and relationships are obtained between useful fabric parameters such as thread spacing and crimp, fabric cover and crimp, warp-and-weft cover, etc. Such relationships help in guiding the direction for moderating fabric parameters. For example, the parameters of a fabric requiring certain crimp in warp and weft even in a jammed state can be calculated. It may be desirable to make a nonjammed fabric with a certain amount of warp and weft. Even fabrics with maximum crimp in either warp-or-weft direction can be estimated. In this chapter, only a few relations are graphically demonstrated to optimize engineering attributes of a plain weave fabric.

Needless to say, the pioneering work of Peirce on the geometrical model provides a basic platform for fabric engineering. Many basic fabric dimensional parameters can be worked out from the geometrical model by use of modern computing methods. Fabric parameters for any relationship between warp-and-weft cover can be evaluated. Last but not the least, the relationship between fabric mass and fabric cover can also be evaluated. This is the strength of the computing method, as the same results cannot be achieved by any other means like graphical or nomogram methods. The basic

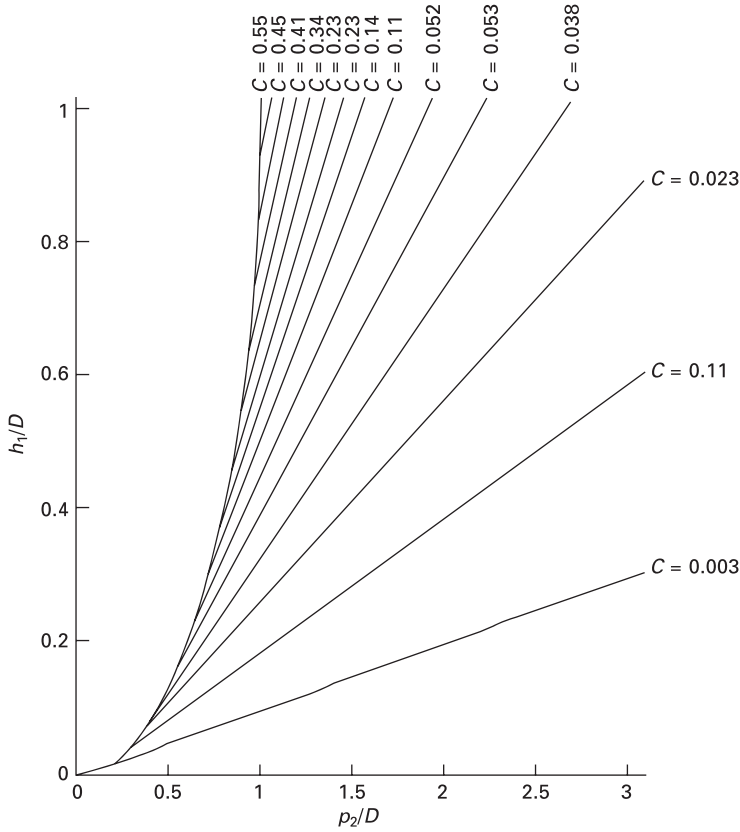


Fig. 7.7 Relation between thread spacing and crimp height.

equations derived from the geometrical model given in Eqs (7.1)–(7.7) are taken as the basis for working out many derived relationships. For example, the solution of p_2/D and h_1/D is obtained for different values of θ_1 (warp crimp angle) ranging from 0.1 to $\pi/2$ rad. Such a relationship is shown in Fig. 7.7. It is a very useful relationship between fabric parameters for engineering desired fabric constructions. One can see its utility for jammed structures, nonjammed fabrics, and even for some special cases in which cross-threads are straight. For jammed structures, Fig. 7.7 shows a nonlinear relationship between the two fabric parameters p and h on the extreme left. In fact, this curve is for jamming in the warp direction. It can be seen that the jamming curve shows different values of p_2/D for increasing crimp. Interestingly, this curve is a part of circle and its equation is

$$\left(\frac{p_2}{D}\right)^2 + \left(\frac{h_1}{D} - 1\right)^2 = 1 \quad (7.8)$$

with centre at $(0, 1)$ and radius equals to 1. For jamming in the warp direction of the fabric the parameters p_2/D and corresponding h_1/D can be obtained either from Fig. 7.7 or from the above equation. The relationship between the fabric parameters over the whole domain of the structure being jammed in both directions can be obtained by developing a suitable algorithm for computation using the following derived equations:

$$p_2 = D \sin \theta_1 = D \sin \frac{l_1}{D}$$

$$h_1 = D(1 - \cos \theta_1) = D \left(1 - \cos \frac{l_1}{D} \right) \quad (7.9)$$

$$\frac{h_2}{D} = 1 - \frac{h_1}{D}$$

$$p_1 = D \sin \theta_2 = D \sin \frac{l_2}{D}$$

$$h_2 = D(1 - \cos \theta_2) = D \left(1 - \cos \frac{l_2}{D} \right) \quad (7.10)$$

From the computation, the relationships between different useful fabric parameters are obtained and are given in Figs 7.8–7.12. Fig. 7.8 gives the relationship between p_2/D and p_1/D . This figure shows that the relationship between these parameters is

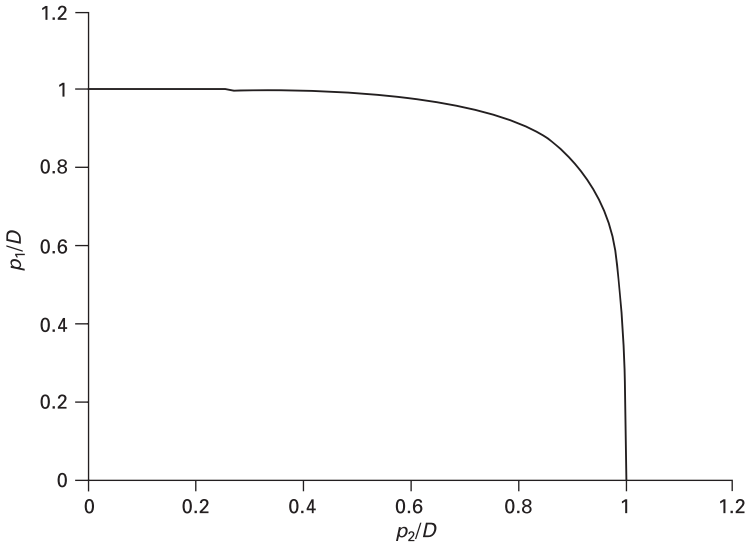


Fig. 7.8 Relation between warp-and-weft thread spacing for jammed fabric.

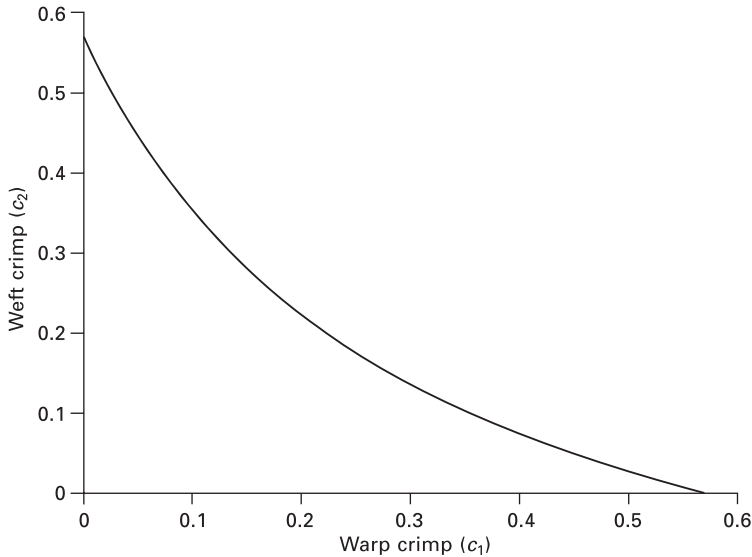


Fig. 7.9 Relation between fraction warp-and-weft crimp for jammed fabric.

less sensitive at the two extreme ends. The relationship is sensitive in a p/D range closer to 1. In fact, this sensitive range corresponds to maximum crimp in one direction only. The scope for change in both p_2 and p_1 lies in the range 0.6–0.9. Beyond this range, change in thread spacing is possible only in one direction.

A useful relationship between the crimps in two directions is shown in Fig. 7.9. It indicates an inverse nonlinear relationship between c_1 and c_2 . The intercepts on the axis give maximum crimp values with zero crimp in the cross-direction. This is a fabric configuration in which cross-threads are straight and all the bending is done by the intersecting threads. It may be concluded here that at either end a small change of crimp in one direction can permit a large change in crimp in the other direction.

Fig. 7.10 shows the relation between h_1/p_2 and h_2/p_1 . This shows linearity between them except at the two extremes. The behaviour is in fact the relationship between the square root of crimp in two directions and the constant is fixed for any jammed fabric. Other practical relations are obtained between warp-and-weft cover factor and between cloth cover factor and fabric mass (gsm).

Fig. 7.11 gives the relation between warp-and-weft cover factor for different ratios of weft-to-warp yarn diameters (β). The relation between the cover factors in two directions is sensitive only in a narrow range for all values of β . The relations between the cover factors in two directions are interdependent for jammed structures. Maximum threads in the warp/weft direction depend on yarn count and weave. Maximum threads in one direction of the fabric will give unique maximum threads in the cross-directions. The change in the value of β causes a distinct shift in the curve. A comparatively coarse yarn in one direction with respect to the other direction helps in increasing the cover factor. For $\beta=0.5$, the warp yarn is coarser than the weft, which causes an increase in warp cover factor and a decrease in weft cover factor.

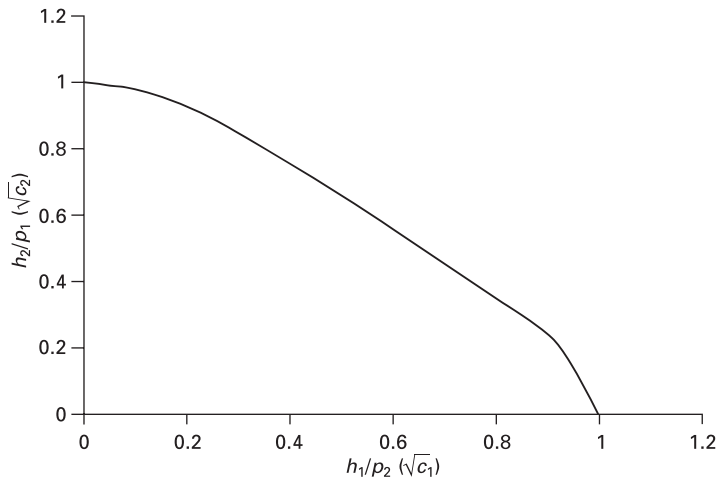


Fig. 7.10 Relation between $\sqrt{c_1}$ and $\sqrt{c_2}$ for jammed fabric.

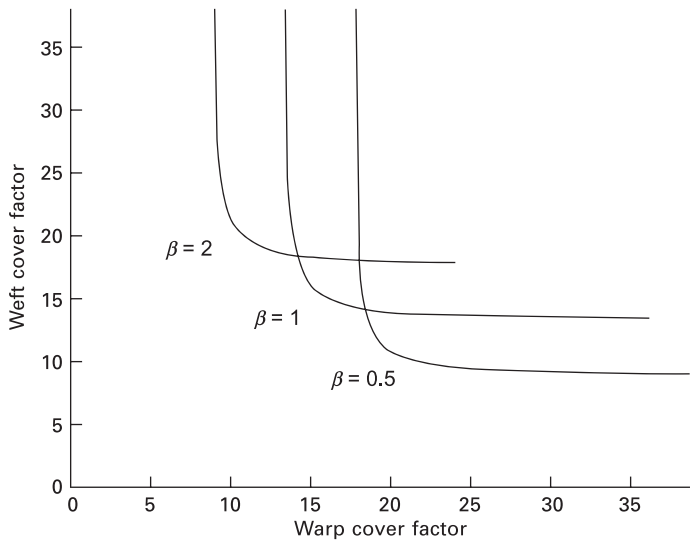


Fig. 7.11 Relation between warp-and-weft cover factor for different β for jammed fabric.

A similar effect can be noticed for $\beta=2$, in which the weft yarn is coarser than the warp yarn.

The relation between fabric mass in gsm with the cloth cover (K_1+K_2) is positively linear as shown in Fig. 7.12. The trend may appear to be self-explanatory. In practice, an increase in fabric mass and cloth cover factor for jammed fabrics can be achieved in several ways such as zero crimp in the warp direction and maximum crimp in the weft direction, zero crimp in the weft direction and maximum crimp in the warp direction,

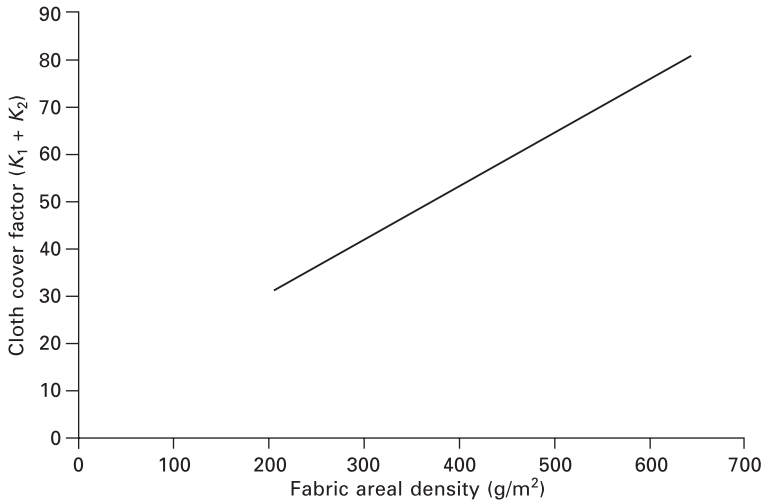


Fig. 7.12 Relation between fabric cover factor and fabric mass for jammed structure.

equal crimp in both directions and dissimilar crimp in both directions. This explanation can be understood by referring to the nonlinear part of the curve in Fig. 7.7.

Similarly for a nonjammed structure, it can be seen that the relation between p_2/D and corresponding h_1/D is linear for different values of crimp. This relationship is useful for engineering nonjammed structures for a range of values of crimp. The fabric parameters can be calculated from the above nonjammed linear relation between p_2/D and h_1/D for any desired value of warp crimp. Then, h_2/D can be obtained from $(1 - h_1/D)$ and for this value of h_2/D , one can obtain the value of p_1/D for the desired value of weft crimp. Thus, all fabric parameters can be obtained for desired value of p_2/D , picks/cm, warp-and-weft yarn tex, warp-and-weft crimp. One can choose any other four parameters to get all fabric parameters. The algorithm mentioned in Fig. 7.1 can be used to get several solutions for the nonjammed fabric.

Considering a fabric in which cross-threads are straight, it may further be realized from Fig. 7.7 that the intersection of horizontal line corresponding to $h_1/D = 1$ gives all possible structures ranging from relatively open to jammed configuration. In this case, $h_2 = 0$, $h_1 = D$. The fabric designer gets the option to choose the possible fabric constructions. These options include jamming and other loose constructions. Using the above logic, it is also possible to get fabric parameters for a fabric jammed in both directions, a fabric with maximum crimp in one direction and cross-threads being straight and a fabric which is neither jammed nor has zero crimp in the cross-threads.

7.5.1.1 Applications of geometrical models

In the weaving and processing industry, computer and mathematical models of fabric can facilitate rapid development of required products without the need to produce many fabric samples. Geometrical modelling can be used as a tool to achieve desired

functionality for industrial fabric production. The model and analysis system would make it possible to realistically model the fabric structure and predict its performance before it is used or even manufactured, thereby saving both time and energy. Examples of some properties for specific industrial applications are discussed below.

7.5.1.2 *Weavability and maximum sett*

This is helpful in realizing maximum areal density of the fabric and the suitability of the fabric for applications like waterproof fabrics and airproof fabrics. A very accurate value of end-and-pick densities can be determined, thereby reducing the extent of experimentation.

7.5.1.3 *Fabric design and engineering*

The fabric can be engineered and designed for specific applications by using the structural parameters such as crimp, thickness, cover factor, etc. An example is filter fabrics, where thickness of the fabric plays an important role.

7.5.1.4 *Manipulation of the fabric shape and structure*

This is possible in some specific applications like stentering and calendering (the geometrical model is very much applicable here because of the type of forces in action) in which, under the application of force, the width or length of the fabric is changed. The final length and width of the fabric can be predicted using the computation method embedded in the algorithm. It may be mentioned here that the geometrical model can predict only the structural parameters of the fabric and therefore, it is of very little use for prediction of mechanical properties of the fabric.

7.5.1.5 *Numerical application*

Q1: Find the weavability limit for a plain weave fabric from 30/45 Tex of warp/weft cotton yarn to have a maximum cover factor in one direction. Assume yarn packing density $\phi = 0.65$, fibre density $\rho_f = 1.52$ for cotton fibre. Predict the areal density for this fabric and crimp in both directions.

$$\text{Thread diameter : } d_1 = \frac{\sqrt{T_1}}{280.2 \sqrt{\phi \rho_f}}$$

$$\text{Warp : } d_1 = 0.01967 \text{ cm}$$

$$\text{Weft : } d_2 = 0.024 \text{ cm}$$

The weavability limit corresponds to the maximum number of ends and picks per unit length that could be woven with the given yarns and weave. That is associated with the jamming condition in the both fabric directions.

The maximum threads density in a direction leads to maximum cover factor in this direction for a given thread linear density (Tex).

$$K_{\max} = 28.02 \sqrt{\phi \rho_f} \text{ for cotton fibre : } K_{\max} = 27.85$$

Case 1: assuming maximum cover factor in the warp direction:

$$K_1 = K_{\max} = 27.85$$

$$K_1 = \frac{E_1 \sqrt{T_1}}{10}$$

$$E_1 = \frac{K_1 10}{\sqrt{T_1}} \text{ thus, } E_1 = 50.8 \text{ threads/cm and } P_1 = d_1 = 0.01967 \text{ cm}$$

From jamming condition: $P_1 = D \sin(\theta_2)$; $D = d_1 + d_2$

$$\theta_2 = 26.77$$

$$\cos(\theta_1) + \cos(\theta_2) = 1 : \theta_1 = 83.84$$

$$L_1 = D \theta_1 : L_1 = 0.0639 \text{ cm}$$

$$L_2 = D \theta_2 : L_2 = 0.0204 \text{ cm}$$

$$P_2 = D \sin(\theta_1) = 0.04342, E_2 = 23 \text{ thread/cm}$$

$$C_1 = \frac{L_1}{P_2} - 1 : C_1 = 0.4716$$

$$C_2 = \frac{L_2}{P_1} - 1 : C_2 = 0.0371$$

$$\text{Gsm} = [T_1 E_1 (1 + C_1) + T_2 E_2 (1 + C_2)] 10^{-1}$$

$$\text{Gsm} = [30 \times 50.8 \times (1 + 0.4716) + 45 \times 23 \times (1 + 0.0371)] 10^{-1} = 328 \text{ g/m}^2$$

$$h_1 = D (1 - \cos(\theta_1)) : h_1 = 0.039$$

$$h_2 = D (1 - \cos(\theta_2)) : h_2 = 0.0047$$

Fabric thickness = $h_1 + d_1$ or $h_2 + d_2$, whichever is higher

$$h_1 + d_1 = 0.058 \text{ cm}$$

$$h_2 + d_2 = 0.028 \text{ cm}$$

Thus, fabric thickness = 0.058 cm

$$K_2 = \frac{E_2 \sqrt{T_2}}{10} = 15.4$$

$$\text{Fabric cover} = K_1 + K_2 - \frac{K_1 K_2}{28} = 27.8 + 15.4 - \frac{27.8 \times 15.4}{28} = 27.91$$

Case 2: assuming maximum cover factor in the weft direction:

$$K_2 = K_{\max} = 27.85$$

$$K_2 = \frac{E_2 \sqrt{T_2}}{10} \text{ thus, } E_2 = 41.6 \text{ thread/cm and } P_2 = d_2 = 0.024 \text{ cm}$$

$$P_2 = D \sin(\theta_1); \theta_1 = 33.34$$

$$\cos(\theta_1) + \cos(\theta_2) = 1 : \theta_2 = 80.52$$

$$L_1 = D \theta_1 : L_1 = 0.0254 \text{ cm}$$

$$L_2 = D \theta_2 : L_2 = 0.0613 \text{ cm}$$

$$P_1 = D \sin(\theta_2) : P_1 = 0.043 \text{ and } E_1 = 23.2$$

$$C_1 = \frac{L_1}{P_2} - 1 : C_1 = 0.058$$

$$C_2 = \frac{L_2}{P_1} - 1 : C_2 = 0.427$$

$$\text{Gsm} = [T_1 E_1 (1 + C_1) + T_2 E_2 (1 + C_2)] 10^{-1}$$

$$\text{Gsm} = [30 \times 23.2 \times (1 + 0.058) + 45 \times 41.6 \times (1 + 0.427)] 10^{-1} = 340.7 \text{ g/m}^2$$

$$h_1 = D (1 - \cos(\theta_1)) : h_1 = 0.007$$

$$h_2 = D (1 - \cos(\theta_2)) : h_2 = 0.0365$$

Fabric thickness = $h_1 + d_1$ or $h_2 + d_2$, whichever is higher

$$h_1 + d_1 = 0.027 \text{ cm}$$

$$h_2 + d_2 = 0.06 \text{ cm}$$

Thus, fabric thickness = 0.06 cm

$$K_1 = \frac{E_1 \sqrt{T_1}}{10} = 12.59$$

$$\text{Fabric cover} = K_1 + K_2 - \frac{K_1 K_2}{28} = 12.59 + 27.8 - \frac{12.59 \times 27.8}{28} = 27.88$$

Q2: To manufacture a plain weave fabric from cotton yarn of 14 Tex for warp and weft with 47 ends per cm and warp/weft crimp percentage of 14/5.4.

What is the pick per cm that could be inserted to make this fabric?

Predict the fabric cover and fabric areal density and fabric specific volume. Assume yarn packing density $\phi = 0.65$, fibre density $\rho_f = 1.52$.

$$\text{Thread diameter : } d_1 = \frac{\sqrt{T_1}}{280.2 \sqrt{\phi \rho_f}}$$

$$\text{Warp/weft : } d_1 = d_2 = 0.0134 \text{ cm}$$

$$P_1 = 1/E_1 = 1/47 = 0.02127$$

$$h_2 = \frac{4}{3} P_1 \sqrt{C_2} = \frac{4}{3} \times \frac{1}{47} \sqrt{0.054} = 0.0066$$

$$D = d_1 + d_2 = h_1 + h_2 : h_1 = 2d - h_2 = 0.0202$$

$$P_2 = \frac{3h_1}{4\sqrt{C_1}} = 0.0404$$

$$E_2 = 1/P_2 = 25 \text{ thread/cm}$$

$$K_1 = \frac{E_1 \sqrt{T_1}}{10} = 17.58$$

$$K_2 = \frac{E_2 \sqrt{T_2}}{10} = 9.35$$

$$\text{Fabric cover factor} = K_1 + K_2 - \frac{K_1 K_2}{28} = 21.06$$

$$\text{Fabric thickness} = h_1 + d_1 \text{ or } h_2 + d_2, \text{ whichever is higher; } h_1 + d_1 = 0.0202 + 0.0134 = 0.0336 \text{ cm}$$

$$\text{Gsm} = [T_1 E_1 (1 + C_1) + T_2 E_2 (1 + C_2)] 10^{-1}$$

$$\text{Gsm} = [14 \times 47 \times (1 + 0.14) + 14 \times 25 \times (1 + 0.054)] 10^{-1} = 111.9 \text{ g/m}^2$$

$$\begin{aligned} \text{Fabric specific volume} &= \text{fabric thickness} / \text{Gsm} = 0.0336 \times 10^{-2} / 111.9 \\ &= 3 \times 10^{-6} \text{ m}^3/\text{g} = 3 \text{ cm}^3/\text{g} \end{aligned}$$

Q3: Find the areal density (gsm) and fabric cover of a plain weave square fabric made from 12 Tex yarn with 32 threads per cm. Find both yarn count and thread per cm to obtain 20% increase in gsm, maintaining the same fabric firmness. Calculate the maximum gsm could be obtained for this fabric when using the same yarn count and when keeping the same threads density for maximum cover. Assume yarn packing density $\phi = 0.65$, fibre density $\rho_f = 1.52$.

In square fabric yarn count, threads spacing and crimp is equal in warp and weft.

$$d_1 = d_2 = d = \frac{\sqrt{T}}{280.2 \sqrt{\phi \rho_f}} = 0.01244 \text{ cm}$$

$$P_1 = P_2 = P = 1/E = 1/32 = 0.03125$$

$$h_1 = h_2 = h = D/2 = d = 0.01244 \text{ cm}$$

$$C_1 = C_2 = C$$

$$\sqrt{C} = \frac{3h}{4P}$$

$$C = 0.09$$

$$K = \frac{E\sqrt{T}}{10} = \frac{32\sqrt{12}}{10} = 11$$

$$\text{Fabric cover} = 2K - \frac{K^2}{28} = 17.6$$

$$\text{Gsm} = [T_1 E_1 (1 + C_1) + T_2 E_2 (1 + C_2)] 10^{-1} = 2[TE(1 + C)] 10^{-1} = 83 \text{ g/m}^2$$

$$\frac{(\text{fabric gsm})_{\text{new}}}{(\text{fabric gsm})_{\text{old}}} = \frac{(\sqrt{T})_{\text{new}}}{(\sqrt{T})_{\text{old}}}$$

$$(\text{Fabric gsm})_{\text{new}} = (\text{fabric gsm})_{\text{old}} \times 20\% = 83 \times 1.2 = 99.6 \text{ g/m}^2$$

For 20% increase in gsm while maintaining the same firmness (same fabric cover factor), it could be achieved by using coarser yarns and fewer threads per cm:

$$(\sqrt{T})_{\text{new}} = \frac{(\text{fabric gsm})_{\text{new}}}{(\text{fabric gsm})_{\text{old}}} (\sqrt{T})_{\text{old}}$$

$$(T)_{\text{new}} = \left(\frac{99.6}{83} \sqrt{12} \right)^2 = 17.28 \approx 17 \text{ Tex}$$

$$\frac{(\text{fabric gsm})_{\text{old}}}{(\text{fabric gsm})_{\text{new}}} = \frac{(\text{Threads/cm})_{\text{new}}}{(\text{Threads/cm})_{\text{old}}}$$

$$(\text{Threads/cm})_{\text{new}} = \frac{(\text{fabric gsm})_{\text{old}}}{(\text{fabric gsm})_{\text{new}}} (\text{Threads/cm})_{\text{old}}$$

$$(\text{Threads/cm})_{\text{new}} = \frac{83}{99.6} \times 32 = 26.66$$

$$K' = \frac{E'\sqrt{T'}}{10} = \frac{26.66 \times \sqrt{17}}{10} = 11$$

$$(\text{Fabric cover})_{\text{new}} = 2K' - \frac{K'^2}{28} = 17.6$$

Maximum gsm for the fabric is obtained with the jamming condition:

$$L = D\theta, P = D \sin(\theta), h = D(1 - \cos(\theta))$$

$$D = h_1 + h_2 = 2h, \text{ for sward fabric}$$

$$2 \cos(\theta) = 1 : \theta = 60$$

$$\text{Thus, } \frac{P}{D} = \sin(60) = 0.866$$

$$C = \frac{1}{P} - 1 = \frac{D \theta}{D \sin(\theta)} - 1 = \frac{\theta}{\sin(\theta)} - 1 = 0.209$$

(i) When keep using the same yarn count:

$$T = 12 \text{ Tex}, d = 0.01244 \text{ cm}$$

To find E:

$$P = D \sin(\theta) = 2 \times 0.01244 \times \sin(60) = 0.0215, E = 46.4$$

$$\text{Gsm} = 2[TE(1 + C)]10^{-1} = 2[12 \times 46.4 \times (1 + 0.209)]10^{-1} = 134.6 \text{ g/m}^2$$

$$K = \frac{E \sqrt{T}}{10} = \frac{46.4 \times \sqrt{12}}{10} = 16$$

$$\text{Fabric cover} = 2K - \frac{K^2}{28} = 22.8$$

(ii) When keep threads density setting on the weaving loom:

$$E = 32 \text{ and } P = 0.03125$$

$$D = P / \sin(60) = 0.03125 / 0.866 = 0.036, d = 0.018$$

$$d = \frac{\sqrt{T}}{280.2 \sqrt{\phi \rho_f}}$$

$$T = \left(280.2 d \sqrt{\phi \rho_f} \right)^2 = 25.13 \text{ Tex}$$

$$\text{Gsm} = 2[TE(1 + C)]10^{-1} = 2[25.13 \times 32 \times (1 + 0.209)]10^{-1} = 194.4 \text{ g/m}^2$$

$$K = \frac{E \sqrt{T}}{10} = \frac{32 \times \sqrt{25.13}}{10} = 16$$

$$\text{Fabric cover} = 2K - \frac{K^2}{28} = 22.8$$

It is interesting to note that a coarser yarn (25.15 Tex) has lower threads/cm (32) and a finer thread (12 Tex) has more threads/cm (46.4) for the same fabric cover.

7.5.2 Mathematical models

Mathematical models are derived from first principles. These models are very appealing because they have their basis in applied physics. They can be used to explain the

reasons that determine structure–property relationships. The main purpose for carrying out these structural analyses is to provide tools to enable the designer to design textile structures to meet various end use specifications.

7.5.2.1 Limitations of mathematical model

Mathematical modelling has certain limitations. The development of theory is cumbersome and requires many years to yield results. The models are normally problem specific and any change in the system requires a new analysis and new programs to solve equations. It often produces large prediction error and the procedures are not user friendly.

7.5.3 Empirical modelling

The most common approach has been to develop predictive models for fabric properties and performance through experimental investigations. In this case, a large number of experiments are carried out under controlled conditions and statistical techniques are used to derive empirical models. Data generated from experimental results are used to develop regression models to predict desired property parameters. The empirical equations are based on the linear multiple regression. In the statistical method of modelling, multilinear regression equations between fabric property and constructional parameters are applied to the same data, to find the predictability of the statistical method. The coefficient of multiple determination (R^2) which defines the fraction of variability in the dependent variable explained by the regression model is taken as a guiding parameter. If the model's R^2 value is high, it suggests that the empirical model fits the data reasonably well.

7.5.3.1 Limitations of empirical modelling

Empirical models can have limited applications for two reasons. First, because the size of the experiments is generally limited due to cost and time factors, the selection of materials and processes can be considered in a narrow range only. Second, the existing tools and techniques are inadequate for accurately modelling and optimizing complex nonlinear processes like woven fabric manufacturing. Hence, there is a need for models that can accurately predict process and product design for woven fabrics.

7.5.4 Finite element modelling

The finite element method is a powerful tool for the numerical solution of a wide range of engineering problems. Application of finite element modelling (FEM) ranges from deformation and stress analysis of automotive, aircraft, building, and bridge structures to field analysis of heat flux, fluid flow, magnetic flux, and other flow problems. In the recent years, finite element analysis has also been applied to flexible materials like textile fabric for modelling and simulation. In this method of analysis, a complex region defining a continuum is discretized into simple geometric shapes called finite elements.

The material properties and the governing relationships are considered over these elements and expressed in terms of unknown values at element corners. An assembly process, duly considering the loading and constraints, results in a set of equations. Solution of these equations gives the approximate behaviour of the continuum.

FEM is considered useful for textiles because the complexity of the structure, the anisotropic properties of yarns and fabrics, and the interaction phenomena between yarns at the contact areas preclude the use of analytical methods. With FEM-based calculation models, an in-depth understanding of the physical phenomena can be obtained, and it is possible to change important parameters in a short time in order to improve textile-based constructions and also to generate new products [42]. From the structural point of view, woven fabrics are discontinuous in microstructure and therefore, they do not satisfy the continuity requirement in solid mechanics. However, discontinuity in the fabric is small in comparison to the finite element mesh size, and therefore, fabric continuity is a reasonable assumption to make. Several research works have been reported in the recent years on the application of FEM analysis for prediction of fabric mechanical properties which can be used for engineering of woven construction. Lloyd [43] has applied FEM to study fabric in-plane deformation using membrane elements with no bending resistance. The fabric deformation considering shell plate elements has been studied by Gan and Ly [44] using nonlinear finite elements. In this study, fabrics are assumed to be linearly elastic and orthotropic. Constitutive relation of fabrics was determined and used in shell elements. Two-dimensional bending of fabrics was studied and the results were compared with the experimental values obtained by cantilever bending test. Bending hysteresis was not accounted for by the finite element analysis.

Jeong and Kang [45] developed a computer model for analysing the compressional behaviour of a woven fabric using FEM. A three-dimensional (3D) unit cell was defined to describe the compressional deformation of fabric in the 3D viewpoint. The geometry of unit cell is determined using the equilibrium requirements of planar-elasticity-boundary value problems. The yarns in the fabric were assumed to be elastic and isotropic. The contact conditions at the yarn crossover point were determined by the equilibrium equations. Two kinds of second-order isoparametric solid elements were used to describe warp-and-weft yarns. The total number of elements and nodes for the modelling of the 3D geometry were 876 and 5426, respectively. The analysis was carried out with the aid of ABAQUS FEM package. The result showed that the compressional resistance of fabric is influenced by the geometrical structure of the fabric unit cell as well as the yarn property. Also, the compressional resistance increased with Poisson's ratio [46].

7.6 Modelling methodologies: Nondeterministic models

Models based on the genetic methods, NNs, chaos theory, and soft logic are nondeterministic models and known as soft computing methods according to the convention for predicting properties and performance. Soft computing is a collection of methodologies, which aim to exploit tolerance for imprecision, uncertainty, partial

truth, and approximation to achieve tractability, robustness, and low solution cost. It differs from conventional (hard) computing in that, unlike hard computing, it is tolerant of imprecision, uncertainty, partial truth, and approximation. The soul of soft computing is to make the computer as soft as the human brain, and is capable of carrying out both quantitative and qualitative computing. Along this direction, fuzzy logic has been developed to handle qualitative information, and in this sense, it is called fuzzy computing. ANN is a kind of soft computing technology as it provides a relatively easy way to acquire information about a system through learning. The inclusion of neural computing and genetic computing in soft computing came at a later stage. There are a number of publications in this field of computing covering a wide range of application domains including that of textiles. Notable ones are a book on soft computing in textile sciences by Sztandera and Pastore [47], a textile institute monograph on artificial neural network (ANN) applications in textiles by Chattopadhyay and Guha [48] and research work carried out by Behera and Muttagi [49–55] on the development of ANN-embedded expert system (ES) for woven fabric engineering.

7.6.1 Fuzzy logic

Knowledge representation and processing are the keys to any intelligent system. In logic, knowledge is represented by propositions and is processed through reasoning by the application of various laws of logic, including an appropriate rule of inference. Fuzzy logic uses the fuzzy set theory and approximate reasoning to deal with imprecision and ambiguity in decision-making. A crisp set is defined by the characteristic function that can assume only the two values $\{0, 1\}$, whereas a fuzzy set is defined by a ‘membership function’ that can assume an infinite number of values; any real number in the closed interval $[0, 1]$. The idea of fuzzy logic was introduced by Lofti A. Zadeh in 1965 in his paper on fuzzy sets [56].

Consider a universe of discourse X with x representing its generic element. A fuzzy set $\underline{A}$ in X has the membership function $\mu_{\underline{A}}(x)$ which maps the elements of the universe onto numerical values in the interval $[0, 1]$:

$$\mu_{\underline{A}}(x) : X \rightarrow [0, 1] \quad (7.11)$$

Every element x in X has a membership function $\mu_{\underline{A}}(x) \in [0, 1]$. $\underline{A}$ is then defined by the set of ordered pairs:

$$\underline{A} = \left\{ \left(x, \mu_{\underline{A}}(x) \right) \mid x \in X, \mu_{\underline{A}}(x) \in [0, 1] \right\} \quad (7.12)$$

A membership value of zero implies that the corresponding element is definitely not an element of the fuzzy set $\underline{A}$. A membership value of unity means that the corresponding element is definitely an element of fuzzy set $\underline{A}$. A grade of membership greater than zero and less than unity corresponds to a noncrisp (or fuzzy) membership of the fuzzy set $\underline{A}$. Classical sets can be considered as special cases of fuzzy sets

with all membership grades equal to unity. Membership functions characterize the fuzziness in a fuzzy set.

Models designed based on the fuzzy logic, usually consist of a number of fuzzy if-then rules expressing the relationship between inputs and desired output. For instance, in the case of two-input single-output systems, it is expressed as

$$R_i : \text{IF } x \text{ is } A_i \text{ and } y \text{ is } B_i \text{ THEN } z \text{ is } C_i \quad (7.13)$$

where R_i is a fuzzy relation representing the i th fuzzy rule; x, y, z are linguistic variables representing two inputs and the output; and A_i, B_i, C_i are linguistic values of x, y, z , respectively. In these models, inputs are fuzzified, membership functions are created, association between inputs and outputs are defined in a fuzzy rule base, and fuzzy outputs are restated as crisp values.

Fuzzy modelling can be categorized into two groups: subjective modelling and objective modelling. In the subjective modelling approach, it is assumed that a priori knowledge about the system is available and that this knowledge can be directly solicited from experts. By contrast, in objective modelling, it is assumed that either there is no priori knowledge about the system, or the expert's knowledge is not trustworthy enough. Therefore, instead of any a priori interpretation of the system, raw input and output data are used to augment human knowledge or even generate new knowledge about the system. This approach was initially proposed by Takagi-Sugeno-Kang [57] and called TSK fuzzy modelling.

7.6.1.1 Applications of fuzzy logic

Fuzzy logic has been used in several areas of textiles which include colour grading of cotton into different classes, prediction of tensile strength, and yarn count of melt spun fibres, an intelligent diagnosis system for fabric inspection and automatic recognition of fabric weave pattern. Raheel and Liu [58] used a fuzzy comprehensive evaluation technique to calculate fabric handle of lightweight dress fabrics. Thickness, weight, flexural rigidity, wrinkle recovery, and 45 degrees filling elongation were used to describe the hand of lightweight fabrics. In order to obtain the fuzzy transformation R , five membership functions corresponding to the five properties were selected. A decreasing half-Cauchy distribution was used to describe the membership degrees of fabric weight, fabric thickness, fabric flexural rigidity, and 45 degrees filling elongation. For wrinkle recovery, a linear membership function was used. From a survey of judges, the importance of each property selected was ascertained and expressed as a weighted vector. By using the weighted vector and the fuzzy transformation matrix, fabric handle was calculated. The same approach was followed by Park and Hwang [59] for predicting total hand value from selected mechanical properties of double weft knitted fabrics and by Chen et al. [60] for grading softness of 100% cotton and cotton/polyester blended fabrics. Huang and Yu [61] investigated the use of fuzzy logic controller for controlling concentration, pH, and temperature in the dyeing process.

7.6.2 Neural networks

The term NN is used to describe a number of different models intended to imitate some of the functions of the human brain, using certain of its basic structures. The development and use of NNs are part of an area of multidisciplinary study that is commonly called neural computing, but is also known as connectionism, parallel distributed processing and computational neuroscience. ANN is a powerful data modelling tool that is able to capture and represent each kind of input–output relationship. ANN is composed of simple elements called neuron or processing element operating parallel, which are inspired by biological neuronal systems. As in nature, the network function is determined largely by weighted connections between the processing elements. The weights of the connections contain the knowledge of the network.

There are different types of NNs. An important distinction can be made between supervised and unsupervised learning. In supervised learning, the network is presented with pairs of input and output data. For each set of input values, there is a matched set of output data. The key point is that if the desired output of the network is known for each set of input values, then the weights of the network can be modified accordingly. Supervised NNs are typically used to solve what is known as function approximation, using examples of the function in the form of input–output pairs. In unsupervised learning, the output is not known; the network is simply presented with input data.

NNs that are based on the multilayer perceptron (MLP) account for approximately 80% of all practical applications. In an MLP, the units are arranged in distinct layers and each unit receives weighted input from each unit in the previous layer. ANN is usually adjusted or trained so that a particular input leads to a specific output. The process of training is adjusting these weight values and sliding down the error surface. Among the various kinds of algorithms for training NNs, back propagation is the most widely used.

ANNs produce the least error, as well as lower spread in the error, compared with mathematical and regression methods of modelling. ANN also has an excellent property of approximating any functional relationship between large numbers of input–output (independent variables–dependent variables) parameters. No prior assumptions are required to be made on the statistical nature of the variables of the data, since ANN are nonparametric in nature. ANN requires a much smaller dataset than that required for conventional regression analysis for capturing the nonlinear relationships between the input and output parameters. Even with a small training dataset, the network generalizes the functional relationships very well. In the industry, where large data are continuously available, ANN can be expected to perform significantly better. The major advantage of ANN is that there is no restriction on the levels of interaction between the variables; therefore, it can capture the dynamics of the real world very well.

7.6.2.1 Back propagation algorithm

The input vectors X for the input layer are expressed in the vector form as $X = (x_1, x_2 \dots x_n)$. Predicted parameters (network outputs) are denoted as Y . As shown in Eq. (7.14), the i th component of the input signal x_i comes out from the unit i and is transferred to the unit j of the model through the synapse weight W_{ji} , where b_j is the bias term connected to the j th unit.

$$u_j = \left(\sum_{i=1}^n W_{ji}x_i + b_j \right) \quad (7.14)$$

The unit j nonlinearly transforms the total input u_j (Eq. 7.14) by means of a transfer function (hyperbolic tangent transfer function used here), which is propagated forward to the unit of the next layer as the input signal y_i (Eq. 7.15):

$$y_j = \frac{2}{1 + e^{(-2u_j)}} - 1 \quad (7.15)$$

The difference in the output y_i from the target output t_j is used to adjust the synapse weights according to the calculated mean squared error (MSE), as shown in Eq. (7.16):

$$MSE = \frac{\sum_{j=0}^p \sum_{i=0}^N (t_{ij} - y_{ij})^2}{NP} \quad (7.16)$$

where y_{ij} is the network output for data set i at neuron j , t_{ij} is the target network output for data set i at neuron j , P indicates the number of output neurons, and N refers to the number of datasets. The ANN is trained by updating the weights with a back propagation rule. The change in synapse weight w_{ji} is based on the gradient descent rule according to Eq. (7.17):

$$\Delta w_{ji} = -\eta \frac{\partial(MSE)}{\partial w_{ji}} \quad (7.17)$$

where η is the learning rate.

7.6.2.2 Applications of ANN

Image processing analysis and NNs have been widely used for fabric defect detection. The basic principles underlying this technique along with numerous applications are detailed by Behera [62]. Lin [63] used feedforward back propagation neural nets to find the relationships between the shrinkage of yarns and the cover factors of yarns and fabrics. A typical multilayer feed-forward network is shown in Fig. 7.13. Beltran et al. [64] also studied the use of MLP-BP NNs to model the multilinear relationships

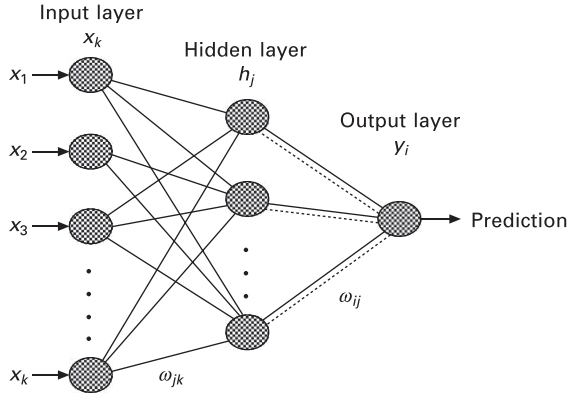


Fig. 7.13 Multilayer feed-forward network.

between fibre, yarn and fabric properties, and their effect on the pilling propensity of pure wool-knitted fabrics. Behera and Muttagi [49] predicted the low-stress mechanical, dimensional, and tensile properties of woven suiting fabrics using back propagation network (BPN) and radial basis function neural network (RBFN). Fibre, yarn, and fabric constructional parameters of wool and wool-polyester blended fabrics were given as input variables. RBFNs were found to have better predictability and are faster to train and easier to design than back propagation NNs. A reverse engineering approach is also reported for prediction of constructional particulars from the fabric properties.

Hui et al. [65] predicted sensory fabric hand from fabric properties using a resilient back propagation (RBP) NN. Shyr et al. [66,67] studied the use of NNs for discriminating generic hand of cotton, linen, wool, and silk woven fabrics. They established translational equations for the total hand value of fabrics using back propagation nets. Wong et al. [68] investigated the predictability of clothing sensory comfort from psychological perceptions by using a feed-forward BPN. ANN-based prediction of fabric appearance index by Behera and Mishra [69,70] can be used as an objective method of fabric engineering to achieve desired aesthetic performance. This work provides measurement of an integrated fabric appearance index given in Eq. (7.18) using image processing and NN computation method. Fabric appearance index is termed as FAI and given by

$$\text{FAI} = \sum_{i=1}^n A_i W_i \quad (7.18)$$

where n is the total number of properties, A_i is the grade of the i th property obtained by digital image processing, and W_i is weighting of the i th property. The properties such as drape, texture, wrinkle, and pilling are used to access the aesthetic appearance of an apparel fabric.

7.6.3 Genetic algorithms

A relatively new area of study in artificial intelligence is that of genetic algorithms (GAs). GAs are a powerful set of stochastic global search techniques that have been shown to produce very good results for a wide class of problems. GAs can find good solutions to nonlinear problems by simultaneously exploring multiple regions of the solution space and exponentially exploiting promising areas through mutation, crossover, and selection operations [71]. GAs are programs that attempt to find optimal solutions to problems when one can specify the criteria that can be used to evaluate the optimal solution. They are useful when a problem has multiple solutions, some of which are better than others. Unlike deterministic, linear and nonlinear optimization models, GAs test a variety of solutions and, through an evolving process, attempt to find the best solution through processes that parallel the metaphors of survival of the fittest, genetic crossover, mutation, and natural selection. Evolutionary algorithms differ substantially from more traditional search and optimization methods. The most significant differences are:

- GAs work with a coding of the parameter set, not the parameter themselves.
- GAs search from a population of designs, not a single design.
- GAs use objective function information, not derivatives or other auxiliary knowledge.
- GAs use probabilistic transition from design to design; they do not use deterministic rules.
- Evolutionary algorithms can provide a number of potential solutions to a given problem. The final choice is left to the user.

In building a GA, six fundamental issues that affect the performance of the GA must be addressed: chromosome representation, genetic operators, selection strategy, initialization of the population, termination criteria, and evaluation measures. The initial population is randomly generated, which is the most common method, while the GA is run for a specified number of generations as its termination criterion. For any GA, a chromosome representation is needed to describe each individual in the population of interest. The representation scheme determines how the problem is structured in the GA and also determines the genetic operators that are used. The operators are used to create new solutions based on the existing solutions in the population. There are two basic types of operators: crossover (recombination) and mutation. Mutation operators tend to make small random changes in one parent to form one child in an attempt to explore all regions of the state space. Mutation serves the crucial role of preventing the system from being stuck in the local optimum. Crossover operators combine information from two parents to form two offspring such that the two children contain a 'likeness' (a set of building blocks) from each parent. The application of these two basic types of operators and their derivatives depends on the chromosome representation used. The selection of individuals to produce successive generations plays an extremely important role in a GA. A probabilistic selection is performed based upon the individual's fitness such that the better individuals have an increased chance of being selected. However, all of the individuals in the population have a chance of being selected to reproduce into the next generation. Evaluation functions of many forms can be used in a GA, subject to the minimal requirement that the function

can map the population into a totally ordered set. The evaluation function is independent of the GA (i.e., stochastic decision rules) [72].

The basic procedure of GAs can be explained as follows:

```

Let P(g) and C(g) be parents and offspring, respectively, in the existing
generation g;
Procedure
for
  g: = 0;
  initialize population P(g);
  evaluate P(g);
  for
    recombine P(g) to generate C(g);
    evaluate C(g);
    select P(g + 1) from P(g) and C(g);
  g: = g + 1
end

```

7.6.3.1 Applications of GAs

GAs are being used to solve a wide variety of problems in textiles right from the production of fibres to apparel design and manufacturing. Amin et al. [73] reported detection of the spinning fault source from spectrograms by using GAs. Blaga and Draghici [74] reported the application of GAs in knitting technology. Lin [75] investigated the use of GA for searching weaving parameters for woven fabrics. A search mechanism was developed to find the best combinations of warp-and-weft counts and yarn densities for fabric manufacturing, taking into account costs. This helps the designer to select appropriate combinations of these parameters to achieve the required weight of fabric at a precontrolled cost. Grundler and Rolich [76] developed an evolutionary algorithm-based software for creating different weave patterns. Only the weave and yarn colour were considered as attributes for fabric appearance and different patterns can be created by various combination of weave and colour of warp-and-weft threads. Jasper et al. [72] investigated fabric defect detection using a GA tuned wavelet filter. Hui et al. [77] studied the application of GA on the roll planning of fabric spreading in apparel manufacturing. It was demonstrated that the use of GAs to optimize roll planning will result in reduced wastage in cutting and hence, can reduce cost of apparel production. Chan et al. [78] investigated the problem of handling the assembly line balancing in the clothing industry. Inui [79] presented a computer-aided system using GA applied to apparel design. In this study, a computer technique that helps consumers to take part in apparel design was presented. An interactive computer-aided system for designing was constructed on the basis of the GA search method.

7.6.4 Hybrid modelling

A trend that is growing in visibility relates to the use of fuzzy logic in combination with neurocomputing and GAs as shown in Fig. 7.14. The marriage of fuzzy logic with computational NNs has a sound technical basis, because these two approaches

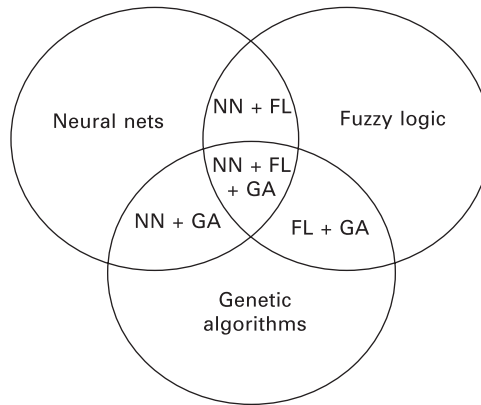


Fig. 7.14 Hybrid models using soft computing tools.

generally attack the design of intelligent systems from quite different angles. NNs are essentially low-level computational algorithms that offer good performance in dealing with large quantities of data often required in pattern recognition and control. Fuzzy methods often deal with issues such as reasoning on a higher (i.e., on a semantic or linguistic) level than do NNs. Consequently, the two technologies often complement each other: NNs supply the brute force necessary to accommodate and interpret large amounts of data and fuzzy logic provides a structural framework that utilizes and exploits these low-level results. NNs are known for their ability to perform complex, nonlinear mapping of input–output data. However, it is difficult to decide which input data, network structure and learning parameters to utilize. GAs can be applied as an optimization search to determine the optimal in NN structure design including input data combination optimization, network structure optimization, learning rate, and momentum optimization. In this way, computational complexity and the time required to design the NN are reduced [80,81].

7.6.4.1 Applications of hybrid modelling

Hybrid modelling has been used in several cases of prediction of fibre, yarn, and fabric properties. The prediction accuracy of the neuro-fuzzy system has been found superior to that of a conventional multiple regression model and comparable with an ANN model. Wong et al. [82] predicted clothing sensory comfort from fabric physical properties by building eight different hybrid models combining statistics, fuzzy logic, and NN methodologies. Results showed that the TS–TS–NN–FL model has the highest ability to predict overall comfort performance followed by the TS–TS–NN–NN model (TS, NN, and FL refer to statistical, NN, and fuzzy logic, respectively). The data reduction and information summation ability of statistics, self-learning ability of neural nets, and fuzzy reasoning ability of fuzzy logic were exploited to develop these hybrid models.

Table 7.2 Prediction performance of the radial basis function neural network

Fabric properties	Absolute prediction error (%)
Warp extension (%)	12.3
Weft extension (%)	13.2
Warp bending rigidity (μNm)	14.8
Weft bending rigidity (μNm)	13.9
Warp formability (mm^2)	14.9
Weft formability (mm^2)	14.3
Shear rigidity (N/m)	12.6
Warp-way breaking strength (N)	10.3
Weft-way breaking strength (N)	4.1
Warp-way breaking elongation (%)	16.2
Weft-way breaking elongation (%)	16.5
Average prediction error (%)	13.02

7.7 Authentication and testing of models

When building mathematical models, one has to use numbers derived from experimental or empirical data, or from analytical or computer-based calculations. Errors are thus produced due to data reading or data manipulation. Normally, researchers use statistics to deal with error. Error is defined as the difference between a measured or calculated value and its true or exact value. Error is unavoidable but how much error is present depends on how skillfully the data are read or manipulated. Therefore, error analysis is an integral part of the modelling process. There are two types of error: systematic error and random error. Systematic error occurs when an observed or calculated value deviates from the true value in a consistent way. This error occurs in experiments when instruments are improperly calibrated. Random errors do not occur due to chance. They arise mainly in experimental work because unpredictable things happen due to ignorance or by accident. There is one absolute error which is defined as the difference between the true or experimental value and the measured value. The true value may be known or it may have an expected value based on a calculation or some other data source. For example, in case of a NN modelling of woven fabric engineering, the ability of the model to predict the fabric structure–property relationships can be judged from percentage error in the prediction of fabric properties for a given set of input fibre, yarn, and fabric constructional parameters. In such cases, the network is trained on fabric constructional parameters such as weave float, thread density, thread resultant tex, yarn crimp, fabric mass and fabric cover as inputs to the networks, and fabric shrinkage, hygral expansion, extension, bending rigidity, formability, shear rigidity, thickness, breaking strength, and elongation as network outputs. Table 7.2 shows the prediction error in percentage as the average of test dataset for each fabric property predicted by the NN. The overall absolute prediction error is 13.02%.

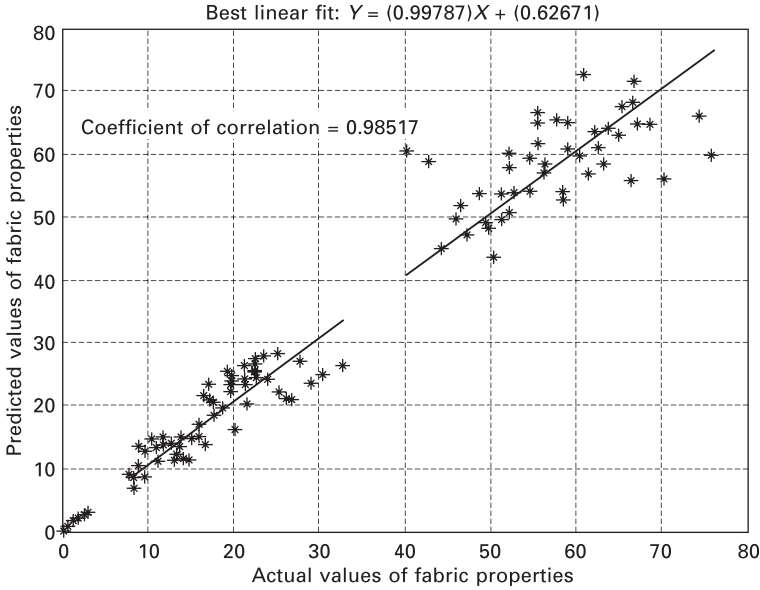


Fig. 7.15 Actual values of fabric properties vs values predicted by neural network.

$$\text{Error}\% = \left(\frac{P - E}{E} \right) \times 100$$

where Error % is the Absolute error %, P the predicted value by the network, and E the experimental value.

The ability of the network to model the fabric structure–property relationships can best be judged from the network’s response to the influence of constructional parameters on fabric properties. This can be further authenticated by plotting the relationship between actual values and predicted values of fabric properties. [Fig. 7.15](#) shows the correlation between actual and predicted values by the network which demonstrates a very good correlation between the actual and the predicted values ($r=0.985$) in this example.

7.8 Reverse engineering

Reverse engineering is the process of discovering the technological principles of a device, object, or system through analysis of its structure, function, and operation. It often involves taking something apart and analysing its workings in detail; used in maintenance or making a new device or program that does the same thing without copying anything from the original [4]. The purpose is to deduce design decisions from end products with little or no additional knowledge about the procedures involved in the original production. Reverse engineering is carried out under several

circumstances like lost documentation (the documentation of a particular device has been lost or was never written and the person who built it is no longer available), product analysis (to examine how a product works, what components it consists of, estimate costs, identify potential), security auditing, removal of copy protection, circumvention of access restrictions, creation of unlicensed and unapproved duplicates, and also for academic-learning purposes. Reverse engineering is taking apart an object to see how it works in order to duplicate or enhance the object. Someone doing reverse engineering on software may use several tools to disassemble a program. The term forward engineering is sometimes used in contrast to reverse engineering in various literatures.

7.9 Future trends in nonconventional methods of design engineering

7.9.1 Knowledge-based systems

The engineering design of woven textile structures is a complex task and makes extensive use of empirical knowledge accumulated overtime. Only few, highly experienced experts in the industry know rule-of-thumb principles and methods of complex structural synthesis under performance constraints. Therefore, if the knowledge and expertise of the experts in the field and from the literature is used to develop a scientific database, then computer software can be prepared with such acquired knowledge, which in turn will provide expert advice on the problem. Such a knowledge-based system is called an ES. It is a system that has been engineered to simulate a human expert. They are well suited to database manipulations, symbolic reasoning, and decision-making. They have conflict resolution principles so that mutually antagonist requirements are satisfied to the greatest extent possible and with minimal compromise. Expert systems permit the use of different design knowledge representational modes such as heuristic, procedural and factual knowledge and the reasoning methods working with each of these representational modes.

The technology of artificial intelligence (AI) and ES enables computers to be applied to less deterministic design tasks, which require symbolic manipulation and reasoning, instead of routine number processing. ES can be used to diagnose, repair, monitor, analyse, interpret, consult, plan, design, instruct, explain, learn, and conceptualize problems. ES is a powerful tool for solving problems like design, which is used for making decisions. Designing is typically a decision-making process, so the application of knowledge engineering and ES is suitable for it. ES is very suitable for database manipulation and decision-making. The modularity of ES enables the changes or modifications to be accommodated easily by changing or adding merely the facts and rules contained in the knowledge [83–85].

In order to construct a successful ES, the problem domain must be well defined, and there must be at least one human expert acknowledged to perform well within the application area; however, additional knowledge relevant to the problem domain can be obtained from other sources. Experts must have special knowledge, judgement,

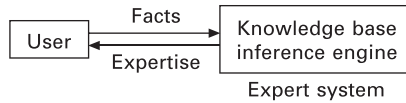


Fig. 7.16 Basic structure of expert system.

and experience. Also, the expert must be able to explain and justify the special knowledge and experience and the methods used to apply them to particular problems. Further, there must also be adequate programming tools, ideally a set of ES software building tools; specific high-level programming languages such as LISP and PROLOG are often considered to be languages of ES development.

7.9.2 Basic structure of ES

The basic structure of an ES is shown in Fig. 7.16. The various components of ES are as follows.

- (1) The knowledge base consists of the domain facts and heuristics associated with the problem area, which must be well bounded and narrow.
- (2) The inference engine is the control structure or strategy for utilizing the knowledge base in the solution to the problem.
- (3) The dynamic and global database is the working memory for keeping track of the problem status, the input data for the particular problem, and the relevant history of what has been done.
- (4) A user-friendly interface to facilitate interaction of the system with the user and provide a human window to its operations, preferably a natural language framework; in addition, an explanation module should be included to allow the user to raise queries and to help understand the reasoning process underlying the system's answers.
- (5) The knowledge acquisition module facilitates the transfer and transformation of problem-solving expertise from the knowledge source to the knowledge base.

Since knowledge is central to intelligence, the performance of ES is primarily a function of the size and quality of the knowledge base it possesses. The facts constitute a body of information that is widely shared, publicly available, and generally agreed upon by experts in the field. The heuristics are mostly private, little discussed rules of good judgement or guesswork that characterize expert-level decision-making in the field. The knowledge must be represented or organized into a suitable form so that the inference engine can readily access it. In order to create a knowledge base for a given problem, the expert's knowledge must be formulated according to the knowledge representation scheme employed by the ES shell. The latter has a debugging facility and represents the knowledge acquisition module. The difference between ES and conventional computer programming can be understood from the following representation:

Data + Algorithm $\rightarrow$ Program

Knowledge + Inference $\rightarrow$ ES.

7.10 Conclusions

With globalization, there is increased need to reduce product lead times. Activities must be performed in parallel (i.e., integrated product development), to ensure that sufficient attention is paid to market needs and manufacturing technologies during the design process for successful product development. Designing of textile products is still based on the traditional techniques, experience, and intuition. This leads to (a) a limited number of experts and their expertise; (b) difficulty in finding a systematic approach for an optimum solution; and (c) increased time and costs. Compared to modelling from first principles and other techniques, computation methods can be a powerful tool to model the nonlinearities and complexities involved in predictions of fabric properties. The system has to be developed to provide scientific databases, overall structure–function relationship, optimization procedures, suitable computer algorithm, and standardization of these algorithms. The successful applications of soft computing in various applications indicate that the impact of soft computing will be felt increasingly in coming years. The employment of soft computing techniques leads to systems which have high machine intelligence quotient (MIQ).

References

- [1] A. Newton, *Fabric Manufacture: A Handbook*, Intermediate Technology Publications, London, 1993.
- [2] A.T.C. Robinson, R. Marks, *Woven Cloth Construction*, The Textile Institute, Manchester, 1973.
- [3] F.T. Peirce, The geometry of cloth structure, *J. Text. Inst.* 28 (3) (1937) T45–T112.
- [4] S. Muttagi, ANN Embedded Expert System for Design of Woven Fabrics, (Ph.D. thesis), IIT Delhi, 2002.
- [5] P.H. Dastoor, H.P. Hersh, S.K. Batra, W.J. Rasdorf, Computer-assisted structural design of industrial woven fabrics, part I: need, scope, background, and system architecture, *J. Text. Inst.* 85 (2) (1994) 85–109.
- [6] J.W.S. Hearle, Fabric mechanics as design tool, *Indian J. Fibre Text. Res.* 19 (1994) 107–113.
- [7] N. Yoshida, et al., Technical report of Fukui Prefecture Technological Center, Japan, No. 9, 1993, p. 55.
- [8] H. Maejima, Technical report of Yamanashi Prefecture Technological Center, Japan, 1995, p. 39.
- [9] M. Ogami, S. Nakamura, *Text Manufac* 43 (2) (1991) 74.
- [10] T. Sakurai, K. Kanemaru, M. Kono, *Text. Manufac.* 43 (2) (1991) 77.
- [11] L. Miller, *Proc Text Inst Annual World Conf*, Hong Kong, (1984) 635.
- [12] T. Kokonoki, T. Tanaka, Technical report of Tochigi Prefecture Text. Ind. Lab., Japan, 1985, p. 75.
- [13] T. Takaoka, T. Kugiya, F. Kosago, Technical report of Yamaguchi Prefecture Technological Center, Japan, No. 5, 1993, p. 55.
- [14] A.V. Della, R. Schettini, *Can Text J* 110 (3) (1993) 27.
- [15] D.C. Rich, *Text. Chem. Color.* 18 (6) (1986) 16.

- [16] D.C. Rich, Proc Natl Tech Conf of Am Assoc Text Chem Color, USA, 1985, p. 36.
- [17] H. Matsuda, Y. Nagata, Y. Arizono, *Fuji Elect. J.* 59 (9) (1986) 626.
- [18] M.A. Hann, G.M. Thomson, *Text. Prog.* 22 (1) (1992).
- [19] M. Osek, B. Koskova, Proc Text Inst Annual World Conf, Hong Kong, 1984, p. 47.
- [20] M. Murai, et al., Technical report of Tokyo Text. Ind. Lab., Japan, No. 34, 1986, p. 27.
- [21] M. Kawarai, et al., Technical report of Tokyo Text. Ind. Lab., Japan, No. 33, 1984, p. 43.
- [22] T. Mukai, Technical report of Yamagata Prefecture Technological Center, Japan, No. 19, 1987, p. 45.
- [23] T. Mukai, Technical report of Yamagata Prefecture Technological Center, Japan, No. 22, 1990, p. 37.
- [24] S. Cao, *J. CTEA China* 5 (3) (1984) 29.
- [25] B. Taylor, *Text. Asia* 20 (11) (1989) 85.
- [26] S. Cao, Proc Text Inst Annual World Conf, Hong Kong, 1984, p. 709.
- [27] Y. Hihuchi, et al., *Jap. Women's Univ. J.* 34 (34) (1987) 71.
- [28] K. Ohta, T. Ishii, A. Nakata, *Text. Mach. Soc. Jpn.* 40 (5) (1994) T103.
- [29] K. Kurihara, K. Kato, Technical report of Tochigi Prefecture Text. Ind. Lab., Japan, 1990, p. 248.
- [30] R. Kaunis, Pattern processing systems for dobby weaving—a review, *Int. Text. Bull. Fabr. Form.* 32 (4/86) (1986) 4.
- [31] K. Nakano, et al., Technical report of Fukui Prefecture Technological Center, Japan, No. 5, 1989, p. 48.
- [32] K. Nakano, et al., Technical report of Fukui Prefecture Technological Center, Japan, No. 3, 1993, p. 108.
- [33] K. Nakano, et al., Technical report of Fukui Prefecture Technological Center, Japan, No. 7, 1991, p. 28.
- [34] W. Aldrich, *Matric Pattern Cutting*, third ed., Blackwell Scientific Publications, London, 1994.
- [35] M.N. Suresh, Conf Proc 24th Text Res Symp, Mt. Fuji, Japan, 1995, p. 127.
- [36] T. Matsuo, *J. Text. Mach. Soc. Jpn.* 39 (4) (1993) 73. English edn.
- [37] J.W.S. Hearle, *Text. Horiz.* 13 (5) (1993) TH15.
- [38] P.D. Dubrovski, M. Brezocnik, *Text. Res. J.* 72 (2002) 187.
- [39] S. Haykin, *Neural Networks: A Comprehensive Foundation*, Macmillan Publishing, New York, 1994.
- [40] J.S.R. Jang, C.T. Sun, E. Mizutani, *Neuro-Fuzzy and Soft Computing*, Prentice Hall of India, New Delhi, 1997.
- [41] D.E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison-Wesley, Boston, MA, 1989.
- [42] Z. Somodi, A. Hursa, D. Rogale, Numerical simulation of textile flexibility testing, *Int. J. Cloth. Sci. Technol.* 15 (3/4) (2003) 276–283.
- [43] D.W. Lloyd, The analysis of complex fabric deformations, in: J.W. Hearle, J.J. Thwaites, J. Amirbayat (Eds.), *Mechanics of Flexible Fibre Assemblies*, Springer, New York, 1980.
- [44] L. Gan, N.G. Ly, A study of fabric deformation using nonlinear finite elements, *Text. Res. J.* 65 (11) (1995) 660–668.
- [45] Y.J. Jeong, T.J. Kang, Analysis of compressional deformation of woven fabric using finite element method, *J. Text. Inst.* (2001) 1–14.
- [46] M. Tarfaoui, S. Akesbi, Numerical study of the mechanical behavior of textile structures, *Int. J. Cloth. Sci. Technol.* 13 (3/4) (2001) 166–175.
- [47] L.M. Sztandera, C. Pastore, *Soft Computing in Textile Sciences*, Springer, New York, 2003.

- [48] R. Chattopadhyay, A. Guha, Artificial neural networks: applications to textiles, *Text. Prog.* 35 (2004) 1–46.
- [49] B.K. Behera, S.B. Muttagi, Performance of error back propagation vis-à-vis radial basis function neural network. Part I: prediction of properties for design engineering of woven suiting fabrics, *J. Text. Inst.* 95 (1–6) (2004) 283–300.
- [50] B.K. Behera, S.B. Muttagi, Performance of error back propagation vis-à-vis radial basis function neural network. Part II: reverse engineering of woven fabrics, *J. Text. Inst.* 95 (1–6) (2004) 301–317.
- [51] B.K. Behera, S.B. Muttagi, Comparative analysis of modeling methods for predicting woven fabric properties, *J. Text. Eng.* 51 (1) (2005).
- [52] B.K. Behera, S.B. Muttagi, Engineering design of polyester-viscose blended suiting fabrics using radial basis function network: Part I—prediction of fabric low stress mechanical properties, *Indian J. Fibre Text. Res.* 31 (2006) 401–408.
- [53] B.K. Behera, S.B. Muttagi, Engineering design of polyester-viscose blended suiting fabrics using radial basis function network: Part II—prediction of fabric constructional parameters from its properties, *Indian J. Fibre Text. Res.* 31 (2006) 489–495.
- [54] B.K. Behera, S.B. Muttagi, Artificial neural network embedded expert system for design of woven suiting fabrics, Part I, *Ind. Text.* 21 (2) (2006). both in English and Romanian.
- [55] B.K. Behera, S.B. Muttagi, Artificial neural network embedded expert system for design of woven suiting fabrics, Part II, *Ind. Text.* 21 (2) (2006). both in English and Romanian.
- [56] L.A. Zadeh, Fuzzy sets, *Inf. Control.* 8 (1965) 338–353.
- [57] T. Takagi, M. Sugeno, Fuzzy identification of systems and its application to modelling and control, *IEEE Trans. Syst. Man Cybern.* SMC 15 (1) (1985) 116–132.
- [58] M. Raheel, J. Liu, *Text. Res. J.* 61 (1991) 31.
- [59] S.W. Park, Y.G. Hwang, *Text. Res. J.* 69 (1999) 19.
- [60] Y. Chen, B. Collier, P. Hu, D. Quebedeaux, *Text. Res. J.* 70 (2000) 443.
- [61] C.C. Huang, W.H. Yu, *Text. Res. J.* 69 (1999) 914.
- [62] B.K. Behera, Image Processing Applications in Textiles, *Text. Prog.* 35 (2/3/4) (2004) 1–193.
- [63] J.J. Lin, *Text. Res. J.* 77 (2007) 336.
- [64] R. Beltran, L. Wang, X. Wang, *Text. Res. J.* 75 (2005) 557.
- [65] C.L. Hui, T.W. Lau, S.F. Ng, K.C.C. Chan, *Text. Res. J.* 74 (2004) 375.
- [66] T.W. Shyr, J.Y. Lin, S.S. Lai, *Text. Res. J.* 74 (2004) 354.
- [67] T.W. Shyr, S.S. Lai, J.Y. Lin, *Text. Res. J.* 74 (2004) 528.
- [68] A.S.W. Wong, Y. Li, P.K.W. Yeung, P.W.H. Lee, *Text. Res. J.* 73 (2003) 31.
- [69] B.K. Behera, R. Mishra, Objective measurement of fabric appearance using digital image processing, *J. Text. Inst.* 97 (2) (2006) 147–153.
- [70] B.K. Behera, R. Mishra, Artificial neural network based prediction of aesthetic and functional properties of worsted suiting fabrics, *Int. J. Cloth. Sci. Technol.* 19 (5) (2007) 259–276.
- [71] Z. Michalewicz, Genetic Algorithms + Data Structures = Evolution Programs, third ed., Springer-Verlag, New York, 1996.
- [72] W. Jasper, J. Joines, J. Brenzovich, *J. Text. Inst.* 96 (2005) 43.
- [73] A.E. Amin, A.S. El-Gehani, I.A. El-Hawary, R.A. El-Beali, *Autex Res. J.* 7 (2007) 80.
- [74] M. Blaga, M. Draghici, *J. Text. Inst.* 96 (2005) 175.
- [75] J.J. Lin, *Text. Res. J.* 73 (2003) 105.
- [76] D. Grundler, T. Rolich, *Text. Res. J.* 73 (2003) 1033.
- [77] P.C.L. Hui, F.S.F. Ng, K.C.C. Chan, *Int. J. Cloth. Sci. Technol.* 12 (2000) 50.
- [78] K.C.C. Chan, C.L. Hui Patrick, K.W. Yeung, F.S.F. Ng, *Int. J. Cloth. Sci. Technol.* 10 (1998) 21.

- [79] S. Inui, *Sen'i Gakkaishi* 50 (1994) 593.
- [80] Y.H. Liang, *Int. J. Qual. Reliab. Manag.* 25 (2008) 201.
- [81] N. Ozturk, *Eng. Comput.* 20 (2003) 979.
- [82] A.S.W. Wong, Y. Li, P.K.W. Yeung, *Text. Res. J.* 74 (2004) 13.
- [83] D.A. Waterman, *A Guide to Expert System*, Addison-Wesley, London, 1986.
- [84] F. Hayes-Roth, D.A. Waterman, D.A. Lenat, *Building Expert System*, Addison-Wesley, London, 1983.
- [85] R. Forsyth, *Expert System*, Chapman and Hall, London, 1984.

3D woven fabrics, structures, and methods of manufacture

8

M. Amirul "Amir" Islam

Bally Ribbon Mills, Bally, PA, United States

8.1 Introduction: 3D woven fabrics and structures

Three-dimensional (3D) fabrics and textile structures have been used in various industries, such as aerospace, NASA, medical, automotive, armoured vehicles, marine, boat and shipbuilding, construction, wind energy, electronic textiles (E-textiles), smart textiles wearable, and other industrial applications. The aerospace and other industries have been using three-dimensional (3D) structures for some time. Putting several plies of fabrics on top of one another, cutting them into shapes, and stitching them together were the original methods of forming 3D structures. These techniques are labour intensive, time consuming, and expensive. Moreover, the fibres are damaged due to stitching, and the joints are weak because no continuous fibres run through the inter-sections. Current 3D structures are generally created by weaving, using a specially built loom, braiding, knitting, filament winding, and pultrusion, amongst other methods. In this chapter, only those 3D structures created using a loom, loom mechanisms, and specially built machines are discussed.

The term 'yarn' is commonly used to describe both warp and fill (weft) in a regular woven fabric. In a 3D woven composite structure, it is preferable to use the fibre tows without any twist. The term 'fibre tows' is used to refer to the fibre throughout this chapter. The warp yarns or fibre tows are referred to as '0degree' or 'X direction fibres' or as 'machine directional fibres'. Warp yarns or fibre tows numbers are expressed in ends per inch. The weft yarns or fibres are called 'fill fibres'. The fill yarns or fibre tows are referred to as 'Y direction fibres' or '90degrees fibres'. Fill yarns or fibre tows numbers are expressed in picks per inch. The yarns or fibre tows through-the-thickness are referred to as 'Z direction fibres' in this chapter.

8.1.1 Definition of 3D fabrics and structures

There are various definitions of 3D fabrics and structures because researchers and scientists differ in their opinions [1–4]. In this chapter, any fabrics which take the shape of three dimensions are considered to be 3D fabrics. Woven structures with substantial thicknesses, thick structures, orthogonal structures or, which have been made using standard loom or special loom mechanisms and any woven three-dimensional shaped structures, are considered to be 3D woven structures in this chapter. Layers are also referred to as 'ply' in the composite industries.

8.1.1.1 3D fabrics

3D fabrics may be classified as:

- Single layer fabrics with an overall 3D shape
- Multilayers flat fabrics
- Contour fabrics
- Spacer fabrics
- Shell fabrics
- Tubular fabrics (straight, bifurcate, tapered, or flared)

8.1.1.2 3D woven structures

3D woven structures may be classified as:

- Solid panel (layer to layer, orthogonal, angle interlock, and combination weaves)
- Load-bearing joints, such as T, Tapered T, X, Cruciform, double cruciform, Pi, Tapered Pi, Intersecting Pi, I-beam, or single and double blade joints
- Fillets (noodle)
- Polar structures/spiral/arched structures
- E-textile structures
- Hollow structures
- Spacer preforms, such as truss core, double truss core
- Complex structure

8.1.2 Various 3D fabrics and structures

Various new applications have been found for three-dimensional woven fabrics and structures and composites made from 3D fabrics; panels and preforms are being increasingly used in aerospace, medical, automotive, armoured vehicles, marine, boat and shipbuilding, construction, wind energy, E-textiles, and industrial applications.

8.1.2.1 3D fabrics

There are many 3D fabrics and structures, a few of which are shown in this chapter. [Fig. 8.1](#) shows a 3D fabric made from carbon fibres. This fabric was made up of six layers. Each layer was connected with the next by a layer-to-layer interlock weave based on satin weave as shown in [Fig. 8.55](#). The fabric was drapable and formed three dimensions without wrinkles. A rapier loom was used to weave this fabric, as shown in [Fig. 8.1](#).

A contour fabric is shown in [Fig. 8.2](#). This fabric, made of carbon fibres and woven on an Iwer (rapier) loom, was made into a composite for a jet engine. Contour weaving technology was used for the circumferential frame applications. Contour fabrics take the shape of the contours they are based on, meaning that they fit well, not only on cylindrical surfaces with different diameters, but also on flanges and complex curvatures. Regular fabrics do not fit so well on the contour surfaces and tend to wrinkle. When infused with resin, contour fabrics also make good composite parts. When used

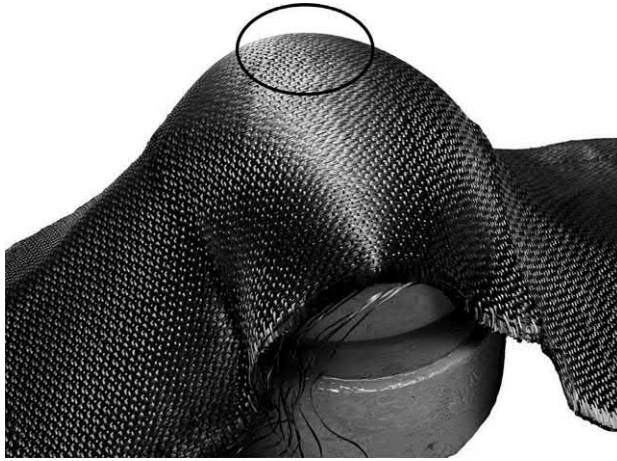


Fig. 8.1 Three-dimensional fabric.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

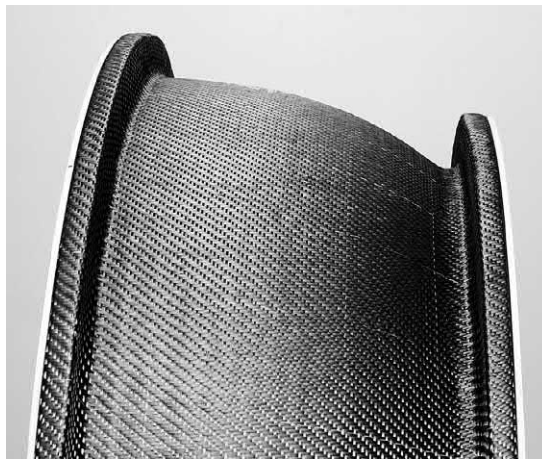


Fig. 8.2 Contour fabric.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

in this way, it is important that the warp and fill fibres align close to 0 degree/ 90 degrees without much angle variation.

Contour Weaving: It is based on the same principles as standard weaving except that the take-up mechanism is modified to accommodate the different lengths of the warp fibres based on the configuration of the contour fabric. The take-up rate of the warp fibres remains the same along the whole width when weaving a regular fabric, which is why they will not conform to curvatures without cutting or darning them. When weaving a contour fabric, the length of every single warp fibre is

calculated based on the specified configuration, and the take up is adjusted accordingly to achieve the right fibre length and orientation. Contour fabrics can therefore easily conform to curvatures without wrinkling.

Contour weaving technology can be used for stiffener and aircraft engine fan blade containment. Aramid fibres are usually used for the latter. The benefits of contour weaving technology are as follows:

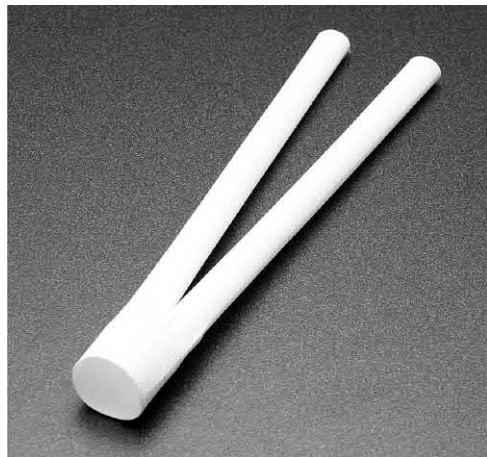
- Reduced manufacturing costs since there is no manual cutting or darting.
- Wrinkles are eliminated.
- Warp and fill are aligned close to 0 degree/90 degrees without much angle variation.
- Continuous and consistent parts are produced.
- Both convex and concave profiles can be created.
- Structures can be made in small scale without a full-scale configuration.

Various processes, such as resin transfer moulding (RTM), vacuum-assisted resin transfer moulding VARTM, and resin film infusion (RFI) can be used to make composite parts.

Tubular fabrics for medical applications

Tubular fabrics are being used for many medical applications, such as vascular grafts, stents, and penile grafts. Fig. 8.3 shows a bifurcate woven vascular graft produced using 40 denier polyester yarns in both warp and fill. There are many types of vascular grafts, such as straight graft, straight bifurcate graft, tapered and flared grafts; etc. A stent is shown in Fig. 8.4. Many woven 3D fabrics and structures using polyester, polyester/spandex, Teflon, poly-tetra-fluoro-ethylene (PTFE), Spectra, Dyneema fibres, and Nitinol wires are being used as implants in the human body [7]. There are a lot of people in the world who have erectile dysfunction (ED). Older people are living their normal sexual life due to penile implants. The people who have diabetes cannot use the tablets, and they have to get the penile implants.

Fig. 8.3 Bifurcate woven graft.
Courtesy of Bally Ribbon Mills, Bally,
Pennsylvania 19503, USA.



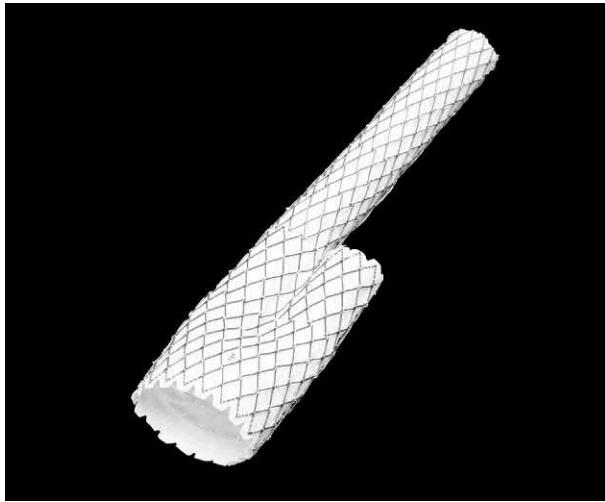


Fig. 8.4 Stent.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

8.1.2.2 3D woven structures

Solid panels

Bally Ribbon Mills has been working with NASA on their woven thermal protection systems (TPS).

- Heat shield for Extreme Entry Environment Technology (HEEET) Program. HEEET is developing a mass-efficient, dual-layers carbon/phenolic system tailored for planetary probe missions for potential Discovery and New Frontiers class missions.
- 3D Woven Multifunctional Ablative Technology (3D-MAT), structural ablative material for the Orion compression pad. Orion compression pads are the interface between Crew Module (CM) and Service Module (SM) to withstand launch and ascent structural loads, pyro-shock (CM & SM separation event), and earth re-entry (high heating, ablation). 3D-MAT is a structurally robust 3D woven Quartz fibres panel with Cyanate Ester resin to meet the needs of the Orion Exploration Mission compression pad. As per NASA, it was scheduled to begin flying in 2018.
- Adaptable Deployable Entry and Placement Technology (ADEPT). The objective of ADEPT is to develop a semirigid low-ballistic coefficient aeroshell entry system concept to perform and entry-descent landing (EDL) functions for planetary missions. This concept would be used to safely deploy scientific payloads or enable long-term exploration to other planets with their associated cargo needs.

Fig. 8.5 shows components of Orion multipurpose crew vehicle. 75 mm thick 3D-MAT Quartz panel is shown in Fig. 8.6.

Fig. 8.7 shows a 3D woven panel of 50 mm thick made from AS4 12K carbon fibres. Orthogonal weave architecture has been used for this panel. 3D orthogonally woven structures consist of noninterlaced reinforcing fibres that generally orient perpendicular or nearly perpendicular to each other in the X, Y, and Z directions. The orthogonally woven structures offer superior mechanical properties and corrosion



Fig. 8.5 Component of Orion multipurpose crew vehicle [8].



Fig. 8.6 Seventy-five-millimetre thick 3D MAT Quartz panel.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

resistance after infusing resin into a composite. The panel as shown in Fig. 8.7 has 61 layers of warp, 62 layers of fill and Z fibres. The typical fibre volume of the panel is around 55%, and X, Y, Z fibre volume fraction are around 40%, 40%, and 20% respectively. The typical Z fibre volume fraction can vary from 3% to 33% depending on the performance requirements of end use.

The panels can be woven using different fibres in each direction (X, Y, and Z). The fibre concentrations in each direction can be varied to achieve desired fibre volume fraction. The different fibres also can be used in the same direction or other directions. The hybrid panel can easily be made. X and Z fibres can be the same fibres, and the fill fibre is a different fibre. The different fibres can be used in different layers even in

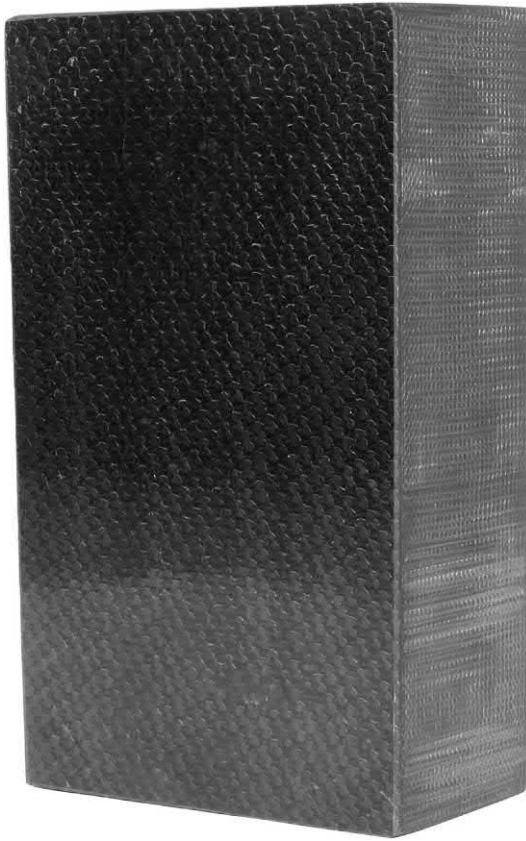


Fig. 8.7 Fifty-millimetre thick 3D orthogonal carbon panel. Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

X direction. The layout of fibres in various layers is decided based on the performance requirements of the finished panel. A 50 mm thick Quartz panel is shown in Fig. 8.8, where Quartz fibres have been used in all three directions.

Fig. 8.9 shows 50 mm thick 3D Orthogonal Pitch Panel. It is difficult to weave a thick panel using all pitch carbon fibres due to poor bending properties of pitch fibres. Pitch fibres are therefore generally served with rayon or polyvinyl alcohol (PVA) fibres, which can withstand the friction and abrasion during weaving. The term ‘serving’ is used to describe the process of wrapping the core fibres with another fibre. In this case, the pitch fibres were wrapped with rayon. The selection of fibres, fibre volume, and fibre volume fraction are determined by the performance requirements of the end product.

Load-bearing joints

Fig. 8.10 shows a T structure made from carbon fibres. Each flap consists of four layers, and all four layers are connected by layer-to-layer interlock weave. IM7-12K carbon fibres were used. A tapered T was woven with tapering all three sides.



Fig. 8.8 Fifty-millimetre thick 3D orthogonal Quartz panel.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.



Fig. 8.9 Fifty-millimetre thick 3D orthogonal pitch panel.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

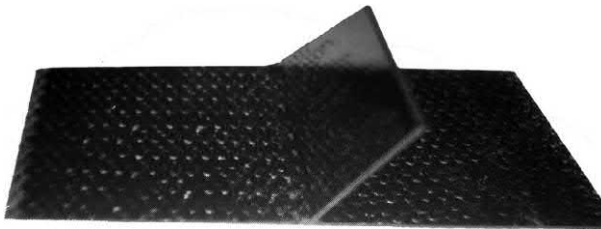


Fig. 8.10 T structure.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

This tapering was created by dropping one layer at a time. A narrow fabric shuttle loom was used to weave the T structure.

A 3D loom [4] was used to weave this T-bar profile (see Fig. 8.11). The mechanism of this machine is discussed later.

Figs 8.12 and 8.13 show a single blade joint and double blade joint. In both cases, IM7-12K carbon fibres were used, and the layers were connected using a layer-to-layer interlock weave based on the plain weave. A narrow fabric shuttle loom was used to weave both structures.



Fig. 8.11 T-bar profile.

Courtesy of Biteam AB, Gothenburg, Sweden.

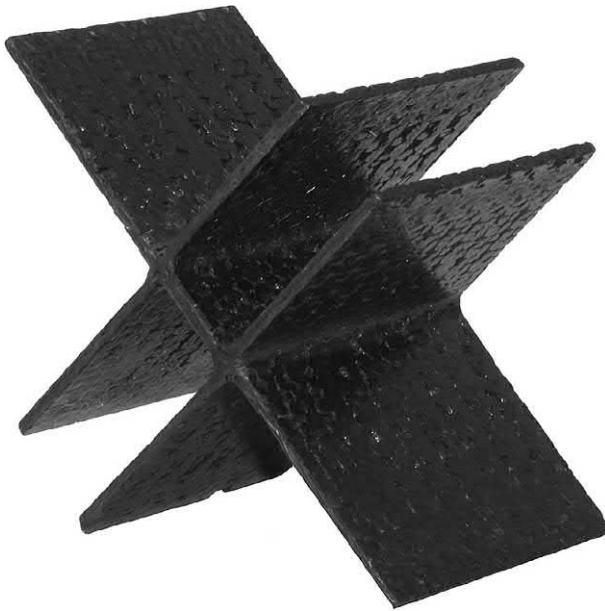


Fig. 8.12 Single blade joint structure without tapering.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

A cruciform structure is shown in [Fig. 8.14](#). The 100% fill fibre of each flap goes through the intersection. Each flap consists of four layers, and again they are connected by layer-to-layer interlock weave based on a plain weave. The typical construction of each layer is 16×16 ends and picks per inch in the case of 6K carbon fibres and 16×8 ends and picks per inch in the case of 6K carbon warp fibres and 12K carbon fill fibres. A double cruciform with all sides tapered also was woven using a modified narrow fabric shuttle loom.



Fig. 8.13 Double blade joint without tapering.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.



Fig. 8.14 Cruciform structure.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

An I-beam is shown in [Fig. 8.15](#). This I beam was woven using carbon fibres and carbon rods. The I-beam can be used as structural elements of aircraft fuselage.

A typical Pi structure with all sides tapered is shown in [Fig. 8.16](#). This Pi structure was woven from 6K and 12K IM7 carbon fibres. The base and clevis are eight layers and upright legs are four layers. A layer-to-layer interlock weave was used. IM7-6K carbon fibre as warp and IM7-12K carbon fibre as fill were used at the base, and IM7-12K carbon fibres were used as both warp and fill for the upright legs. The construction of each layer consisted of 16×9 ends and picks per inch. The gradual tapering was achieved by terminating one layer at a time.

The Pi structure had been woven from carbon, fibreglass, ceramic fibre, silicon carbide, and even from metallic wires at Bally Ribbon Mills. This Pi structure has been



Fig. 8.15 I-beam structure.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

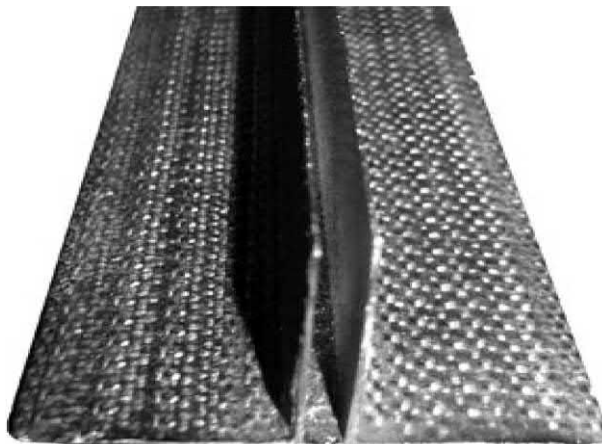


Fig. 8.16 Pi structure.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

patented [9, 10], and it is widely used in the aerospace industry for structural joints. The base, clevis, and upright legs of the Pi structure can consist of any combination of layers based on the performance requirements.

The Pi and double cruciform structures designed Bally Ribbon Mills were used in the NASA Composite Crew Module (CCM) [11]. One of the significant benefits of 3D woven joints [5, 6] over traditional metallic structures is that they can be easily formed into complex shapes that may be structurally efficient.

An intersecting Pi structure is shown in Fig. 8.17. This intersecting Pi preform was woven as one piece in a modified narrow fabric shuttle loom. Each flap consists of four

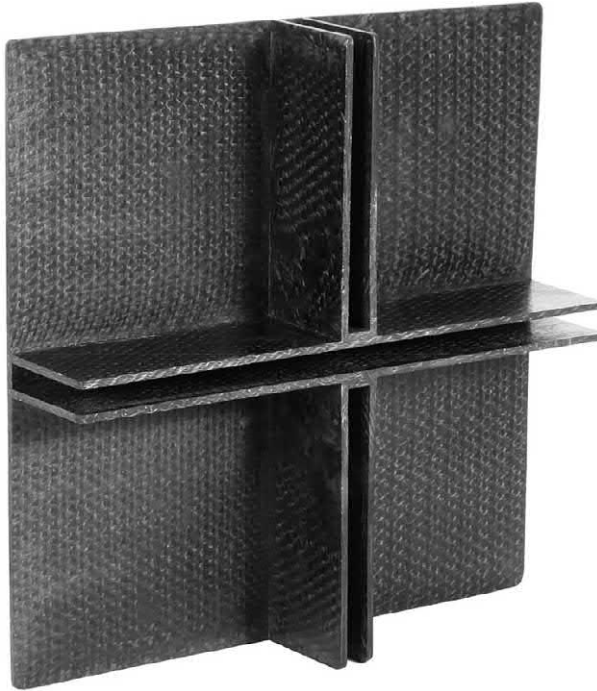


Fig. 8.17 Intersecting Pi structure.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

layers, and they are connected by layer-to-layer interlock weave. IM7-12K carbon fibres were used. All sides of this intersecting Pi were woven edges.

Fillets (noodles) Fig. 8.18 shows a solid model of a fillet, and a woven carbon fillet (noodle) is shown in Fig. 8.19. A bifurcate carbon fillet (noodle) is shown in Fig. 8.20. These fillets are used at joints to avoid resin-rich areas.

Polar structures/spiral/arched structures

Polar/spiral weaving One 3D weaving technique, which forms a two-dimensional (2D) flat fabric into a three-dimensional shape is called polar weaving. A typical polar woven material is shown in Fig. 8.21. The solid model of a typical polar structure is shown in Fig. 8.22. The polar weaving process modifies the typical orthogonal (0 degree, 90 degrees) fibre orientation of a woven product and produces a circular woven material, with the fibres orientated in the circumferential (hoop) and radial directions. The material produced on a loom, modified for polar weaving, produces a continuous woven cloth with a set inner and outer diameter. When producing polar woven material, the polar woven material will spiral on top of itself like a spring and make a thick wall cylinder. The thickness of the cylinder will depend on the thickness of each polar woven layer and the number of layers making the cylinder.

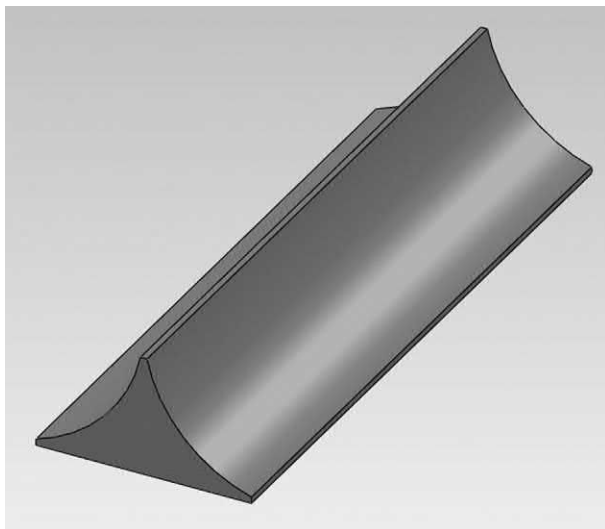


Fig. 8.18 Solid model of a fillet.



Fig. 8.19 Carbon fillet (noodle).

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.



Fig. 8.20 Carbon bifurcate fillet (noodle).

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

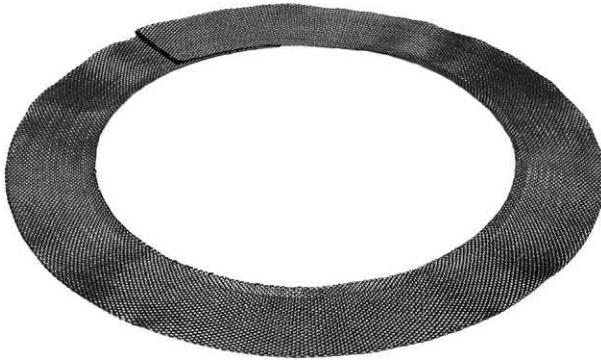


Fig. 8.21 Typical polar structure.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

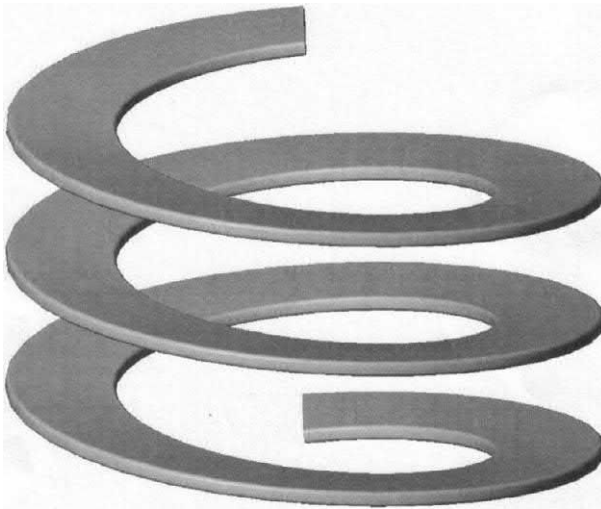


Fig. 8.22 Solid model of a typical polar structure.

Since the fill fibre is orientated in the radial direction, the material has a gradient from inside diameter (ID) to outside diameter (OD) and the fabric areal weight and material thickness will decrease from inner diameter to outer diameter. 3D multilayers Silicon Carbide woven polar material is shown in [Fig. 8.23](#) with a very small ID (inside diameter) and a large OD (outside diameter).

Several variations of polar weaving have been developed to make more complex shapes or preforms. [Fig. 8.24](#) shows a curved T structure. One variation incorporates traditional orthogonal weaving with polar weaving (or Ortho/polar weaves), which produces a single woven material with a section of orthogonal woven and another section with a polar weave creating a cylinder with a flanged end. The polar/spiral woven

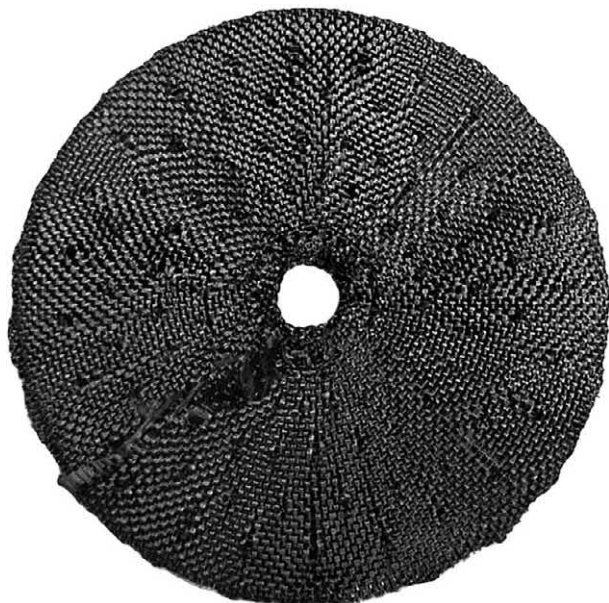


Fig. 8.23 Silicon carbide polar structure.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.



Fig. 8.24 Curved T structure.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.



Fig. 8.25 Polar/orthogonal structure.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

material change the typical 0 degree/90 degrees woven materials into a circular structure with hoop and radial fibre alignment. The polar/ortho woven materials allow the woven materials to include sections of orthogonally woven (0 degree/90 degrees) and polar woven (hoop/radial) material into a single profile which rotates around a single axis of rotation. Fig. 8.25 shows a polar/orthogonal structure.

A modified polar/spiral weave technology was used to weave an aircraft window frame. A composite window frame is shown in Fig. 8.26. The window frame weaving technique was developed [12] to overcome the limitation of contour weaving. The window frame technique will allow weaving flanged 'L' preforms. The upright section of the L preform will always remain orthogonal, but the flanged section of the L preform changes from polar to orthogonal and back to polar. This technique will also allow weaving of rectangular or square flanged preforms with a corner radius.



Fig. 8.26 Composite window frame.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

E-textiles

The electronic textiles (E-textiles) may be defined as textiles with electronic properties.

E-textiles are found in the following applications [12–15]:

- Wearable technology
- Fitness and wellness
- Personal protection application
- Military and defence application
- Antenna application
- Space (NASA/European Space Agency)
- Telemedicine and sports health
- Professional sports
- Medical/ageing population/health care trends
- Sleep apnea monitoring system
- Infotainment
- Fashion
- Industrial and Commercial
- Others

Various sensors [16] can be integrated with textiles, such as:

- ECG (heart rate, heart rate variability, heart activity)
- EEG (brain activity)
- EMG (muscle activity)
- Bio-impedance (body composition, lung activity, dehydration)
- SCR (skin conductivity, emotions, activity)
- Temperature
- Inductive/capacitive (heart rate, muscle activity)
- Accelerometers (motion, postures)
- Optical sensors (heart rate, blood oxygen level)
- Acoustics (joint fatigue, heart rate)
- Pressure sensors
- Gas sensors
- Biosensors
- Humidity sensors

Many companies are working on wearable technology on a textile platform. Wearable technology covers textiles and wearable accessories that incorporate advanced electronic technologies. The wearable technologies are textile based and nontextile based. The market growth of wearable technology is tremendous.

The integration of electronics to wearable technology on textile platform requires a multidisciplinary approach which includes expertise in the fields of materials, textiles, mechanical, electrical and electronics, and information technology. The electrical conductivity can be integrated into textiles platforms in many ways [17–20]:

- Conventional electronic elements like resistors or integrated circuit chips attached to the garments/uniforms or textile substrate
- Flexible and stretchable electronics can be integrated into textile substrate.

- Conductive fibres and yarns, E-textile yarns are used in the textile substrate during manufacturing.
- Complex electronic geometrical patterns can be incorporated into textile substrate by hand stitching.
- E-textiles circuit construction can be made using conductive threads/yarns by embroidery techniques.
- Conductive ink may be applied to textile substrates by various printing techniques, such as screen printing, ink-jet printing, flexo printing, gravure printing, other printing types (nano imprinting/embossing, transfer printing). Conductive ink and stretchable conductive ink are available from Du Pont.
- Conductive coating, conductive films, and/or vapour deposition
- Textile circuitry (circuits incorporated into a textile platform)

Conductive fibres and yarns Conductive fibres are usually made by spinning a fibre having an electrically conductive sheath of thermoplastic polymer formulated with carbon black and a nonconductive core from the thermoplastic polymer. Conductive fibres are a cross between the world of electric wires and the world of textiles, with attributes of each. Conductive fibres consist of a nonconductive or less conductive substrate, which is then either coated or embedded with electrically conductive elements. Substrate fibres typically include cotton, polyester, nylon, and stainless steel to high performance fibres such as aramids, HDPE, PBI, PBO, PTFE, carbon nanotubes, and so on.

The conductive fibres plied and or twisted with a nonconductive fibre can also form conductive yarns. E-textile yarns [17] can be made by using insulated copper wires wrapped around a cotton/nylon/polyester core yarn that demonstrates electrical and mechanical properties. The conductive yarns and fibres are replacing traditional heavy solid or twisted wires which are too fragile and break down after repeated bends.

The conductive yarns and fibres are rapidly becoming the smart choice for engineers and designers in a variety of areas, such as, aircraft, military and defence applications, space, smart textiles for personal protection, health and sports, EMI shielding, and much more.

There are many conductive fibres and yarns available. Conductive Fibre Manufacturing Council (CFMC) [21] has published a Manufacturer and Product Directory. A full list of conductive fibres can be seen by going to CFMC website (<http://cfibermfg.com>). The Conductive Fibre Manufacturers Council (CFMC) is the international trade and business development resource for companies that manufacture conductive yarns, threads, and fibres. The mission of CFMC is to increase understanding and utilization of conductive fibres and fabrics through information dissemination, advocacy, research, and administration of programmes to the members' benefit and the advancement of their industries.

Shakespeare's [22] (Jarden Applied Materials) patented carbon suffusion process chemically saturates the outer skin of nylon or polyester fibre with electrically conductive carbon particles. The carbon becomes part of the structure of the fibre, which retains the strength and flexibility of the nylon or polyester while maintaining excellent conductivity. These characteristics make it ideal for mechanical, chemical, and thermal manufacturing processes. Their suffusion process produces a fibre with a

durable, conductive sheath that will not crack, flake, or lose its conductivity during flexing or extension. Jarden Applied Materials' Resistat fibres are available as monofilaments, multifilament yarns, tow, staple, and supported yarn configurations.

R.STAT's [23] silver suffusion process makes polyamide fibres conductive and antibacterial. The layer of silver enables the synthetic fibre to keep its main original textile characteristics. Polyamide (R.STAT/N) or polyester (R.STAT/P) fibres are made conductive with a thin layer of metallic salt (copper sulphide) suffused into the polymer. This thin layer of copper sulphide does not modify the textile characteristics of the original polymer.

Textro-Yarns produced by Textronics [24] are elastic, highly conductive yarns with constant and high conductivity over a wide range of elongation. Textro-yarns are used for apparel heating, wearable electronics and lighting, power conduits, electrodes, EMI shielding, and textile antennas. Textronics can produce elastic conducting yarns with various physical and electrical properties.

Straddling the worlds of textiles and wires, conductive fibres are sold either by weight or length, and measured in denier and AWG (American wire gauge). Nanowires are often included in the definition of conductive fibres either because nanotechnology is used by some conductive fibre producers, or because the nanowires constitute an electrical conduction means which does not fit the conventional definition of a wire.

Conductive fibres or yarns can be woven, knit, embroidered, braided, sewn, etc., thus becoming conductive textiles. When woven into or sewn on to a tape, stranded or braided, or connected between two points, conductive yarns act like wires. When knit or woven in a mesh, the yarns act as an EMI (electro-magnetic interference) shield or a ground plate.

Uses for conductive fibres and textiles may include static dissipation, as a germicide, EMI shielding, radio frequency antennas, signal and power transfer in low resistance versions, and as a heating element in higher resistance versions. Their benefits over solid or stranded metal wires come from conductive fibres' flexibility and ability to use in existing textile machinery (weaving, sewing, braiding, etc.). The conductive fabric can also be used to make electrodes for EEG; in other medical applications, such electrodes were used in a commercially available sleep monitoring device.

Multilayer fabrics or 3D fabrics are often necessary to integrate electronics into textiles. E-textile antenna are multilayer interwoven panels, and each layer depends on the other to work properly. The 3D fabrics are also necessary for nodes and network configurations.

Electrically conductive pattern (E-textile circuit) Scientist of NASA Johnson Space Center [20] demonstrated flexible, electrically conductive patterns on textile substrate for many applications including high-speed digital circuits, antennas, and radio frequency (RF) circuits. E-textile circuit can be constructed using conductive threads by embroidery, but embroidery conductive threads do not provide sufficient surface conductivity for many high speed digital and RF applications. E-textiles circuit can be made by selecting woven conductive and nonconductive fabric layers. The woven conductive layer should have established surface conductivity specifications.

Dielectric constant, loss tangent, and thickness are some of the parameters to be considered for the nonconductive fabric layer. The circuit design of the conductive fabric layer is secured onto a nonconductive fabric layer using sewing, embroidery, adhesive means, and/or 3D weaving. Embroidery conductive threads do not provide sufficient surface conductivity for many high speed digital and RF applications. Multilayer circuits can be built using conductive threads to make electrical connections between layers.

A review [19] on smart fabric sensors and E-textile technologies summarizes the basic principles and approaches employed when building fabric sensors as well as most commonly used materials and techniques used in E-textiles. The paper [19] identified three categories of smart fabric transducers (SFT):

Sensors: Fabrics with sensing properties of diverse physical properties, such as capacitive, resistive, optical, and solar

Actuators: Fabrics able to actuate or move some aspect of their environment, such as electroactive and auxetic fabrics

Batteries and energy harvesting: Fabric-based batteries and fabrics which use the kinetic energy or the thermal energy of the wearer or their environment to generate electric power

Clothing + (Jabil Circuit Inc.) is one of the largest providers of textile-integrated electronics. Clothing + developed a heart-rate sensor shirt and heart-rate sensor strap. Adidas also has developed a heart-rate sensor shirt for Elite team system.

Tapes, webbings, and 3D preforms for E-textiles applications Conductive tapes, webbings, fabrics, and 3D preforms are being used for E-textiles applications.

Fig. 8.27 shows conductive tapes. The conductive threads (nylon core with carbon black) have been used with regular polyester yarn as warp, and plied yarn of conductive threads with polyester has been used as fill. The conductive tape meets the resistivity specification of $2K-100K \Omega/in$.

Static electricity is generated at the surface of two substrates, and it creates a discharge, ultimately creating spark. The effects of spark are uncomfortable electric shocks, malfunction of electric devices, and might be fire or explosions. These conductive tapes are being used to neutralize the static electricity.



Fig. 8.27 Conductive tape.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.



Fig. 8.28 Elastic webbing with cable.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

Fig. 8.28 shows elastic webbing with cable. This webbing is used for undersea communication. This elastic webbing with cable is woven in a loom at the same time.

Fig. 8.29 shows a tape with fibre-optics. The fibre-optic as warp and polyester as fill were used.

The tape has been used as a light emission tape.

A conductive 3D webbing is shown in Fig. 8.30. The ground warp is the conductive threads of carbon black with nylon core. The fill is the polyester monofilament. When the top and bottom layer comes together, it works as a 'on and off' switch.

Top view of 3D woven E-textile antenna is shown in Fig. 8.31. Conductive patch of stainless steel and U shaped slot are shown at the top. The challenge inherent to many advanced communication and navigation applications is achieving wideband operation from a single antenna. One such antenna architecture which is capable of achieving the types of bandwidth required is the slotted patch antenna. This antenna used a thick substrate (~ 1.5 cm) and the U shaped slot in order to increase the bandwidth.

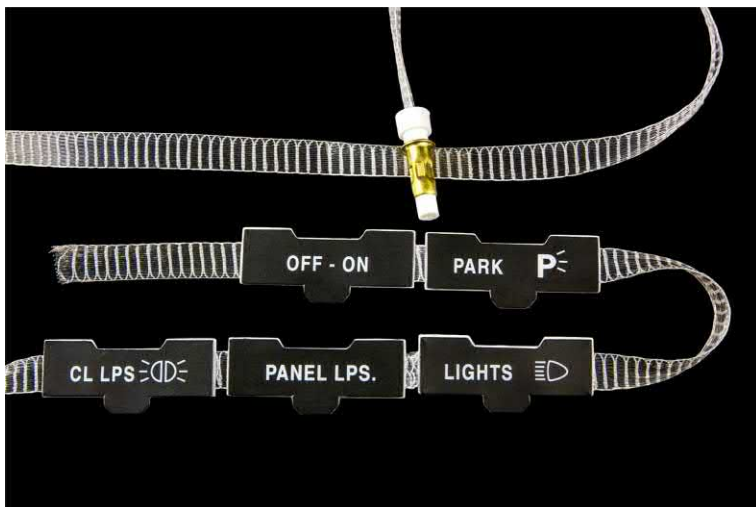


Fig. 8.29 Fibre-optic tape.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.



Fig. 8.30 Conductive webbing with interlinking.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.



Fig. 8.31 E-textile antenna.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

Fig. 8.32 shows a conductive layer of stainless steel on the face of the lower spacer of E-textile antenna. This E-textile antenna was woven with Quartz fibre spacers, conductive stainless steel, conductive stripline, and conductive patch with Quartz fibre.

Research [12] showed that the performance of the E-textiles antenna equalled that of antenna produced by conventional methods while the cost and weight were significantly reduced. This technology using textile components and methods allows a microwave and an ultra-high frequency antenna. These antennas can be used on a variety of projects to realize battlefield wireless antenna or to incorporate antenna into airframes or vehicles. E-textile antenna could be incorporated into composite structures during the manufacturing process. The use of composite antenna encapsulation allows radar and communications antenna to be incorporated into airframes and ship hulls in a manner not before possible. This advanced E-textile based antenna process



Fig. 8.32 E-textile antenna.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

can find application in the incorporation of antennas and other microwave circuits into UAV's and vehicles. Government and commercial application of this technology include the incorporation of these wireless antennas into uniforms, truck covers, tents, and seats. They can stitch onto carpets, ceiling tiles, and headliners as well as tapestries and many other textile products that surround us every day.

Researchers [25] from North Carolina State University have developed a new, stretchable antenna that can be incorporated into wearable technologies, such as health monitoring devices. "Many researchers – including our lab – have developed prototype sensors for wearable health systems, but there was a clear need to develop antennas that can be easily incorporated into those systems to transmit data from the sensors, so that patients can be monitored or diagnosed," says Dr. Yong Zhu, an associate professor of mechanical and aerospace engineering at NC State and senior author of a paper describing the work. The researchers wanted to develop an antenna that could be stretched, rolled, or twisted and always return to its original shape because wearable systems can be subject to a variety of stresses as patients move around. To create an appropriately resilient, effective antenna, the researchers used a stencil to apply silver nanowires in a specific pattern and then poured a liquid polymer over the nanowires. When the polymer sets, it forms an elastic composite material that has the nanowires embedded in the desired pattern. This patterned material forms the radiating element of a microstrip patch antenna. By manipulating the shape and dimensions of the radiating element, the researchers can control the frequency at which the antenna sends and receives signals. The radiating layer is then bonded to a 'ground' layer, which is made of the same composite, except it has a continuous layer of silver nanowires embedded.

The researchers [25] also learned that, while the antenna's frequency does change as it is stretched (since that changes its dimensions), the frequency stays within a

defined bandwidth. The researchers claim that it will still communicate effectively with remote equipment while being stretched. In addition, it returns to its original shape and continues to work even after it has been significantly deformed, bent, twisted, or rolled. As the frequency changes almost linearly with the strain, the antenna can be used as a wireless strain sensor as well. "Other researchers have developed stretchable sensors, using liquid metal, for example," Zhu [25] says. "Our technique is relatively simple, can be integrated directly into the sensors themselves, and would be fairly easy to scale up." The work on the new, stretchable antenna builds on previous research from Zhu's lab to create elastic conductors and multifunctional sensors using silver nanowires.

Fig. 8.33 shows three-strand conductive webbing for current and or signals for integration into garments or as external cabling for headsets, mobile phones, USB, etc. Conductivity has been added to this webbing; whereas, the traditional textile properties, such as, softness, flexibility, strength, surface texture, colour fastness and washability are preserved. The outer material is polyester, and there are three conductors of Litz wires. Each conductor consists of 14 copper single coated threads wrapped around polyamide core. The resistance is $0.4\Omega/\text{m}$. The webbing is attached with a hot melt process to a standard jack connector or washable connector depending on the garment or application.

Fig. 8.34 shows four-strand conductive elastic webbing for current and or signals for integration into garments or as external cabling for headsets, mobile phones, USB, etc. The elastic webbing offers the properties of elastics as a new design element. Wiring inside the textile webbing is polyurethane-insulated Litz-wire in a wavy form to allow elongation and retraction. The outer material is polyester and there are four conductors. Each conductor consists of 14 copper single-coated threads wrapped around polyamide core. The resistance is $0.4\Omega/\text{m}$. The webbing is attached with a hot melt process to a standard jack connector or washable connector depending on the garment or application.

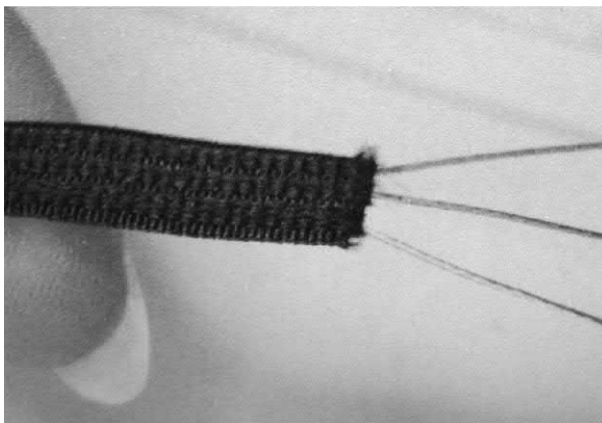


Fig. 8.33 Three strands conductive webbing.
Courtesy of Ohmatex, Denmark.

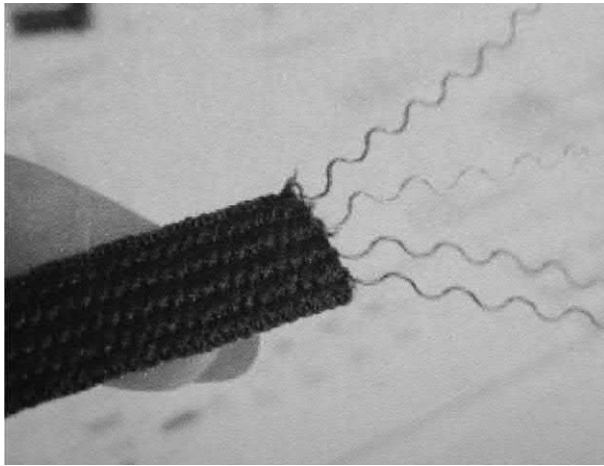


Fig. 8.34 Four strands elastic webbing.
Courtesy of Ohmatex, Denmark.



Fig. 8.35 RIP belt for thorax.
Courtesy of Natus Neurology Incorporated, (www.Natus.com), Middleton, WI, USA.

Fig. 8.35 shows Embla XactTrace reusable belt for thorax for sleep apnea monitoring. Fig. 8.36 shows Embla XactTrace reusable belt for abdomen. These belts do not require any additional modules and plug directly into the amplifiers. Direct connection to the amplifier eliminates bulky interfaces required by many other systems since it provides power to the belt through the amplifier. It comes in multiple sizes: paediatric, small, medium, and large.

Hollow structures

Fig. 8.37 shows a hexagonal structure. Other hollow structures are shown in Fig. 8.38 (hexagonal and diamond shapes) and Fig. 8.39 (diamond shape). Many types of hollow structures can be woven.



Fig. 8.36 RIP belt for abdomen.

Courtesy of Natus Neurology Incorporated, (www.Natus.com), Middleton, WI, USA.

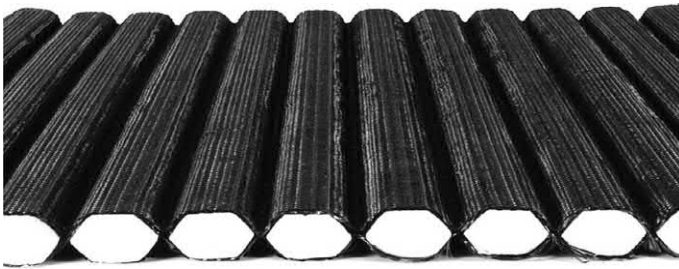


Fig. 8.37 Hexagonal structure.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

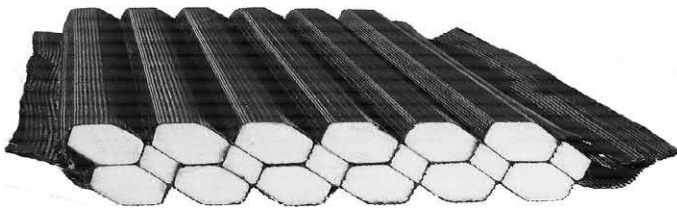


Fig. 8.38 Multiple cell structure.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

Truss cores

An interwoven triangular truss core with face sheets is shown in Fig. 8.40. A double interwoven truss core with face sheets is shown in Fig. 8.41. The integrally woven cells were made to reduce the delamination of the composite materials to withstand multiple impacts.

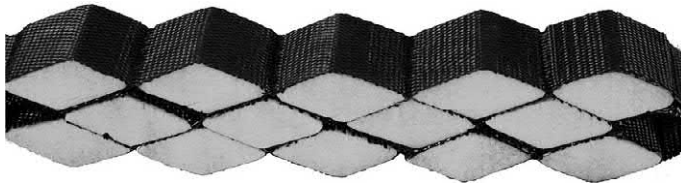


Fig. 8.39 Multiple cell structure.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

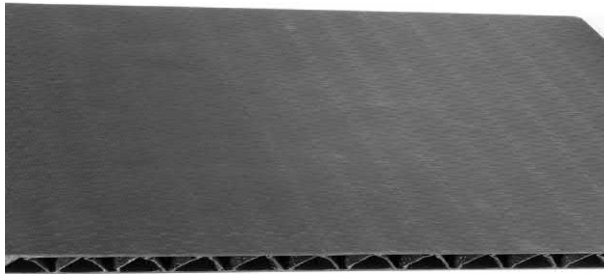


Fig. 8.40 Triangular truss core.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

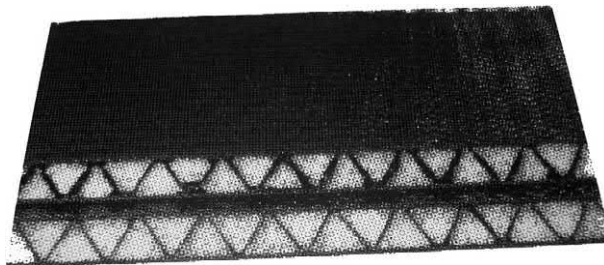


Fig. 8.41 Double truss core.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

Complex structures

An outlet guide vane (OGV) for a jet engine is shown in [Fig. 8.42](#). A combination weave was used, and the thickness varied in both width and length directions. Snecma (SN) and Albany Engineered Composites (AEC) have developed woven composite fan blades for jet engines [\[26\]](#). 3D woven preforms produced by layer-to-layer interlock pattern are processed into composites by resin transfer moulding (RTM). The advantage of composites fan blades include improved damage tolerance and increased thrust to weight ratio by lowering the mass of the fan. A woven Sine-Wave structure is shown in [Fig. 8.43](#). A complex woven preform is shown in [Fig. 8.44](#). Electronics and photonics can be placed into those slots for various applications.

Fig. 8.42 Composite woven engine vane.
Courtesy of Bally Ribbon Mills, Bally,
Pennsylvania 19503, USA.



Fig. 8.43 Sine-wave structure.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

In partnership with Bally Ribbon Mills, SONACA of Belgium [27] developed a new concept of structural European launcher cryogenic upper interstage composite ring as part of the European Space Agency (ESA) Future Launchers Preparatory Program (FLPP). This challenging programme targeted the replacement of an ARIANE traditional aluminium ring by a lighter and affordable multifunctional composite structure. Fig. 8.45 shows a composite ring. An integral multiple T stiffener is shown in Fig. 8.46.



Fig. 8.44 Complex woven preform.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.



Fig. 8.45 Composite ring.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

8.1.3 Applications

Joints entirely made from composites are being used in aerospace applications to alleviate the need for fasteners. Fillets are being used at the joints to avoid resin-rich areas. The aerospace industries also are looking into the possibility of composite window frames. Composite truss cores are used in fuselage areas, and the composite vane and fan blades are used in the jet engine. Polar woven carbon material is used for carbon/carbon brakes. The automobile industries are using carbon panels, and the construction and boat industries are using fibre glass panels. NASA, meanwhile, in partnership with Bally Ribbon Mills, is developing woven



Fig. 8.46 Integral multiple T stiffener.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

3D structures to use as a thermal protection system (TPS) [28] for their future missions to Mars and beyond. In the medical industry, hollow woven structures, such as tubular and bifurcate tubular, tapered tubes, and tapered bifurcates are being used as vascular grafts and stents. Expandable tubes as penile grafts are being used as implants in the human body.

8.1.4 Advantages of woven 3D structures

3D woven structures are woven directly into net shapes. The advantages of woven 3D preforms are as follows:

- No plying, cutting, and stitching
- Near net shape
- Minimum machining to achieve required shape and size
- Automated process
- Consistent products
- Minimized time for manufacturing
- Increased production
- Eliminates delamination, which is the primary damage mechanism in laminated composites
- Reduces cost
- Better performance

The cost of manufacturing preforms is a major portion of the total cost. The benefits of using composites instead of metallic structures are that they are light weight, stronger, and corrosion free. The saving in weight is tremendous. Prichard [29] suggests that the use of 3D fabrics and structures could lead to a 30% reduction in aircraft weight, and every pound of weight saved could save one million dollars over the life of the aircraft. The saving in weight also reduces the aircraft fuel cost. The greatest advantage of using 3D woven composites and structures is the elimination of delamination.

8.2 Weaves

8.2.1 Basic weaves

The type of weave used is decided based on the stability, strength, flexibility, drapability, permeability/shape and desired final product. Plain, twill, and satin are the three basic weaves. All other weaves are modified, altered, combinations, or derivatives of these. Three basic weaves are shown in the following figures for ready reference in order to understand 3D weaves.

A plain weave, in which each warp end passes over and under each fill fibre, is shown in Fig. 8.47. This types of weave is also called a 1/1 weave. Plain weave has the maximum number of binding points and is the most stable, but also has the potential for causing more fibre damage due to friction and abrasion during weaving. A 2/2 twill weave is shown in Fig. 8.48 where two ends are up and the next two ends are down. Twill weave has fewer numbers of interlacement than plain weave. A 5 harness satin and 8 harness satin weave are shown in Figs 8.49 and 8.50 and a four harness satin (crowfoot) is shown in Fig. 8.51. There is only one binding point in one repeat in one direction in a satin weave, which has typically the lowest number of binding points of three basic weaves.

Satin weave has the potential for minimum fibre damage during weaving, but it is the least stable weave. Twill is more stable, and plain weave is the most stable. Three types of satin weaves (four, five, and eight harnesses) are commonly used in the fabric industry for textile composites. The maximum number of ends and picks can be inserted into satin weave due to it having the lowest number of binding points.

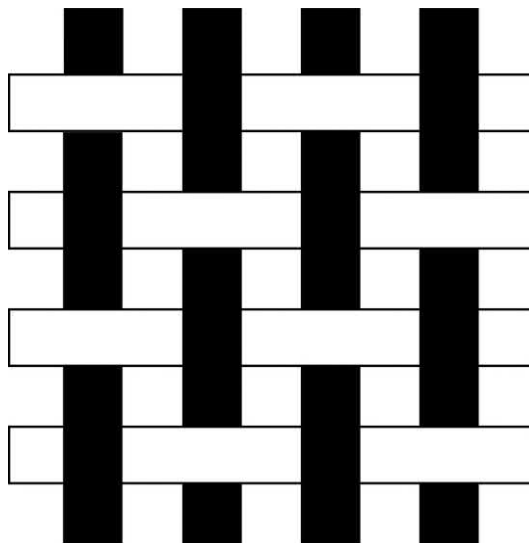


Fig. 8.47 Plain weave.

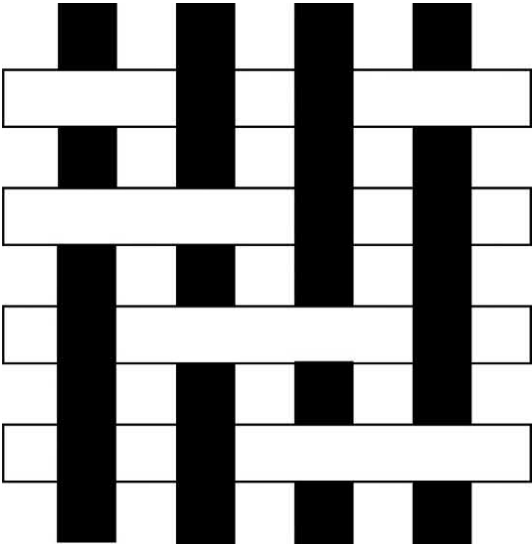


Fig. 8.48 2/2 Twill weave.

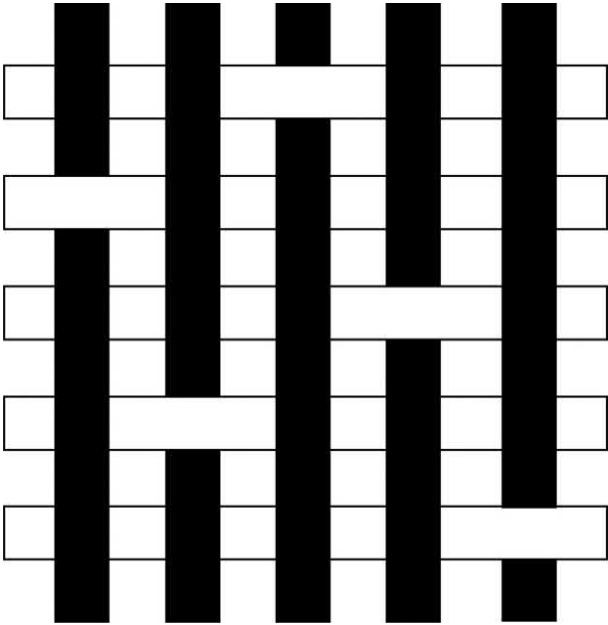


Fig. 8.49 Five harness satin weave.

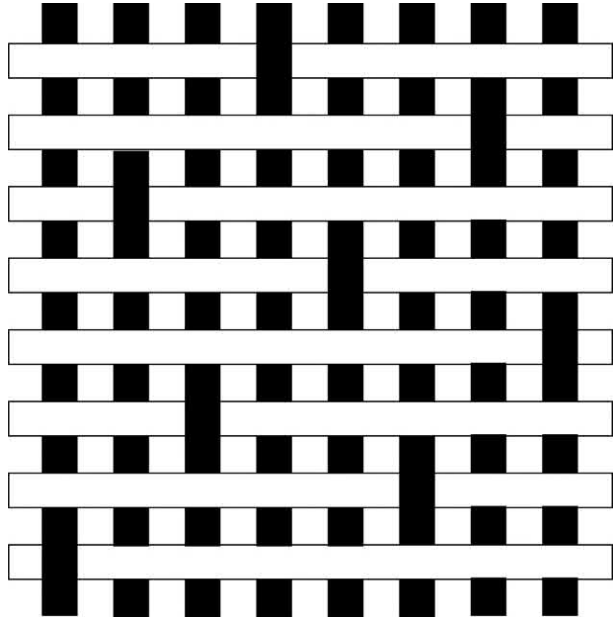


Fig. 8.50 Eight harness satin weave.

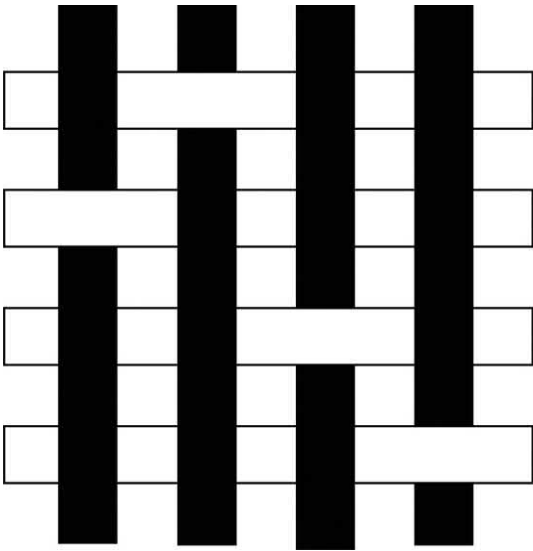


Fig. 8.51 Four harness crowfoot.

8.2.2 3D weaves

The weaves used to manufacture woven 3D fabrics and structures are considered to be 3D weaves. There are many types of 3D weaves, and their selection is determined according to the end use and performance criteria of the 3D preforms. 3D weaves are generally based on the three basic weaves (plain, twill, and satin) and are adapted using modifications, alterations, or combinations of these.

8.2.2.1 Layer-to-layer interlock weaves either by warp or filling

A typical layer-to-layer interlock weave based on a plain weave is shown in Fig. 8.52, and another example based on a twill weave connection is shown in Fig. 8.53. Both figures show four layers joined together, but any number of layers can be joined together using the same technique. In this example, the dark circles denote the warp ends and the curved lines indicate the filling path. The warp layers are joined by filling. The layers could, however, be joined by the warp ends, in which case the dark circles would denote the picks, and the curved line would indicate the warp ends. The decision as to whether the layers should be joined either by the warp end or filling is based on the performance requirements of the 3D preforms.

8.2.2.2 Layer-to-layer interlock weave with Z fibres

A typical layer-to-layer interlock weave with Z fibres is shown in Fig. 8.54. Z fibres are added to the layer-to-layer interlock weave. The dark circles denote the warp ends, and the curved lines show the filling path. Z fibres run through the fabric thickness. In the example figure, Z fibres are perpendicular to the warp, but Z fibres also can be inserted at various angles, such as 30 degrees, 45 degrees, and 60 degrees.

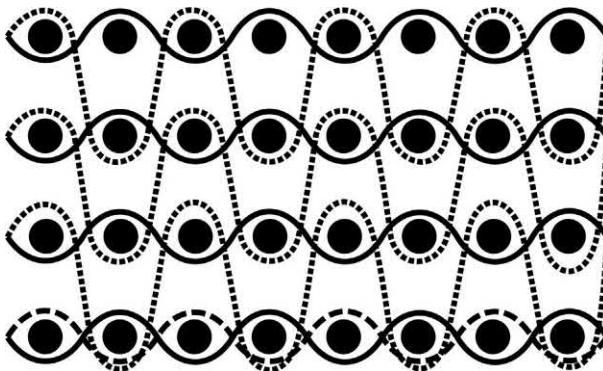


Fig. 8.52 Typical layer-to-layer (ply to ply) interlock weave based on a plain weave [2, 5, 6].

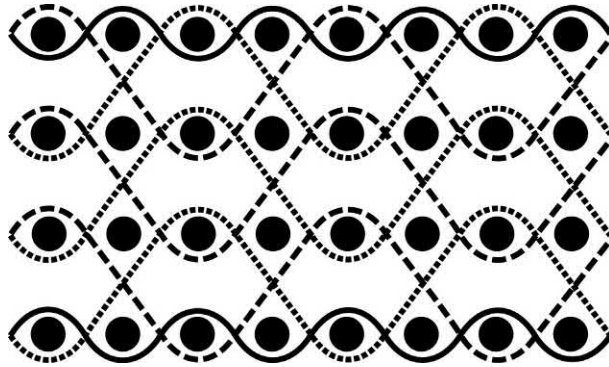


Fig. 8.53 Typical layer-to-layer interlock weave based on twill weave connection [2, 5, 6].

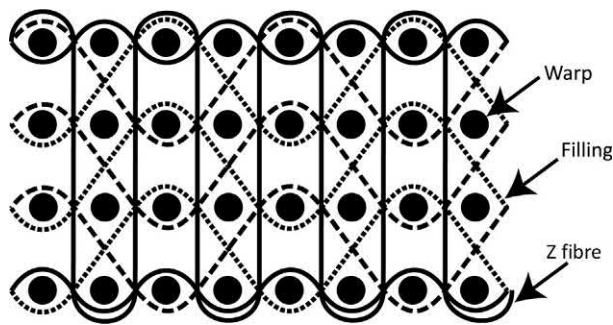


Fig. 8.54 Layer-to-layer interlock weave with Z fibres [2, 5, 6].

8.2.2.3 Layer-to-layer interlock weave based on satin weave

Fig. 8.55 shows a typical layer-to-layer interlock weave based on satin weave. The curved line shows warp, and the circles denote the fill. There are five warp layers and six fill layers, which are joined by the warp ends. The layers of 3D fabric as shown in Fig. 8.1 are joined together using this method.

8.2.2.4 Layer-to-layer angle interlock weave either by warp or filling

A typical layer-to-layer angle interlock weave is shown in Fig. 8.56. In this type of weave, either the warp or the filling runs through the fabric thickness at an angle. The joining of layers, either by the warp ends or the filling, is selected based on the performance requirements of the end product.

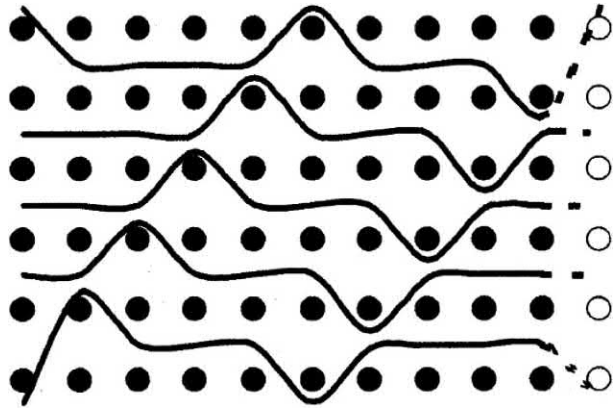


Fig. 8.55 Layer-to-layer interlock weave based on satin weave [2, 5, 6].

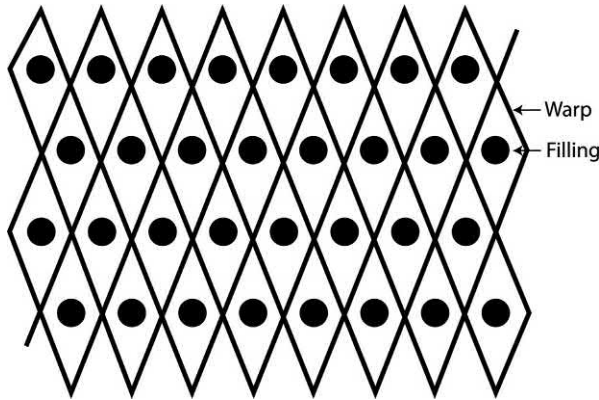


Fig. 8.56 Layer-to-layer angle interlock weave [2, 5, 6].

8.2.2.5 Layer-to-layer angle interlock with stuffer threads

Stuffer threads can be added to the layer-to-layer angle interlock structure to increase the thickness and tensile strength. A typical angle warp interlock with stuffer threads is shown in Fig. 8.57.

8.2.2.6 Orthogonal weave

In this type of structure, the warp and the filling run straight without crimping, and the Z fibre binds all the layers. In a regular woven fabric, there are crimps in the warp and the fill due to their interlacement. Such crimps are undesirable for maximum composite mechanical properties. The use of a Z fibre throughout the fabric thickness

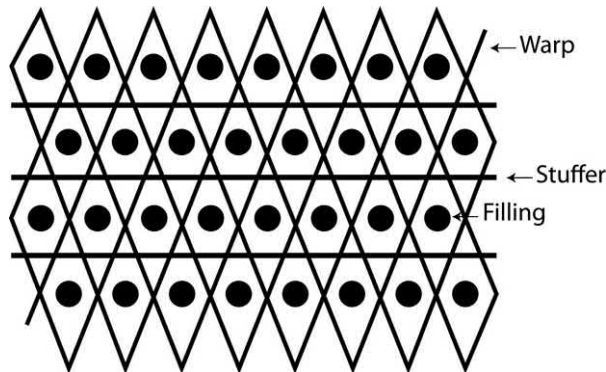


Fig. 8.57 Layer-to-layer angle interlock with stuffer threads [2, 5, 6].

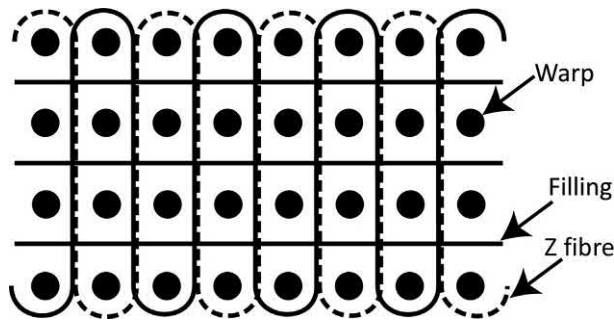


Fig. 8.58 Orthogonal weave architecture [2, 5, 6].

effectively eliminates delamination as a failure mode. An orthogonal weave with Z fibres is shown in Fig. 8.58. This type of structure is also called noncrimp fabric (NCF).

The composite industry prefers this type of orthogonal weave. The benefits of orthogonal weave architecture are that the fibres in all three directions run straight which makes the orthogonal structure rigid. Higher fibre volume can be achieved for this type of structure due to absence of fibre crimp in all three directions. However, the disadvantage of this type of weave is that, if the Z fibres break, there is nothing to hold all the layers together.

8.2.2.7 Different numbers of layers in various locations for complex shapes

Different numbers of layers are used in various locations to achieve various thicknesses in this type of structure. A typical four-layer weave architecture is shown in Fig. 8.59 in which four layers have been reduced to one layer. The circle shows the warp fibres, and the line indicates the filling path. The same technique is used

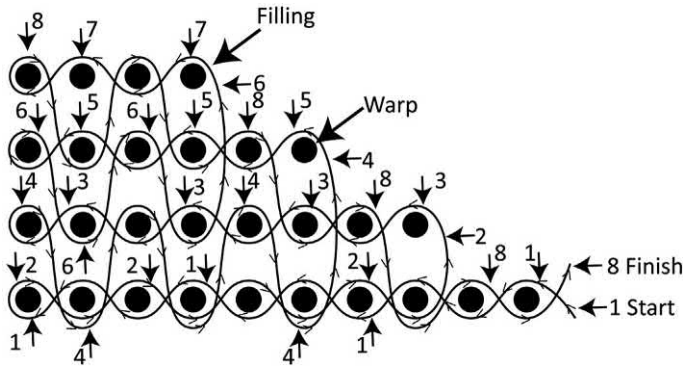


Fig. 8.59 Weave architecture for tapered or complex shapes [2, 5, 6].

to make a tapered structure. The gradual tapering in thickness is achieved by terminating one layer at a time. The base of Pi as shown in Fig. 8.16 has eight layers, and each layer was dropped from eight layers to a single layer.

8.2.2.8 Combination weaves for complex shapes

A combination weave or modified weave can be used in order to create complex structures and to achieve specific properties. A combination weave made up of an orthogonal weave and a plain weave is shown in Fig. 8.60. The top and bottom layers are plain weave, and the layers in-between are orthogonal weave. There are two straight warp layers between the top and bottom plain weaves, and Z fibres bind all the layers. Layer-to-layer interlock weave is more flexible, but it has less tensile strength due to interlacement and more fibre damage during weaving. An orthogonal weave is more rigid, but has a higher tensile strength due to the lack of interlacement and lower fibre damage during weaving. Layer-to-layer interlock weave based on plain, twill or satin,

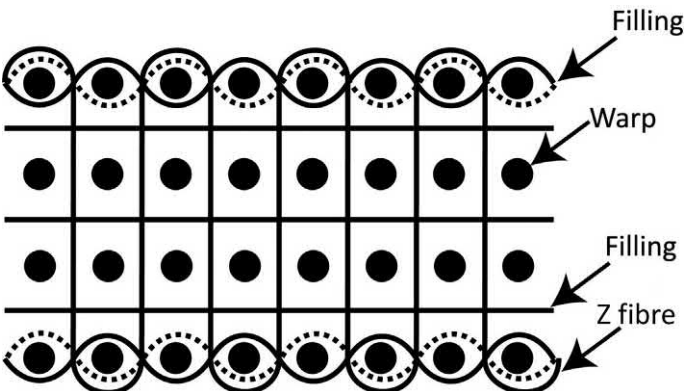


Fig. 8.60 Combination weave architecture [2, 5, 6].

and orthogonal weaves can be combined in many ways. The sequence can be varied; for example, x number of layers joined by layer to layer, and then y number of layers orthogonal, or x layer, then y layer and so on. The optimum combination can be selected based on the performance requirements of the end structure.

8.2.3 Weave architecture

In this chapter, the weave architecture means the schematic view of a complete weave pattern. It shows the filling path in relation to warp and Z fibres. The structure means the shape of the woven material.

The typical weave architecture of a four-layer T structure created using layer-to-layer interlock weave based on plain weave [2, 5, 6] is shown in Fig. 8.61. The warp fibres of both sides of T are shown spaced apart for clarity. The black circle shows the warp fibre, and the curved line denotes the filling. The four layers are joined together by a layer-to-layer interlock weave based on plain weave [2, 5, 6], and the upright flap is joined with the base flap by filling.

The typical filling path for a four layer base, four-layer clevis and two layer upright legs for a Pi structure without tapering is shown in Fig. 8.62. The warp fibres of the clevis are shown spaced apart for clarity. The filling path for an eight-layer base, eight layer clevis, and four layer upright legs can be shown in the same way. The black circle shows the warp fibre, and the curved line denotes the filling. The four layers are joined

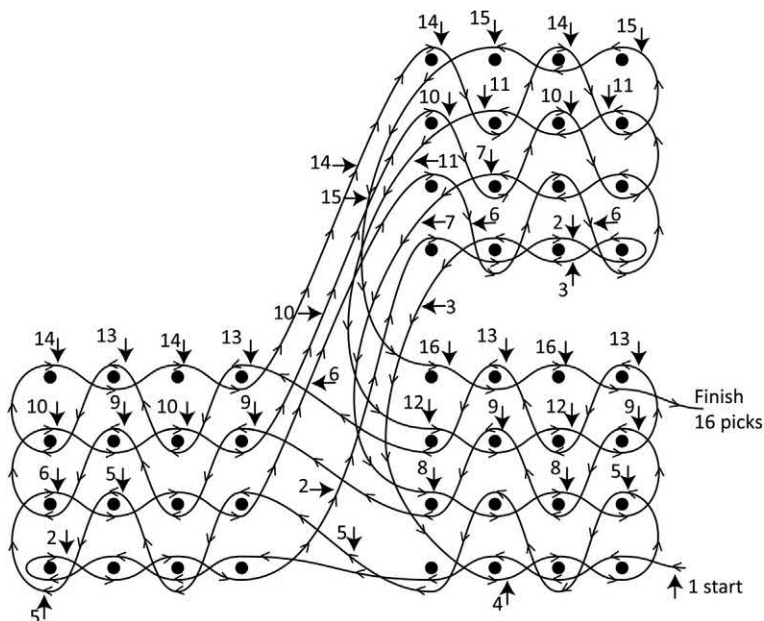


Fig. 8.61 Typical filling path of T structure [9].

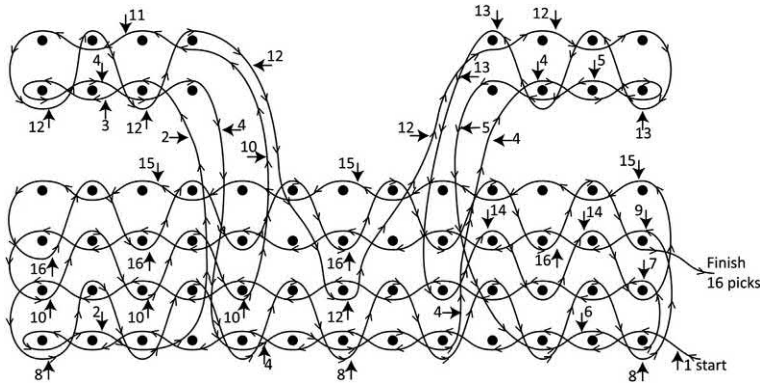


Fig. 8.62 Typical filling path of Pi structure [9].

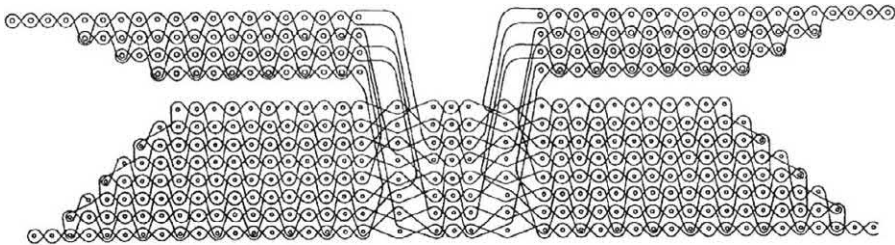


Fig. 8.63 Weave architecture of a tapered Pi preform [9, 10].

together by a layer-to-layer interlock weave based on plain weave [2, 5, 6], and the upright legs are joined with the base by filling.

Fig. 8.63 shows the weave architecture of a tapered Pi preform in which all the sides are tapered. The base and clevis are made up of eight layers and the upright legs of four layers. The gradual tapering was achieved by dropping one layer at a time. All layers are joined together using a layer-to-layer interlock weave based on a plain weave [2, 5, 6]. The upright legs are joined to the base by the filling. The warp fibres at the clevis are shown spaced apart for clarity. Any combination of layers for a tapered Pi preform can be woven in the same way. The isometric view of the tapered Pi [9, 10] is shown in Fig. 8.64. The tracer fibres, comprising a coloured strand and an X-ray opaque, shown using arrows, are used at the beginning of the tapers and identify where the thickness of the legs or base begins to decrease for an accurate dimensional inspection of the preform.

8.2.4 Properties of 3D weaves

The selection of 3D weaves is very important. The selection of weave architecture depends on the end use of 3D fabrics and 3D structures, and their required performance criteria.

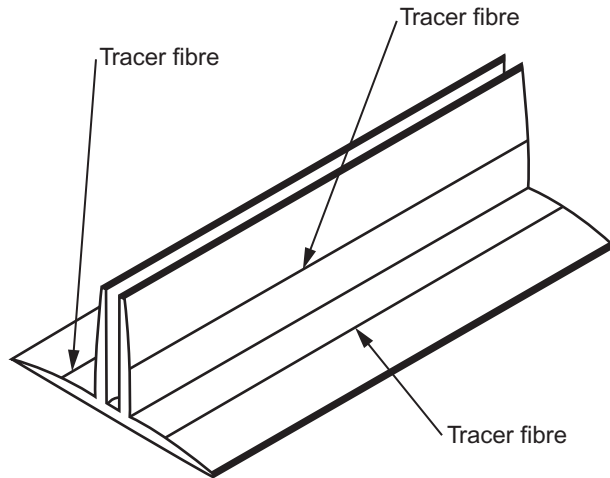


Fig. 8.64 Isometric view of the tapered Pi preform [9, 10].

8.2.4.1 3D weave-based on satin weave

If 3-D fabrics have to conform to a three dimensional shape, then the layers have to be joined using satin weave as shown in Fig. 8.55. Multilayer satin weave fabrics are drapable and easily conform to the shape. A multilayer thick panel can be woven by joining layers using satin weave.

8.2.4.2 3D weaves based on plain weave

Multilayer panels or 3D structures can be woven using a layer-to-layer interlock weave based on the plain weave as shown in Fig. 8.52. The warp end or fill are used to join the adjacent layers. If the joining threads are broken, then only a portion of one layer will fall apart, not the whole structure. This is one of the greatest benefits, but it means a lower tensile strength because the fibres are crimped by their interlacement. The likelihood of fibre damage during weaving is increased due to this high number of interlacements.

8.2.4.3 3D weaves based on orthogonal weave architecture

In orthogonal weave architecture, the fibres in all three directions (XYZ) run straight, as shown in Fig. 8.58. Maximum fibre properties can therefore be achieved due to noncrimping. Orthogonal weave architecture is used to make thick panels or structures as shown in Figs 8.6–8.9. The maximum number of warp fibres (X fibres), picks (Y fibres), and Z fibres can be inserted because of the lack of interlacements. That means, that a higher fibre volume percentage can be achieved from orthogonal weave architecture; however, the disadvantage is that the whole structure falls apart if the Z fibres break. Fibre damage during weaving is less likely because there are no interlacements.

8.2.4.4 3D weaves based on combination weave

Often, a combination weave is selected based on the end product's performance criteria. An orthogonal weave is used to make thick panels and to achieve maximum performance properties. A combination weave made up of layer-to-layer interlock weave and orthogonal weave would be selected to achieve maximum performance properties without the layers falling apart.

8.3 Manufacturing technologies

8.3.1 Weaving preparation

Yarn preparation for regular fabrics has been discussed in [Chapters 2–4](#). The scope of yarn preparation for weaving 3D structures is not the same as that for a regular fabric. The following steps are used.

8.3.1.1 Yarns or fibres

The preference for a 3D woven composite structure is to use the fibre tows without any twist. Occasionally this is difficult to achieve, in which case, a very small amount of twist is inserted. If the customer does not want any twist, fibre tows with a higher sizing percent are used to facilitate weaving. As an example, Carbon fibre tows usually come with a less than 1% sizing.

Some fibres, such as pitch carbon and silicon carbide, are difficult to weave. Pitch carbon fibres break easily due to their very poor bending rigidity. For this reason 'difficult to weave' fibres are usually served with polyvinyl alcohol (PVA) yarn or rayon to facilitate the weaving process. A machine called a 'serving machine' is used for this purpose. The serving machine wraps the 'difficult to weave' fibres with rayon or PVA. The rayon or PVA takes the abuse of weaving, and the core fibres remain undamaged. Rayon is removed using heat, and PVA is removed by dissolving it in warm water after weaving.

8.3.1.2 Winders

Fibre manufacturing companies usually supply fibre in large packages. Since these fibres are costly, it is necessary and economical to transfer fibre from larger to smaller packages on a suitable winding machine.

8.3.1.3 Creels

Unlike weaving regular fabrics, warp beams are not usually used for weaving 3D structures and instead, creels are the preferred method of feeding the warp. It is very important to maintain uniform tension on each package. A good creel is a prerequisite for weaving any 3D structures and complex shapes. A reciprocating creel, which takes out the slack during weaving, is used for more complex shapes.

Many thousands of ends are needed to weave a thick wide panel. Creels, which can accommodate such a large number of ends, are very expensive and occupy a lot of space. In these cases, warp beams are used for the X or 0 degree fibres, and a creel is used for the Z fibres. A combination of beams and creels can be used for tapered and complex structures.

8.3.2 Weaving technologies

The following machinery can be used in the production of woven 3D fabrics and structures:

- Conventional 2D loom
- Modified 2D loom
- 3D loom
- Specially built loom or machine

8.3.2.1 Conventional loom

Conventional 2D loom mechanisms have been discussed in [Chapter 5](#). The shedding mechanism is one of the primary motions of a loom. A Jacquard shedding mechanism is used for 3D structures because the individual warp fibres are controlled independently by Jacquard harness cords. A 3D fabric can be woven on a 2D conventional rapier loom, but there is a fabric thickness limitation when using any conventional 2D loom.

Loom set up

Proper loom set up plays a significant role in reducing warp breaks during weaving and is therefore key in increasing productivity. Loom set up is even more important when weaving 3D fabrics and structures in order to minimize fibre damage during weaving to achieve maximum mechanical properties. The maximum translation of fibre or yarn properties to fabric for tensile strength [\[30\]](#) is dependent upon:

- The damage suffered by the fibre or yarn during weaving
- The fabric structure such as:
 - Fibre or yarn size (linear density)
 - Fibre or yarn absolute diameter depending on fibre density
 - Ends and picks per inch
 - Warp and filling yarn crimp
 - Warp and filling yarn interlacement angle
 - Cover factor
 - Weave type and number of binding points between warp and fill

Tensile strength realization in the fabric is primarily dependent on the weaving process, meaning that minimal fibre or yarn damage during weaving will improve the fabric tensile strength and weavability. Research [\[30\]](#) shows that fibre damage during weaving can be minimized in the following ways:

- By setting up the harness on an elliptical path in order to keep the same warp tension
- By reducing friction and abrasion at every contact point of the fibre during weaving

- By reducing beat-up force
- By using round eye heddles to reduce the coefficient of friction between the fibre and the heddle
- By reducing the warp tension variation
- By increasing the optimum open air space in the reed dent

Fibre damage

In Fig. 8.65, it appears that the damage to the warp increases gradually as the warp passes through the heddles and reed. There is a somewhat steeper increase in warp damage between the heddle and the cloth fell and a very large increase in warp damage between the region immediately in front of the cloth fell and the fabric itself.

The movement of the warp during the weaving process causes various stresses and strains [31, 32]. The let-off and shedding motions, together with the movements of the back rest roller and of the cloth fell, influence the total warp tension. Shedding is one of the main factors which contribute to the total warp tension during normal loom operation.

Taking into account the mathematical relationship between tension on the two sides of the heddle eye:

$$\frac{T_f}{T_b} = e^{\mu\theta} \quad (8.1)$$

where: e = the base of Napierian Logarithms, μ = the coefficient of friction between warp yarn and heddle eye, θ = the lap angle at the heddle eye in radians, T_b = the warp tension before passing through heddle eye, and T_f = the warp tension after passing through heddle eye.

Since tension = strain $\times$ elastic modulus, Eq. (8.1) can be written in terms of the strain ratio assuming that the strain is entirely due to shedding.

$$e^{\mu\theta} = \frac{W_f (\text{Warp strain in front shed})}{W_b (\text{Warp strain in rear shed})} \quad (8.2)$$

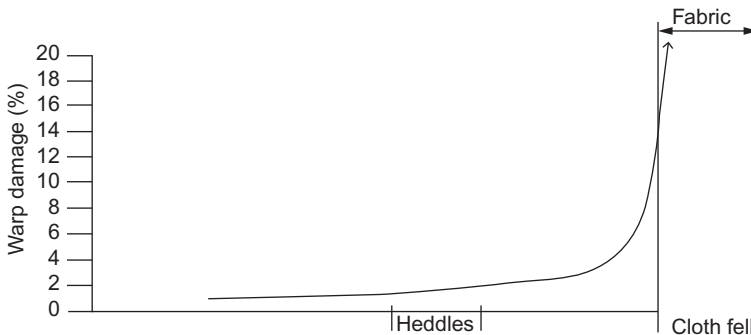


Fig. 8.65 The warp damage [30].

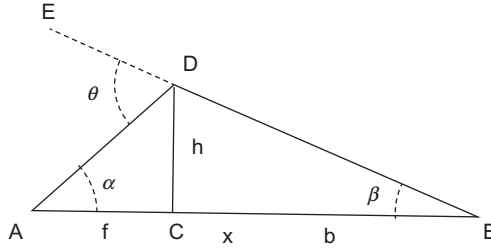


Fig. 8.66 Geometry of the warp yarn path due to shedding [31].

Let: $P_f = AD/AB$ in Fig. 8.66 the normalized distance from the cloth fell to the heddle eye during shed formation, $P_b = BD/AB$ in Fig. 8.66, the normalized distance from the back rest to the heddle eye during shed formation, $H = CD/AB$, the normalized shed height, $F = AC/AB$, the normalized front shed length, α = the front shed opening angle, and β = the rear shed opening angle. Then:

$$P_f = \sqrt{F^2 + H^2} \text{ in terms of } F \text{ and } H \quad (8.3)$$

$$P_f = \frac{\sin \beta}{\sin(\alpha + \beta)} \text{ in terms of } \alpha \text{ and } \beta \quad (8.4)$$

$$P_f = \sqrt{F^2 + (F \tan \alpha)^2} \text{ in terms of } F \text{ and } \alpha \quad (8.5)$$

Similarly for P_b

$$P_b = \sqrt{(1 - F)^2 + H^2} \quad (8.6)$$

$$P_b = \frac{\sin \alpha}{\sin(\alpha + \beta)} \quad (8.7)$$

$$P_b = \sqrt{(1 - F)^2 + (F \tan \alpha)^2} \quad (8.8)$$

Let X be the point on the closed shed line AB , which is in contact with the heddle eye at D . $F_\mu = AX/AB$, the normalized length of yarn which forms the front shed during shedding. The warp strain increments in the front shed $W_{f\mu}$ and rear shed $W_{b\mu}$ are given by:

$$W_{f\mu} = \frac{P_f - F_\mu}{F_\mu} \quad (8.9)$$

$$W_{b\mu} = \frac{P_b - (1 - F_\mu)}{1 - F_\mu} \quad (8.10)$$

From Eq. (8.2):

$$\frac{P_f - F_\mu}{F_\mu} = e^{\mu\theta} \frac{(P_b - 1 + F_\mu)}{1 - F_\mu} \quad (8.11)$$

Hence:

$$P_f - P_f F_\mu - F_\mu + F_\mu^2 = e^{\mu\theta} F_\mu (P_b - 1 + F_\mu)$$

Or,

$$F_\mu^2 (e^{\mu\theta} - 1) + F_\mu (e^{\mu\theta} P_b - e^{\mu\theta} + P_f + 1) - P_f = 0$$

Therefore,

$$F_\mu = \frac{-C + \sqrt{C^2 + 4(e^{\mu\theta} - 1)P_f}}{2(e^{\mu\theta} - 1)} \quad (8.12)$$

where: $C = e^{\mu\theta} P_b - e^{\mu\theta} + P_f + 1$

The warp strain increments using Eqs (8.9), (8.12) is shown in Fig. 8.67.

If the front shed opening angle and the normalized distance from the cloth fell to the harness are measured or calculated, then the warp strain can be found from the equations and from Fig. 8.67. This figure is also a guide for how to set up the harness in

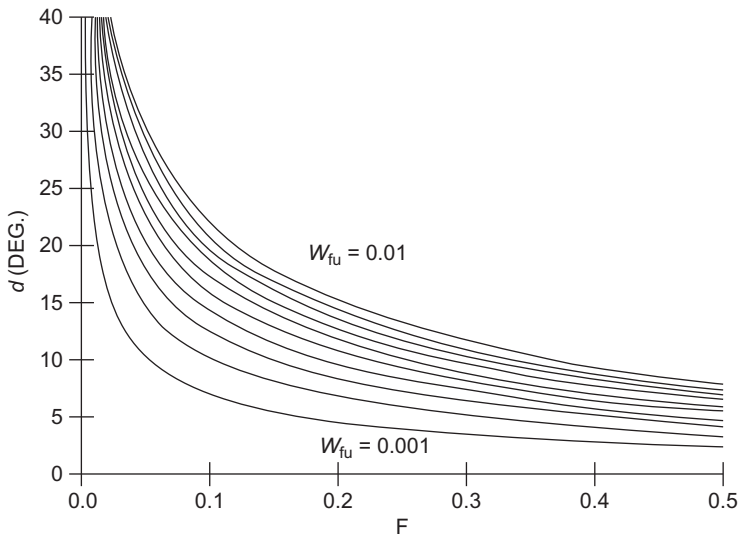


Fig. 8.67 Dependence of warp strain increment (W_{fu}) in the front shed on α and F when $\mu = 0.30$ at the heddle eye (Eqs 8.9, 8.12). Curves of constant strain increment at intervals of 0.001 [31].

order to maintain the same warp tension or to minimize the warp tension variation. It is very important to minimize the fibre damage for 3D woven composites.

For example: in Fig. 8.66

$$AC = 6.75'', CB = 23.00'', CD = 1.65'' \text{ and}$$

$$AB = 6.75'' + 23.00'' = 29.75'', \text{ then}$$

$$H, \text{ the normalized shed height} = \frac{CD}{AB} = \frac{1.65}{29.75} = 0.0555$$

$$F, \text{ the normalized front shed length} = \frac{AC}{AB} = \frac{6.75}{29.75} = 0.2269$$

$$\tan \alpha = \frac{CD}{AC} = \frac{1.65}{6.75} = 0.2444$$

$$\alpha, \text{ the front shed opening angle} = \tan^{-1} 0.2444 = 13.7339 \text{ degrees}$$

$$\tan \beta = \frac{CD}{CB} = \frac{1.65}{23.00} = 0.0717$$

$$\beta, \text{ the rear shed opening angle} = \tan^{-1} 0.0717 = 4.1033 \text{ degrees}$$

$$\begin{aligned} \theta, \text{ the lap angle at the heddle eye} &= \alpha + \beta = 13.7339 \text{ degrees} + 4.1033 \text{ degrees} \\ &= 17.8372 \text{ degrees} = 0.3113 \text{ rad} \end{aligned}$$

P_f , the normalized distance from the cloth fell to the heddle eye during shed formation is given by:

$$\begin{aligned} P_f &= \sqrt{F^2 + H^2} \text{ in terms of } F \text{ and } H \\ &= \sqrt{0.2269^2 + 0.0555^2} \\ &= \sqrt{0.0515 + 0.0031} \\ &= \sqrt{0.0546} \\ &= 0.2337 \end{aligned}$$

$$\begin{aligned} P_f &= \frac{\sin \beta}{\sin(\alpha + \beta)} \text{ in terms of } \alpha \text{ and } \beta \\ &= \frac{\sin 4.1033}{\sin(13.7339 + 4.1033)} \\ &= \frac{\sin 4.1033}{\sin 17.8372} \\ &= \frac{0.0716}{0.3063} \\ &= 0.2337 \end{aligned}$$

$$\begin{aligned}
 P_f &= \sqrt{F^2 + (F \tan \alpha)^2} \text{ in terms of } F \text{ and } \alpha \\
 &= \sqrt{0.2269^2 + (0.2269 \times 0.2444)^2} \\
 &= \sqrt{0.2269^2 + (0.0555)^2} \\
 &= \sqrt{0.0515 + 0.0031} \\
 &= \sqrt{0.0546} \\
 &= 0.2337
 \end{aligned}$$

Similarly, P_b , the normalized distance from the back rest to the heddle eye during shed formation is given by:

$$\begin{aligned}
 P_b &= \sqrt{(1 - F)^2 + H^2} \text{ in terms of } F \text{ and } H \\
 &= \sqrt{(1 - 0.2269)^2 + 0.0555^2} \\
 &= \sqrt{0.7731^2 + 0.0555^2} \\
 &= \sqrt{0.5977 + 0.0031} \\
 &= \sqrt{0.6008} \\
 &= 0.7751
 \end{aligned}$$

$$\begin{aligned}
 P_b &= \frac{\sin \alpha}{\sin(\alpha + \beta)} \text{ in terms of } \alpha \text{ and } \beta \\
 &= \frac{\sin 13.7339}{\sin(13.7339 + 4.1033)} \\
 &= \frac{\sin 13.7339}{\sin 17.8372} \\
 &= \frac{0.2374}{0.3063} \\
 &= 0.7751
 \end{aligned}$$

$$\begin{aligned}
 P_b &= \sqrt{(1 - F)^2 + (F \tan \alpha)^2} \text{ in terms of } F \text{ and } \alpha \\
 &= \sqrt{(1 - 0.2269)^2 + (0.2269 \times 0.2444)^2} \\
 &= \sqrt{(0.7731)^2 + (0.0555)^2} \\
 &= \sqrt{0.5977 + 0.0031} \\
 &= \sqrt{0.6008} \\
 &= 0.7751
 \end{aligned}$$

$$e^{\mu\theta} = e^{0.30 \times 0.3113} = e^{0.0934} = 1.0979$$

Assuming μ , the coefficient of friction between warp yarn and heddle eye = 0.30.

From Eq. (8.12):

$$\begin{aligned}
 C &= e^{\mu\theta} P_b - e^{\mu\theta} + P_f + 1 \\
 &= 1.079 \times 0.7751 - 1.0979 + 0.2337 + 1 \\
 &= 0.8510 - 1.0979 + 1.2337 \\
 &= 2.0843 - 1.0979 \\
 &= 0.9868 \\
 F_\mu &= \frac{-C + \sqrt{C^2 + 4(e^{\mu\theta} - 1)P_f}}{2(e^{\mu\theta} - 1)} \\
 &= \frac{-0.9868 + \sqrt{(0.9868)^2 + 4(1.0979 - 1) \times 0.2337}}{2(1.0979 - 1)} \\
 &= \frac{-0.9868 + \sqrt{0.9738 + 4 \times 0.0979 \times 0.2337}}{2 \times 0.979} \\
 &= \frac{-0.9868 + \sqrt{0.9738 + 0.0915}}{0.1958} \\
 &= \frac{-0.9868 + \sqrt{1.0653}}{0.1958} \\
 &= \frac{-0.9868 + 1.0321}{0.1958} \\
 &= \frac{0.0453}{0.1958} \\
 &= 0.2314
 \end{aligned}$$

$W_{f\mu}$, the warp strain increments in the front shed:

$$\begin{aligned}
 W_{f\mu} &= \frac{P_f - F_\mu}{F_\mu} \\
 &= \frac{0.2337 - 0.2314}{0.2314} \\
 &= \frac{0.0023}{0.2314} \\
 &= 0.0099
 \end{aligned}$$

$W_{b\mu}$, the warp strain increments in the rear shed:

$$\begin{aligned}
 W_{b\mu} &= \frac{P_b - (1 - F_\mu)}{1 - F_\mu} \\
 &= \frac{0.7751 - (1 - 0.2314)}{1 - 0.2314} \\
 &= \frac{0.7751 - 0.7686}{0.7686} \\
 &= \frac{0.0065}{0.7686} \\
 &= 0.0085
 \end{aligned}$$

- The results have been up to 4 decimal points for all calculations.

If the warp strain increments either in front shed or rear shed exceeds the breaking strain of the warp, then the warp ends will break. If the values of AC , CB , and CD in Fig. 8.66 are known, then the warp strain increments either in front shed or rear shed can easily be calculated following the above example.

The damage to warp can be minimized by reducing the strains caused by shedding motion, whether normal or distorted by traps. Damage can also be minimized by using round heddle eyes and by reducing strain due to friction and abrasion at all contact points. Minimum fibre damage during weaving will improve the fabric's tensile strength and weavability.

Narrow fabric loom

The performance requirements, shape of the end product, and cost dictate the selection between the shuttle and the needle loom in the narrow fabric industry. A narrow fabric is defined by the American Narrow Fabrics Institute as any fabric with a width not exceeding 12 in. (300 mm). The Narrow Fabrics Institute (NFI) is the industry organization for manufacturers of narrow fabrics, and it is a division of Industrial Fabrics Association International (IFAI).

Narrow fabric shuttle looms are used to produce many 3D structures. There are different kinds of narrow fabric shuttle looms, such as, single deck (horizontal and circular), double deck (upper and lower), two shuttles batten (both shuttles run together in the same station in two sheds), and multiple shuttles loom. Two shuttles batten, where two sheds are formed by dobby or three positions jacquard is used to weave tear tape, spacer fabrics, bifurcate, and others. Two shuttles run simultaneously through the sheds to weave two separate fabric layers and Z fibres (binders) bind both layers. In a narrow fabric shuttle loom, the shuttle movements are positively controlled in a batten with rack and pinion unlike fly shuttle broad loom. Typical speed of a narrow fabric shuttle loom is 100 picks per minute; however, it is reduced to weave brittle and 'hard to weave' fibres. These looms are being replaced with high

Table 8.1 Characteristics of shuttle and needle looms.

	Shuttle loom	Needle loom
Speed	Low	High
Edge	Woven edges	Woven and knitted edge
No. of stations (typical)	Up to 84	Up to 20
Picks/shed	Single	Double

speed needle looms offering increased productivity. The main differences between the characteristics of narrow fabric shuttle and needle looms are given in [Table 8.1](#).

There are multiple stations in a narrow fabric shuttle loom. That means the same structure in multiple stations or different structures can be woven on the same loom depending on the capacity of the jacquard hooks and the total picks per inch in the structure. It is difficult to produce 3D and complex shapes using carbon and brittle fibres on a needle loom. A narrow fabric needle loom [\[33\]](#) also can be used to produce some 3D structures. A typical narrow fabric needle loom is shown in [Fig. 8.68](#). The selvedge on the side of the filling insertion needle is a true woven selvedge, while the selvedge on the latch needle is a knitted selvedge. With the needle system, the fabric has always double picks. A narrow fabric shuttle loom is used for a



Fig. 8.68 Typical needle loom.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.



Fig. 8.69 Narrow fabric shuttle loom weaving Pi structures.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

perfect tube, uniform mesh size for filtration, medical textiles [7], 3D preforms, near net shape preforms, and complex woven structures. The narrow fabric shuttle loom with electronic Jacquard Head is used for weaving thick panel and complex 3D structures. With the advent of electronic Jacquard Head, it is much easier to change the weave design.

The 3D structure on a conventional 2D loom is woven in a flat form. The first step in weaving of 3D structures on a conventional 2D loom is to figure out how to flatten [34] the structure. Once it is determined, it is followed by the subsequent set up of the loom and the weave architecture. The filling path, based on the performance requirements of 3D structures, has to be carefully selected. Fig. 8.69 shows weaving of carbon-tapered Pi structures in a narrow fabric shuttle loom.

8.3.2.2 Modified loom

The 2D conventional loom is modified to weave various 3D woven preforms. What kind of modification(s) should be carried out depends on the nature of structures to be produced. The take up and shedding motions are modified in many ways along with other tools that are also installed. Modified looms are used to produce thick panels, contour materials, polar materials, and complex 3D structures. Unlimited number of 3D structures and complex shapes can be woven on a modified loom with electronic Jacquard. Fig. 8.70 shows a narrow fabric shuttle loom weaving 50 mm thick carbon panel. An orthogonal weave has been used with a dead pick motion so that X, Y, and Z fibres are perpendicular to each other.

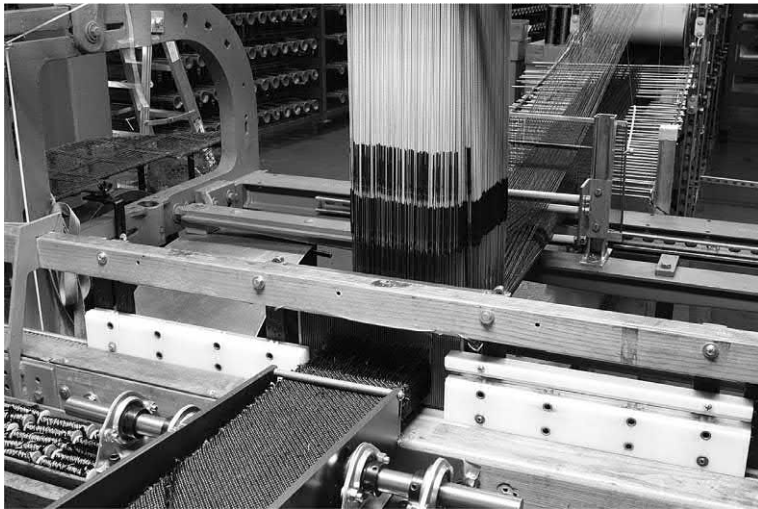


Fig. 8.70 Modified 2D loom weaving 50mm thick carbon panel.
Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

8.3.2.3 3D looms

A few companies have developed 3D looms [35–39]. Mohamed [35] and 3Tex [36] have developed 3D looms. Fig. 8.71 shows the filling insertion from both sides. The warp fibres are fed either from bobbins positioned on a creel or from beams. They are separated into layers to allow for fill insertion. These warp layers are fixed open to form sheds without shedding mechanism.

According to Mohamed [35], the warp ends are not required to be drawn through the heddles of the shedding mechanism, leading to less fibre damage during weaving. Multiple fill yarns or fibres can be inserted through the sheds (layers) by needles or rapiers from both sides simultaneously or alternately according to cross sectional shapes. The filling is inserted from one side in a regular needle loom [33].

Several needles (rapiers) containing double fill fibres are inserted horizontally through the layers in one motion as shown in Fig. 8.71. The fill fibres are temporarily held on the opposite side by a vertical selvedge needle. The rapiers are then withdrawn to their original position, leaving a set of double fill fibres. The Z fibres are fed into the machine parallel with the warp and separated into two layers controlled by the harness movement. When the bottom Z fibre layer is moved to the top, and the top Z fibre layer is moved to the bottom achieved by crossing the harnesses, a vertical fibre is added. A reed is brought forward for a beat up. The selvedge needles are lowered and the structure is moved corresponding to the pick spacing. The reed is moved back, and the entire cycle is repeated.

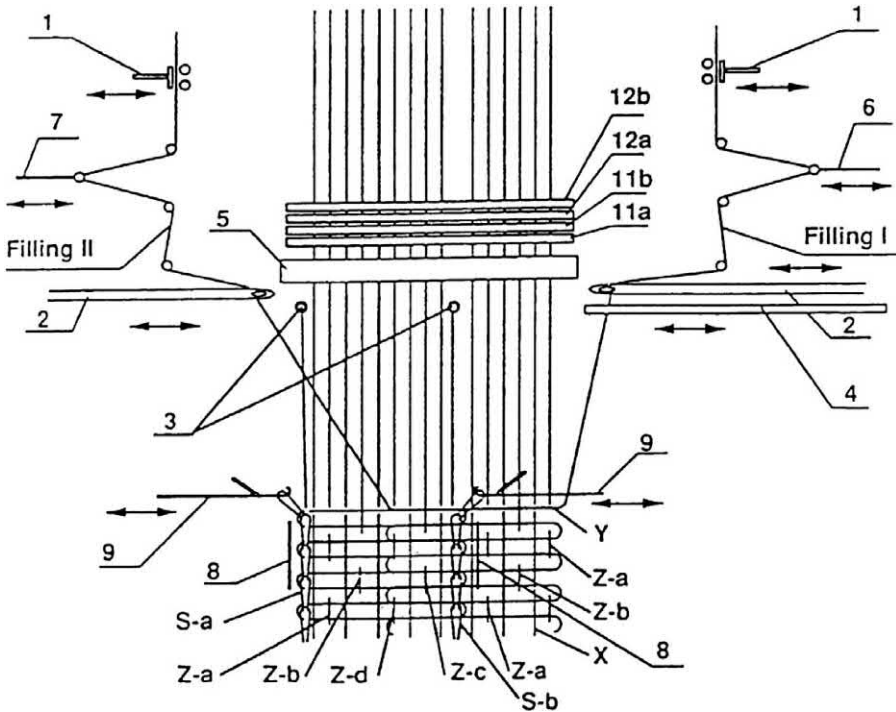


Fig. 8.71 Filling insertion by needles from both sides [35].

Mohamed [35] also developed 3D loom where the warp (0degree) fibre, the fill (90 degrees) fibre, Z fibre and +/- bias fibres can be inserted. The bias fibres can only be positioned on the front and back faces of the 3D preform.

In Fig. 8.71, I denotes filling lock and selvedge lock; 2 shows filling insertion; 3 shows selvedge needles; 4 shows selvedge hold rod, 5 shows beat up, 6 and 7 show filling tension I and II, 8 shows loop forming rods, 9 shows selvedge latch needles, and 11 and 12 show harnesses.

3Tex [36] has built a commercial 3D loom. The number of layers is limited to 14 as per report [40]. Bally Ribbon Mills [12] is weaving various panels with 30, 48, 61, and 101 warp layers. The thickness of the panel is currently up to 75 mm. Bally Ribbon Mills is working on to weave panels with 150 mm thick.

Biteam [4, 37] has developed a 3D loom where shedding can be formed in both horizontal and vertical positions. In a conventional weaving machine, the interlacement occurs between the two orthogonal sets of yarns: the warp and the fill. It does not bring the interlacement of three sets of orthogonal yarns. Biteam's loom provides a dual directional shedding method to form sheds in the column-wise and the row-wise

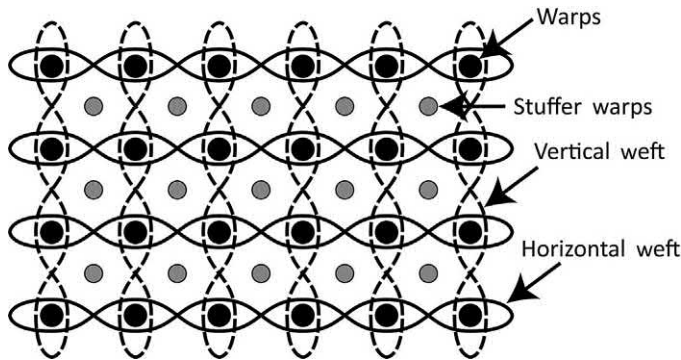


Fig. 8.72 Weave architecture of 3D fabric.
Courtesy of Biteam AB, Gothenburg, Sweden.

directions of a multilayer warp to enable interlacement of the multilayer warp and two orthogonal sets of fill.

The Weave architecture is shown in Fig. 8.72.

The vertical fills and horizontal fills are inserted into the created sheds of multilayers warp. The warp fibres interlace with two sets of filling, thus creating an interlaced woven 3D fabric. The 3D fabric produced by this method may be cut into any desired shape without the risk of splitting up, but the resulting structures have crimped fibres in all three directions. The fibres are likely to be damaged to a high extent due to dual shedding mechanisms. It is highly desirable for composite reinforcements to minimize the fibre damage.

Uchida et al. [38] developed three-dimensional weaving machines including an improved bias yarn feeding apparatus as an integral part. Fig. 8.73 shows a side view of 3D weaving machine. Fig. 8.74 shows a schematic perspective view showing a specific configuration of a 3D woven fabric produced by 3D weaving machine. In Fig. 8.73, the warp X , bias yarns $B1$ and $B2$, and vertical yarn Z are fed from each beam and guided to a frame 5 through a dancer roller and a split guide 6 in a cloth fell section 7. A filling insertion mechanism inserts the fill between the warp layers and outside the set of two biased yarn layers. The vertical yarns Z are inserted from top and bottom by 9A and 9B. The 3D woven fabric passes through a woven fabric shape retention section 11 and is wound around a fabric winding section 12.

Short Brothers plc of Northern Ireland, part of Bombardier Aerospace developed a narrow weaving machine [39] called 5 axis weaving to produce Spatially Reinforced Composites (SpaRC). These Spatially Reinforced Composites are designed to have fibre tows oriented in 5 axes, 0 degree, 90 degrees, ± 45 degrees, and Z directions. A preform with one layer of ± 45 degrees was woven on this loom. Quinn et al. [41] shows that, by increasing the amount of Z fibres in 3D orthogonal structures,

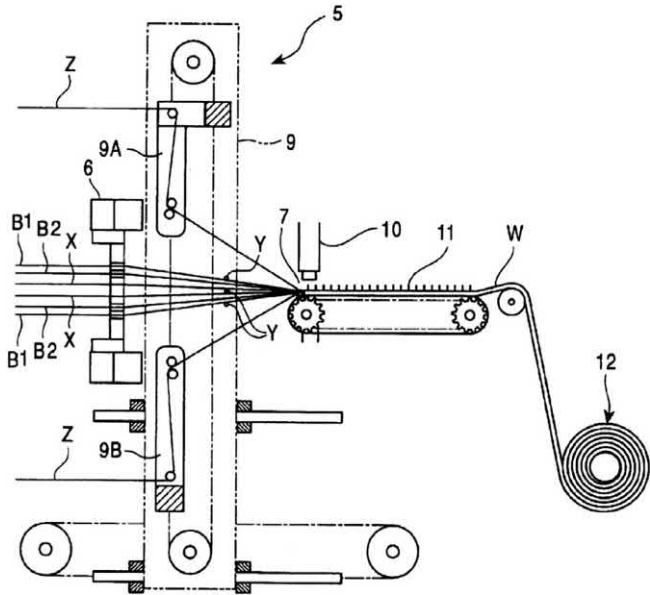


Fig. 8.73 Side view schematically showing 3D weaving machine [38].

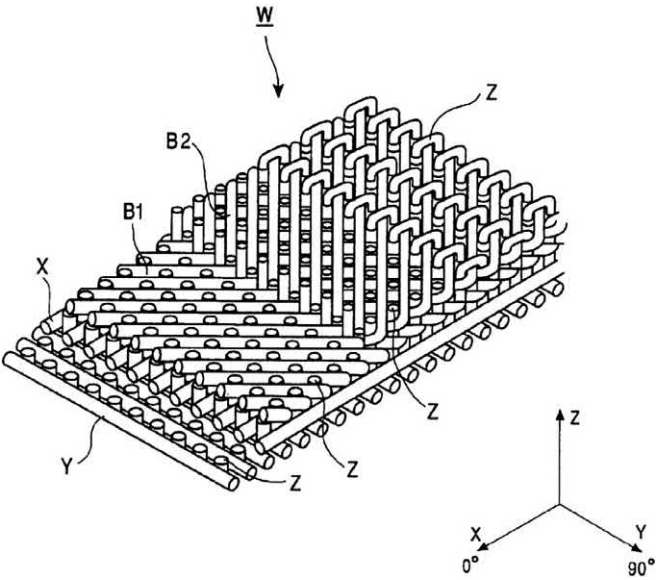


Fig. 8.74 View of 3D fabric produced by 3D weaving machine [38].

the damage area after impact was reduced and low crimp, multiaxis, multilayer woven structures offer improved damage tolerance.

8.3.2.4 Specially built machine

Bally Ribbon Mills (BRM) [12] has developed a patented weaving machine [42–44] where fibres can be inserted in X , Y , Z , $+45$ degrees, and -45 degrees directions. Various 3D structures, such as, Π , T , cruciform have been woven. The test shows improved results in Π structures produced in this machine over woven Π structure with $+45$ degrees/ -45 degrees ply.

Fig. 8.75 shows the rear section of the loom, whereas Fig. 8.76 shows the front section of the BRM's specially built machine. The X direction (0 degree) fibres were controlled by an electronic Jacquard harness which formed the shedding. Z fibres were also controlled by an electronic Jacquard harness. The filling insertion was carried out by a specially built shuttle operated by a servo motor. $+45$ degrees and -45 degrees fibres were also controlled by servo motors. The beat up was carried out by individual reed blade. The take up was controlled by a servo motor. There were multiple vertical columns for bias fibres. There were nine positions in each vertical column. Eight positions were filled with fibre bobbins, and one position was left empty. The bobbins in each vertical column can move vertically (up and down) as well as move horizontally by servo motors. The bias fibres can be placed in any locations up to eight locations between the layers and outside the structure.

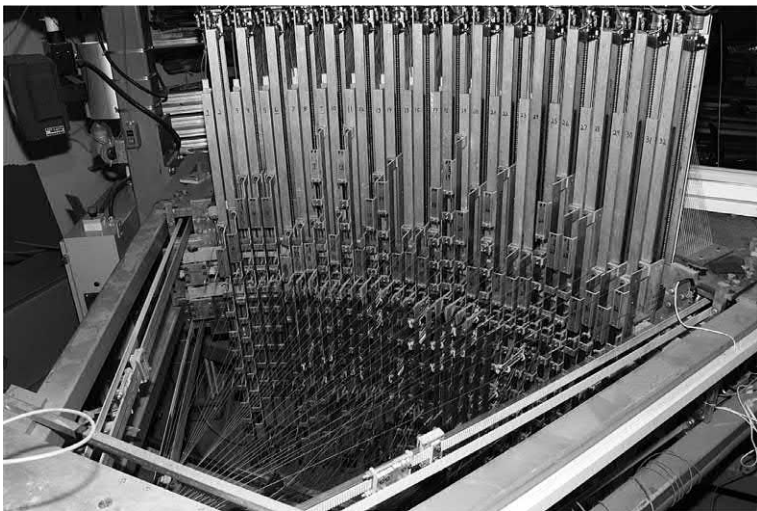


Fig. 8.75 Rear section of the machine.

Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

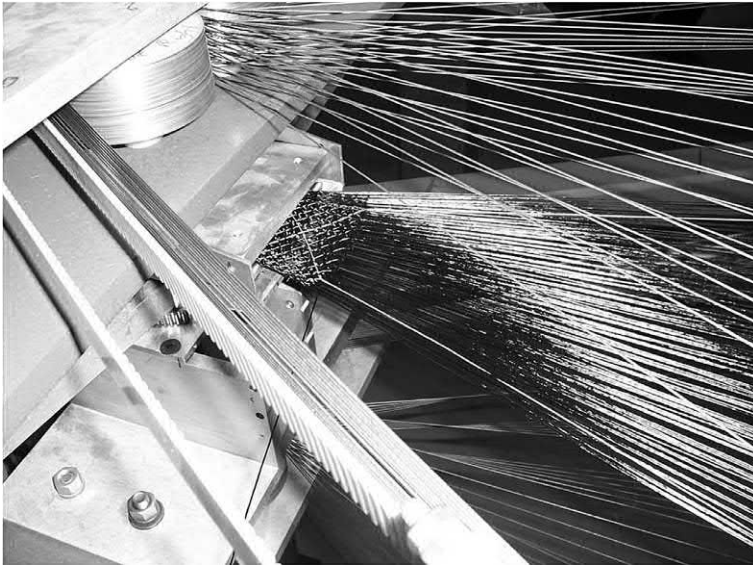


Fig. 8.76 Front section of the machine.
 Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.

Many structures, such as, Pi, T, cruciform can be woven using fibres in five directions. BRM has built another machine with higher speed, and it can produce various 3D structures.

8.4 3D weaving calculations

When designing 3D textile preforms for the composite industry, often the textile engineer is required to calculate the 3D preform construction from a cured composite specification, supplied by the composite manufacturer or the end user. The composite design engineer typically supplies the textile engineer with the following information about the cured composite:

- Cured Composite Part Thickness (CPT)
- Fibre Volume (V_f)
- Fibre Orientations or Fibre Percentages (%X, %Y, and %Z)
- Fibre Type/Fibre Density (ρ_f)/Fibre Linear Density (yard/lb)

Many times the end user will not have all items specified, and it is up to the textile engineer to understand the composite part requirements in order to recommend a suitable preform construction. In particular, the fibre linear density is a variable

which needs close review by the textile engineer. For high performance composite applications, the composite design engineer may specify fine denier fibres that exceed the jacquards capacity or worst yet, are physically impossible to weave. If there is a problem with the customer's supplied specification(s), the textile engineer must find a solution, often making compromises between performance and manufacturability.

To find out 3D preform construction for each direction (X, Y, Z directions), the areal weight (AW) is first calculated by the following equation, and then multiplied by the specified fibre volume fraction percentage and fibre yield.

$$\text{Areal weight (lb/in.}^2\text{)} = \text{Cured part thickness (CPT)} \times \text{fibre density } (\rho_f) \times \text{fibre volume} \quad (8.13)$$

Where, Areal weight (AW) in lb, cured part thickness in inch, density (ρ_f) in lb/in.³, and fibre volume in %.

$$\text{Fibres required in each direction} = \text{Areal weight} \times \text{fibre volume fraction} \times \text{fibre yield} \times 36 \quad (8.14)$$

Where, fibres in each direction in inch, areal weight in lb, fibre fraction in %, fibre yield in yards/lb.

By using the above equations, the total ends per inch (EPI) and total picks per inch (PPI) and Z fibres are easily calculated. Depending on the weave pattern and fibre crimp, the 3D preform construction may need adjusting. The number of warp layers and fill layers depend on the Jacquard harness configuration and other factors.

For example, a 3D woven preform is needed to make a 1.5" thick composite panel using standard modulus carbon fibre with an epoxy matrix. The composite panel is required to have a fibre volume of 57%. A 12K standard modulus carbon fibre should be used in all three directions with a density of 0.065 lb/in.³ and a yield of 567 yards/lb. An orthogonal weave pattern with 45% of the fibre orientated in the warp (0 degree/X) direction, 40% of the fibre orientated in the fill/weft (90 degrees) direction, and 15% of the fibre orientated through the thickness (Z) direction would be used. Based on this information, the ends per inch, picks per inch, and Z fibre of the 3D orthogonally woven preform could be calculated using Eqs (8.13), (8.14) with 30 warp layers and 31 fill layers.

Answer:

$$\text{Areal weight (AW)} = 1.5''(\text{thickness}) \times 0.065 (\text{density}) \times 0.57 (\text{fibre volume}) \\ = 0.0556 \text{ lb}$$

$$\text{Total ends per inch} = 0.0556 (\text{AW}) \times 0.45 (\text{warp fibre fraction}) \times 567 (\text{yield}) \\ \times 36 = 510$$

$$\text{Ends/inch/layer} = \frac{\text{Total ends/inch}}{\text{Warp layers}} = \frac{510}{30} = 17$$

$$\begin{aligned} \text{Total picks per inch (PPI)} &= 0.0556 (\text{AW}) \times 0.40 (\text{fill fibre fraction}) \\ &\quad \times 567 (\text{yield}) \times 36 \\ &= 454 \end{aligned}$$

$$\text{Picks/inch/layer} = \frac{\text{Total picks/inch}}{\text{Fill layers}} = \frac{454}{31} = 14.6$$

To calculate the total number of Z fibres required per square inch of 3D orthogonal woven preform, the preform thickness must be taken into account. It is assumed that each Z fibre travels through the entire preform thickness.

$$\text{Z fibres per inch} = \frac{0.0556 (\text{AW}) \times 0.15 (\text{Z fibre fraction}) \times 567 (\text{yield}) \times 36}{1.5 (\text{thickness})} = 113$$

8.5 Future trends and applications

As 3D woven fabrics, structures and composites become more popular and inexpensive, they will be increasingly used in various industries for a range of new applications, such as: consumer products, sporting goods, boat industries, automotive, construction and bridges, bicycle, or alternative energy sector.

Although there are some simulations available for a few 3D structures, the weave design software currently available is limited. As a result, engineers have to spend a considerable amount of time figuring out how to weave the particular structure and coming up with a weave design. As software and the range of simulations improve, the time spent designing the weave structure will significantly decrease and the whole process of manufacturing 3D woven fabrics and structures will become much faster and cost effective.

The properties of 3D preforms are dependent upon fibre properties, weave architecture, and fibre damage during weaving. It is very important to minimize fibre damage in woven reinforcements for composites. Research is in progress to predict the properties of 3D structures based on the weave architecture. The loom set up and fibre damage have to be considered in addition to the weave architecture for modelling the properties of the woven composites. Unfortunately, composite engineers lack textile knowledge, and textile engineers lack composite knowledge. An improved understanding and knowledge of one another's subject areas would significantly improve the situation. Advanced research and developments in the areas of computerized weave design and simulation would also be beneficial.

Acknowledgements

The author would like to express his sincere thanks to Raymond Harries, CEO of Bally Ribbon Mills for allowing him to write this chapter. The author is thankful to Mark Harries, Curt Wilkinson, and Lorraine Hornig for their help with the line drawings and photographs. The author would also like to express his sincere thanks to his wife Ruksana Rita Islam for her support and cooperation.

References

- [1] M.H. Mohamed, Three-dimensional textiles, *Am. Sci.* 78 (1990) 530–541.
- [2] M.A. Islam, 3-D woven near net shape structures, in: ASME International Congress & Exhibition, November 14–19, 1999, Nashville, TN, USA, 1999.
- [3] X. Chen, J.W.S. Hearle, Developments in design, manufacture and use of 3D woven fabrics, in: 9th International Conference on Textile Composites, Recent Advances in Textile Composites, University of Delaware, Newark, DE, USA, October 13–15, 2008.
- [4] N. Khokar, Second generation woven profiled 3D fabrics from 3D weaving, in: First World Conference on 3D Fabrics and their Applications, Manchester, UK, April 10–11, 2008.
- [5] M.A. Islam, Designing of narrow woven fabrics: 3-D woven near net shape structures, in: Narrow Fabrics Conference of Clemson University, November 10–11, 1999, Charlotte, NC, USA, 1999.
- [6] M.A. Islam, 3-D woven near net shape and multi-axial structures, in: The Textile Institute 80th World Conference, 16–19 April, 2000, Manchester, UK, 2000.
- [7] M.A. Islam, Narrow fabrics for medical textile applications, in: Medical Textiles Conference, Clemson University, Clemson, SC, USA, September 9–10, 1997.
- [8] J. Feldman, et al., Development of an ablative 3D quartz/cyanate ester composite for the orion spacecraft compression pad, in: 249th ACS National Meeting, Denver, CO, USA, March 22–26, 2015.
- [9] Schmidt, R.; Bersuch, L.; Benson, R.; Islam, A. Three Dimensional Weave Architecture, US Patent No. 6,712,099 B2, March 30, 2004.
- [10] Schmidt R., et al., Woven Preform for Structural Joints, US Patent # 6, 874,543 B2, April 5, 2005.
- [11] NASA Engineering and Safety Center (NESC) Website on Composite Crew Module.
- [12] Courtesy of Bally Ribbon Mills, Bally, Pennsylvania 19503, USA.
- [13] K. White, R. Spray, Q. Horn, Wearable devices: integrating textiles, electronics and portable power, in: Techtextil North America Conference, Atlanta, Georgia, USA, May, 2014.
- [14] C. Dalsgaard, R. Sterrett, White Paper on Smart Textile Garments and Devices: A Market Review of Smart Textile Wearable Technologies, Ohmatex, Denmark, March 2014.
- [15] J. Hayward, Wearable technology, in: IDTechEx Conference, November 18, 2014, Santa Clara, CA, USA, 2014.
- [16] A. Reho, Textile-integrated wearable electronics, in: Clothing +, IDTechEx Conference, Santa Clara, CA, USA, November 18, 2014.
- [17] J. Slade, Infoscitex Corporation: design and fabrication of electronic – textile clothing systems, in: Techtextil North America Conference, Atlanta, GA, USA, May, 2014.

- [18] J.S. Jur, Process for textile applications in photoluminescence and electronics, in: *Techtextil North America Conference*, Atlanta, GA, USA, May, 2014.
- [19] L.M. Castano, A.B. Flatau, Smart fabric sensors and e-textile technologies: a review, *Smart Mater. Struct.* 23 (5) (2014), 27 pages.
- [20] NASA Tech Briefs, Making Complex Electrically Conductive Patterns on Cloth, (29 May, 2008).
- [21] Conductive Fiber Manufacturers Council (CFMC), www.cfibermfg.com.
- [22] Shakespeare Conductive Fibers, LLC (Part of Jarden Corporation), North Carolina, USA.
- [23] R.STAT, France.
- [24] Textronics (Part of Adidas Group), Chadds Ford, Pennsylvania, USA.
- [25] North Carolina State University News, March 18, 2014.
- [26] B. Dambrine, et al., Development of 3D woven, resin transfer molded fan blades, in: *9th International Conference on Textile Composites, Recent Advances in Textile Composites*, University of Delaware, Newark, DE, USA, October 13–15, 2008.
- [27] H. Fischer, et al., Composite ring made of 3D woven preform injected by RTM, in: *SAMPE Conference*, Long Beach, CA, USA, May 23–26, 2016.
- [28] NASA Office of Chief Technologist Press Release on “Development of New Game Changing Technologies” November, 2011.
- [29] A.K. Prichard, Presentation at First World Conference on 3D Fabrics and Their Applications, Manchester, UK, April 10–11, (2008).
- [30] M.A. Islam, The Damage Suffered by the Warp Yarn during Weaving (Ph.D. thesis), The University of Manchester, England, 1987.
- [31] M.A. Islam, Shed and Shedding Trap Geometry (M.Sc. thesis), The University of Manchester, England, 1985.
- [32] M.A. Islam, Designing of narrow woven high temperature fabrics, in: *25th International SAMPE Technical Conference*, October 26–28, 1993, Philadelphia, PA, USA, 1993.
- [33] Narrow Fabric Weaving, by Hans Walter Kipp, English Edition: Kurt Greenwood, Verlag Sauerlander, 1989.
- [34] K. Greenwood, M.A. Islam, L. Downes, Research into narrow fabrics opportunities, *Melliand Narrow Fabric and Braiding Industry Magazine* 29 (1992).
- [35] Mohamed, et al., US Patent # 5, 085, 252 February 4, 1992 and US Patent # 5, 465, 760 November 14, 1995, North Carolina State University, North Carolina, USA.
- [36] 3Tex, Carry, North Carolina, USA.
- [37] Khokar, Nandan, Woven 3D Material, US Patent # 6,338, 367 B1, January 15, 2002.
- [38] Uchida, H., et al., Three Dimensional Weaving Machine, US Patent # 6,003,563 December 21, 1999.
- [39] S. Wilson, et al., SPARC 5 Axis, 3D woven, low crimp preforms, in: *Bombardier Aerospace, Resin Transfer Molding SAMPE Monograph No. 3*, Short Brothers plc, 1999.
- [40] Buckley, Marcel; n.d. A report on 3D preform technologies for advanced aerospace structures, Airbus, UK.
- [41] J. Quinn, et al., 5 Axis weaving technology for the next generations of aircraft-mechanical performance of multi-axis weave structures, in: *9th International Conference on Textile Composites, Recent Advances in Textile Composites*, University of Delaware, Newark, DE, USA, October 13–15, 2008.
- [42] Bryn, L.; Islam, M. Amirul; Lowery, W.L. & Harries, H.D., Three Dimensional Woven Forms With Integral Bias Fibers and Bias Weaving Loom, US Patent # 6, 742, 547 B2, June 1, 2004.

- [43] Bryn, L.; Nayfeh, Samir A.; Islam, M. Amirul; Lowery, W.L. & Harries, H.D., Loom and Method of Weaving: Three Dimensional Woven Forms with Integral Bias Fibers, US Patent # 6, 892,766 B2, May 17, 2005.
- [44] Nayfeh, Samir A et al., Bias Weaving Machine, US Patent # 7,077,167 B2, July 18, 2006.

Author biography

Dr. Islam has a BS, MS, and PhD in Textiles from India, Japan, and England. He has 40+ years hands on experience in designing, engineering, and developing new products and 3D woven textile structures. He is recognized internationally as an expert on 3D woven textile composite structures. He can be reached at dramirislam1@gmail.com; amirislam@ballyribbon.com.

Part Three

Applications of woven textiles

Woven textiles for automotive interiors and other transportation applications

9

J.M. Hardcastle

The Textile Institute, Manchester, United Kingdom

9.1 Introduction

The transportation market covers a wide range of products with each sector having its own special requirements in terms of design, colouration, fabric surface characteristics, technical requirements, price, weight, density, air permeability, abrasion, etc. Although, using large quantities of decorative fabrics, the transportation market has been broadly classified as an industrial user of textiles. These products include woven fabrics to a very large degree, and the sector as a whole is the largest consumer, in terms of quantity, of all industrial uses of textile products, and has, therefore, developed worldwide into a very important part of the textile fabric market.

The transportation market can broadly be split into the following categories:

- Automotive – mainly cars, 4 × 4 vehicles, etc., but also including commercial goods vehicles such as trucks often made by a subdivision of the same companies. Automotive is by a large margin the biggest user of textile products within the entire transportation sector.
- Buses and coaches – predominantly use woven pile fabrics but also more and more flat woven fabrics. The fabrics are mainly decorative but have to be made to high levels of performance particularly in terms of fire retardancy.
- Aircraft – use decorative fabrics in the seating areas and industrial fabric types in other areas such as escape chutes, etc. Use is also made in aircraft of composite materials, some of which incorporate woven fabrics, to replace metal and other heavy weight items in the aircraft in order to reduce overall weight.
- Marine – use traditional furnishing fabrics where considerations of design and colour are very important in such areas as drapes and bedding, etc., in cruise liners to industrial fabrics in the more specialized craft.
- Rail – in terms of volume the use is largely confined to specialized decorative fabrics with special properties, for example, woven wool fabric with Kevlar woven into the back of the fabric to prevent/reduce knife damage.

9.2 Automotive applications of woven fabrics

The automotive business is awash with statistics but, by any measure it is a vast business and one which textile suppliers the world over eye with envy in terms of fabric consumption. However, it is a very difficult industry to supply successfully due to very

high entry costs, particularly in terms of quality, very demanding delivery requirements, design, research and development plus very high-quality requirements and with globalization the need to be able to deliver the same products globally to the same specifications and quality standards.

However, since it is by far the biggest fabric consumer within the transport sector, we shall devote most of the space in this chapter to examining the way in which woven fabrics have developed and have met the needs of the industry.

In 2016, over 72 million cars were produced worldwide (slightly up on 2015 which was a record peak year). Compare this with the fact that 8 years early in 2018, 52 million were built and in 1999 just less than 40 million! Cars are broadly defined as passenger carrying vehicles with no more than eight seats and comprise around 85%–87% of the total vehicles on the road. The remaining 13%–15% or so comprise commercial vehicles (trucks, etc.) and buses and coaches.

The total amount of fabric used in the car is probably in the region of 18 kg plus, or between 45 and 60 m², of which approximately 18% by weight is seating fabrics, 22% is taken up by carpets, 30% by tyres, sound damping and other interior items, and 30% by composite textile materials. Some of these replace items formerly made of metal or plastic. The textile items that are visible and appreciated as part of the interior are seating, carpets and headlining material, door panels, and sometimes even dashboards. The seating areas and door panels are often produced from woven fabrics – either flat woven or pile woven – whereas for the headlining (i.e., interior roof space), a light-weight knitted structure is often used for its ability to be moulded easily to curved shapes. In all cases, the fabrics are likely to be either *bilaminates* or *trilaminates*. This means that the face fabric has been usually laminated to a foam and sometimes as well to knitted scrim or polyester nonwoven fleece, a process we shall look at later in this chapter.

Wherever the fabric is used, it is subjected to severe testing procedures before approval and it is the form which these tests take that determines the types of fabric that can be used. These tests are reasonably uniform throughout the industry but the methods used do vary according to the standards laid down by the various original equipment manufacturers (OEMs, which in effect are the car manufacturing companies themselves).

The overall objective is to determine the suitability of the fabric for the intended end use. In the interior fabrics, which include most of the woven products used, the main objective would be to test the ‘wearability’ of the product. This term ‘wearability’ is a coverall for the ability of the fabric to survive the rigours of use during the lifetime of the vehicle. It has very many parts of which probably the most important ones are abrasion resistance, in various forms, light and ultraviolet (UV) degradation in terms of colour fading and strength loss. It was this aspect which was the main factor in the near disappearance of nylon from the exposed areas within the interior of the vehicle (with the notable exception of seat belts), which thanks to improvements in polymer and changes in colouration techniques particularly colouring the yarn during extrusion, are now far more resistant to light degradation.

9.2.1 Test requirements for interior fabrics

This list of test requirements is not exhaustive, but covers the main areas in the standard test regimes of most OEMs.

9.2.1.1 Abrasion

The resistance of fabrics to surface abrasion is one of the most critical requirements, but the standards required are more severe than most of those required by traditional upholstery fabrics. Special tests have been devised which put the fabric under great stress. Different OEMs specify different test methods and these in turn tend to favour different fabric types. Three of the methods are described below:

- *Martindale test.* This is a fabric-to-fabric test where a standard crossbred wool cloth is abraded, under a standard pressure, against the test specimen. The number of rubs required to create thread breakage is recorded or a set number of cycles, e.g., 50,000 is specified with an appearance standard used to compare the performance of the fabric in question. This test is particularly severe on pile surfaces but less so on flat woven cloths.
- *Taber test.* This uses an abrading wheel made of rubber with aluminium oxide abrasive particles which is rotated in pressurized contact with the fabric until wear occurs.
- *Hook fastener test.* This uses the hook part of specified Hook fastener material to measure the fabric's resistance to the hooks under pressure being dragged across the fabric's surface in a prescribed manner.

In terms of woven fabrics, there are many features which affect the results, such as the tightness of the cloth structure, the fibre denier, yarn construction and surface finishes, etc.

9.2.1.2 Pilling

This is the formation of small balls of fibre on the surface during wear. This is tested either by the use of the Martindale machine or a special Imperial Chemical Industries (ICI) pill box where the fabric is wrapped around rubber tubes, face outmost, and placed inside rotating cork-lined boxes for a given time and the 'pills' compared to photographic standards on a scale of 1–5 (5 being the worst). Pilling used to be a significant problem but through improvements in polymer chemistry making the fibres more resilient and better knowledge of woven structures and their finishing is less of an issue today. Further all of the above failure modes can be reduced by using a back coating on the fabric which is common practice with automotive fabrics particularly in the United States and Asian markets, although this coating does create other issues associated with reduced fabric flexibility.

9.2.1.3 Light fastness and degradation

This is an important test for interior cloths since they are subject to high amounts of light and heat (up to 120°C in hot climates), although different tests are used including 'weatherometres' which add moisture during the test procedure and also includes other features.

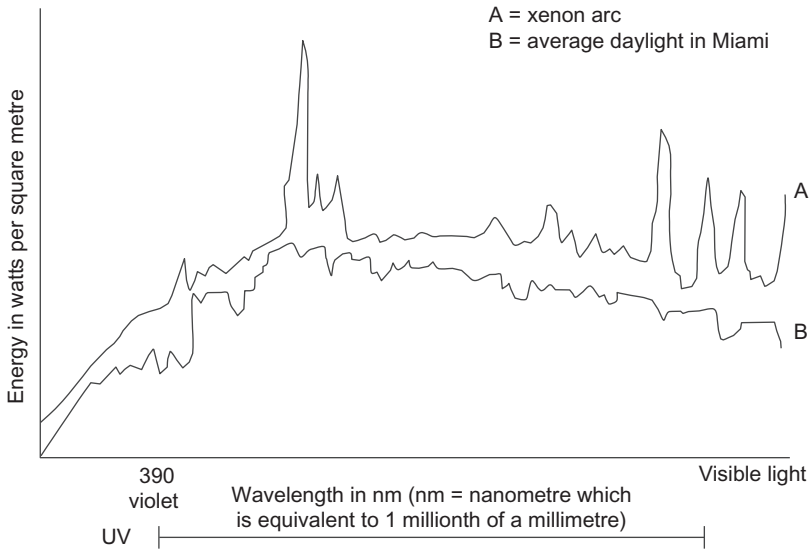


Fig. 9.1 Comparison of daylight and xenon arc [1].
Used with permission from Woodhead Publishing Ltd.

The fabric sample is prepared and exposed to very powerful arc lamps which simulate the different wavelengths of natural sunlight. Fig. 9.1 shows the similarity of the xenon lamps, when fitted with suitable filters, to the strong sunlight in Miami. These lamps are fitted to machines in which the sample is exposed for specified amounts of time. In addition to light, they create a lot of heat (and, in the case of weatherometers, moisture). The sample is then assessed against a grey scale 1–5 or a blue scale 1–8 (in the case of the blue scale a series of standard dyed wool samples are exposed at the same time and the test sample compared to these after exposure). In both cases, the higher the number the lower the amount of fading.

In some tests, the samples are tested for abrasion and strength before and after the light test.

9.2.1.4 Flammability

The flammability test is less severe than the ones used for public transport, airliners, and cruise ships. The reason for this is not very clear but could have to do with the fact that to pass the critical tests for public transport, it is often necessary to use inherently flameproof fibres, most of which are very expensive and they may not be able to pass the other rigorous tests required of automotive cloths. Another reason is that in most cases interior car fabrics can be nonflammable when coated with fire retardant or laminated to nonflammable foam and the resultant laminate can then meet the requirement. This could be because escape from a burning airliner or ship is more difficult, whereas private cars have two or four doors, and fire is seen as a lesser risk.

The test requires a horizontal strip of fabric to be ignited at one end and the length in centimetres burned in 1 min before it extinguishes is measured. This distance can vary

according to the OEM specification and also according to where in the car the fabric is used. The main minimum standard FMVSS 302 ISO 3795 is to ensure that the fabric does not burn more than 100 mm/min, though for safety reasons on statistical grounds some OEMs specify a rate of 80 mm/min.

9.2.1.5 Dimensional stability

This measures properties like stretch and recovery, shrinkage after immersion in water and drying out, and very often again varies according to the OEM and also to where the fabric is being used. These parameters are often specified for a particular car model and may vary significantly for a different model. This is a very important set of properties particularly for ease of seat build and to ensure that the seat covers have no creases on the surface which is unsightly, or do not go baggy after time due to poor elastic recovery.

9.2.1.6 Fabric strength

There are four aspects: tensile strength, tear strength, bursting strength, and seam strength/seam fatigue. Each of these require their own test regime and the only one which is less relevant to woven fabrics is the bursting strength test which is applied mainly to knitted fabrics which are less robust than wovens in this respect and are often used in areas where extreme fabric stretch is required.

The tensile test reveals any problems with the fabric structure or yarns used. The seam test reveals problems due to loose weaves, which allow the yarns to slip over each other opening up gaps in the sewing, etc. It also reveals problems with yarns and the friction between them due to other factors, which will be discussed in [Section 9.3](#). The tear strength can be effected by the coatings applied to the fabric and also the weaves used; the tighter the fabric structure the more susceptible it is to tearing.

There are many other tests applied such as handle and drape, breathability, soiling, snagging, environmental ageing, recovery from stretch, dimensional stability, anti-static, frosting and fogging, etc., but these are beyond the scope of this chapter. They can be referred to in detail in Fung and Hardcastle [1]. These tests define, to a large extent, the types of fabric, fibres, and yarns which can be used in the car and in the following section, we look at the use of woven fabrics in particular.

9.3 Woven fabrics in car interiors

The use of fabrics in cars goes back probably to the early years of the mass production of the motor vehicle. The first seat coverings were mainly leather or imitation leather, but also included wool and cotton before synthetic and other man-made fibres were available. The war years and afterwards saw the introduction of vinyl, both in the form of imitation leather and fabric made from fibres and yarns spun from a derivation of vinyl. This had the advantage of being able to be pigment dyed or spun dyed in the melt state before fibre extrusion to a very high standard of light fastness. Nylon made an appearance during and just after the war and also found its way into the car sometimes blended with other fibres. The technical requirements were nowhere near as

stringent as they are today, but even then durability, the ability to be cleaned easily and fastness to light all were important.

During this time, polyvinyl chloride (PVC)-coated fabric was an important development when applied to woven and knitted base fabrics since it allowed 'leather look' fabrics to be produced, particularly when embossed to imitate the surface appearance of the real leather. The colours were light fast and the product had acceptable durability and a certain amount of stretch, particularly if the base cloth was a warp knit structure. These attributes meant that this product in various forms became very widely used in mass-produced cars up until the early 1970s. However, PVC had some big drawbacks, among them being the 'stickiness' in hot weather and poor breathability, both of which led to it being somewhat uncomfortable when sat on for long periods, especially in hot weather. Nylon fabrics began to be used more widely again to try and add some much needed variation.

In addition to this, rising living standards were leading to an increasingly selective customer base demanding a greater amount of styling appeal both inside and outside the car, which was not being addressed by the limited textile products on offer. This was further emphasized when the Arab-Israeli war of 1973 created oil shortages and unprecedented increases in fuel costs which led to a concentration of effort on exterior styling to reduce drag, etc., and to increase fuel efficiencies. Greater use was made of glass and sleek, sloping windscreens, and larger windows all of which increased the amount of light – and UV plus heat in many countries – inside the car, putting even greater strains on the fabric performance.

All these factors resulted in many cars being designed with very similar exterior lines which in turn caused the car companies to add more expertise and styling to the interior to differentiate their model lineup, thereby creating a demand for more adventurous fabrics in terms of design and colour. At the same time, the engineers were placing ever more severe performance requirements on the fabric suppliers.

A new approach was needed for the fabrics to be used within the car.

9.3.1 The new age of car fabrics

The driving forces mentioned above sent the fabric suppliers back to the drawing board to reengineer the fibres, yarns, and fabrics available to them to address this emerging requirement. There was no doubt that textile fabric had the edge over PVC-coated products in many respects, not only in terms of comfort and breathability but also most of all in design and colouration potential. The use of nylon and polypropylene was becoming suspect after many failures in use of these products due to severe degradation in strength and abrasion caused by UV exposure. Many OEMs discouraged their use in areas which were exposed to sun such as upholstery, but not in other areas like seat belts, or carpets. The search for an 'all round' fibre at an economic price became urgent and was ultimately filled by polyester which, due to its suitability for almost all textile applications, has often been referred to as the universal fibre.

Table 9.1 shows the relative properties of the main fibres available to the manufacturer for transportation.

Table 9.1 Basic properties of fibres [1].

	Density (g/cm ³)	Melting point (°C)	Tenacity (g/den)	Stiffness (flexural rigidity) (g/den)	Limiting oxygen index (% oxygen)	Abrasion resistance	Resistance to sunlight
Acrylic	1.12–1.19	150d	2.0–5.0 (HT)	5.0–8.0	18	Moderate	Excellent
Modacrylic	1.37	150d	2.0–3.5	3.8	27	Moderate	Excellent
Nylon 6	1.13	215	4.3–8.8 (HT)	17–48	20	Very good	Poor–good When stabilized
Nylon 66	1.14	260	4.3–8.8 (HT)	5.0–57	20	Very good	Poor–good When stabilized
Polyester	1.40	260	4.2–7.5 (HT)	10–30	21	Very good	Good–excellent When stabilized
Polypropylene	0.90	165	4.0–8.5 (HT)	20–30	18	Good	Poor–good When stabilized
Wool	1.15–1.30	132d	1.0–1.7	4.5	25	Moderate	Moderate
Cotton	1.51	150d	3.2	60–70	18	Moderate	Moderate

Table listing basic fibre properties which are important for fabrics intended for transportation. Note the low melting point for polypropylene which is not much above temperatures which can be reached in car interiors in tropical climates. Items marked 'd' indicate that this is the temperature at which the fibre starts to degrade since they do not melt in the traditional sense.

From this it can be seen that polyester, while not the best in every category, reaches a high and acceptable standard in all the important areas.

Used with permission from Woodhead Publishing Ltd.

9.3.1.1 Yarn development

Polyester had many properties which made it suitable for many applications inside the car, including the major areas of seating and door panels. However, this was only part of the problem since every year the requirements of the OEMs were being ramped up; whenever a requirement had been met, the process of continuous improvement meant that the requirement had to be increased. So ways of improving abrasion were looked at and dramatic improvements made by the development of polyester air-textured continuous filament yarns using the Taslan process pioneered by Du Pont. This was a process in which continuous filament yarns were passed through a jet of high-pressure air causing intimate entanglement of the filaments in the yarn cross section, thereby creating small continuous loops which were locked in position (see Fig. 9.2). The effect this had on the stability and surface abrasion resistance of the woven fabric was dramatic and air-textured polyester yarn quickly established itself first in Europe then gradually worldwide as *the* yarn to use for decorative applications within the car where abrasion was a critical issue.

Many methods and variations were developed – parallel textured, core and effect textured, multiple feedstock yarns with variable input rates of the feedstock yarns to create slub-type effects, etc. (Fig. 9.3). The yarns were available in ecru for yarn or piece dyeing and also as colour spun using predyed or melt-dyed filaments for the feedstock yarn, which has overtime become the preferred colouration method for the European market and which is now spreading to the United States and Asian markets where piece dyeing in particular has been strong.

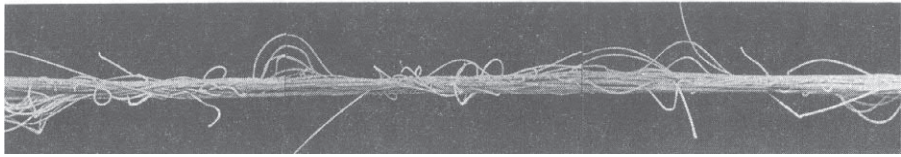
Due to the complex process, and inevitable increase in yarn count caused by the bending of the fibres through the texturing process, the textured yarns were quite expensive and therefore, alternatives were tried such as the ‘false twist’ process which had a similar effect in creating bulk. This bulk is created by clamping a heated yarn between two spinning points, either discs or belts which thus impart twist into the yarn. This twist is then held in place by nipping the yarn together with air. The effect of this process is that the twist which had been heat set and nipped into the yarn is then trying to untwist itself and thus creates the bulk of the textured yarn. The nip points in the yarn also help stabilize the yarn for further processing, as shown in Fig. 9.4.

This process created an attractive high bulk yarn via a cheaper route but the ballooning of the filaments between the ‘nips’ initially caused severe abrasion issues and could only be used if the fabric was very heavily back coated or the yarn was buried in the fabric or used on the back of the fabric and protected by a dominant air-textured weft yarn. Despite this, however, it found a major use particularly in head liners where

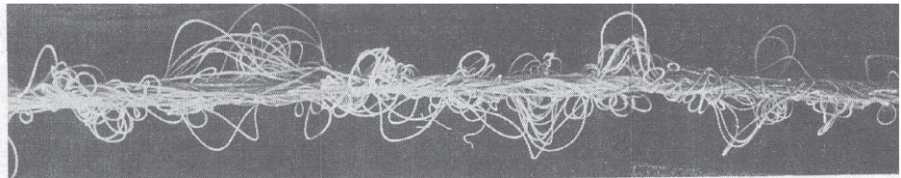


Fig. 9.2 Air-textured yarn showing the entanglement of the filaments which are locked in position to create a high abrasion resistant yarn but with limited stretch. See Fig. 9.3 for an illustration of different rates of overfeed of the component yarns to give varying surface texture effects.

Jet overfeed



Parallel textured yarn where all the filaments are fed equally into the texturing head, giving lower bulk but strong and hard-wearing yarn

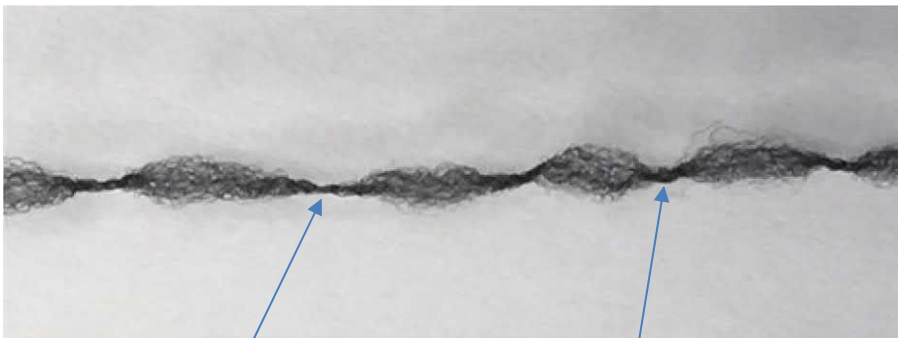


Core filaments

Effect filaments

Core and effect yarn. The core yarn is low texture and the effect filaments are overfed into the texturing head and held in position by the core giving a stable, higher bulk yet softer touch yarn

Fig. 9.3 Comparison of core and effect yarns.
Used with permission from Sage Automotive.



Intermingling point

Intermingling point

Fig. 9.4 False twist yarn (FT or FTF) in relaxed condition showing how the crimp develops. The intermingling points are introduced to hold the yarn together and permit easier processing. Between these points, the filaments are loose and can cause abrasion problems if the yarn axis is exposed on the cloth surface. This method, however, is one of the cheapest ways of creating high bulk filament yarns.

abrasion was less of a problem and as knowledge of their application and technology improved is now the main yarn used globally in automotive woven textiles.

These yarns came in two main types false twist fixed (FTF, which underwent a setting process) and FT (missing the setting process). The FTF yarns were more stable but less stretchy and the Ft yarns were unstable and had a tendency to shrink but had more stretch.

Staple spun yarns have always been used in automotive applications, usually in twofold form, particularly spun polyester, wool, polyester wool blends, and even in rare cases blends with spun viscose and acrylic. Spun yarns almost always create a more friendly and comfortable handle than air textured yarns but apart from price issues they almost always had a lower abrasion result unless the fabric construction was increased. These factors mean that often spun yarns were used in combination with textured yarns or if used 100% they find their way to the top end of the market for higher trim levels in fabrics of high construction and short float lengths. Mercedes, for instance, used spun yarns in wool and wool blends for several trim levels.

Constructed or 'fancy' yarns are used but have to be specially developed for automotive fabrics to pass abrasion specifications. Boucle yarns have to be well bound to avoid loops being pulled out in the snagging test but now due to the use of Hook fastener fabrics in clothing are now no longer used. Chenille yarns have to have their tufts well anchored into the core (sometimes by using low melt polyester in the core which melts during the stenter finishing process which binds in the tufts).

Flock yarns were used in large quantities by BMW for many years producing heavier, robust fabrics but were expensive and difficult to trim on more complex seats. This proved to be one instance where polyester did not meet the criterion, since it has a much lower resistance to fracture (i.e., it is more brittle) than nylon which bends and recovers (one of the reasons it is used in blends with wool for carpets, etc.) so it proved to be unsuitable for use as the pile component or flock. Yarns had to be developed with nylon pile and viscose core where the nylon was treated to increase resistance to light, UV degradation, and fading (see Fig. 9.7 for view of flock yarn compared with chenille). In almost all cases, these 'fancy' yarns are used today sparingly for decorative effect along with the standard 100% polyester ground yarns, as cost and seat build performance drove the usage down.

9.3.1.2 *Introducing stretch*

Another requirement becoming very apparent was the need for fabrics used in interiors to have flexibility and stretch. This was to make seat fabrication easier and also to address the problem covering the deep draw door panels which were becoming increasingly three-dimensional (3D) and moulded into quite remarkable shapes. An example of this is illustrated in Fig. 9.5, but many cars have this feature to a greater or lesser extent. Historically, this presented a serious problem for woven cloths, whether flat woven or pile woven velvet types, and if they were not to lose market share to knitted structures it was important that it was solved.

Woven cloths comprising warp-and-weft yarns laid straight in the cloth at right angles were in fact the most stable structures known, so either they had to be modified



Fig. 9.5 Moulded door panel and armrest on VW Golf showing the stretch required in the fabric to mould around the deep contours. A flat woven fabric is used in the illustration.

through the finishing process or new yarns had to be researched and developed which were more suitable for this end use. However, it was necessary to define what kind of stretch was required. Did it need to be two way (i.e., stretch *and* recover)? Or was one way sufficient (i.e., the ‘chewing gum’ effect) where the yarn or fabric stretched but did not recover?

9.3.1.3 Two-way stretch solutions

The use of false twist yarns was one partial solution since these had a lot more stretch than air-textured yarns, but had the abrasion problem. Elastomeric fibre content (e.g., Lycra) was the obvious solution but again the elastomeric component had to be small and well hidden due to high cost and poor abrasion and light degradation. However, despite the disadvantage it did give high amounts of recoverable stretch and was widely used in door casing fabrics, usually incorporated into the yarn before weaving.

However, this changed due to cost and advancements in 100% polyester fabrics. Fabric finishing was another way in which some low amounts of extensibility could be induced either by totally relaxing the cloth to induce high yarn crimp or designing special properties by weaving tensions and finishing technique. Fig. 9.6 and Table 9.2 show the theory behind this. The technique is based on altering the fabric geometry during the finishing process to interchange crimp and therefore, potential stretch. This technique was not really a total solution but was useful for making cloths easier to fabricate on doors and with advances in door manufacturing techniques, became somewhat of a standard.

Another method similar to the introduction of elastomerics was to use stretch polyester made from special polyester polymer known as polybutylterephthalate (PBT).

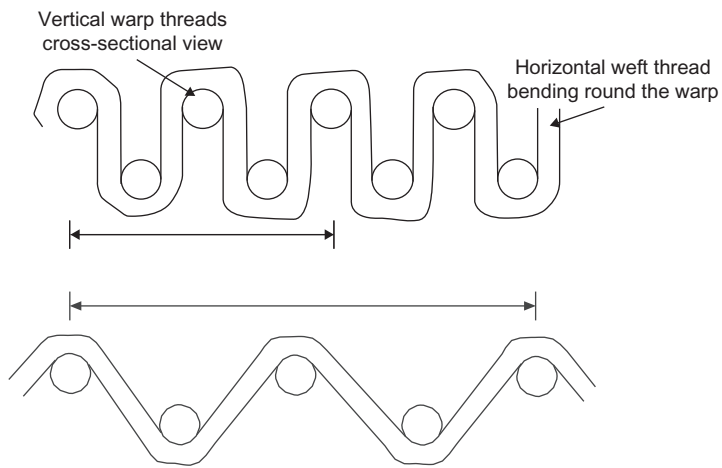


Fig. 9.6 Illustration of how the introduction of high yarn crimp in a fabric by weaving and finishing techniques can help to increase extensibility into the fabric to make it more manageable in the engineering of car interior components [1].
Used with permission from Woodhead Publishing Ltd.

Table 9.2 Weaving and finishing tensions [1].

	Weaving tension	Greige stretch	Finishing tension	Finished stretch	Effect
Warp A	High	Low	High	Lowest	Lowest warp stretch (length gain)
B	High	Low	Low (or overfeed)	High	Crimp interchange (length loss)
C	Low	High	High	Low	Crimp interchange (length gain)
D	Low	High	Low (or overfeed)	Highest	Highest warp stretch (length loss)
Weft E	High	Low	High	Lowest	Lowest weft stretch (width gain)
F	High	Low	Low	High	Crimp interchange (width loss)
G	Low	High	High	Low	Crimp interchange (width gain)
H	Low	High	Low	Highest	Highest weft stretch (width loss)

Used with permission from Woodhead Publishing Ltd.

This had stretch and recover properties and was capable of being dyed, albeit at lower temperatures. The stretch potential and power of recovery of PBT were very much less than elastomerics but sufficiently capable of filling certain requirements. It was mainly used in air-textured wefts as the core yarn and has proved to be a popular technical solution.

9.3.1.4 One-way stretch solutions

This is an important property of woven fabrics when applied to door panel material and also to head linings (see Fig. 9.5) due to the requirement to apply the fabric to the casing in a 3D mould often under pressure. The fabric had to be capable of being easily stretched around the curves but once in place there was no requirement to recover from the deformation. This problem was addressed by the use of yarns composed of partially orientated filaments; the yarn is known as partially orientated yarn (POY).

When any synthetic filament, including polyester, is extruded and the filaments are drawn together to create the yarn (before further processing such as texturing) they are 'drawn' or stretched out. This drawing process reduces the thickness and denier of the filaments and at the same time increases the strength and reduces the potential to stretch further afterwards. In other words, it stabilizes the yarn to a large extent. The extent of the drawing process is carefully controlled and when completed the yarn is known as fully orientated yarn (FOY). If this drawing process is only partially completed, it creates the POY version, leaving a potential for the yarn to be stretched or drawn out further. This potential can be realized either in yarn form or in fabric form after weaving with no danger of the fabric trying to recover afterwards.

This, therefore, is an ideal fabric to use in moulding applications. Stretch fabrics referred to earlier can also be used but they tend to be more expensive and always had the danger of 'creep', creating faults if the moulding process has not entirely removed the potential recovery property.

9.4 Fabric constructions and finishing processes

9.4.1 Cloth and yarn structures

We have taken some time to study the yarns used for automotive applications, as they are really the most important element when considering the development of these fabrics. The actual fabric constructions are often specified based on the past experience of successful cloths which are reliable – OEMs don't like dramatic changes, better safe than sorry! So the introduction of a brand new yarn is quite a significant change in this application. Design and colour, however, are a different matter.

These days colours and dyestuffs can be changed without too much risk due to years of development by dyestuff manufacturers such as Huntsmann, Dohman, or Clarion. The most important dye stuff in automotive today is in fact a pigment or a carbon-based black which is introduced to the yarn during its extrusion.

The air texturing process itself can create interesting colour effects by using coloured feedstock yarns where the filaments are dyed in the melt before fibre

Table 9.3 A selection of fabric structures used for automotive interiors.

Warp	Ends cm (in.)	Weft	Picks cm (in.)	Singles g/m ² (oz/yd ²)	
420 dtx (14 cc or 2/28 cc)	20 (51)	830 dtx (7 cc or 2/14 cc)	17 (43)	236	(7.0)
540 dtx (11 cc or 2/22 cc)	20 (51)	830 dtx (7 cc or 2/14 cc)	16 (41)	254	(7.5)
420 dtx (14 cc or 2/28 cc)	40 (101)	540 dtx (11 cc or 2/22 cc)	20 (51)	289	(8.5)
540 dtx (11 cc or 2/22 cc)	25 (64)	830 dtx (7 cc or 2/14 cc)	18 (46)	298	(8.8)
420 dtx (14 cc or 2/28 cc)	30 (76)	830 dtx (7 cc or 2/14 cc)	20 (51)	307	(9.0)
830 dtx (7 cc or 2/14 cc)	20 (51)	830 dtx (7 cc or 2/14 cc)	16 (41)	315	(9.3)
1300 dtx (4.5 cc or 2/9 cc)	15 (38)	1300 dtx (4.5 cc or 2/9 cc)	12 (30.5)	368	(10.8)
830 dtx (7 cc or 2/14 cc)	25 (64)	830 dtx (7 cc or 2/14 cc)	18 (46)	375	(11)
600 dtx (10 cc or 2/12 cc)	40 (101)	600 dtx (10 cc or 2/12 cc)	30 (76)	441	(13)

Note that most of the yarns would be polyester and frequently air textured [1].
Used with permission from Woodhead Publishing Ltd.

extrusion. By this method, multicolour marl and mixture effects are possible, without changing the basic performance of the yarn. However, due to cost and the size of batches required, multicoloured marl yarns have almost all died out. Where marl yarns are used, they tend to be black and white mixed with the fabric then over dyed.

By using colour and weave effects, subtle and interesting fabrics can be created. Jacquard woven fabrics are of course widely available as piece dyed or colour woven. In the early days of the development of air-textured yarns and fabric, the jacquard option was not thought to be possible due to the fibrous nature of the yarn, making weaving extremely difficult through the traditional jacquard harnesses, but improvements in both harness design and careful yarn development resulted in successful fabrics being developed. This aspect is described in more detail in the section on jacquard flat woven cloths below.

The actual constructions used often vary from one manufacturer to another but a few well tried and tested examples are shown in [Table 9.3](#).

9.4.1.1 Preferred yarn and fibre types

Due to ever increasing standards of (mainly) abrasion, strength, and resistance to sun-light and the ever present need to keep costs down, the polyester fibre rose to prominence along with the air-jet texturing method of yarn production.

Table 9.1 shows the main basic properties of the various fibre types and it can be seen that, while polyester is not the best at everything (e.g., nylon is stronger, hence used in seat belts, and acrylic has better lightfastness), when considered overall it possesses all the main attributes required of automotive trim cloths to a standard which is 'good enough' for the job while at the same time retaining a low-cost base. It is for this reason that polyester has risen to be *the* preferred fibre for use in these applications. However, this is mainly for the seating areas and other areas exposed to light and requiring high strength. Other areas such as carpets, seat belting, sound damping, etc., do not require these properties to the same extent and therefore, other fibres are often used, such as polypropylene for carpets and nylon for seat belts.

Wherever a spun yarn is used, it is almost always in the twofold form to maximize abrasion resistance. In yarns, the air-textured route probably offers the ultimate in abrasion strength and resistance to thread slippage during seat manufacture. However, this does not mean that other yarn structures are not used to create special effects and reduce prices. For cost reduction and for flexible easy trim woven fabrics, the false twist method is frequently used, often as a warp yarn but also increasingly as weft, but in all cases attention to the weave structures must be given. Float lengths and at the interface between one weave type changing to another, care must be given as to how those two structures fit together, as any single or loose threads may be a cause of a testing failure.

In the past, the use of viscose and cotton was rare, although in lower-cost models acrylic was sometimes used. Environmental concerns, however, have aroused interest in trying to incorporate natural fibres and those not using hydrocarbons during manufacture. However, in the main, when environmental issues are raised then the use of recycled polyester is often the default position.

In higher trim levels, and more expensive car models, wool is sometimes used to add greater comfort, mainly due to better moisture absorption, but even then it is often used in conjunction with, or blended with, polyester. Indeed for some high-end trim levels, woven or nonwoven microfibre fabrics such as Dinamica™ or Alcantara™ are used.

Pile yarns were often used in woven structures since they produce a pile surface which naturally has high abrasion and are cheaper than true woven velvet and competed mainly with weft and warp-knitted pile fabrics in automotive trim uses. There are two main types of pile yarns: chenille and flock.

Chenille yarns used in the Asian market are constructed by twisting two or more fine core yarns together while at the same time introducing at right angles the pile yarn and securing them in position by the twist of the core yarns. The pile yarn is cut to between 1 and 2 mm and thereby creates a pile surface to the yarn. This can be seen in Fig. 9.7. There are various techniques for making these yarns, which is an art in itself, and because of this and the heavy nature of the yarn, they tend to be expensive. The main problem is the tendency for the short pile tufts to pull out of the yarn during use. However, ways have been devised to introduce low melt yarns into the core which melt and fuse the pile to the core during subsequent heat processing.

No such problems exist in the other main pile yarn which is the flock yarn. In this, the pile is chopped up into short lengths of 1–2 mm and given an electrostatic charge to

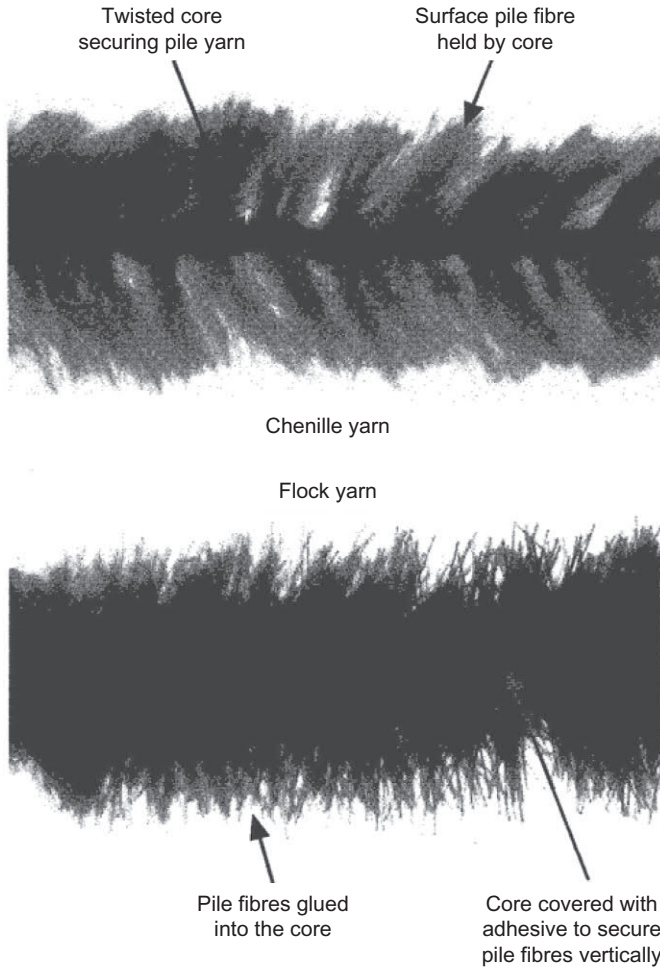


Fig. 9.7 Comparison of chenille and flock yarns [1].
Used with permission from Woodhead Publishing Ltd.

create a positive and negative charge before depositing onto the core which is also charged (and incidentally is often viscose coated with an adhesive). Due to the charges, the short-pile fibres all assume a position at right angles to the axis of the core yarn and the result can be seen in Fig. 9.7. This creates a more rigid yarn than chenille but with higher abrasion. As described above, when discussing BMW, the flexural rigidity of polyester as compared with nylon means that nylon is often used in these yarns as the pile but with extra UV stabilization.

The yarn counts which are used have over the years become somewhat standardized, although technically there is really no limit to the range which can be produced.

In filament yarns generally, and also to some extent in man-made spun yarns, the denier of the individual filaments (known as denier or decitex per filament (DPF)) can affect both handle and abrasion and it is usually a trade-off.

- Finer DPF (2 and below) = better handle = poorer abrasion
- Coarser DPF (3 and above) = coarser handle = better abrasion

540–620 dtx with 3 den per filament feedstock yarns air textured either parallel or core and effect is often used as is 420 and 830, whereas heavier count yarns such as 1340 and 3000 are now seldom used if at all. False twist yarns are usually available in 110 or 167 dtx as the basic building block, with 2/167/48 or similar filament counts are the largest runner in woven fabrics due to their cost, performance, and ease of use. Most have filaments that are round in cross section but certainly in Europe yarns containing Octo-lobal cross-section filaments are also used to get a more ‘cottony’ look. One significant and increasing trend is the use of recycled polyester chip in creating these yarns. Today the performance of a recycled polyester is almost identical to that of a yarn made from virgin polyester. This trend is set to increase, driven by consumer demand and legislation.

9.4.1.2 Woven fabric structures

Table 9.3 indicates various flat woven fabric structures which have been used for car seats. The ultimate suitability of these structures is determined by a combination of:

- yarn properties: count, DPF, strength, stretch, fibre types, thickness, surface characteristics including texture
- weave of the fabric which is the way in which the warp-and-weft threads interlace
- float length (i.e., the number of threads warp/weft yarns float over in the weave)
- fabric density or setting (i.e., the number of warp-and-weft threads per unit length)
- subsequent finishing techniques.

Although originally most automotive fabrics were plain or dobby woven, they are now available in many jacquard woven patterns and designs, so much so that the car companies or OEMs employ qualified textile designers to create the designs and colours.

Frequently, the interior fabrics are designed to offend the fewest and this means that they are often understated in terms of design and colours. Black or dark grey becoming the prominent colour. In jacquard fabrics, smaller-scale designs are preferred since these do not clash with other interior features and are also less troublesome to make up into the seats and door panels. This type of jacquard also adds a feeling of slight opulence to the interior and is often used in higher trim levels. This is illustrated in [Fig. 9.8](#) which shows a design which has been used in the Mercedes E class. More brash designs in brighter colours and larger repeats are sometimes used in cheaper models to brighten up what could be a drab interior or to target a particular segment of the market. The growing trend when using jacquard fabrics is to have patterns that are single large repeats that fit singly into the seat back or cushion of a car seat. These are referred to as ‘placement designs’.



Fig. 9.8 Typical automotive jacquard seating fabric. Main features are understated design in muted self-colour and small scale to avoid dominating other interior features of the car.

9.4.1.3 Jacquard flat woven cloths

When the ‘new age’ of colour woven car fabric using predyed air-textured polyester yarns began to emerge in the 1970s, the design aspect took most of its input and inspiration, and to some extent colouration, from the apparel trade – men’s, ladies suitings, etc. – and fabric suppliers began researching the latest trends and colours. By adapting these to approved automotive structures, special automotive ranges were incorporated into travelling presentations to the individual car companies worldwide. However, most of the designs were of a simple or geometric type woven on dobby looms, generally typical of suiting type designs, making good use of colour and weave effects.

As the decade gave way to the 1980s, new directions were investigated and one of these was the possibility of developing jacquard fabrics. Jacquards had been extensively used before in automotive and also transport textiles in general, but as described earlier the move to air-textured yarns for performance reasons caused quality problems during manufacture due to the fine jacquard harnesses. An intensive development programme which the author was very much involved in, saw the development of new parallel textured yarns which performed well and one of the first jacquard ranges in these newly developed structures was put into production by the Rover Group.

Following this, the use of jacquards in the new fabrics for automotive applications using air-textured yarns, including warp yarns, exploded all over Europe and then the

world. Table 9.3 illustrates some fabric structures which have been approved in the past for jacquard fabrics.

For a while Jacquard fabrics were the main pattern, but through the drive to develop lower-cost fabrics and looking at a trend for regimented pattern, large-scale jacquards dropped off rapidly in the mid to late 1990s to be replaced by dobby fabrics using colour, and weave or simple construction effects.

The more technical aspects of developing these fabrics are beyond the scope of this chapter but are a very interesting part of the story.

9.4.1.4 *Dobby wovens*

As automotive fabrics developed, through cost pressure, more and more flat woven dobby fabrics came into existence. These were divided into two main areas. The inserts became more and more geometric and therefore simple. This meant that instead of complex Jacquard patterns being created, designs that were made from simple small scale pattern repeats, became popular. This allowed the use of lower cost, higher speed dobby machines to be used. Here a set series of yarns are raised and lower in series, rather than individually, resulting in these smaller scale patterns. The second use of dobby fabrics is today the single most used technique for automotive fabrics. Here, very simple designs such as twills, plain weaves and hopsacks create plain fabrics that at first were used on the seat backs and sides, particularly for high wear areas and then into the inner 'insert' part of the seat. These plain fabrics could then be modified by being stitched, embossed or surface treated in different ways, but due to their large volume and lack of complexity commanded the lower price points sort by the car companies.

9.4.1.5 *Yarn and fabric colouration*

The colouration of automotive and transport fabrics in general falls into one of two categories (and very occasionally a combination of both):

- Colour weaving from precoloured yarns. This in turn can be subdivided into package dyed yarns and colour spun or spun dyed yarns.
- Fabric (i.e., piece) dyeing where the fabric starts life in the ecru form.

As has been described earlier, car interior fabrics have to withstand a lot of wear and misuse and the yarn air-jet texturing technique has proved over the years to be the most able to withstand this. It also has another advantage in terms of ease of colouration mainly by the colour weaving route as detailed above.

It is always necessary when designing trim fabrics to have the ability to 'fine tune' the colours so that either all, or at least a major part, of the fabric matches or coordinates well with the other interior items such as plastic trim, dashboard, leather, which may also be part of the interior or even the same seat. This matching is a big issue when different materials are involved and the OEMs place stringent requirements on the suppliers to achieve a nonmetameric match.

Metamerism is the ability for a single colour to appear different when viewed under different lighting conditions, for example, in daylight and in tungsten light, so it is

possible for a metameretic seating material to match the dashboard in daylight but be a total mismatch when viewed by the car interior lights. Dye technology has advanced to a point where this can to a large extent be predicted and avoided, but it all adds time and cost to the development process.

The use of air-jet textured yarns made this problem easier to deal with by the employment of yarn package dyeing, in which packages of the yarn are impregnated with dye in a pressure vessel. This enables small samples to be prepared to achieve a good match on a short timescale. The package dyeing technique also offers great potential in the creation of a virtually unlimited colour range which is a massive advantage to the designer.

That said, yarn dyeing is now a very minor colouration technology in terms of automotive fabric usage, due to two main factors:

Cost as yarn dyeing uses expensive dyestuff and is an additional process. Performance as the package dyeing technology tended to kill any elasticity within the yarn.

Another yarn colouration technique is the use of colour spinning or the colouring of the melted 'dope' before it is extruded into filaments. This is often referred to as 'spun dyed' or 'melt dyed' in that the filaments are dyed before being brought together to form the yarn. This is generally the cheapest method of colouring yarn and also gives the highest lightfastness, improved physical performance but it requires large volumes to be really economic. However, many European suppliers have adapted their processes to be more flexible offering much smaller production lot sizes. One method to improve the economics has been to standardize colour across a range of an OEM's vehicles to increase volume and reduce complexity. It is fair to say that the VW group has been the master of such activity standardizing not only colours but also fabrics as well.

A third way is to combine several spun dyed feedstock yarns (usually 167 dtx) within one air-textured yarn. For example, an 830 dtx air-textured yarn could comprise four or five individual feedstock yarns each of which could be a different colour. This would create a tweed or heather mixture yarn and these were very popular with designers. Since the colours of the feedstock yarns are fixed for reasons mentioned earlier, subtle colour changes can only be achieved by changing texture levels or changing one of the feedstock yarns. This method, however, again fell from grace due to design trend and cost reasons.

Although colour weaving is a very convenient way of creating fabrics for interior uses, the piece dyeing technique is also used particularly where the fabric is of a plainer character – seat backs and bolster fabrics for instance – can work out cheaper in certain circumstances, usually when the required colours are lighter. It lacks the versatility to create the very subtle design and colour effects that were often required, but as the trend for lower cost, monochromatic seats evolved, piece dyeing remains a strong colouration method especially in Asia and in the United States where lighter-coloured interiors and fabrics remain popular. Sometimes the two methods are combined in which partly coloured fabric is overdyed but this is only used in special cases.

The piece dyeing of polyester has to be carried out at around 130°C or higher and therefore, requires a pressurized dyeing vessel called a Jet.

9.4.2 Finishing processes

All fabrics go through some form of finishing and exactly what is involved in this process depends to a large extent on which part of the vehicle the fabric is to be used. If the fabric is to be coloured by piece dyeing, then this will be the first process to be followed by the others, which also are used on colour woven fabrics. All fabrics are either scoured to relax the structure and/or stentered at or around 130°C to heat set the fabric to remove creases and prevent subsequent shrinkage. Sometimes during heat setting, some form of acrylic back coating is applied usually by the foam application method often with an additive to impart some flame retardancy (FR). The foam method is simply a way of mixing the compound with air to create a bubble-filled foam and is often used since it is a very economical way of applying compounds to fabrics and it allows great control of thickness and consistency. The process is illustrated in Fig. 9.9.

The coating process has several uses: it allows just enough compound to be applied to ensure that the fabric passes the fire retardancy requirements, and makes a substantial contribution to improving face abrasion and snagging resistance by anchoring the filaments of the yarns into the structure. However as a downside, it tends to stiffen the fabric leading to more difficult processing when being made into seats.

After heat setting and sometimes instead of coating, the fabric is often laminated to a polyurethane or polyester foam and nylon scrim to create what is known as a trilaminate structure. If the foam is a special fire retardant variety, the FR coating can be dispensed with since the FR foam will be sufficient to apply the necessary FR property to the fabric. This process is illustrated in Fig. 9.10.

The reason for creating these trilaminate (or sometimes bilaminate) structures with scrim on the back is to allow the fabric to be tightly stretched over the seating ‘bun’ (also made from polyurethane foam) and manipulated into place since the scrim is able to slide over the foam bun.

A bilaminate without the nylon scrim and with thinner foam may be used as door panelling to give a soft and resilient touch.

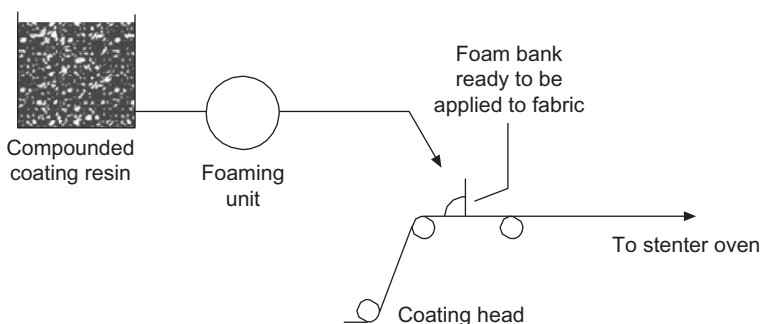


Fig. 9.9 Schematic of knife over air foam coating [1].

Used with permission from Woodhead Publishing Ltd.

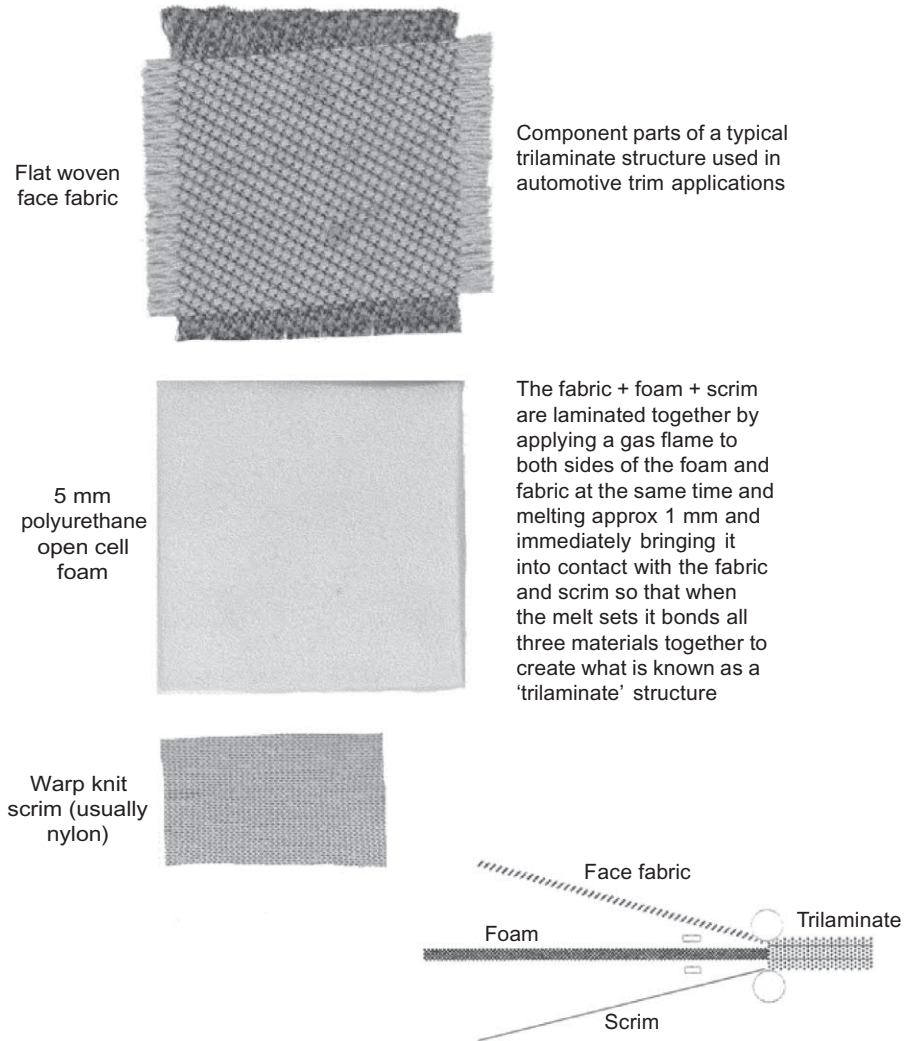


Fig. 9.10 Automotive trillaminate fabric.

Other finishing processes include spray on antistatic agents or sometimes antislip compounds to ensure that the warp-and-weft yarns do not slip at the seams.

It should be noted that the majority of woven textiles used today in the automotive sector are plain in colour. There are increasingly stringent requirements to ensure that the fabrics are easy to trim. This invariably incorporates not only the use of solution dyed false twist yarn to give the fabrics the best chance of elasticity but also the use of bulking machines during finishing that improve the drape and elasticity of the fabrics

further, giving the seat producers the best chance of making crease free seats. This trend has increased further with the need for flexible wovens to work well on increasingly complex seats.

One further trend that should be noted is that the laminated woven fabrics are then often further embellished by the use of embossed patterns, stitching, printing, and high-frequency welding.

9.5 Other transport applications

Although the automotive application is by far the largest in terms of volume of fabric used, almost all other forms of transport use textile products including woven fabrics in some degree. The fabrics all have to perform similarly in term of abrasion strength, etc. The one area which is far more critical in public transport is fire retardancy where very different and very much more stringent requirements are placed on the suppliers to the point where often inherently flameproof or retardant yarns and fibres have to be incorporated.

9.5.1 Commercial heavy goods vehicles

Often these are made by the same OEMs who manufacture cars and frequently use the same interior trim fabrics, although special fabrics made from 1100 dtx yarns to create heavier materials with enhanced ‘wearability’ are sometimes specified, although they are subject to the same performance test requirements.

However, heavy goods vehicles (HGVs) also use very large quantities of tarpaulin fabrics in their side curtains. These fabrics are often flat woven structures made from either high tenacity polyester or nylon in base fabric weights ranging from 100 to 300 g/m². However, these are then subject to substantial posttreatment of coating and lamination. PVC multilayer coating is often applied to both sides of the fabric ending up with fabric total weight of 1000 g/m² or even more. At the better quality end, an additional polyurethane or acrylic lacquer with UV additives is often applied as a final coat to improve lightfastness, abrasion, and resistance to soiling.

9.5.2 Buses and coaches

The interior seating and trim fabrics used in this market are in fact different from the automotive product both in terms of fabrics and also design and colour. Also, due to the heavy use over the lifetime of the vehicle, a different emphasis is applied to the physical requirements. Shampooing is often carried out to keep the seats clean and therefore, colour fastness to this procedure is an important test requirement – this hardly features in automotive cloths.

Abrasion testing is usually carried out by Martindale where 80,000 rubs or more is needed. Fire retardancy is also stricter and sometimes requires the use of fire blocker interlining fabrics. Toxic fumes from the fire source are an important issue and the

materials have to be selected carefully. Comfort of the passenger is of greater importance in buses and coaches and this requires the material to absorb moisture without feeling damp, particularly in hot climates.

When considering all these issues together, fabrics which tend to meet the overall requirements best are those containing wool, particularly when blended with nylon with the comfort aspect best served by the use of pile fabrics. Mainly for these reasons, a pile comprising 85/15 blends of wool/nylon in moquette or woven velvet fabrics were first developed to meet these requirements and are still an important segment of the market. The fabrics are invariably back coated and total weights are in the 800–900 g/m² range. However, fibre developments, cost pressures, and the fact that polyester is inherently a cheaper fibre than nylon, have seen other blends appear such as wool/polyester in 80/20 and even 100% polyester and also polypropylene have entered the market particularly from overseas manufacturers.

Frequently quite bold design and colour work is used to make specific statements about the coach or bus company and this is often met by the use of bright multicolours and the velvet jacquard machine. The Belgian company Michel Van de Wiele is in the forefront of supplying weaving machines for this market.

9.5.3 Railways

For the same reason as for coaches, the 85/15 wool/nylon velvet at around 800 g/m² is a large part (but by no means all) of the market. Again FR requirements are very stringent and sometimes these are more easily met by the use of inherently flameproof fibres such as Trevira CS (this is a flameproof polyester fibre produced by Trevira GmbH, previously a subsidiary of Farbwerk Hoechst AG) either alone or as blends with wool. The fabric types are generally woven and either cut pile velvet or sometimes moquette, which is a form of velvet traditionally woven as a single fabric with the pile yarns being lifted over wires during weaving to create a raised loop pile surface as illustrated in Fig. 9.11. Using this technique, it is possible to create both cut and uncut pile in the same cloth and to use the difference in appearance to create the design effect. However, since it is a single cloth construction, it is only used either for loop (uncut) or a combination of both since it is too expensive to be used as a way of creating only cut pile. This can be produced even more cheaply on the face-to-face principle where two cloths are woven simultaneously one above the other and separated by a traversing knife.

Apart from high nonflammability requirements, fabrics used for trains are often subject to vandalism and ways of combating this, have been developed, albeit at high cost, by using cut-resistant fabrics made from high modulus polyethylene fibre such as the Spectra produced by Honeywell. Although mainly developed for military uses and body armour, they are one possible solution to combat wilful damage. However, Spectra fibres have a disadvantage in terms of design and colour potential, and of course cost.

It is interesting to note that, unlike the automotive and HGV applications, both bus and coach and also railway segments have been noted for the creation of iconic designs for seat materials in both velvet and moquette. Many of these were produced over the years by both Firths and also John Holdsworth (now owned by Camira

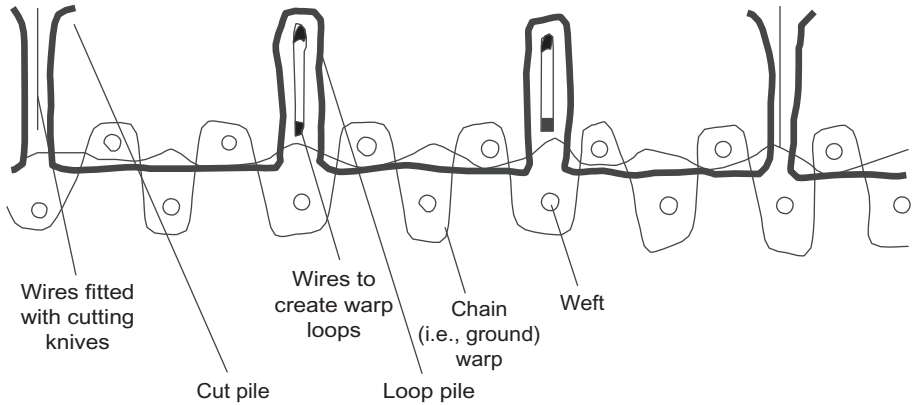


Fig. 9.11 Illustration of moquette cut and uncut pile.

Fabrics), West Yorkshire, who have been producing transportation fabrics for over 200 years. The bus, coach, and rail segments seem more prepared to push the boundaries in terms of design and colour than the more conservative automotive sector. They also use colour for practical as well as aesthetic purposes. An example of this is Transport for London, who in the 1990s refurbished their trains with moquette upholstery allocating a different design to each underground line and where the predominant colour in the designs reflected the colour of the lines on the original Harry Becks underground map (yellow for circle, turquoise for Victoria, etc.). Other innovations have been tried by Transport for London using the fabric designs to convey a message or advert such as a trial in 1998 where a train was refurbished in a moquette design specially commissioned to advertise the London Yellow Pages telephone directory. Further information and illustrations of the moquette designs and much more can be seen on the London Transport Museum website at <https://www.ltmuseum.co.uk> and typing 'moquette design' into the search box.

9.5.4 Aircraft

The use of colour woven fabrics with high design and colour content is increasing in aircraft, although in volume terms it hardly registers when compared with automotive. Increasing competition drives manufacturers and airlines to try to differentiate their interiors and make them more passenger friendly, but it is often the safety aspect, particularly the nonflammability and low toxicity properties of the fabrics, which occupies a lot of development time bearing in mind that fire and smoke inhalation causes over 25% of possibly survivable deaths in air accidents.

Weight reduction is also an important issue but the production of extremely hard-wearing fabrics required of the rail, coach, and car businesses is not so important, hence softer and more aesthetically pleasing flat woven fabrics are possible. It is probable that the first textile fabrics made specifically for aircraft were developed in the early 1940s by Collins and Aikman in the United States for the Douglas Aircraft company.

An important property of textile fabrics is their ability to carry design and colour, enabling corporate logos and colours to be incorporated. Much effort is being put into making the cabins appear more spacious with softer surfaces and woven textile fabrics, including jacquard woven fabrics.

All fabrics have to pass the vertical burn test such as BS3119 or DIN 53906 or the International FAR 25.835 b and c in which the product has to be self-extinguishing in 15 s after removing the flame. Fabric foam seat composites have to resist a burner applied to the seat for 2 min. In order to pass this very rigorous test, fire blocker fabrics have sometimes to be included as part of the assembly along with fire-resistant foam. The role of the fire blocker fabric is to enclose the foam and considerably enhance the overall fire retardancy of the seat and for this reason the fire blocker fabrics are made from nonflammable or extremely low flammable, and frequently woven, fabrics.

The main fibre used in fabrics for aircraft is wool which has been ZIRPRO treated. This is a treatment developed by the International Wool Secretariat (IWS) to improve FR of wool fabrics. A special 'low-smoke' version has been developed specifically for aircraft manufacturers.

Other uses for woven fabrics in aircraft are for escape chutes which are mainly woven polyester or nylon which has been polyurethane coated.

9.5.5 Marine

Among the traditional marine applications for woven products are: specialized polyester for the sails, coated heavy fabrics for inflatable life rafts, boat coverings, awnings, composite materials using woven textile fabrics as part of the composite and used in the actual structure of the vessels. Again strength and reduced flammability are some of the more important properties in these applications. Most of these are quite specialized and relatively low volume. Another rapidly growing sector, which has strong connections with the past, is the cruise liner business. Nowadays, these are often massive constructions possibly the largest to date is the 'Allure of the Seas' owned by Royal Caribbean at over 220,000 gross tons around 1/4 mile long and holding over 6000 people on 18 passenger decks.

There are many more, which are not a lot smaller, cruising the world's oceans and all need furnishing with carpets, curtains, and bedding, most of which will be woven fabrics. This is a very large fabric requirement which needs replacing on a regular basis and at the moment it is growing. The fabrics are similar to and as diverse as the domestic and contract home furnishing market but with the added requirement of stringent FR and low toxicity of the emissions. The fibres used are: cotton with fire retardant 'Pyrovectex' treatment, also Trevira CS with permanent FR properties and ZIRPRO-treated wool, particularly for carpets.

9.6 Future trends

Environmental concerns are a big issue which the automotive industry has been trying to deal with for many years. It is becoming even more important with the rising price of oil and the need to reduce fuel consumption and address the recycling problem.

Weight reduction has been one way to address this with the increasing use of lighter materials such as aluminium, magnesium, and also titanium and carbon fibre composite. Some are more successful than others and all have problems not least of which is the cost. Fabric in terms of weight reduction has effectively halved in weight, with fabrics that were made at 500 g/m^2 , now reduced to on average 250 g/m^2 .

In addition, it is also possible to redesign the car body to use less material, but it always has to meet strict safety standards and minimum strength, and also be capable of economic manufacture. The use of woven textile fabric in car bodywork is not new, soft top convertibles have been used for decades. However, the use of a textile fabric to totally replace the metal panels in the whole of the body is, or was, an innovative approach and was initiated by a well-known German-based automotive company and launched in 2008. It was an experimental project and has not progressed through to the production but it did illustrate the uses to which a textile material could be put with careful design of both the material and car. The material was a specially developed coated polyurethane-polyurea copolymer stretch material and was stretched over metal hoops to form the body shape.

Other ways of reducing the carbon footprint and also the reliance on oil are being tried. For example, some automotive manufacturers have developed so-called bio-fabrics which are modifications of the normal oil-based synthetic products like polyester by incorporating as part of the process plant-based raw materials (e.g., corn and terephthalic acid) which can use up to 15% less energy through the production process.

The Green agenda, in addition to driving the search for new synthetic fibres, is also seeing the reintroduction of natural fibres such as linen, flax, and hemp. This can be either as a replacement for some of the synthetic fabrics with possible performance reductions or as a composite with other materials to replace some of the heavier items within the car. However, recycled polyester is increasingly being used in vehicles with companies such as Ford stipulating a global requirement for a minimum 25% content of recycled polyester.

New fabrics have also been seen in the development of inflatable seat belts which, like air bags, are blown up on impact by explosive gas to protect the occupants.

Whenever a new vehicle is developed with new propulsion systems, such as electricity or hydrogen or even hybrid variations, it is becoming axiomatic that the OEM will want to use textile products which follow the same thought process of carbon reduction, and it is up to the fibre and fabric manufacturers to be developing answers to these requirements.

'Smart textiles' also need to be borne in mind. These are textile-based structures with the ability to sense and react to stimuli. This could be a traditional woven cloth incorporating a conductive filament which can sense changes and transmit data. How could they be used inside a vehicle? This is up to the designer and engineer to determine in the never-ending quest to create a competitive edge for their company.

The automobile industry is well known for its desire to continually push the boundaries and address concerns of safety, weight reduction, carbon footprint, recycling, and explore all ways of reducing the environmental impact and dependence on oil throughout the life of the vehicle. In this scenario, the future of textile products within the automotive and transportation industries can only be good provided manufacturers

keep themselves well informed and up to date about the latest thinking and developments of both the OEMs and the major fibre manufacturers.

Acknowledgements

The author thanks the following people and organizations in kindly providing information, permissions, and also in helping to check the manuscript. Textile Institute, Woodhead Publishing, London transport Museum, Tiffany Daneff, Saga Magazine, Karlheinz Merkens, and Walter Fung.

Reference

- [1] W. Fung, M. Hardcastle, *Textiles in Automotive Engineering*, Woodhead Publishing, Cambridge, 2001.

Sources of further information and advice

- [1] B.K. Behera, P.K. Hari, *Woven Textile Structure*, Woodhead Publishing, Cambridge, 2010.
- [2] W. Fung, M. Hardcastle, *Textiles in Automotive Engineering*, Woodhead Publishing, Cambridge, 2001.
- [3] A.R. Horrocks, S.C. Anand, *Handbook of Technical Textiles*, Woodhead Publishing, Cambridge, 2000.
- [4] W.D. Schindler, P.J. Hauser, *Chemical Finishing of Textiles*, The Textile Institute and Woodhead Publishing, Cambridge, 2004.
- [5] The Textile Institute, *Textile Terms and Definitions*, The Textile Institute, Manchester, 1993.
- [6] B.J. Tortoro, P.G. Collier, *Understanding Textiles*, Prentice-Hall, Englewood Cliffs, NJ, 1997.
- [7] http://www.motortrend.com/future/concept_cars/112_0806_bmw_gina_light_visionary_model/viewall.html.

Woven apparel fabrics

10

Nicola A. Redmore

School of Art, Design and Architecture, The University of Huddersfield,
Huddersfield, United Kingdom

10.1 Introduction

Woven fabrics for apparel are extensive in range and diverse in nature, and have developed over the centuries to meet a wide range of requirements and end uses. Functional, decorative, traditional, or high performance, the combinations of fibre, yarn, texture, weave, colour, and finish provide a vast range of possible options. This chapter will focus on the more widely used woven apparel fabrics, their characteristics, performance, and applications.

10.2 Performance requirements

10.2.1 Overview of the manufacturing process

The majority of woven apparel fabrics are produced on one of three loom types: a tappet loom, dobby loom, or a jacquard loom. Tappet looms are used to produce designs that require 12 shafts or less and are more economical than dobby looms. Dobby power are used for small-scale patterns beyond the capability of the tappet loom and are generally used for designs that require over 12 shafts and up to 32 shafts. Fabric types produced on these two loom types include are fabrics of all weights and in any type of fibre from natural to man-made fine voile's, silk satin's, and cotton shirting, through to heavier weight denim and woollen tweed jacketing. Jacquard looms are used to create larger figured designs, which cannot be produced on a dobby loom and where the warp threads are controlled individually through a patterning mechanism, which can be a mechanical one or linked to a computer-aided design system. Fabric types produced on this type of loom include the ornate and decorative, brocade, damask, and cloqué. The fabrics produced on both of these loom types are termed flat woven but there is another category of apparel fabrics that require specialist looms in order to form a pile on the surface of the cloth.

Pile woven fabrics including velvet and corduroy consist of a base ground fabric with an extra layer of loops formed in either the warp or the weft direction by an extra set of yarns. The loops formed by these extra yarns may be left intact, that is, uncut, as in the case of terry towelling or cut (either on or off the machine in the finishing process) creating a raised surface of yarn tufts or pile for fabrics like velvet and velveteen.

Apparel fabrics may be woven in ecru (undyed, natural colour) ready to be piece-dyed on demand, or colour woven (fibre or yarn-dyed), as is the case with tweed and tartan fabrics. Woven fabrics also make up a large percentage of the base cloths used in the printing industry, where their inherent stability makes them an ideal substrate for achieving good print registration and clarity of design.

The textile industry has continued to develop, more flexible loom technology capable of manufacturing the multiple cloth qualities required to supply the fast fashion apparel industry. Quick style changes and economy in the production are being facilitated by improvements that include automatic drawing-in machines and automatic leasing. The continuous design innovation required to compete globally has led to the development of sample looms and associated equipment by companies including CCI Tech Inc. This dedicated sampling equipment is designed to allow mass production on full width looms to continue, without the need to stop for sampling or to fulfil small orders.

10.2.2 Trends and design

The popularity of woven fabrics for fashion is subject to seasonal trends influenced by catwalk collections and by the trend prediction companies that specialize in creating key directions for the colour, texture, and patterning. The demand for the cloth types that make up the clothing staples of shirts, suits, jeans, and coats remains fairly constant, but are subject to minor seasonal changes in terms of colour, fibre composition, and finish. This continuous development keeps them up to date and in line with current taste.

The design content of woven fabrics can vary, dependent on the fabric type and the desired end use. Plain or semiplain fabrics that have been in use for hundreds of years require little design beyond the minor changes in construction or finish, but change may be driven by a change to the proposed fibre or yarn type. The development of a fabric woven from a new sustainable fibre, for example, may require some special loom settings, fabric sett, weave structure, and finishing route before the optimum result is achieved. At the other end of the scale, jacquard woven designs and colour-and-weave fabrics (e.g., a Prince of Wales check) may necessitate multiple trials of possible weave design and or colour options before a new design is signed off. Fabric options may be offered in multiple colourways in a sample book, or in a design blanket (as is often the case in the worsted suiting industry).

The majority of the manufacturing for apparel fabric sold to the British High Street is now situated overseas in order to be able to produce material at the price point and quantity needed in order to remain competitive. A core manufacturing base dominated by China, continue to supply a diminishing number of fabric qualities as demanded by global clothing brands whose purchasing decisions are driven by lower prices. The companies that do retain a manufacturing and weaving presence in the United Kingdom are usually specialists in the production of high-end, bespoke, or high-performance fabrics for end uses including suiting, coating, and ties. These specialists retain a presence in areas of the country that traditionally concentrated on the production of worsted, woollen, tweed, cotton, or silk manufacture, drawing on hundreds of craftsmanship in those regions. The eco-conscious consumer and a rising demand

from brands for a less harmful product portfolio is pushing forward demand for new innovation and technologies that can reduce the impact on the environment. Innovation in recycling, eco-friendly dyes, reduction in water use, and adoption of new finishing technologies are all part of the move to developing closed-loop or cradle-to-cradle production systems.

10.2.3 Fabric specification

When specifying or selecting a fabric for apparel end use, a number of considerations need to be taken into account. The fashion designer, having designed or selected a specific garment shape, will be looking to maximize certain characteristics through the careful selection of a fabric that will compliment and fulfil the vision for their collection. A sensitivity to and knowledge of the characteristics of fabrics, along with a creative approach to their use is essential and central to the sourcing of the appropriate cloth for a given garment. Consideration of how the fabric will drape on the body and how it will be affected by the cut of the garment should be considered, along with inherent properties such as how open or dense, stiff or floppy, fluffy, or smooth it is. Fabric comfort can be described as the extent of stretch and its recovery from extension. Woven fabrics are not naturally as stretchy as knitted constructions, but ‘stretch woven fabrics’ can be created through the use of elastomeric yarns.

The target customer and garment style needs to be considered when selecting a fabric, in order to match the performance of the cloth to its intended end use. How much will the garment be worn, in what situations will it need to perform, how long is it expected to last, and how will it be laundered? These are all key questions to be answered along with the cost constraints of the range. Product lifecycle management (PLM) systems allow real-time information visibility throughout the life cycle of a product increasing efficiency and cost effectiveness, from ideation, design, and manufacture, through service and final disposal. There are still many opportunities for the digitization of the apparel industry both for product sourcing and for design as well as virtual prototyping, virtual showrooms, and catwalks.

10.2.3.1 Fabric selection

When choosing the type of fabric, it is important to match the performance of desired fabric properties to the end purposes. Fabrics for work wear need to have good durability, abrasion resistance, and cleanability. Outerwear needs to protect, insulate, and be hardwearing. Conversely finer and lightweight fabrics for eveningwear or lingerie are selected for their aesthetic qualities, drape, and handle. The combination of yarn and fibre type along with the weave, gives the designer further options to engineer a fabric to meet the garment requirements. A fibre such as wool has better extension than say flax (linen cloth), which is inherently stiff and has poor crease recovery.

More densely packed threads in the warp can help to improve tensile strength, than a higher pick rate in the weft, and a higher twist in the yarn will help give further strength to cope with the stresses and strains during weaving.

10.2.3.2 *Weave properties and characteristics*

Fabric properties are diverse, with weave structure, fibre type, fabric sett, yarn type and finishing route all affecting the characteristics of a given cloth. Some properties are inherent to a fibre type such as its stiffness, thermal properties, handle, or drape. The weave type including the length of floats in the structure will also influence these properties. The amount and direction of the twist in a yarn affects the handle, drape, and other surface and physical properties.

One of the simplest weave structures, plain weave produces a plain, non-directional surface that may be fine or coarse dependant on linear density of the warp-and-weft yarns. Taffeta is a good example of a fabric woven in plain weave, a weave that is used for many lightweight and sheer fabrics. The high number of binding points (also known as interlacements) in this structure gives firmer and stronger fabrics than that in a twill weave structure using the same fabric sett and yarn linear density. Plain weave is less susceptible to distortion of the threads in the fabric.

Twill weaves in which the yarns are usually more loosely bound than plain weave provide fabrics that are more supple and have a degree of natural stretch especially when cut on the bias (45° to the selvedge direction). Twills have a distinctive appearance as in the example of cavalry twills and the double-twill in this cloth not only defines the look of the cloth, but also the way in which it handles. In the case of denim, the longer floats in the warp direction of the twill (3/1 twill is most common) can be used to hide the undyed weft.

Hopsack has a greater resistance to tearing compared to a fabric constructed from plain weave, as the pairs of ends work together in the structure. Hopsack fabrics can, however, create problems with seam fatigue, where it is more difficult to secure the more loosely bound ends and picks with the sewing thread. Loose weaves with long floats, do have better tear strength as the threads slip and move past each other rather than ripping straightaway.

The smooth face of satin woven fabrics creates an ideal surface for printing, embossing, or embroidery applications.

The durability and appearance retention of cord and velvet fabrics should be considered when designing as they have a tendency to wear out through pile loss or flattening of the pile. In the case of velvet, a 'w' weave where the tufts are locked in place by two picks rather than one will help the pile retention.

10.3 Types of woven apparel fabric

Apparel woven fabrics can be categorized according to their end use whether it be for intimate apparel, dresses, shirting, casual wear, outerwear such as suiting, coating or for a performance or sports wear (see [Table 10.1](#)). An easier approach to classifying the broad range of fabrics for fashion is to group them according to their weight as followed in this chapter.

Table 10.1 Key characteristics of woven fabrics.

Fabric weight	Fabric type	Applications	Properties
Lightweight	Foulard Gauze Habutai Mousseline Muslin Organdie Organza	Dress fabrics Evening wear Bridal wear and veils Trimmings Scarves Blouses	Fluid Transparent Soft Sheer Stiff
Medium lightweight	Lining Madras Oxford Sateen Satin Taffeta	Shirting Dress fabric Lining Intimate apparel	Smooth Silky Supple Airy
Medium weight plain	Calico Crepe Flannelette Gosgrain Percalé Poplin Seersucker Terry	Toiles Night wear Shirting Dress fabric	Ribbed Crinkled Puckered Textured Smooth
Medium weight patterned	Brocade Cloqué Damask	Evening wear Ladies jackets	Figured Textured
Medium weight suiting	Barrathea Serge Worsted suiting	Suits Trousers	Uniform Smooth
Jacketing	Flannel Gabardine	Coats and jackets	Felted Smooth
Workwear	Calvary twill Chino Denim Drill Moleskin	Trousers Jeans Jackets	Dry Stiff Smooth
Pile and texture	Bedford cord Corduroy Piqué Velvet Velveteen	Evening wear Trousers Jackets	Raised Pile Soft Textured
Heavy weight	Loden Tweed Harris Tweed	Coats and jackets	Soft Textured Hairy
Performance	Goretex® Ripstop	Coats and trousers	Crisp Smooth

10.3.1 *Lightweight fabrics*

Supple, lightweight, silky, smooth, transparent, open, cool, and crisp, are all words that describe fabrics that go into garments ranging from lingerie, to shirting and into evening wear.

Fabrics in this category include: foulard, gauze, leno, habutai, muslin, and organza.

- Foulard is a soft, lustrous, lightweight fabric, traditionally woven in silk yarns and using a 2/2 twill weave, making it suitable for ties, scarves, and linings. More often than not this apparel fabric is printed and is now also widely produced using synthetic yarns such as viscose, polyester, or acetate.
- Gauze and leno are used for veils and trimmings; these are fabrics with an open semitranslucent construction that imparts a fluid, floppy handle. Constructed in plain weave or a leno construction that gives a more stable fabric (the warp ends use special heald wires cross over one another to trap the weft).
- Habutai is the name of this soft, silk cloth originates from the Japanese word, meaning lightweight. The fabric is woven with silk yarns that still contain the natural gum from the silk cocoon, and using plain weave to create cloth suitable for dresses, blouses, and scarves.
- Muslin is a lightweight cloth suitable for dresses, scarves, and blouses. Woven in an open construction to form a soft, fine fabric, usually made from cotton, this quality typically weighs no more than 68 g/m². Muslin fabrics are usually woven in grey form (undyed ready for bleaching, dyeing, or printing) and the construction used is either plain weave or a leno weave.
- Organza fabric is used primarily for evening and wedding dress fabrics, where a stiff, sheer fabric is required. Plain weave in construction with an open sett, organza can be made from silk or man-made fibres that have a high twist to produce a cloth of around 25 g/m². Additional stiffness is imparted into the fabric through the application of gum or resin in the finishing process.

10.3.2 *Medium lightweight*

Functional, textural, plain, semiplain, checked, or finished to a high shine, these fabrics are used extensively for shirting, dress fabrics, and nightwear. Mechanical finishing processes such as mercerization or a schreiner finish give an even sheen and smooth appearance to satin and taffeta-type fabrics.

Fabrics in this category include: acetate lining, madras, oxford, satin, sateen, and taffeta.

- Acetate lining – acetate fabric is as the name suggests, made from acetate fibres or yarns and is primarily used for lining fabrics, dress fabrics, and some lingerie.
- Madras – originally produced in the Indian city of the same name (now called Chennai), and now synonymous with shirting fabric that is plain woven, striped, or checked. Madras has a fine, lightweight, and airy handle and often colour woven, an effect that was traditionally created with vegetable dyes. The tendency for these dyes to bleed has led to the use of colour fast yarns being employed in the production of today's woven fabrics.
- Oxford is an inexpensive cotton or cotton/polyester shirting fabric named after a shirt worn by the undergraduates at the University of Oxford; this cloth is soft with a slight lustre. Two warp yarns are woven as one, in hopsack weave construction and typically with a white ground and coloured stripes or checks. The easy care nature of this fabric makes it suitable for casual shirts and blouses.

- Sateen is a completely weft-faced structure that is named after another of the four elementary weave structures, and is commonly used as a lining fabric for suits. The weave structure resembles the back of a satin cloth, but differs in a lower density of warp threads and a high number of picks per centimetre. Five-end sateen is the usual weave structure used in conjunction with a weft yarn that is usually coarser than the warp and may be mercerized (in the case of cotton) or given a 'schreiner' finish to give a smooth lustrous look.
- Satin derives its name from the weave structure used in this fabric, where the longer warp floats produce a smooth even surface with no obvious patterning. The longer the warp threads as in the case of an eight-end satin (each warp thread floats over seven weft picks) the more luxurious the cloth. Duchesse satin is an example of this. Traditionally made from silk yarns, but now also produced in a range of man-made fibres and other natural fibres such as cotton, there are a wide range of qualities and weights that are produced to meet many different end uses. Satin cloth for intimate apparel is typically lustrous in appearance as a result of using high lustre yarns in either silk or a man-made fibre such as polyester.
- Taffeta is a medium-weight fabric at $\sim 80 \text{ g/m}^2$, constructed in plain weave fabric that forms a slight ribbed appearance in the weft direction, resulting in a crisp hand a lustrous appearance. Taffeta is most often used for formal wear, and is usually produced in a solid colour but is also woven with contrasting colours in the warp and weft into give a change ant effect.

10.3.3 Medium-weight plain

Calico is one of the staples of the fashion industry through its extensive use for toiles and mock-ups of garments. Texture features heavily in this category in fabrics like seersucker that use chemical finishes or differential shrinkage to achieve surface interest and crepe which uses the weave structure to create a pebbly feel to the cloth.

Fabric in this area includes; Calico, Crepe, Flannelette, Grosgrain, Percale, Poplin, Seersucker, Terry:

- Calico is often woven in unbleached cotton, characterized by the presence of flecks of seed matter from the plant. Plain weave is used for this utility fabric, a fabric that creases easily and is frequently sized to give it an added stiffness diving a resultant weight of $153\text{--}158 \text{ g/m}^2$. Used in its plain state for use as toiles in dress making it also seen printed with small bright floral patterns in the United States.
- Crêpe is a lightweight fabric of silk, rayon, cotton, wool, man-made, or blended fibres, with a distinctive crinkled surface. This fabric type has a number of variations including crepe de chine, crêpe marocain, crêpe chiffon, and moss crêpe. The crinkled surface is obtained through the use of either crêpe yarns (yarns that have such a high twist that the yarn kinks) a combination of yarns with alternating 's' and 'z' twist, by a chemical treatment causing areas to shrink and pucker, embossing, or through the weave itself (usually with thicker warp yarns and thinner filling yarns).
- Flannelette is frequently used in nightwear for both men's and women's pyjamas. This fabric is usually constructed in a twill or plain weave, using cotton yarns where the surface fibres have been raised in finishing to give a soft handle. Flannelette was traditionally used for sheets, but is less commonly used since the introduction of central heating.
- Grosgrain fabrics are traditionally used for ties and the appearance of this fabric is described by the translation of grosgrain, which literally means 'large cord'. A strong cloth usually made from silk or man-made continuous filament, it can be quite expensive due the weight of the heavier weft yarns and highly sett warp yarns (Fig. 10.1) Woven in a plain weave construction, the combination of sett and yarns makes this an ideal fabric on which to create

Fig. 10.1 Grosgrain fabric.

moiré effects popular for dresses and eveningwear. A moiré fabric has a watermark effect on the surface created by one of two methods. The rib or corded nature of this type of fabric is essential in creating a true moiré fabric which is a mix of flattened and still rounded areas of the cloth, that result after two fabrics are stitched face-to-face and pressed through two heated, smooth and heavy rollers. The other method for creating a moiré effect uses an embossed roller with the characteristic watermark pattern engraved onto its surface, thus flattening the ribs of the fabric to this pattern.

- Percale is used for shirts and dresses in apparel and has a fine smooth handle due to the closely sett yarns. This fabric produced in combed cotton or Egyptian cotton yarns and either piece dyed, printed, or just bleached.
- Poplin was originally made for the pope and referred to a 'Papalino' this is a lustrous and hardwearing fabric. A light cross-rib effect is formed through the use of plain weave combined with a warp sett that could have up to twice as many ends per centimetre as weft picks. Poplin is used for functional fabrics including, jackets, dresses, shirts, and linings.
- Seersucker fabrics are traditional used in summer weight shirts, or informal suits. The characteristic puckered stripe effect is either created through controlled tension differences in sections of the warp during weaving, through the use of yarns with differential shrinkage, or using chemical finishes (Fig. 10.2).
- Terry is produced on a loom fitted with a terry mechanism and an extra warp (pile warp) that forms uncut loops or pile on one or both sides of the fabric. Cotton fibres are usually used in the production of this cloth, where its inherent absorbency is suited to its use in dressing gowns.

10.3.4 Medium-weight patterned

This category of fabrics is characterized by complex ornate patterns formed by jacquard weaving. Metallic threads, lustrous yarns and sumptuous textures, create a beautiful range of fabrics used in exclusive and high-end garments.

Fabrics include: brocade, cloque, and damask.



Fig. 10.2 Seersucker fabric.

- Brocade is an ornamental fabric usually produced on a jacquard loom, to achieve highly patterned, multicoloured, richly figured patterns for use in evening dress fabrics and accessories. Traditionally figured with gold or silver thread, brocade was woven in silk, and the resulting cloth was of a heavy weight in comparison to damask. Brocade fabrics are usually designed so that only the face of the fabric shows the true pattern, combining simple ground weaves (twill, plain weave, satin, sateen) and supplementary figuring yarns in the warp or weft direction.
- Cloqué is characterized by the three-dimensional (3D) blister effect that is created in this apparel fabric, produced by weaving a double cloth fabric that combines warp and weft yarns with differential shrinkage. A blister effect results in the finishing process and may also be produced through a combination of weave structures that allow for more or less shrinkage (Fig. 10.3). These fabrics are used in a range of ladies apparel including, lingerie, eveningwear, and blouses.
- Damask jacquard fabric's opulent appearance makes it most suitable for eveningwear, and it is characterized by large-scale classical patterns, more frequently seen for interior and tablewear uses. Satin and sateen weaves are used to create this reversible fabric, which has a subtle sheen in the warp direction, contrasted with a more matt weft yarn.

10.3.5 *Suiting fabrics*

Smart, uniform, hard-wearing conservative and classic. The timeless elegance of the woven fabrics used in suiting is little changed in essence, but these fabrics have retained their importance as staples in both workwear and business attire.

Suiting fabrics include, worsted, barrathea, and serge:

- Worsted fabrics are made from fine long-staple fibres that have been carded and combed to align the fibres in parallel. Worsted yarns are tightly twisted and woven to form smooth, fine surface texture that has a crisp and firm hand. Usually woven in a twill weave, the resulting

Fig. 10.3 Cloqué fabric.

fabric is more durable than woollen spun fabrics, and more expensive to produce. Used predominantly for suiting and formal work-wear in part due to the clean-cut appearance of the fabric that has a flat and smooth finish. Suiting weights typically vary from 220 to 280 g/m² depending on the season and therefore, warmth required from the cloth. Wool is the most common fibre used in worsted fabrics, but at the high end of the market blends that mix merino wool with cashmere, silk, or the extremely rare Qivuiik fibre are also used.

- Barrathea fabric is used for neckties, uniforms, and trousers, this fabric has a smooth pebbly surface is usually woven for worsted suitings. The weave is a twilled hopsack, but other broken-rib variations are used in the production of cotton and silk fabrics.
- Serge is a hardwearing worsted-wool cloth; with a 2/2 twill weave construction. Compactly woven with high-twist yarns, it usually has a smooth face that becomes shiny with wear. End uses include coats, skirts, suiting, and uniforms, where the fabric's natural ability to hold a crease is invaluable.

10.3.6 Jacketing fabrics

Warmth and protection from the elements are combined in these hard-wearing cloths.

Medium-weight jacket fabrics include; flannel and gaberdine.

- Flannel is medium weight at 360 g/m², and is normally a plain or twill weave fabric that is typically made from cotton, a cotton blend, or wool. This fabric is finished to give a very soft hand; by brushing on both sides the fibre is lifted to create a soft, slightly fuzzy surface.
- Gaberdine is a functional fabric with clearly defined diagonal twill lines on the face. This fabric is most suited to outerwear such as raincoats, jackets or trousers, skirts, and sportswear at 260 g/m². It can be made from cotton/polyester, polyester, or viscose, but the best quality fabrics are made from wool (Fig. 10.4). Tightly woven, the smooth uniform finish helps to make the fabric water repellent and hardwearing.



Fig. 10.4 Gabardine fabric.

10.3.7 Work wear and casual wear

These fabrics are widely used both in the workplace and also extensively for casual wear. A mixture of traditional and conservative fabrics, including others that change each season following the latest whims of fashion are all represented in this section.

Fabrics include; cavalry twill, chino, denim, drill, and moleskin.

- Cavalry twill fabric is formed by a steep pronounced double twill, this fabric is ideal for trousers, jackets, coats, and as it was originally, for uniforms (Fig. 10.5). Made from woollen or worsted yarns traditionally, it is now also produced in other natural and man-made fibres to give a strong wearing fabric.
- Chino cotton or cotton/polyester fabric also uses a warp-faced twill weave as its structure. Hardwearing with a slight sheen, its name has been adopted for a style of casual trouser in the United States but originates from China where it was first made.
- Denim a hardwearing utility cloth has developed into one of the staples of the apparel industry. Denim which is full to the touch, has diagonal ribbing formed with a twill weave (2/1 or 3/1 twill) uses contrasting colours in the warp and weft (typically blue warp and white weft). Traditionally made from cotton, but now available in polyester/cotton blends, lyocell and combined with an elastomeric to give added comfort, this fabric is produced in a vast number of variations for both men's and women's wear. A cloth sett at 60 ends/in. and 40 picks/in. using 7's cc in the warp and 6's cc in the weft is typical for denim fabrics.
- Drill fabric covers a variety of materials that are used for shirts, suitings, and uniforms. A 3/1 twill is often used in combination with good quality, high-twist, cotton yarn to form very durable woven fabric, where the twill lines run in the opposite direction (bottom right to top left) to other fabrics. Drill may be undyed, warp striped, or piece dyed as in the case of Khaki, a colour that gave its name to this army uniform cloth.
- Moleskin has a fine-brushed nap on the surface of this cloth, giving it the appearance of fine suede. This medium-weight fabric is usually made from cotton and woven using a satin-based weave with short weft floats on the surface, which are raised in finishing to give the suede-like handle. Trousers, work wear, and jackets are all produced in this cloth.

Fig. 10.5 Cavalry twill fabric.



10.3.8 *Pile and texture*

Surface texture including exaggerated ribs, cut-pile surfaces, and sumptuous soft hand are all created through the use of weave structure, special yarns, and in the case of velvet and corduroy, cut brushed fibres aligned in finishing. Ranging from the casual look of cord through to the luxurious opulence of velvet, these fabrics can suffer from the trends of fashion.

Fabrics of pile construction are velvet and velveteen and corduroy whereas Bedford cord and Pique create ridges or cords using the weave structure alone.

- Bedford cord can be seen in use in coats, trousers, uniforms, and other outerwear. A specific weave construction is used to create cords in the fabric that are formed by the tightly sett warp, in contrast to weft floats on the back of the cloth that causes the fabric to buckle. The name of this firm hardwearing cloth comes from the duke of Bedford who used the cloth to clothe his troops in the 15th century.
- Corduroy fabric is formed from raised and cut-pile ribs of pile running down the length of the fabric. Usually woven in cotton, and of varying width (expressed in wale's per inch) this fabric is suitable for trousers, jackets, and skirts.
- Pique derives its name from the French word to quilt, and has an embossed look. Double cloth weaves are used in conjunction with one fine and one thicker warp yarn that stitch together at intervals forming cords or ribs on the surface. Used in sportswear, dress shirts, and waistcoats, the fabric is usually of cotton and piece dyed.
- Velvet is a medium-weight cut-pile fabric in which the cut pile stands up very straight to give an even, uniform surface. It is woven using two sets of warp yarns; the extra set creates the pile. Velvet, a luxurious fabric used for eveningwear, accessories, and jackets, is commonly made with a filament yarn for high lustre and a smooth, soft hand. There are many variations of velvet that are defined by the finish applied, fibre content or length of the pile. Crushed velvet, for example, is a solid-coloured velvet that is passed through heated rollers in order to press the pile flat in an irregular pattern. Façoné velvet has a pattern 'burnt-out' using a

devoré process to selectively remove the pile to reveal the ground weave composed of yarns resistant to the chemicals applied.

- Velveteen fabric is made in a similar way to velvet, but an extra set of weft yarns are used to form the pile instead of an extra set of warp yarns. The resulting fabric has more body than velvet but with less drape.

10.3.9 Heavy weight

These protective outerwear fabrics with textural, hairy surfaces have served as coating fabrics for many generations. The soft colour of the heathered tweed fabrics are influenced by the surrounding landscape and are dyed in fibre form to create complex blends colour woven into simple weave structures.

The main fabric types in this category are; loden, tweed, and Harris Tweed:

- Loden is traditionally woven in the Tyrol region of Austria, this fabric has a brushed, raised surface giving it a warm, tactile surface, usually dyed to a specific green colour. The felted effect on the surface of this woollen fabric imparts a natural water-repellence ideal as a coating fabric.
- Tweed is traditionally a term that describes fabrics that are made from wool and are heavy weight and have a rougher, hairy handle. The yarns used to produce tweed fabrics are fibre dyed and blended to produce colours that have a melange effect (Fig. 10.6). The rougher surface texture of this fabric type, originally made on the banks of the river Tweed in the borders means that it is most suitable for outerwear such as coats and jackets that can be lined. Tweed fabrics are produced in weights termed, light, medium, and heavy weight and range from 350 to 775 g/m².
- Harris Tweed is the best known of all the tweeds and is exclusively woven in the Outer Hebrides, on either the Isle Harris or Lewis. Still produced in the homes of the islanders with Scottish wool, dyed locally the colours reflect the landscape of the area, and the fabric is finished in the region and can be accredited with the 'Harris Tweed' trademark. Twill,



Fig. 10.6 Tweed fabric.

herringbone, and plain structures are used to produce these expensive fabrics yet exclusive fabrics that weigh in at 470 g/m^2 .

10.3.10 Performance apparel fabrics

Protective, functional, breathable, and durable fabrics are the mainstay of the outdoor pursuits and performance sportswear business. Performance apparel is a growing sector of the international clothing industry, with new fibre developments emerging to satisfy the consumer demand for comfort and high performance across a wide range of active sports. Engineered to protect the wearer from the elements or to control the climate of the wearer, garments that use woven fabrics in this category are highly specialized and tested to high standards.

- Goretex fabric was developed by W.L. Gore and Associates, Inc. and was one of the first fabrics to fill the demand for a waterproof breathable fabric suitable for outdoor pursuits. Goretex is essentially a sandwich of a woven face fabric (such as polyester) and a membrane of fluorocarbon and a backing fabric. The latest development Gore-tex Active, taps into the trend for higher-intensity athletic activities carried out for shorter periods of time, reducing the weight of the fabric whilst increasing comfort with a softer more supple membrane combination.
- Quick dry cotton fabrics have been developed through collaboration between Cordura and Cotton Incorporated. The durability and performance and functionality of Cordura is added to the natural comfort of cotton for use in a variety of applications for activewear, outdoor clothing, and workwear.

10.4 Practical design applications

Matching the fabric to the end use requires some knowledge of fabric properties and characteristics, characteristics that can be used to enhance the look, structure, or aesthetic of a garment.

Fabric shows such as Premier Vision are vital in the fabric selection and development activities of fashion designers. Apparel fabrics at Premiere Vision are promoted through trend direction forums based around such categories as; relax-distinction (wool suiting, shirting, jeans and cotton), deduction (fluid and fancy, silks, fancy woollens, and prints), pulsation (technical and performance fabrics, extreme sports fabrics, and lingerie), and Atelier Denim. Designers and fabric selectors need to be assured that the performance of the material meets their parameters for performance in a given garment. New and novel fabrics offered by suppliers may not have gone through such rigorous testing or field trials, requiring a leap of faith from the buyers. Conversations between the designers and producers at these fairs can lead to a valuable exchange of information regarding the performance of previous products and possibly the development of exclusive fabric ranges.

10.4.1 Surface interest – Felted appearance

A level of milling or brushing applied to a fabric through finishing them with a combination of heat, pressure, and friction gives rise to thick dense fabrics with a felted appearance that do not fray easily. A felted wool garment can be left with unfinished

edges, abutted seams, or top-stitched hems. Fabrics such as Loden and Melton are ideal candidates for this approach.

10.4.2 Surface interest – Texture

The texture of a fabric can alter depending on how we perceive the colour, especially in the case of velvets where the angle at which the fabric is viewed changes the depth of shade. Pile fabrics absorb light and can also have a greater thickness that imparts a rich luxurious look to a garment.

Novelty fabrics where texture is created using fancy, boucle, tape, and slub yarns woven into colour and weave structures like dogtooth checks are a staple of jackets in the Chanel's collections where cost is not such an issue.

10.4.3 Stretch

Stretch may be imparted into a fabric through finishing. It may as well be inherent in the fibre type or be added through the use of stretch yarns that use fibres such as Spandex or Lycra. The comfort of denim and corduroy is improved through the use of cotton/lycra fibre blends which impart a degree of stretch to the fabric, so that not only is comfort improved, but also wrinkle resistance and fit. Stretch woven fabrics have also contributed to the development of fabrics that perform for sportswear and outdoor pursuits as well as redefining garment shaping for snug streamlined silhouettes.

10.4.4 Transparency

Fabrics used to produce garments with transparency have beautiful qualities but are also more difficult to work with due to their fineness, slippery surface, and tendency to mark. Organza and organdie are examples of semitransparent or transparent crisp fabrics. Softer fabrics in this category are chiffon, georgette, and crepe chiffon, whereas voile, shirtings, and gauze sit somewhere between the two.

Considerations when pattern cutting and choosing fabrics are the weight, the thickness, shear (distortion of in the warp and weft directions), drape, and stretch of the fabric.

10.4.5 Pattern

Directional or large-scale patterns in traditional weave designs like dogtooth and Prince of Wales check require additional care when matching up seams than an equivalent semiplain all over design. Fashion trends influence the popularity and scale of patterned fabrics, as well as the proportions of the garment they are aimed at. Large-scale jacquard motifs need to be carefully placed or used in garments with a greater volume of fabric to fold and drape, and smaller-scale patterns are suited to closer fitting garments. Fabric utilization may well be affected by the matching of these large-scale patterns, with more wastage in the pattern cutting stage.

10.4.6 Tailored garments

The right choice of fabrics used in combination is significant in creating a well-fitted tailored garment such as a suit. Woollen fabrics for suits may be constructed from yarns produced on the worsted or woollen systems. Worsted yarns are composed of fibres that are longer and finely combed, with a resulting firm flat fabric used for the majority of business suits. Woollen yarns are composed of shorter, uncombed fibres, which are loosely twisted, creating softer, bulkier, hairier fabrics, of which Harris Tweed is a well-known fabric. In these types of garments fabrics needed for hidden support include; Melton for the collar, and pockets with canvas for other lighter weight interfacings.

10.4.7 Support fabrics

Corsetry requires fabrics to fulfil a role not unlike that of an engineered material, where the body is controlled, or distorted to fit a desired shape. Lustrous and opulent fabrics like satin and silks are supported by carefully chosen control fabrics that impart strength, stability, and body to the garment. Canvas is used in corsetry to control the deformation or stretch of the face fabric in the garment, whereas, a cotton drill woven in twill weave provides a strong, natural flexibility suitable for the foundation of the corset. Other support fabrics include organdie, muslin, and organza.

Cotton pocketing uses a closely woven twill or plain weave and has good durability due to the twofold yarns used. Interlining fabrics such as a stiff organza must have the same shrinkage resistance as the other fabrics in the garment, or be fully shrunk already.

10.5 Application examples

10.5.1 Chanel and Linton Tweeds

The long-established relationship between Chanel and Linton Tweeds is a rare example in today's fast fashion, globally sourced, price sensitive world. Originally, a producer of 100% woollen cloth, Linton Tweeds faced stiff competition from all the other woollen manufacturers in Scotland and Yorkshire. This Carlisle-based weaver, established in 1912 and synonymous with good quality, took steps to differentiate itself from the competition in the late 1960s. In order to make themselves more unique, they developed fabrics that used more exotic and man-made yarns, as well as developing machinery to manufacture their own unique fancy yarns.

A long association with the couture houses of Paris had brought the company a high profile but little financial reward, but this was helped when the introduction of the ready-to-wear collections took off for their haute couture customers such as Chanel. Linton's expanded their horizons to supply markets in Japan and the United States, and they now promote their ranges at Premier Vision in Paris, as well as in Milan, Japan, and New York.

The novelty woven fabrics that Linton's create are elegant, fancy tweeds suitable for ladies jackets, skirts, and coats. The fabrics that they produce for Chanel and other couture names are woven in short runs and are usually nonrepeatable. Typical fabric

constructions are based on hopsack, herringbone, basket weave, leno weaves and colour and weave effects including the four-point star and the hounds-tooth check.

The Chanel suit became the status symbol of the 1950s generation, and was updated by Karl Lagerfeld when he took over design at the label in the 1980s. Using inspiration from past collections, lighter tweed fabrics with a softer look using new yarns were developed for use in the iconic collarless-style jacket now synonymous with Chanel. The tweed fabric from Linton Tweeds continues to be reinvented, updated and transcends fashion having established itself as one of the signature looks of Chanel.

10.5.2 Denim

Denim is more than just a cotton fabric; it inspires strong opinion within the hearts of historians, designers, teenagers, movie stars, reporters and writers [1].

First produced in Nimes, France, the name of this cloth originated from the town that it was originally woven in and was described as ‘de Nimes’ (from Nimes) a name that evolved into name, denim that we know today. This hardwearing serge cloth was originally imported in the 1850s into the United States as a canvas for tents, and was adapted for work wear during the gold rush by Loeb (Levi) Strauss. Denim jeans did not start their rise into mainstream fashion until the 1950s with the teenage rebellion around James Dean and his film ‘Rebel without a cause’. In the 1960s and 1970s, denim became a staple of fashion trends, adapting its look to fit the style of those eras. Denim has elevated its status even further since the 1980s, as it has been styled, finished, and labelled, to command high prices in the collections of the top fashion brands. The art of finishing denim has created a whole new area of specialist knowledge around the colouration and fit of jeans as well as the destruction, manipulation, and embellishment of this seemingly simple fabric.

The blue colour synonymous with denim originally came from the natural Indigo dye, and then moved to a synthetic version in the 19th century. Cotton is still the dominant fibre type used in the manufacture of jeans, with other synthetic fibres such as Lyocell, a cotton-like cellulosic, taking a small market share. The comfort and stretch of denim is enhanced where cotton and lycra are blended, and other properties have been developed by mixing cotton with polyamide or polyester.

One of the first companies to introduce a ‘distressed denim’ look in the 1980s was Italian company, Diesel. Their ‘aged/already worn’ look was slow to take off, but this aesthetic is now at the forefront of trends for denim worldwide.

The art of finishing denim, that has used sandblasting, acid washing, bleaching, resin treatments, stone washing with pumice and whiskering to produce a range of worn and faded effects is moving to more sustainable and ethical alternatives. Spanish company Jeanologia are leading the field in developing laser technology to recreate traditional denim looks and more importantly to offer new solutions that will eliminate harmful chemicals, save energy, and reduce water use. Throughout all these changes, the one constant factor that characterizes denim has been the 3/1 twill structure.

Reference

- [1] L. Downey, *A Short History of Denim*, Levi Strauss, Amherst, MA, 2007.

Bibliography and sources of further information

- [1] A.W. Fabric, *Form and Flat Pattern Cutting*, second ed., Blackwell Publishing, Oxford, 2008.
- [2] A. Fisher, *Construction*, AVA Publishing, Lausanne, 2008.
- [3] D. Gioello, *Understanding Fabrics. From Fibre to Finished Cloth*, third ed., Fairchild Publications, New York, 2002.
- [4] C. Hallett, A. Johnston, *Fabric for Fashion. A Comprehensive Guide to Natural Fibres*, first ed., Laurence King Publishing, London, 2010.
- [5] M. Hardingham, *Illustrated Dictionary of Fabrics*, Studio Vista, London, 1978.
- [6] S. Keiser, M. Garner, *Beyond Design: The Synergy of Apparel Product Development*, Fairchild Publications, New York, 2008.
- [7] A. Seyam, ITMA 2015 technology: weaving, *Textile World Asia* (2015).
- [8] M. Taylor, *Technology of Textile Properties*, third ed., Forbes Publications, Odiham, 2007.
- [9] J. Wilson, *Classic and Modern Fabrics: The Complete Illustrated Sourcebook*, Thames & Hudson, London, 2010.

Websites

- [1] Worth Global Style Network, www.wgsn.com.
- [2] Design Boom®, www.designboom.com/eng/education/denim2.html.
- [3] The Woolmark Company & Australian Wool Innovation, www.wool.com.

Trade shows

- [1] Apparel Sourcing, www.apparelsourcing.fr.messefrankfurt.com.
- [2] Intertextile Beijing, www.intertextile.com.
- [3] Premiere Vision, www.premierevision.com.
- [4] Techtextil, www.techtextil.messesfrankfurt.com.
- [5] Texworld, www.texworldusa.com.
- [6] Tissu Premier, www.tissu-premier.com.

Woven textiles for medical applications

11

S. Rajendran, S.C. Anand
University of Bolton, Bolton, United Kingdom

11.1 Introduction

With the increasing demand for novel textiles, structures, and their associated products for various applications, it is worthwhile to mention that conventional woven textiles are still largely used to a significant extent in healthcare and hygiene sectors such as antimicrobial and associated textiles used in hospitals, although nonwoven, knitted and emerging spacer structures are increasingly dominant. Weaving technology is also employed in manufacturing various hi-tech medical devices such as vascular grafts, tendons, and wound dressings. Woven structures are used for a wide spectrum of healthcare, medical, and surgical products. Woven fabrics are commonly used for gauze dressings, capillary dressings, support and compression bandages, plasters, vascular prostheses, scaffolds for tissue engineering, surgical gowns, drapes, hospital textiles such as sheets, blankets, pillowcases, uniforms and a wide range of operating room (OR) garments, hospital bed linen, and staff uniform garments. A variety of different structures/shapes such as flat sheets, narrow tapes, straight tubes, bifurcated tubes, tapered tubes, and fenestrated tubes can also be produced by using woven technology. Woven fabrics are extremely versatile in terms of the type of yarns and structures that can be engineered on the loom but suffer from the tendency of fraying when cut into shapes and the anisotropic nature of their properties. The woven structure tends to scissor when extended in the bias direction which could be detrimental for some applications such as mattresses for pressure sores and garments for hypertrophic scarring treatment.

The market potential for healthcare and medical textile devices is considerably high. It is forecasted that the world medical textiles market would be worth USD 20.23 billion by 2022 [1]. In the EU alone the sales of medical textiles already account for 10% of the technical textile market. The United States is the largest consumer of medical devices followed by Western Europe. With the rise in income levels and increasing adoption of health insurance, the demand for healthcare is expected to grow in Asian countries such as India and China. The Indian healthcare market is growing faster mainly because peoples' living standards, mainly in cities/town, are improving and patients from abroad are attracted by high quality and low-cost medical treatment. The healthcare market is expected to increase to US\$ 133.44 billion by 2022 [2]. The development of the medical textile industry in recent years in China is relatively rapid. The US Health Industry Manufacturers Association (HIMA) acknowledges that China

is the world's fastest-growing market in fibre-based biomedical products that include wound dressings, surgical sutures, artificial lungs, artificial kidney dialysers, vascular grafts, and artificial heart valves with an average annual increase of 28% since 1996. In the United Kingdom the medical device market is dominated by the National Health Service (NHS) accounting for approximately 80% of healthcare expenditure, even though there are fewer private sectors.

The healthcare and medical devices market is driven by various factors and these include population growth, rising standards of living and higher expectations of quality of life and ageing of the population. It is forecasted that there will a significant shift in the population with a major increase in the number of people over 65, 20.5% by 2026 [3].

It has been predicted that there is a substantial market potential for advanced wound dressings. The advanced global wound care market is expected to reach USD 13.07 billion by 2022. In 2017, the market was dominated by North America followed by Europe and this trend is predicted to continue in the forthcoming years. The European wound care market is expected to register a Compound Annual Growth Rate (CAGR) of 3.6% during 2018–23. An ageing population creates increased demand for ulcer treatment. In the United Kingdom, the pressure ulcer treatment accounts for 4% of the NHS annual budget. The annual cost of treating diabetic foot ulceration accounts for 5% of the total NHS budget. The treatment of venous leg ulcer creates considerable demands upon healthcare professionals throughout the world.

11.2 Application of woven textiles in managing acute and chronic wounds

11.2.1 Medical devices

It should be stressed that specialized textile products, irrespective of their structures (woven, nonwoven, knitted, and spacer) and production techniques, used in humans are classified as medical devices and are regulated by regulatory agencies. Generally, it covers most of the textile medical devices such as simple wound dressings to life-saving implantable devices. The EU Commission has issued the following three CE marking directives related to medical devices:

- The Medical Devices Directive (MDD) (1992): Applies to all general medical devices not covered by the Active Implantable Medical Devices Directive or the In Vitro Diagnostics Directive.
- The Active Implantable Medical Devices Directive (AIMDD) (1990): Applies to all active devices and related accessories intended to be permanently implanted in humans.
- In Vitro Diagnostics Directive (IVDD) (1998): Applies to all devices and kits used away from the patient to make a diagnosis of patient medical conditions.

Since 14 June 1998, no medical device covered by the MDD 93/42/EEC shall be placed on the market that does not carry a CE mark. The only devices not requiring a CE mark are 'custom-made devices' and 'devices intended for clinical investigations', where the manufacturer must keep documentation in accordance with MDD.

In the United Kingdom, the Medicines and Healthcare Products Agency (MHRA) regulates medicine and medical devices. The agency implements the EC medical devices directives into UK law. In the United States, the US Food and Drug Administration (FDA) regulates via its MEDWATCH programme. Medical devices in Canada are regulated by Therapeutic Products Directorate. The Canadian Medical Device Regulations largely consist of the best features of the European MDD and US MEDWATCH programme.

11.2.2 Classification of wounds

Wounds can be classified into acute wounds and chronic wounds. While acute wounds take only a few weeks to heal, chronic wounds require several months to heal completely. Chronic wounds include venous leg ulcers and pressure sores. Generally, the wound healing process involves four phases:

- Hemostasis phase, which starts when blood leaks out of the body and blood clot occurs.
- Inflammatory phase, which occurs immediately after injury to tissue and during which swelling takes place.
- Proliferation period, in which new tissues and blood vessels are formed.
- Maturation phase, in which tissues laid down during the proliferation stage are remodelled.

11.2.3 Wound management

The care and treatment of wounds are a matter of clinical judgement. The wounds should first be examined to determine the amount of exudate and whether the symptom of infection exists. In addition, the surrounding tissue should be assessed to establish the extent of ulceration. The first stage of treatment (debridement) often requires the removal of foreign material and dead tissue from the wound in order to prevent infection and promote healing. Subsequent stages in wound management include control of exudate, stimulation of wound healing and wound protection. Briefly, the various stages involved in wound management are:

- autolytic debridement using the body's own enzymes and moisture to dissolve and clean the dead tissues;
- mechanical debridement that consists of wet-to-dry technique utilizing saline-moistened gauze and injecting pressurized saline solution (pulse lavage) on the wound bed; This technique is not recommended in the United Kingdom but National Institute for Health and Care Excellence (NICE) recommends the use of a soft pad, for instance – Debrisoft [4];
- chemical debridement which involves the use of topical enzymatic gels and solutions to dissolve and remove dead tissues from the wound;
- surgical debridement by utilizing surgical instruments such as scalpel, forceps, scissors, laser; and
- bio-debridement using live maggots.

11.2.4 *Woven wound dressings*

The healing of wounds depends not only on medication but also on the use of proper dressing techniques and suitable dressing materials. Dressing materials include woven, nonwoven, and knitted structures of which nonwoven dressings are increasingly used because they are soft and highly absorbent. Generally, the dressing is placed directly over the wound (primary dressing) and is covered with an absorbent pad (secondary dressing). The whole dressing is then retained with adhesive tape or a suitable bandage, depending on the location of the wound in the body. The primary dressing is expected to maintain the wound temperature and moisture level to permit respiration and to allow epithelial migration. The secondary dressing must not be too absorbent as it may cause the primary dressing to dry out too quickly. Different shapes are available which are suitable for dressing wounds in difficult positions such as heels, joints, digits, and the perineal area.

An ideal dressing is normally expected to:

- provide a barrier against microorganisms, dirt, and other foreign bodies;
- provide a humid environment at the wound surface;
- control exudates; and
- be capable of being removed without trauma.

Dressings are also used to protect against further injury and abrasion by acting as a cushion and also help to promote rather than interfere with the healing process. Traditionally, woven cotton gauze is used for dressings because of its good absorption properties and soft handle. A gauze dressing or bandage is a woven piece of material that covers an injury or a wound to prevent microorganisms from entering into the affected area. It also can hold a dressing in place and may contain ointment to enhance healing. However, it has been established that cotton gauze allows moisture to evaporate from the wound which means that cotton gauze dressings do not maintain the moist environment to facilitate faster wound healing [5]. Furthermore, cotton gauze adheres to the wound bed. This means that patients suffer pain when the gauze is removed. Also, cotton gauze requires frequent changes. In view of the above disadvantages, the woven cotton gauze is no longer in use in European hospitals. However, it is still considered a popular choice of dressing in the majority of countries in Asia, Africa, and Middle East, mainly because it is affordable to treat different wounds both in hospital and home environments. Dry gauze dressings are used as a primary dressing for open wounds with heavy exudate and are also used to protect a closed wound from additional trauma and infection. In some situations, wet-to-dry woven gauze dressings can be used for mechanical debridement to remove dead tissues from the wound bed. Moist gauze dressings help to maintain a moist wound healing environment and are often considered as wet-to-moist or damp dressings. This type of dressing can be used on a granulating wound. Illustration of commercial wound dressings is published elsewhere [6].

It should be stressed that the traditional gauze dressing consists of an open woven structure made from 100% cotton. Commonly available woven dressing comprises a number of layers of such gauze material and is of a predetermined shape. It absorbs

fluids secreted from the wound and on drying up, the gauze tends to stick to the wound and loose cotton fibres often get caught in the wounds. This causes irritation, trauma, and even further injury when the dressing is changed. In addition, the cotton dressings, once dry, cannot provide a moist environment which is essential for faster wound healing. There are a number of patents relating to nonadherent/low adherent wound dressings. Nonwoven structures made from gel-forming fibres, for example, alginate are considered to be preferred dressings for managing exudating wounds. However, these dressings have a less tensile strength in both wet and dry states than that of woven dressings. Moreover, the nonwoven dressings have little integrity, once used on the wound, to remain intact. Although alginate fibres are preferred for achieving nonadherence by gelling on contact with wound fluid, the fibres are expensive and have comparatively poor strength. The main drawback in using alginate dressing is that, if allowed to dry, the dressing may adhere to the wound [7] and, therefore, it is not suitable for dry wounds.

To overcome the above limitations, the University of Bolton, United Kingdom, has developed a nonadherent wound dressing by using a plain woven structure for managing both the exudating and dry wounds. The dressing uses a single-layered fabric woven using dense huckaback weave. The fabric is treated in a solution of a nonionic flocculent and a softening agent. On one side of the fabric, a laminated hydrophobic film is coated to prevent seepage. The nonionic flocculent reacts with the exudate to form a film of gel between the dressing and the wound and, thereby, prevents the dressing from sticking to the wound. The ratio of nonionic flocculent to softening agent used is in the range of 1:3 to 1:6 per litre of water. The softening agent is a fatty acid amide derivative and the flocculent is a polyacrylamide.

The above-mentioned gauze dressing (Table 11.1) is engineered using 100% cotton yarn. The fabric is woven using conventional two shafts with the warps and wefts following a set pattern and it possesses a greater absorption capability stipulated in BP method [8] (Table 11.2). In addition, such fabric has greater strength and the tendency to shed loose fibres is rare. This unique weave for gauzes allows the use of a single layer in place of 8–12 layers. A number of fabric layers are clubbed together to form a swab. These layers absorb any secretion from the wound. On drying up, the swab tends to stick to the wound and the area around it. The absorbed liquid, however, is dissipated from the gauze upon the application of pressure to the wound.

Table 11.1 Huckaback cotton wound dressing

Particulars	Area density (g/m ²)	Thickness (mm)	Bulk density (g/cm ³)
Grey fabric	149	1.2	0.12
Scoured and bleached	212	1.4	0.15
Scoured, bleached and nonadherent finished	202	1.3	0.16

Table 11.2 Absorbency of woven cotton gauze dressings

Number of ply	Initial weight (g)	Final weight (g)	Liquid absorbed (g)	Absorbency (g/g)	Absorbency (g/25cm ²)	Absorbency (g/100cm ²)
1	0.0425	0.2572	0.2147	5.1	0.2	0.9
2	0.0819	0.5586	0.4767	5.8	0.5	1.9
3	0.1257	0.9294	0.8037	6.4	0.8	3.2
4	0.1661	1.3660	1.1999	7.2	1.2	4.8
5	0.2113	1.8840	1.6727	7.9	1.7	6.7
6	0.2424	2.1988	1.9564	8.1	2.0	7.8
7	0.2924	2.8201	2.5277	8.6	2.5	10.1
8	0.3309	3.2381	2.9072	8.8	2.9	11.6

The above-mentioned dressing meets the following requirements of an ideal wound dressing:

- produces gels on contact with wound fluid that facilitate nontraumatic dressing removal
- soft and easy to handle, so no gelling in the dry state; they can also be used on dry wounds, unlike alginate dressings
- maintains a moist environment at the wound site that promotes healing
- enhances the absorption of body fluid
- softening agent serves to soften the fabric and also increases the absorption capacity of the wound dressing
- free from toxic, irritant, and allergic characteristics

In addition to the above-mentioned woven gauze wound dressing, some research into wound management has already been carried out using woven gauze. A noteworthy piece of research includes the development of a novel cotton gauze that absorbs neutrophil elastase present in chronic wounds [9]. It is known that the success of postoperative treatment for split-thickness skin graft (STSG) depends on maintaining graft integrity, preventing graft, and wound desiccation and minimizing infections. Researchers applied one layer of woven mesh gauze dressing (Xeroform) impregnated with bismuth tribromophenate onto STSG followed by layers of dry gauze dressings, and observed the growth of the graft after 5 days. The results revealed that minimal postoperative nursing care is sufficient and this is not possible in the case of other dressings for skin grafts. Cotton gauze impregnated with medical grade Manuka honey is used as a primary wound dressing for partial and full-thickness wounds, leg ulcers, pressure ulcers, first and second-degree burns, diabetic foot ulcers, minor abrasions, and lacerations. It also helps in promoting moist healing in difficult-to-heal wounds and assists in autolytic debridement. Chitosan impregnated gauze dressing (ChitoGauze) and CombatGauze (impregnated with kaolin, which is a china clay) are used for maximize haemostatic performance and reduce the risk of re-bleeding. ChitoGauze also provides antibacterial property against a wide range of Gram-positive and Gram-negative bacteria. A study involving 66 patients demonstrated that ChitoGauze reduced haemorrhage [10]. It is also established that Chitogauze provides haemorrhage control with less blood loss than CombatGauze. A recent study showed that conventional cotton gauze, which was previously impregnated with a solution of

chitosan containing povidone-iodine loaded with alginate microcapsules and silver nanoparticles, showed antibacterial shield against Gram-negative (*Escherichia coli*) and Gram-positive (*Staphylococcus aureus*) bacteria. In addition to the antibacterial property, the above-modified cotton gauze possesses higher water absorbency, water holding capacity, and vertical wicking by 55%, 28%, and 33%, respectively, in comparison with the control sample [11]. An illustration of a few commercial gauze dressings are depicted in Table 11.3 [12].

It should be noted that there are numerous types of wound dressings available for the management of different kinds of acute to chronic wounds (Table 11.4), but typically a modern wound dressing is composed of absorbent layers held between a wound contact layer and a base material (Fig. 11.1). The absorbent layers absorb blood, body fluids, and exudate. The wound contact layer is low-adherent and can

Table 11.3 Illustration of a few commercial gauze dressings

Product	Company	Description
Meditull Jelonet Dressing	Fleming Medical	A leno weave fabric of 100% absorbent cotton thread, impregnated with white soft paraffin. It is used as a primary contact layer for especially granulating wounds
Euronet Paraffin	Pharmacy Line	Absorbent cotton thread gauze, impregnated with white soft paraffin ointment. Nonadherent and nonallergenic dressing. Used as a primary wound contact layer in the treatment of burns, ulcers, skin grafts and a variety of traumatic injuries
Paranet	Synergy Health	Sterile gauze dressing is made from 100% cotton open-mesh leno weave, impregnated with yellow soft paraffin. Use on superficial wounds, burns, skin grafts and traumatic injuries
Bactigras	Smith and Nephew	Leno weave impregnated with white soft paraffin BP containing 0.5% Chlorhexidine. Protect the wound and allow free passage of viscous exudate. Maintain shape and resist fraying. Used for minor burns and scalds – lacerations, abrasions and other skin loss wounds
Pharmatull Plus	Biologica Pharmaceutical	Leno gauze of 100% absorbent cotton thread impregnated with white soft paraffin jelly which makes it nonadherent and nonallergenic dressing. Contains chlorhexidinedigluconate B.P. 0.5% (w/w) which has antimicrobial effect

Continued

Table 11.3 Continued

Product	Company	Description
UniTulle	ZENTA	Leno weave evenly impregnated with soft paraffin B.P. Low adherent, non allergic, protecting and healing the wound allowing easy drainage and easily removable without damage of wound surface and newly formed epithelium
JELONET	Smith and Nephew	Paraffin impregnated tulle gras dressing made from open leno weave. Used for minor burns, lacerations, abrasions and leg ulcers
Sofra-tulle	Hoechst Marion Roussel Ltd	Leno weave cotton fabric impregnated with white soft paraffin, anhydrous lanolin, and 1% (w/w) framycetinsulphate. Used as a primary wound contact layer in the management of infected wounds

easily be removed without disturbing new tissue growth. Generally, the material is placed directly over the wound (primary dressing) and covered with an absorbent pad (secondary dressing) and the whole dressing is retained with a tape or a suitable bandage depending on the location of the wound in the body. The primary dressing is expected to maintain the wound temperature, moisture level, permits respiration, and allows epithelial migration. The secondary dressing must not be too absorbent as it may cause the primary dressing to dry out too quickly [13].

Table 11.4 Illustration of commercial wound dressings and their applications

Commercial name	Major application
<i>Low-adherent dressing</i>	
Adaptic, Release, Melolin, Telfa, Skintact, Mepore, Primapore, Tricotex, NA Ultra, Jelonet, Paranet, Paratulle, Unitulle, Vasaline gauze, Inadine, Sofra-Tulle, Silicone NA, Mepitel, Metalline	Reduces risk of adherence to wounds Less trauma
<i>Semipermeable film dressing</i>	
Mefilm, Tegaderm, Bioclusive, Cutifilm, Epi View, Opsite Flexigrid	Lightly exuding wounds, superficial pressure sores, primary dressing and secondary dressing in combination with alginates and hydrogels

Table 11.4 Continued

Commercial name	Major application
<i>Odour adsorbing dressing</i>	
Actisorb Plus, Carbonet, Kaltocarb, Metrotop, Cliniflex	Undesirable odour producing wounds
<i>Hydrocolloid dressing</i>	
Aquacel, Granuflex, Comfeel, Combiderm, Cutinova Foam, DuoDerm, Tegisorb, Hydrocoll	Light to medium exuding wounds. Not suitable for infected wounds
<i>Hydrogel dressing</i>	
AquaForm, Sterigel, Purilon Gel, Intrasite Gel, Granugel Hydrocolloid Gel	Dry and necrotic wounds. Lightly exuding wounds and granulating wounds. Not suitable for infected and heavily exuding wounds
<i>Polyurethane foam dressing</i>	
Allevyn, Tielle, Lyofoam, Sterigel, Nu-Gel, Purilon Gel, Intrasite Gel, Granugel, Flexipore, Spyrosorb	Light to medium exuding wounds. Not recommended for dry superficial wounds
<i>Alginate dressing</i>	
Sorbsan, Tegagel, Kaltostat, Algosteril, Algisite, Algoderm, Melgisorb, Kaltogel, Tegagel, Algosteril and Comfelseasorb	Mainly primary dressing for medium to heavily exuding wounds and cavity wounds. Not suitable for dry wounds
<i>Alginate-collagen dressing</i>	
Fibracol	Suitable for dressing foot ulcers and heel pressure sore

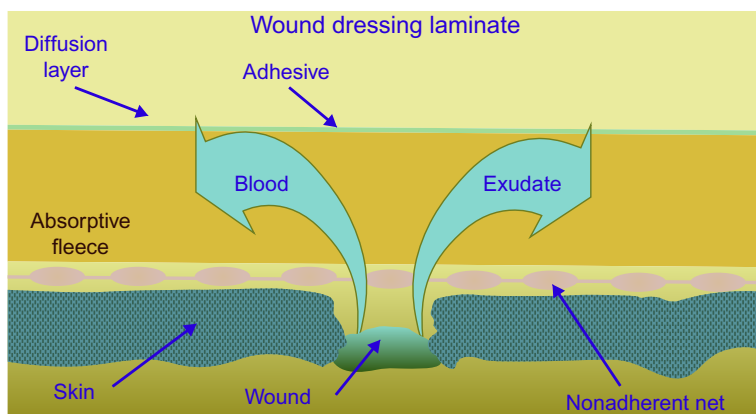


Fig. 11.1 Wound dressing concept.

11.2.5 Woven wound bandages

11.2.5.1 Bandage types

Bandages can be used for many purposes including dressing retention, support, and compression:

- retention bandages are used to retain dressings in the correct position
- support bandages provide retention and prevent the development of a deformity or change in the shape of a mass of tissue due to swelling or sagging
- compression bandages are employed mainly for the treatment of leg ulcers and varicose veins

Modern bandages are either woven or knitted and are designed to provide prescribed levels of compression in accordance with specified performance-based standards [14, 15] (Table 11.5).

Table 11.5 Compression properties of bandages

Bandage type	Selected leading brand names	Remarks
Retention bandage	Easifix, Slinky, Stayform, Tensofix	Exerts very little pressure on a limb
Support bandage	Crepe BP, Elastocrepe	Prevents formation of oedema and support joints. Exerts various amounts of pressure, according to the type, on a limb
Light compression (3a)	J-Plus, K-Crepe	Gives subbandage pressures of 14–17 mm Hg at the ankle
Moderate compression (3b)	Granuflex Adhesive Compression, Veinopress	Gives subbandage pressures of 18–24 mm Hg
High compression (3c)	Setopress, SurePress, Tensopress	Gives subbandage pressures of 25–35 mm Hg
Extra high compression (3d)	Bilastic Forte, Blue Line	Gives subbandage pressures of up to 60 mm Hg
Paste bandage	Webbing Ichtaband, Quinaband, Tarband, Zincaband	Woven cotton fabric impregnated with a medical cream or paste. Used for the treatment of eczema and dermatitis
Tubular bandage, elasticated	Tubifast, Tubigrip	Dressing on awkward sites
Foam padded	Netelast, Tubipad	Provides padding and protection against physical damage

Compression bandages are harmful if not applied properly. They provide high tension as well as high pressure. A thorough assessment involving several criteria is therefore essential before applying a compression bandage on a limb. For example, it is important to consider the magnitude of the pressure, the distribution of the pressure, the duration of the pressure, the radius of the limb and the number of bandage layers. Illustration of bandages used in compression therapy is published elsewhere [16].

Bandages are selected according to their level of performance rather than their construction. An ideal compression bandage should:

- provide compression appropriate for the individual;
- provide pressure evenly distributed over the anatomical contours;
- provide gradient pressure diminishing from the angle to the upper calf;
- maintain pressure and remain in position until the next change of dressing;
- extend from the base of the toes to the tibial tuberosity without a gap;
- function in a complementary way with the dressing; and
- possess nonirritant and nonallergenic properties.

Woven structures have been in use for designing compression bandages for venous leg ulcer management for a long time. A patent describes a narrow woven compression bandage constructed from cotton weft yarns and textured stretch nylon multifilament warp yarns having total deniers in the range of 210–560. The construction consists of from 10 to 16 picks per inch and from 30 to 40 warp yarns per inch. Spaced apart across the width of the fabric are pairs of warp yarns interwoven with the weft yarn in a leno construction that provides high frictional resistance to slippage between those warp yarns and the weft yarns. The ratio of leno pairs to nonleno warp yarns is in the range of from 1/6 to 1/14. The nonleno warp yarns and the weft yarn are interwoven in a 1×1 weave. The leno pairs are in a pretensioned state when the bandage is in an unstretched condition [17]. Elastomeric yarns such as spandex are used at intervals across the width of the woven bandage with inelastic cotton yarn [18].

A woven short stretch crepe bandage made from 100% high twist cotton yarns is used for the treatment of varicose veins. It provides compressive postsurgery or light orthopaedic support. It is also used for support to joints and ligaments after mild strains. ProGuide (Smith & Nephew) is a two-layer bandage system in which the first layer is a nonwoven and the second layer is a woven elastic compression bandage coated with a pressure sensitive hot melt adhesive which is applied in a ladder pattern to reduce slippage and keep the system in place for extended periods.

As described above, support bandages provide retention and prevent the development of a deformity or change in the shape of a mass of tissue due to swelling or sagging. These can be either flat, tubular, or shaped bandages and can be used either on their own or as a part of a series of bandages for the management of venous leg ulcers.

The specifications and manufacturing details of a woven support Profore No. 2 Flow Wrapped Bandage (10cm wide $\times$ 3m long) are given below:

Loom specifications	Bonas 2/110 or 2/175
Number of heald shafts	2
Latch needle type	7762G07
Front reed gauge	7.2 dents per cm
Yarn specifications	Warp: Beams 1 and 2; 2/78 dtex textured polyamide filament twisted with 20 tex ecru cotton, 125 turns per metre Weft: 36.9 tex (1/16 Ne) unbleached cotton yarns Catch thread: 1/44 dtex/13 filaments polyamide yarn
Weave	Plain
Ends per bandage	152
Picks per cm	7.0 ± 2
Fabric width	10 cm
Fabric area density	80 g m^{-2}
Cut length	3.0 m
Stretched length	4.5 m
Bandage performance	BS 7505: 1995
Bandage type	Type 2
Tension ratio (%) S	≥ 40
Working extension (%) E	≥ 20
Differential extension	
Factor (%) F	≥ 1.5

It has been highlighted that tightly woven fabric structure creates an ideal environment for the growth of microorganisms by maintaining a moist and warm environment [19].

11.3 Woven vascular prostheses and meshes

Textile-based vascular grafts are widely accepted as one of the most important medical devices to manage vascular diseases. In 1952, Blakemore et al. [20] successfully deposited fibrin within the interstices of the fabric and found that ingrowth of fibroblast from adjacent soft tissue occurs first and then endothelium migration would follow. This finding led researchers to further research to develop vascular prostheses. The first commercial attempt was made by Edwards [21] in 1955 using a braided polyamide and subsequently replaced polyamide with PTEE in the form of Teflon in 1957. PET was introduced in both warp and weft in 1961 [22]. Today, implants are made from a variety of synthetic fibres. The majority include polyethylene terephthalate (PET), expanded PET (ePET), polytetrafluoroethylene (PTFE), expanded polytetrafluoroethylene (ePTFE), and polyurethane. However, PET, ePET, and PTFE are the most commonly used fibres in the commercial vascular prosthesis. The ePTFE graft is nonporous and popularly used for femoro-popliteal and axillo-femoral by-passes. The most common commercial grafts are listed [23] in Table 11.6.

An artificial vascular prosthesis was first experimented in dogs and subsequently, it was implanted in humans to replace an aneurysm (dilation) of the abdominal aorta [20].

Table 11.6 Commercial vascular grafts

Manufacturer	Material
Bard	PET (woven, weft knit, velour weft and warp knit)
Meadox	PET (woven, warp knit, velour warp knit, umbilical vein)
Golaski	PET (weft knit, velour weft knit)
Sorin Biomedica	PET (carbon coated woven and knitted double velour)
Rhone Poulenc	PET (velour warp knit)
Coates-Paton Intermedia CS	PET
Gore	ePET
Impra	ePET
Johnson & Johnson	ePET, bovine carotid
St Jude Medical	Bovine carotid
Socol	Bovine carotid
Genetics Lab	Umbilical vein

The essential criteria for an ideal vascular graft are [24]:

- mechanical strength and compliance to withstand long-term hemodynamic stresses
- nontoxicity, nonimmunogenicity, biocompatibility, ‘off-the-shelf’ availability in various sizes for emergency care
- operative suturability and simplicity of surgical handling
- resistance to in vivo thrombosis
- ability to withstand infection
- complete incorporation into the host tissue with satisfactory graft healing and ability to grow when placed in children

In addition to the above, it is essential to consider parameters such as biocompatibility of fibres in the graft, nonfraying textile structure, flexibility, durability, and resistance to sterilization. The fibrous structure of the graft must have sufficient porosity to allow tissue growth as well as the formation of a thin fibrin-based blood clot resistance layer (nonthrombogenic) on the inner surface of the graft. The porosity of the commercial grafts is relatively constant and does not change with time because the grafts are constructed by using a plain nonabsorbable polyester (Dacron).

It should be noted that Dacron (Du Pont) graft has been one of the preferred choices since it was introduced in the 1950s. The original grafts were woven constructions but subsequent development of manufacturing technology led to the production of knitted and velour grafts. Vascular prostheses are either woven or knitted. Woven grafts exhibit a high degree of stability in both warp and weft directions, high strength, and low porosity (50–200 mL/min/cm²). Because of their low porosity, the prostheses are used without precoating in large-calibre, high-flow arteries [23]. Since woven structures provide greater strength and stability, they are therefore more suitable for high stress locations such as the thoracic aorta. Woven structures also provide high

dimensional stability, low permeability to blood and less kinking. The main disadvantages of plain and associated woven structures for use as vascular fabrics are that they fray at cut edges, have low healing porosity, poor compliance, and difficulty in suturing. However, velour woven fabrics, which are made by reducing the number of intersections along both warp and weft directions, are more flexible and produce loose surface structures which promote tissue attachment and ingrowth that conventional woven fabrics do not have.

The South India Textile Research Association (SITRA), Coimbatore, India has developed a seamless woven PET (Polyethylene terephthalate) polyester grafts (Fig. 11.2) [25]. The woven graft contains 75 denier texturized polyester yarn with a porosity of $200 \pm 50 \text{ mL/min/cm}^2$ of normal saline at 120 mmHg. The in vitro and in vivo clinical trials were conducted at Sree Chitra Tirunal Institute for Medical Sciences and Technology, Thiruvananthapuram, India. The clinical trials involving 10 patients revealed that all patients had excellent recovery without mortality or device-related adverse effects. During healing, the structural integrity of the woven graft was well preserved and the anastomotic suture lines appeared and covered with a transparent fibrin layer separating the flowing blood in the prosthesis. The silk bifurcated woven endovascular prosthesis (BWEP) has recently been fabricated by using the modified rigid rapier weaving loom [26]. The wall thickness and water permeability of the prosthesis were tested and the study concluded that the pure silk BWEP endovascular prosthesis is suitable for use in human body transplant.

Knitted prostheses are either single jersey or warp knitted velour structures. In knitted structures, the strength and porosity of the graft are influenced by loop configuration. Knitted grafts generally have higher porosity (2000 mL/min/cm^2) and lower strength than the woven ones. The average porosity of the graft is described by the internodal distance (IND) and the optimal IND of $60 \mu\text{m}$ (high porosity) is experimentally proposed for tissue ingrowth and endothelialization of 4-mm ePTFE grafts [27].

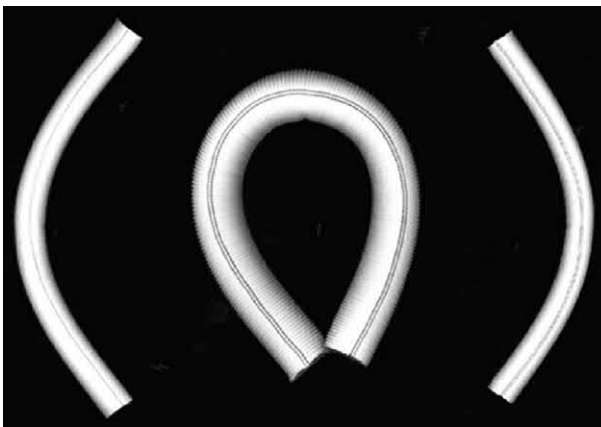


Fig. 11.2 Seamless woven polyester graft developed at SITRA.

High pore grafts are precoated with collagen or albumin or gelatine to decrease the porosity/permeability and to avoid the need for blood preclotting prior to implantation. In the early years of development, it was a common practice to precoat the graft with human blood before implantation to prevent blood leakage. However, the development of a new technique has eliminated the need for precoating the prosthetic tube. The technique involves:

- the immersion of the tube in water;
- draining the excess water from the inside surface; and
- coating the inner walls, making use of a suitable biocompatible elastomer.

The coating material is usually a copolyester-based polymer. However, collagen, albumin, chitosan, and elastane derivatives are also used to coat the graft [23]. Carbon is used for the coating to improve the thermogenic features of Dacron prostheses [23].

Unlike knitted grafts, woven grafts do not rely on looping of the yarn around a needle and the grafts are therefore more compact. However, the stiffness of the woven structure makes the graft more difficult to handle and suture during implantation. The intraoperative handling qualities of knitted grafts are preferred by surgeons although they possess larger pores than the woven grafts. Velour construction increases the growth of tissues and closely-woven double-velour synthetic vascular grafts are less porous and facilitate rapid tissue ingrowth. Gelweave Valsalva (Vascutek) is the woven polyester root graft that is used for repair and replacement of damaged and diseased thoracic aorta (Fig. 11.3) [28].

The performance of woven and collagen-impregnated knitted arterial prosthetic grafts has been directly compared. A randomized trial was conducted using 141 and 126 patients who received woven and knitted grafts, respectively. The graft handling qualities, operative blood loss, associated complications, and potency rates were assessed on discharge and at 1 year by the duplex imaging technique. The study reveals that both woven and knitted grafts have similar clinical performance but less blood loss is observed in knitted graft perhaps due to the collagen coating. After 1 year of implantation, a reduction in diameter of the woven grafts and an increase in diameter of the knitted grafts are observed. The study further suggests that less expensive woven graft may be the choice of graft unless haemorrhagic complications are anticipated. It does not support the view that bifurcated prostheses made of knitted and impregnated Dacron graft have better patency equivalents [29].

It is established in another study involving biophysical, histopathological, and ultrastructural aspects that the fibre structure and resistance to degradation are better in woven grafts than the knitted grafts [30]. The stability of the structure of woven graft helps to withstand more resistance to stress than the knitted graft where the loose structure is more prone to deterioration. Scott et al. [31] studied in vivo the dilatation of 74 woven and 69 knitted aortic grafts and found that knitted and woven grafts suffered a dilatation of 49% and 28%, respectively. CT scan evaluation also reaffirmed the finding that the dilatation of knitted grafts is higher than the woven grafts [32]. A 2-year CT scan study involving woven polyester prosthetic grafts (Gelweave) and knitted grafts (Gelseal) concluded that, in contrast to the woven prostheses, the knitted prostheses show an early and slow late dilation [33]. The merits and demerits of PET

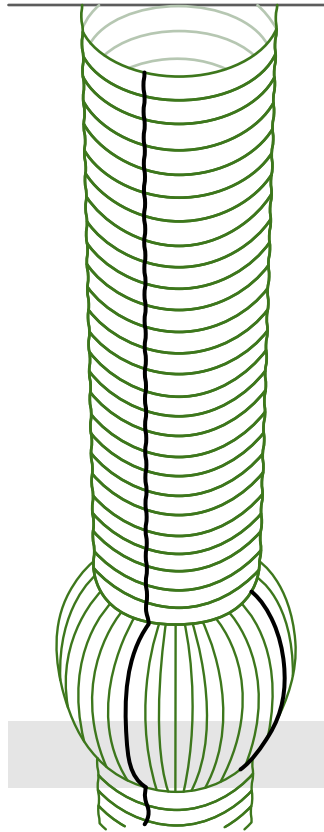


Fig. 11.3 Gelweave Valsalva (Vascutek) woven polyester graft.

woven and knitted grafts, and also the ePTFE- and polyurethane-based grafts (Table 11.7) are published elsewhere [34].

In order to enhance the functional properties of vascular prostheses in the in vivo environment, woven vascular fabrics were developed using both the nonabsorbable (polyester) and absorbable (polyglycolic acid; PGA) yarns [35]. Table 11.8 shows the fabric characteristics and properties of such bicomponent vascular fabrics.

Yu and Chu [35] found that the incorporation of absorbable yarns in the weft of a woven bicomponent vascular graft promotes faster tissue growth by being loose and porous. On the other hand, the absorbable yarns in the warp do not exhibit this unique surface. The following advantages are derived from the bicomponent vascular fabrics containing nonabsorbable and absorbable yarns:

- soft
- adequate strength and stability
- high integrity
- increase in porosity
- enhanced tissue ingrowth

Table 11.7 Merits and demerits of woven and knitted grafts

	PET (Dacron, Terylen)		ePTFE (Teflou, Gore-Tex)		Polyurethane	
	Woven	Knitted	Low-porosity (<30µm IND)	High-porosity (>45µm IND)	Fibrillar	Foamy
Advantages	Better stability, lower permeability and less bleeding	Greater porosity, tissue ingrowth and radial distensibility	Biostability, no dilation over time	Biostability, better cell ingrowth	Compliance, good hemo-and biocompatibility, less thrombogenicity	
Disadvantages	Reduced compliance and tissue incorporation, low porosity, fraying at edges, infection risk	Dilation over time, infection risk	Stitch bleeding, limited incorporation infection risk, perigraft seroma formation	Late neointimal desquamation in 90µm IND, infection risk	Biodegradation in first generation, infection risk, carcinogenic?	
Healing	Inner fibrinous capsule, outer collagenous capsule, scarce endothelial islands	Fibrin luminal coverage, very sporadic endothelium, transanastomotic endothelialisation in animals	Luminal fibrin and platelet capet, connective tissue capsule with foreign body giant cells, no transmural tissue ingrowth	Macrophages and polymorphonuclear invasion, capillary sprouting, fibroblast migration, certain angiogenesis, thicker neointima, endothelialisation in animals	Thin inner fibrin layer, outside foreign body cells, limited ingrowth	Better ingrowth with bigger pores

Table 11.8 Fabric specifications and properties of woven vascular fabrics

Fabrics	Ends/ inch	Picks/ inch	Thickness (cm)	Weight (g/cm ²)	Fabric density (g/cm ²)	Bending stiffness (mg cm)	Bursting strength (kg/cm ²)	Water permeability (mL/cm ² /min/mm Hg)
W1	168	104	0.034 ± 0.001	0.0205 ± 0.0026	0.6029	G _{x1} = 2640	15.0	300 ± 25
W2	78	128	0.050 ± 0.002	0.0300 ± 0.0022	0.6000	G _{x1} = 1430	11.61	650 ± 70
W3	78	136	0.053 ± 0.002	0.0360 ± 0.0017	0.6792	G _{x1} = 823	13.51	880 ± 20
W4	156	128	0.052 ± 0.008	0.0300 ± 0.0022	0.5769	G _{x1} = 670	22.3	400 ± 10
DeBakey woven	135	94	0.025	0.017	0.68	G _{x1} = 420	26.3	250 ± 3
						G _{x1} = 810		
						G _{x1} = 1045		
						G _{x1} = 1895		
						G _{x1} = 1345		

A woven graft for the repair of an abdominal and aortic aneurysm, a weakened wall of the aorta between the renal arteries and the bifurcation of the iliac arteries has been developed [36]. The thin polyester graft fabric has a double wall thickness of less than 0.51 mm and can be woven into a seamless tube or a woven fabric sheet can be formed into a cylinder and sewn to provide the desired shape. It is claimed that the ends of the graft minimize the formation of gaps between the implant and the vessel wall that enhances tissue ingrowth and provides a smooth transition for blood flow.

11.4 Application of woven structures in hospitals

11.4.1 Infection control

Woven textiles, specifically plain and twill weaves, are largely used in hospitals as reusable materials, such as patient's bed sheets and curtains. Their contribution in spreading infection is enormous. Textiles in any form used in hospitals are susceptible to bacterial growth under appropriate moisture and temperature conditions. Patients shed bacteria and contaminate their pyjamas and sheets. The temperature and humidity between the patients and the bed are appropriate conditions allowing for effective bacterial proliferation. Several studies have found that human contact with contaminated textiles is the source of transmission of microorganisms to susceptible patients.

It must be pointed out that infection control is a growing problem in places where hygiene is required and most particularly in hospitals. It is known that microorganisms which include bacteria, virus, and fungi create and aggravate problems in hospitals and other environments by transmitting diseases and infections through clothing, bedding, etc. Patients in hospitals are more prone to infection because of their illness and the Hospital Acquired Infections (HAIs) are among the top ten leading causes of death. The majority of Surgical Site Infections (SSIs) are acquired at the time of surgical procedures. A healthy individual can disperse to the air approximately 5000 bacteria-carrying skin scales per minute during walking. The particles are 5–60 μm in size and the average number of aerobic and anaerobic bacteria carried is estimated to be about five per skin scale. In spite of great deal research, clinicians are still facing problems with 'super-bugs' such as Methicillin resistant *Staphylococcus aureus* (MRSA) and Methicillin susceptible *Staphylococcus aureus* (MRSSA) bacteria in hospitals. When antibiotics are used incorrectly (e.g., to treat colds and flu) and too frequently, bacteria will adapt and become resistant to antibiotics. It is well established that microorganisms create and aggravate problems in hospitals and other environments by transmitting diseases and infections through clothing, bedding, etc. (cross-infection). In this situation, it is essential that the textile materials used in hospitals have the capability to eradicate/minimize cross-infection.

11.4.2 Antimicrobial activity

Antimicrobial textiles play a vital role in protecting the spread of diseases not only in hospitals but also in other environments where people gather in large numbers, for example, hotels, restaurants, swimming pools, and public mode of transportation.

Rajendran highlighted [37], an interview with AATCC, that ‘unfortunately, there is growing evidence that textiles act as disease vectors, transmitting infectious diseases from person to person’. These textiles are not meant to have a therapeutic effect but only serve as protection from cross-contamination. He foresees that more natural antimicrobial agents, including chitosan, honey, aloe vera, and tea tree oil, are being used on textile products in a medical setting in the future. Their main benefits are that they are nontoxic, and compatible with human cells.

With a view to developing antimicrobial textile materials, considerable research has already been carried out making use of organic and inorganic compounds, antibiotics, heterocyclics, quaternary ammonium compounds, etc. The biocidal properties of silver compounds have been known for thousands of years, and have been increasingly used nowadays to impart antibacterial properties to textile materials for hospital use. It is interesting to note that the cross-linking agent, dimethylol-5,5-dimethylhydantoin (DMDMH), commonly used in the wet processing industry to improve functional properties of textile fabrics, possesses a certain level of antibacterial effect on plain woven cotton and polyester/cotton (65/35) plain woven fabric [38] (Table 11.9).

The use of natural products as potential antimicrobial agents on textiles has currently received much attention due to the awareness of environmental issues. It is stressed that, although the synthetic antimicrobial agents are effective against a range

Table 11.9 Antibacterial activity of woven fabrics treated with dimethylol-5,5-dimethylhydantoin (DMDMH)

Fabric	Microorganism	Log reduction of bacterial challenge	
		2% DMDMH	6% DMDMH
Cotton	<i>E. coli</i>	6	6
Cotton/PET	<i>E. coli</i>	6	6
Cotton	<i>Staph. aureus</i>	6	6
Cotton/PET	<i>Staph. aureus</i>	6	6
Cotton	<i>Salmonell</i>	6	7
Cotton/PET	<i>choleraesuis</i>	7	6
Cotton	<i>Shigella</i>	6	6
Cotton/PET	<i>Shigella</i>	6	7
Cotton	<i>Candida albicans</i>	2	6
Cotton/PET	<i>Candida albicans</i>	6	6
Cotton	<i>Brevibacterium</i>	8	8
Cotton/PET	<i>Brevibacterium</i>	8	8
Cotton	<i>Pseudomonas aeruginosa</i>	6	6
Cotton/PET	<i>Pseudomonas aeruginosa</i>	6	6
Cotton	<i>Methicillin-resis. Staph. aureus</i>		3
Cotton/PET	<i>Methicillin-resis. Staph. aureus</i>		6
Cotton	<i>Vancomycin resis. Enterococcus</i>		6
Cotton/PET	<i>Vancomycin resis. Enterococcus</i>		6

of microorganisms and provide a durable effect on textiles, they possess limitations in use such as associated side effects, action on nontarget microorganisms and water pollution. Longer durability of antimicrobial effects can be achieved by imbuing antibacterial agents into the structure of fibres rather than depositing them on the surface. It is important that antimicrobial textiles provide protection against a wide range of Gram-positive and Gram-negative bacteria that include ‘super-bugs’.

Research on 100% cotton plain weave fabric finished with a synergistic system of formulation comprising inorganic chemicals involving a metal salt of a monocarboxylic acid, a carbamic acid derivative, a chelating agent, a boron compound, a dimethylene siloxane derivative, and an alkane polymer has shown that the treated fabrics imparted antimicrobial activity in arresting the growth of several bacteria (Gram-positive and Gram-negative), fungi, and mildew [14, 15].

Bed linens, patients’ gowns, and staff aprons were tailored using both the treated and untreated fabrics and were put to use in postoperative, gynaecology, and labour wards of a reputed hospital. The presence of bacteria on treated and untreated items was tested after several use-wash-use cycles. It is observed from the results after 50 cycles (Table 11.10) that while the untreated samples are rich in some types of bacteria, the treated ones are almost devoid of them. It should be mentioned that the users did not experience any discomfort such as skin irritation, disagreeable odour, and unpleasantness during the trial. The treatment also prevents the deterioration of fabrics by microorganisms (Figs 11.4 and 11.5).

Plain and twill weave woven fabrics (Table 11.11) are used as reusable OR surgical gowns [39]. Microbial barrier effect has been achieved by using microfilament polyester as well as controlling the pore size in the woven structure. It is established that the barrier efficiency of the woven fabrics depends directly on the arrangement of the filaments in the yarn and the construction of the woven fabric.

Recent research indicates that a desized, scoured, and bleached plain weave cotton fabric weighing 130 gm⁻² finished with a natural antimicrobial agent, neem seed, showed 99.5% antibacterial activity against *Staphylococcus aureus* [40]. It should

Table 11.10 Antibacterial activity of 50 times washed woven fabrics: Hospital trial

Wards	Organisms isolated from aprons, gowns and linen	Observation (growth of organisms)	
		Untreated	Treated
Postoperative	<i>Escherichia coli</i>	Moderate	Nil
	<i>Klebsiella aerogens</i>	Moderate	Nil
	<i>Staphylococcus pyogens</i>	Heavy	Insignificant
Gynaecology	<i>Escherichia coli</i>	Moderate	Nil
	<i>Staphylococcus pyogens</i>	Moderate	Nil
	<i>Pseudomonas pyocynans</i>	Moderate	Nil
Labour	<i>Escherichia coli</i>	Heavy	Heavy
	<i>Klebsiella pneumoniae</i>	Heavy	Heavy
	<i>Staphylococcus pyogens</i>	Heavy	Insignificant



Fig. 11.4 Untreated woven fabric on storage.



Fig. 11.5 Antimicrobial treated woven fabric on storage.

be mentioned that neem seed is obtained from the neem tree, *Azadirachta indica*, which is abundantly found in the Indian subcontinent. It has excellent potential as an antimicrobial agent and its main constituents such as azadirachtin, salannin, and meliantriol are proven insect growth regulator and antifeedant [41]. It is observed that the particle size of the natural polymers influences the antibacterial activity [42]. The antibacterial activity of normal chitosan, nanochitosan, and silver loaded nanochitosan applied on woven polyester fabrics shows that chitosan gets much enhanced antibacterial activity in nanoparticle form, as indicated by a reduction in minimum inhibitory concentration (MIC) from 0.5% to 0.01%. The silver loaded chitosan nanoparticle shows a further increase in activity (MIC 0.001%) due to the

Table 11.11 Specifications of plain and twill weave operating room (OR) surgical gowns

Sample	Type of weave	Fineness of filament in dtex		Cross-section of filament		Number of filaments in the yarn		Fineness of filament yarn in tex		Yarn density/ 10cm		Fabric density (g cm^{-3})
		Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft	
P 4	Plain	0.85	0.85	Deformed	Deformed	112	102	9.5	8.5	456	370	0.55
P 5	Plain	2.60	1.25	Triangular	Round	48	198	13.0	25.0	572	313	0.98
P 6	Twill 2/1	0.60	1.35	Round	Round	206	69	9.5	12.5	458	362	0.37

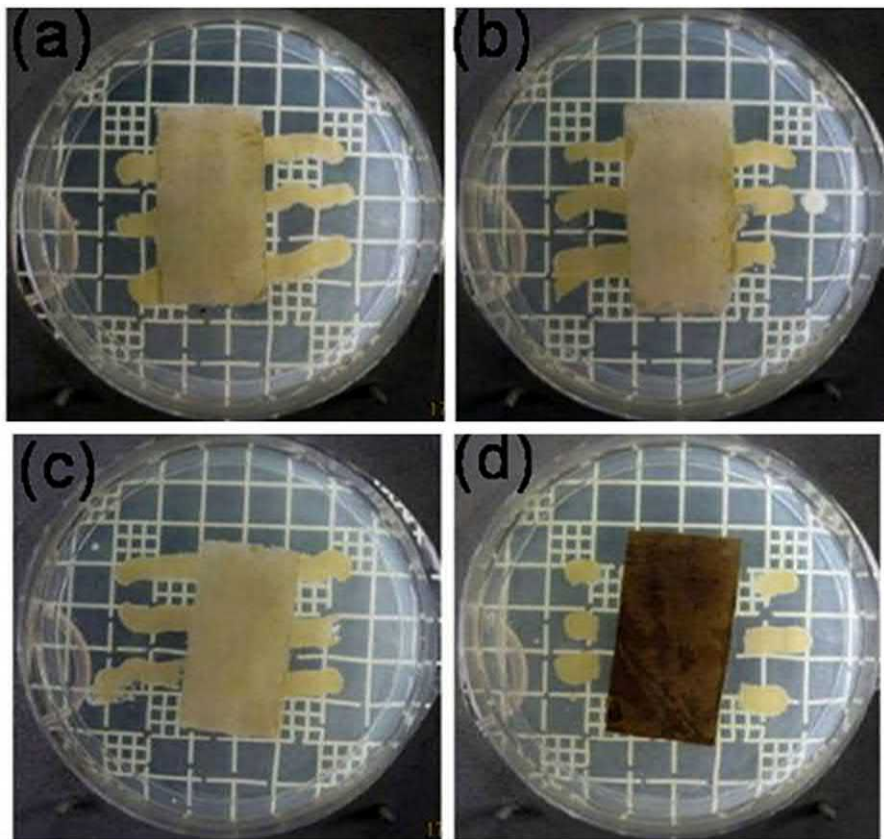


Fig. 11.6 (A) Untreated polyester woven fabric; (B) chitosan treated polyester woven fabric; (C) nanochitosan treated polyester woven fabric; and (D) nano silver-chitosan treated polyester woven fabric.

synergistic effect of Ag^+ and chitosan nanoparticles. These particles additionally show a release mechanism as evident from a clear zone of inhibition (Fig. 11.6A–D).

Recent research described the antimicrobial activity of bioactive-treated fabric (BTF) that contains silver for use in the hospital environment [43]. Unlike other biocides used in hospital fabrics, the prolonged use of silver has not been related to the appearance of resistant bacteria or cross-resistance to antibiotics, in spite of being extensively used in some treatments. The antibacterial activity of the treated fabrics was tested against 33 hospital strains and a significant reduction was found in the number of bacteria present on the BTF. The physical, mechanical, moisture-vapours transmission, and water repellent properties of antibacterial cotton/amicor woven fabrics containing different woven structures that are intended for use as antimicrobial hospital sheets are published elsewhere [44]. It will be borne in mind that amicor is an acrylic-based fibre into which organic antibacterial and antifungal additives are imbued.

11.5 Other medical applications of woven structures

The University of Bolton has developed novel reusable incontinence products for the benefit of the elderly community. The product specifications are given below.

Face fabric	Comfortable, dry, stable, good even appearance
Soaker material	Highly absorbent, stable, washable at 95 °C up to 200 washes/ tumbling cycles
Barrier material	Nonleaking, light, stable, nonshrinking
Nonslip material	Good surface friction, good even appearance
1. Wings	Plain woven polyester
2. Face fabric	Loop raised warp knit polyester (125 g m ⁻²)
3. Soaker fabric	Needle-punched 60% polyester/40% viscose
4. Barrier fabric	PVC coating (500 g m ⁻²)
5. Nonslip fabric	Weft-knitted polyester (60 g m ⁻²)

A number of woven structures are being used as electronic conductive materials by integrating sensors for biomedical applications. Sensors integrated into clothing ensure a noninvasive measurement method without interfering in the human body. A company in Italy, Soliani SML, has recently developed an electroconductive woven structure by using silver for ECG measurement [45]. Meshes are implanted mainly to reinforce soft tissues. The application includes:

- hernia repair (abdominal, inguinal, diaphragmatic, epigastric, gastroesophageal, hiatal, intermuscular, mesenteric, paraperitoneal, rectovaginal, retrocecal, uterine, and vesical)
- abdominal wall repair
- prolapsed tissue support/repair
- perforated tissue repair
- general tissue repair (pelvic floor, bladder, and thoracic wall)

In addition, the use of mesh grafts on humans also includes protection of esophagogastrostomy, treating a damaged kidney by external splinting or encapsulation, repairing pelvic peritoneum and replacing the membrane covering the brain. In repairing/reinforcing abdominal wall defects, polyester (Mersilene), polypropylene (Marlex), ePTFE (Gore-Tex), PGA (Dexon), and polyglactin (Vicryl) have been used for many years. However, none of these materials has proved entirely satisfactory for repairing large or difficult defects. No single mesh graft has gained universal acceptance.

Woven, nonwoven, and knitted structures are used in surgery for the repair, reconstruction or substitution of tissues. The utilization of mesh grafts in humans is based on the fact that, during the absorption period, a neomembrane is formed in the site where the mesh has been implanted. Initially, animals were employed for in vivo studies. A polyglactin (Vicryl) mesh placed in the thoracic aorta of a pig as a patch graft facilitated the early growth of muscle cells around the mesh and subsequently the mesh was completely absorbed in 40 days. It has been recently reported that the tensile strength of Vicryl woven mesh has increased 30 days after being implanted in rats [46]. An illustration of a mesh implant is shown [47] in Fig. 11.7.

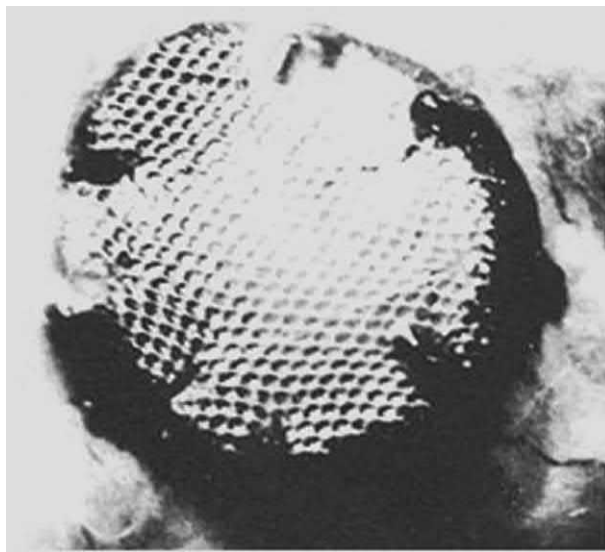


Fig. 11.7 Polyester-carbon composite mesh implant after 5 weeks of implantation.

The combination of nonabsorbable PTFE, a copolymer of hexafluoroethylene, and tetrafluoroethylene fibres encased in a bioabsorbable polymer composite mesh has been utilized for the repair of defects in the abdominal wall of rats [48]. It was demonstrated that the nonabsorbable component made of knitted, woven or nonwoven structures serves as a reinforcement material in preventing hernia formation. A recent study highlights the risk factors and the long-term effect of an e-PTFE synthetic mesh [49]. The study, involved 156 adult patients, has found that e-PTFE synthetic meshes used for repairing abdominal wall hernias are safe and durable.

Heim and Gupta [50] have discussed the application of woven fabric for designing textile heart valve prostheses. They studied the long-term fatigue behaviour of polyester woven fabric for engineering heart valve prosthesis. The findings of the study may pave the way to develop criteria for designing a highly suited woven fabric for heart valve application. It is demonstrated during the development of special woven polyester fabric for heart valve prosthesis that the woven structure gives the heart valve tissue a macroscopic behaviour that closely resembles the collagen-elastin heart valve tissue structure [51]. The effect of cyclic mechanical stimulation on a composite structure that consists of a woven fabric scaffold and tendon fibroblasts has been studied in vitro to overcome the complications associated with mechanical and structural incompatibility between implanted devices and host tissue [52]. A novel low permeable woven polyester fabric (Bard DeBakey) has been developed for use in outflow tract repairs, patch graft angioplasty and septal defects. The woven polyester patch was utilized to develop a new technique which promotes active exercise immediately after surgery without cast immobilization [53].

11.6 Conclusions

The application of woven textiles and their products in the healthcare and hygiene sectors has been updated. It is demonstrated that conventional weaving technology still plays a crucial role in designing and engineering hi-tech medical devices such as prosthetic grafts and heart valves. The application of woven textiles in wound dressings, bandages, implant products, and meshes has been critically appraised. Medical products for hygiene and healthcare uses have also been discussed. The contribution of woven structures for use in hospital fabrics is well recognized, although nonwovens are equally used as disposable products. Commercial names of some of the medical products and their corresponding uses have been tabulated which may serve as 'ready-reckoners'. This review contradicted the myth that medical application of woven fabrics is limited and they are used only for manufacturing cotton gauze for wound management. With the arrival of novel woven technologies such as 3D weaving, it is expected that the contribution of woven structures in medicine will be enormous.

References

- [1] Anon, Medical Textiles Market Size to Reach \$20.23 Billion by 2022, Available at: <https://www.grandviewresearch.com/press-release/global-medical-textiles-market>, 2016. Accessed 20 June 2018.
- [2] Anon, Healthcare Industry in India, Available at: <https://www.ibef.org/industry/healthcare-india.aspx>, 2018. Accessed 24 June 2018.
- [3] M. Randall, Overview of the UK Population: July 2017, Available at: <https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/articles/overviewoftheukpopulation/july2017>, 2017. Accessed 22 June 2018.
- [4] NICE, The Debrisoft Monofilament Debridement Pad for Use in Acute or Chronic Wounds, Available at: <https://www.nice.org.uk/guidance/mtg17>, 2014. Accessed 25 June 2018.
- [5] S. Rajendran, S.C. Anand, High performance textiles for wound care, in: C.L. Lawrence (Ed.), *High Performance Textiles and Their Applications*, Woodhead Publishing, Cambridge, 2014, pp. 190–222.
- [6] S. Rajendran, S.C. Anand, Developments in medical textiles, *Text. Prog.* 32 (4) (2002) 1–42.
- [7] H. Chang, S. Wind, M.D. Morries, Moist wound healing, *Dermatol. Nurs.* 8 (3) (1996) 174–176, 204.
- [8] Anon, *Alginate Dressings*, British Pharmacopoeia: HMSO, London, 1995, p. 1706.
- [9] J.V. Edwards, D.R. Yager, I.K. Cohen, R.F. Diegelmann, et al., Modified cotton gauze dressings that selectively absorb neutrophil elastase activity in solution, *Wound Repair Regen.* 9 (1) (2001) 50–58.
- [10] R. Te Grotenhuis, P.M. Van Grunsven, W.M.J.M. Heutz, E.C.T.H. Tan, Prehospital use of hemostatic dressings in emergency medical services in the Netherlands: a prospective study of 66 cases, *Injury* 47 (5) (2016) 1007–1011.
- [11] H. Hajimirzababa, R. Khajavi, M. Mirjalili, M. KarimRahimi, Modified cotton gauze with nano-Ag decorated alginate microcapsules and chitosan loaded with PVP-I, *J. Text. Inst.* 109 (5) (2018) 677–685.

- [12] R. Erdem, Advances in fabric structures for wound care, in: S. Rajendran (Ed.), *Advanced Textiles for Wound Care*, second ed., Woodhead Publishing—An imprint of Elsevier, Duxford, 2019, pp. 509–540.
- [13] L. Foster, P. Moore, Acute surgical wound care 3: fitting the dressing to the wound, *Br. J. Nurs.* 8 (4) (1999) 200–210.
- [14] S. Rajendran, S.C. Anand, Application of textile materials and products in healthcare, in: *Technical Textiles Markets*, Textile Intelligence Electronic Publishing, Wilmslow, UK, 2001, pp. 25–49 2nd quarter, No.45.
- [15] S. Rajendran, S.C. Anand, Development of a versatile antimicrobial finish for textile materials for healthcare and hygiene applications, in: *Proceedings, Medical Textiles '99 Conference*, 24–25 August, Bolton, UK, Woodhead Publishing, Cambridge, 2001, pp. 107–116.
- [16] S. Rajendran, S.C. Anand, Hi-tech textiles for interactive wound therapies, in: V.T. Bartels (Ed.), *Handbook of Medical Textiles*, Woodhead Publishing, Cambridge, 2011, pp. 38–75.
- [17] R. Hampton, F.P. Hanes Jr., Woven Elastic Compression Bandage, (1980), US Patent 4207885.
- [18] S. Gosh, A. Mukhopadhyay, M. Sikka, Compression bandages, in: V.K. Kothari (Ed.), *Progress in Textiles: Science & Technology*, IAFL Publications, Delhi, 2008, pp. 280–320.
- [19] L. Teufel, A. Pipal, K.C. Schuster, et al., Material-dependant growth of human skin bacteria on textiles investigated using challenge tests and DNA genotyping, *J. Appl. Microbiol.* 108 (2) (2010) 450–461.
- [20] A.H. Blakemore, A.B. Voorhees, The use of tubes constructed from vinyon “N” cloth in bridging arterial defects – experimental and clinical, *Ann. Surg.* 140 (3) (1954) 324–333.
- [21] W.S. Edwards, Clinical experience with Teflon grafts, in: S.A. Wesolowski, C. Dennis (Eds.), *Fundamentals of Vascular Grafting*, McGraw-Hill, New York, 1970, p. 367.
- [22] G.P. Noon, S. DeBakey, Debakey, Dacron prosthesis and filamentous velour graft, in: P.N. Sayer, M.S. Kaplitt (Eds.), *Vascular Grafts*, Appleton-Century Crofts, New York, 1978, p. 177.
- [23] M. Grigoriu, C. Daniele, G.B. Avenio, V. Barbaro, Biomechanics and hemodynamics of grafting, in: M. Rahman, M.G. Satish (Eds.), *Vascular Grafts Experiment and Modelling*, WIT Press, Southampton, 2003, p. 41.
- [24] J.D. Kakisis, C.D. Liapis, C. Breuer, B.E. Sumpio, Artificial blood vessel: the Holy Grail of peripheral vascular surgery, *J. Vasc. Surg.* 41 (2) (2005) 349–354.
- [25] M. Unnikrishnan, S. Viswanathan, K. Balasubramaniam, et al., The making of indigenous vascular prosthesis, *Indian J. Med. Res.* 143 (6) (2016) 769–781.
- [26] Z. Liu, G. Li, Y. Li, Y. Li, X. Wang, Fabrication and water permeability of bifurcated woven endovascular prosthesis, in: *Paper Presented at the Textile Bioengineering and Informatics Symposium Proceedings 2017 – 10th Textile Bioengineering and Informatics Symposium*, TBIS 2017, 2017, pp. 1–9.
- [27] M.A. Golden, S.R. Hanson, T.R. Kirkman, et al., Healing of polytetrafluoroethylene arterial grafts is influenced by graft porosity, *J. Vasc. Surg.* 11 (6) (1990) 838–844.
- [28] Anon, Aortic Root Designs, Leaflet, Gelweave™, Vascutek, Renfrewshire, 2011. 2011.
- [29] J.W. Quarmby, K.G. Burnand, S.J.M. Lockhart, et al., Prospective randomised trial of woven versus collagen-impregnated knitted prosthetic grafts in aortoiliac surgery, *Br. J. Surg.* 85 (6) (1988) 775–777.
- [30] E. Tardito, B. Blondo, V. Caputo, et al., Biodegradation of Dacron vascular prostheses: physico-chemical, histological, morphometric and ultrastructural study, *Minerva Cardioangiol.* 41 (3) (1993) 59–80.

- [31] S. Scott, M.D. Berman, C. Glenn, M.D. Hunter, et al., Application of computed tomography for surveillance of aortic grafts, *Surgery* 118 (1) (1995) 8–15.
- [32] Y. Alimi, C. Juhán, N. Morati, Dilation of woven and knitted aortic prosthetic grafts: CT scan evaluation, *Ann. Vasc. Surg.* 8 (3) (1994) 238–242.
- [33] E. Mattens, P. Engels, R. Hamerlijncx, J. Kelder, Gelseal[®] versus Gelweave[®] Dacron prosthetic grafts in the descending thoracic aorta: a two-year computed tomography scan follow-up study, *Cardiovasc. Surg.* 7 (4) (1999) 432–435.
- [34] J. Chlupac, E. Filova, L. Bacakova, Blood vessel replacement: 50 years of development and tissue engineering paradigms in vascular surgery, *Physiol. Res.* 58 (Suppl. 2) (2009) S119–S139.
- [35] T.J. Yu, C.C. Chu, Bicomponent vascular grafts consisting of synthetic biodegradable fibres. Part 1. In vitro study, *J. Biomed. Mater. Res.* 27 (10) (1993) 1329–1340.
- [36] Anon, *Medical Textiles*, vol. 6, International Newsletters Ltd, 1999, 7.
- [37] M.C. Thiry, Prescription textile protection, *AATCC Rev.* 10 (1) (2010) 30–36.
- [38] G. Sun, X. Xu, J.R. Bickett, J.F. Williams, Durable and regenerable antimicrobial finishing of fabrics with a new hydantoin derivative, *Ind. Eng. Chem. Res.* 40 (4) (2001) 1016–1021.
- [39] D. Aibibu, B. Lehmann, P. Offermann, Qualitative evaluation of the barrier effect of textiles in use, in: S.C. Anand, J.F. Kennedy, M. Mirafteb, S. Rajendran (Eds.), *Medical Textiles and Biomaterials for Healthcare*, Woodhead Publishing, Cambridge, 2006, pp. 168–176.
- [40] M. Joshi, S. Wazed Ali, S. Rajendran, Antibacterial finishing of polyester/cotton blend fabrics using neem (*Azadirachta indica*): a natural bioactive agent, *J. Appl. Polym. Sci.* 106 (2) (2007) 793–800.
- [41] A. Chatterjee, S. Pakashi, A. Chatterjee, S.C. Pakrashi (Eds.), *The Treatise on Indian Medicinal Plants*, vol. 3, Publications & Information Directorate, New Delhi, 1994, p. 76.
- [42] S. Wazed Ali, S. Rajendran, M. Joshi, Synthesis and characterization of chitosan and silver loaded chitosan nanoparticles for bioactive polyester, *Carbohydr. Polym.* 83 (2) (2011) 438–446.
- [43] A. Mariscal, R.M. Lopez-Gigosos, M.B. Carnero-Varo, J.B. Fernandez-Crehuet, Antimicrobial effect of medical textiles containing bioactive fibres, *Eur. J. Clin. Microbiol. Infect. Dis.* 30 (2) (2011) 227–232.
- [44] R. Harpa, C. Piroi, I. Cristian, Study regarding the physical-mechanical properties of cotton/amicor woven fabrics for medical use, in: *ITC and DC: Book of Proceedings of the 4th International Textile, Clothing and Design Conference – Magic World of Textiles*, 2008, pp. 769–774.
- [45] J. Zieba, M. Frydrysiak, L. Tesiorowski, M. Tokarska, Textronic clothing to ECG measurement. in: *MeMeA 2011 – IEEE International Symposium on Medical Measurements and Applications*, Proceedings, 2011, pp. 564–568, <https://doi.org/10.1109/MeMeA.2011.5966770>.
- [46] R.D. Rice, F.S. Ayubi, Z.J. Shaub, Comparison of Surgisis, AlloDerm, and Vicryl woven mesh grafts for abdominal wall defect repair in an animal model, *Aesthet. Plast. Surg.* 34 (3) (2010) 290–296.
- [47] R.J. Minns, Development of a knitted mesh/woven composite implant for the repair of abdominal defects in the human, in: S.C. Anand (Ed.), *Proceedings, International Conference on Medical Textiles '96*, Woodhead Publishing, Cambridge, 1997, p. 102.
- [48] Anon, *Medical Textiles*, vol. 8, International Newsletters Ltd, 1992, 6.
- [49] T. Ünek, S. Sökmen, T. Egeli, et al., The results of expanded-polytetrafluoroethylene mesh repair in difficult abdominal wall defects, *Asian J. Surg.* 42 (2019) 131–143.

- [50] F. Heim, B.S. Gupta, Textile heart valve prosthesis: the effect of fabric construction parameters on long-term durability, *Text. Res. J.* 79 (11) (2009) 1001–1013.
- [51] F. Heim, B. Durand, N. Chakfé, A new concept of a flexible textile heart valve prosthesis, in: *Transactions – 7th World Biomaterials Congress*, Sydney, 17–21 May, 2004, p. 1656.
- [52] E. Karamuk, J. Mayer, G. Raeber, Tissue engineered composite of a woven fabric scaffold with tendon cells, response on mechanical simulation in vitro, *Compos. Sci. Technol.* 64 (6) (2004) 885–891.
- [53] M. Ishizuki, The polyester patch: a new technique to promote early motion exercises in extensor tendon transfers, *Tech. Hand Up. Extrem. Surg.* 6 (3) (2002) 114–118.

J.P. Singh

Department of Textile Technology, UPTTI Kanpur, Kanpur, India

12.1 Introduction

Fabrics made from the interlacement of yarn, either two sets of yarn or more than two sets of yarn, are woven fabrics. Different from core uses of woven fabrics like clothing or garments for the purpose of decoration and covering; these woven fabrics can be used in many other fields, such as sportswear, medical textiles, textiles for electronics, air bag construction in automotive engineering, and also as a filtration fabrics for the purpose of filtrations. Woven fabrics, generally more durable and stable, are used for the purpose of filtration and can be added with some properties for more efficient work as a filter media. Examples of such properties include: oil absorbing, chemical binding, bacteria and virus killing (antibio fouling). These textiles with extra properties are termed as the 'intelligent textiles'. They can also have the capability to withstand various conditions, such as heat, powerful chemicals, and abrasive properties of the insoluble particles [1, 2].

Fig. 12.1 depicts the picture of various forms of woven fabrics as filter bags. The structure of woven fabrics is different according to their end use in different fields, and it depends upon the weave, thread density, crimp, and yarn count. Fig. 12.2 shows the various [2] structures of woven filter fabrics. Their usage varies from material type to structure as per its end uses for air filtration or for water filtration. Even though filter fabric appears to be very small in size, they have a major role of filtration in many industries. Woven filter press cloths are used in distilling the solid from the liquid. These filters are designed in a manner to trap the solid particles easily, efficiently, and also allow the smooth flow of the water through the filter press cloth.

12.2 Applications of woven filter fabrics according to their structure

There is diversity in the form of the fabric filter cloths according to their end uses. Some different types of fabric filters which are used as filter press cloth are as follows.

12.2.1 Centrifugal bags

Centrifugal bags are the most common used filter media for the separation of solid from the liquid or, in better words, for the separation of solid components from the suspension. Fig. 12.3 shows the diagram of a centrifugal bag [3, 4].



Fig. 12.1 Various forms of woven filter fabrics.



Fig. 12.2 Structures of woven filter fabrics.



Fig. 12.3 Centrifugal bag.

These filter bags work on the concept of centrifugal force and thus use centrifugal energy for the filtration purpose. The wall of the filter bags allows the filtrate to pass through it, leaving the solids on the surface. These solids on the surface of the filter bags can further be removed. The centrifugal filter bags are made by using special fabrics depending upon filtration and porosity factors of the product. Centrifugal filter bags can be of mesh made up of woven fabrics or can be made of felt fabrics. Fabrics which are suitable for the manufacturing of the centrifugal filter bags are: cotton, polyester, polypropylene multifilament, polypropylene spun, nylon, etc. Following are the different fields where centrifugal bags are used:

- Purification of dairy products
- Elimination of yeast and dust during beer processing
- Filtration of fine chemicals from coarse chemicals
- Filtration of medicine and water to take away particles and visual clarity

12.2.2 Fluid bed dryer bags

According to their name, fluid bed dryer (FBD) bags are in the form of beds over which the drying gas is passed. During this process, the controlled air velocity is necessary to keep the bed in a fluidized state that promotes high heat transfer and drying rate [5]. Hence, it can be said that FBD is the system of heat transfer by forced convection. In FBD process, input is in the form of crystal or granular, and the end product is in powder form. FBD filter bags are available in various shapes and sizes [6, 7]. These filter bags can be of various quality fabrics such as cotton, nylon, PP polyester, PP antistatic, and polyester antistatic. Fig. 12.4 shows the picture of FBD bags; Figs 12.5 and 12.6 show the working position of the FBD bags.

FBD bags have the following features:

- (1) These bags are durable according to their construction.
- (2) They are available in variety of sizes as per the user's requirement.
- (3) Installation is easy.
- (4) Wear and abrasion resistance of the FBD bags is excellent.
- (5) High flow rate is observed in it, and this particle retention encourages efficiency.

12.2.3 Nutsche filter bags

Nutsche filter bags use the batch filtration technique in which vacuum or pressure is applied for the process of filtration in a closed vessel; this minimizes cake contamination, enables very high solvent recovery, and also maintains the safety throughout the process. Nutsche filter bags are of cylindrical shape with a welded flat bottom. The base plate grips the filter fabric with the arrangement of the bolting bar. Under filter cloth, an appropriate level of support mesh is provided to smooth the progress of the flow of filtrate [8, 9].

The advantages of this filter bag over others is that it gives less risk to the operator, reduces product handling, and provides environmental protection against solvent vaporization. These filter bags can be commonly used in dye and paint production, pharmaceuticals, waste water treatment, and fine chemical applications. Fig. 12.7 shows the image of nutsche filter bag.



Fig. 12.4 FBD bags.



Fig. 12.5 FBD machine.



Fig. 12.6 Working position of FBD bags.



Fig. 12.7 Nutsche filter bag.

12.2.4 Vacuum filter bags

Vacuum filter bags are used in the vacuum cleaner device with the basic purpose to collect dust particles. Dirt bags are placed at a position to catch the dust which is sucked in with the air. Air can pass through, but dust cannot so it effectively acts as a filter. Bags are made up of porous woven material with the tiny holes of appropriate size to let air particles pass by and avoid dust particles passing through.



Fig. 12.8 Vacuum filter bag.

A variety of vacuum bag designs are available according to the different sizes of vacuum cleaners. The woven cloth vacuum cleaner bags are reusable.

The main features that a vacuum filter bag must possess include: a good bursting strength, low dust loading, and high air filtration efficiency. These features depend upon the material used and construction of the filter bags. Fig. 12.8 shows the image of a vacuum filter bag [10, 11].

12.2.5 ETP panel filter

ETP panel filters are available in various sizes and shapes according to their place of application; they are used in various industries like pharmaceuticals, food, beverages, chemical industries, etc. Polypropylene and polyamide fibres are used for the manufacturing of ETP panel filters [12]. The fibres used can be in the form of staple, multifilament, or monofilament and also can be mixed together. Fig. 12.9 shows the image of the ETP panel filters.

12.3 Application of woven fabrics for filtration in various industries

12.3.1 Baghouse

The polluted air released from the commercial processes must be cleaned up before releasing it in the environment in order to remove the toxicity of the air. A baghouse or fabric filter is used for this process as an air pollution control device whose major task

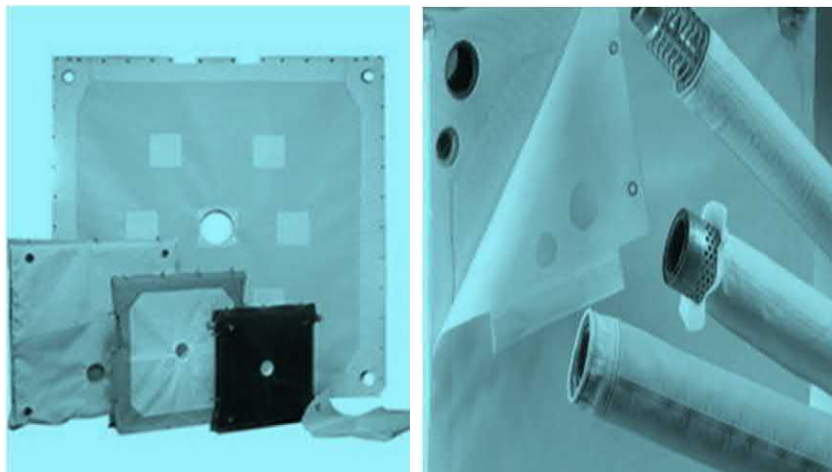


Fig. 12.9 ETP panel filters.

is to remove air particulates from the polluted air. Pharmaceutical producers, steel plants, power plants, and other industries often use baghouses for controlling emission of air pollutants.

Baghouse has long and cylindrical bags made up of woven or felted fabrics as a filter medium. Air with impurities enters the baghouse through the hopper and then it passes through the baghouse chamber. The cleaning of air is completed by allowing fresh air to pass through the fabric filters, and a layer of dust is formed on the surface of filter media until it gets choked. The cleaning of the bag is done after a sufficient pressure drop due to accumulation of dust on the filter media surface [13]. The cleaning can be done on process or off process. After the filter bags are cleaned, the filtration process starts again immediately.

There are basically three methods for the cleaning of the baghouses which are: mechanical shaker method, reverse air flow method, and pulse jet method. Figs 12.10–12.12 show the above cleaning methods respectively.

These filter bags generally have tube-like structures made of woven or nonwoven materials. The length and diameter varies from 15 to 30 ft and 5–12 in. respectively. The bags may be constructed by using cotton, nylon, polyester, fibre glass, or any other material to suit the chemical or moisture content, temperature, and other conditions of the gas stream. Fig. 12.13 gives a clear picture of woven filter bags.

There are definite repeated patterns in the woven filters. The patterns allow lower energy cleaning methods, such as reverse air or shaking method. The amount of space between the individual yarns can be increased or decreased by changing weave and constructional parameters of the fabric. These changes affect the permeability and strength of the fabric. A tighter weave with fine counts, higher ends, picks per inch, and higher cover factor lowers the permeability and therefore increases the efficiency of capturing fine particles.

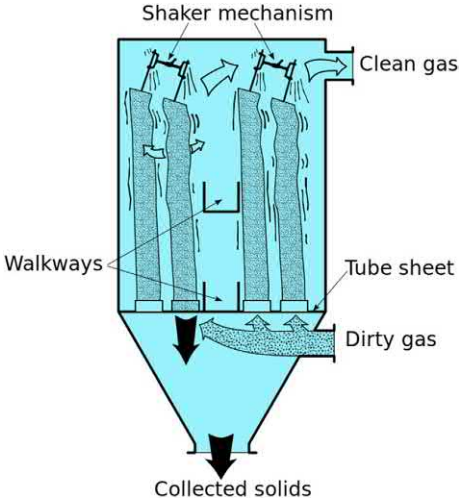


Fig. 12.10 Mechanical shaker cleaning method.
Courtesy: Gorantek-en – Own work derivative of Mechanical-Shaker Baghouse.png, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=30458370,71,72>.

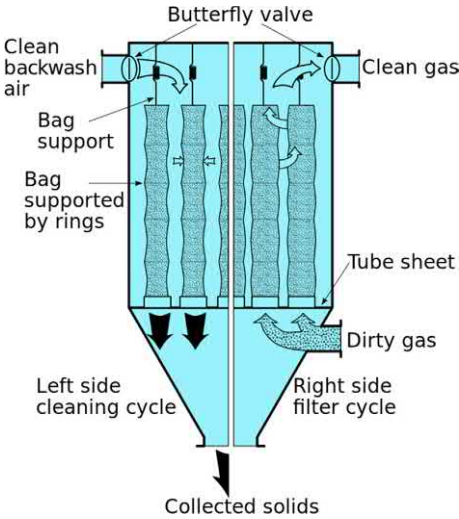


Fig. 12.11 Reverse air flow cleaning method.

12.3.2 In automobiles

High precision woven [14] filter is used for the purpose of filtration in automobile engines. The major work of these fabric filters is to collect big dust particles from the air in order to avoid the blockage of the engine due to the collection of dust over it; also, a series of filter systems are used to protect sensitive components from sudden

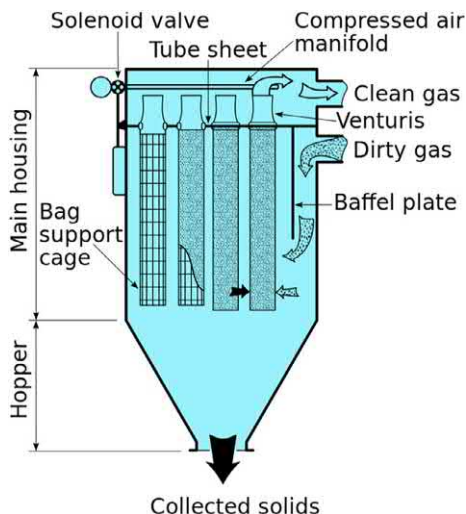


Fig. 12.12 Pulse jet cleaning method.

Courtesy: Gorantek-en – Own work derivative of Mechanical-Shaker Baghouse.png, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=30458370,71,72>.



Fig. 12.13 Woven filter bags.

choke. There are also some needle punched and needle-punched thermo-bonded non-woven as prefilters in the production of antiallergic dust filters for the filtration of air in the car passenger compartments.

12.3.3 In electronic devices

Woven fabric is also used in many electronic devices, such as acoustic devices, loud-speakers, and microphones. The major work of filters in these types of devices is to enhance the sound and speech quality by adsorbing unwanted frequency peaks. They

also protect the sensitive electronic equipment from moisture, dust, and dirt. Centrifugal filter bags are commonly used in electronics for the removal of carbon.

12.3.4 Paper and pulp industries

These industries use liquid filtration technique as they have to deal with chemicals. In the chemical pulping process, the caustic used to dissolve the pulp creates pollution, so it needs to be recovered for environmental and economic betterment [14]. Properly controlling the clarity of the liquor coming out from the units helps the plant to utilize pressure vessel for recausticization. Candle filter bags having different membranes and finishes improve the recausticization process. Dryness of cake is very crucial as it takes a high cost of energy if done in the kiln. Generally, woven polypropylene fabric is used here as it gives even 2% more dryer cake, and its weave design allows quick liquid discharge.

12.3.5 Paint industries

Precipitation of metal oxides from solvent slurries is a typical process involved in pigment processing. The precipitate is then separated from the slurry in a solid/liquid separation. The actual product is the cake left on the filter which is then washed to remove all traces of the solvent. The solvent is expensive, so it is also important that the filtrate be clear for reuse. A recessed chamber filter press is the most common type of liquid separation filter which is mostly fitted with the diaphragm squeeze option. To separate aqueous-based slurries where mother liquor concerns are less, some special pigments like titanium dioxide and kaolin clay is used which utilizes large rotary drum vacuum filters.

12.3.6 In the medical field

Consistent results of pharmaceutical plants require high performance/high efficiency filter media. Pharmaceutical filtration is mostly done in batches. The shape and consistency of the finishes applied to the filter fabrics make the filtration of slurries difficult. Woven PTFE filters with microtek membrane can be used for filtration because of their construction techniques and highly efficient filter media. These are the robust, durable, and extremely efficient filters.

12.3.7 In food industries

12.3.7.1 Flour cleaning

Wheat and corn flour are among the important flours used in food processing industries worldwide. The flour is produced by using the process of milling. Mostly the dry milling process is used. During milling, a fine flour dust is created which is released in the atmospheric air. The cleaning and formulation of flour is done in air streams. The

final product is often collected by filtration of these air streams using some type of air filter. Fabric bag dust collectors and baghouses are used in the process [14].

12.3.7.2 *Brewing*

Filter presses, pressure leaf, and candle filters are used in major breweries to separate wort (vegetable impurities) from mash and to polish finished beer. Tight filtration, high flow rate, and good cake release is the basic requirement for separating wort from mash. Depending upon the fuel source, the filter bags used in the baghouses must be resistant to blinding and high temperatures.

Fabric filter press cloths are mostly used in major breweries and micro-breweries. Sometimes fabric filters are also used in place of candle filters and pressure leaf. Industrial boiler baghouses extensively use woven fibreglass filter bags. An upgraded version of such bags is Mikrotex, which is PTFE membrane laminated onto the woven fibreglass substrate. The membrane increases filtration efficiency by lowering the pressure drop across the filter. The membrane increases the bag life up to 200%.

References

- [1] <http://blog.allaboutfiltration.com/uses-of-filter-fabrics-for-filtration-media>.
- [2] <https://www.textilemates.com>.
- [3] <http://www.filterclothindia.co.in/liquidsolid-separation-2/centrifuge-filter-bags>.
- [4] <https://www.indiamart.com/greenplanet/centrifuge-filter-bag.html>.
- [5] <https://www.indiamart.com/proddetail/fbd-bag-10489868348.html>.
- [6] <http://www.filterclothindia.co.in/drying/fbd-filter-bags>.
- [7] <http://www.theadarshengineering.com/filter-cloth-bags.html>.
- [8] <https://dir.indiamart.com/impcat/nutsche-filter-bag.html>.
- [9] <http://www.ddpsinc.com/blog-0/understanding-the-nutsche-filtration-and-drying-process>.
- [10] <http://mtbfilterindustries.tradeindia.com/etp-filter-press-cloth-849707.html>.
- [11] <http://gkvacbags.com/how-a-vacuum-bag-works/>.
- [12] <https://www.webstaurantstore.com/49727/vacuum-cleaner-bags-and-filters.html>.
- [13] www.globalspec.com/learnmore/manufacturing_process_equipment/air_quality/baghouses.
- [14] <http://www.menardifilters.com>.

Index

Note: Page numbers followed by *f* indicate figures, and *t* indicate tables.

A

Abrasion

- Hook fastner test, 397
- Martindale test, 397
- properties, 31
- resistance, 9, 121
- Taber test, 397

Acetate yarns, 4–5

Acetate lining, 428

Acrylic fibres, 6–7, 10

Active filling tensioners, 211, 211*f*

Active Implantable Medical Devices

- Directive (AIMDD), 442

Acute and chronic wounds

- classification, 443
- management, 443
- medical devices, 442–443
- woven wound bandages, 450–452
- woven wound dressings, 444–449

Adaptable Deployable Entry and Placement

- Technology (ADEPT), 333

Adhesives, 126, 451

Adjustable disc tensioner-type DT, 94

Adjustable waxing device, 108, 109*f*

Air consumption indicator (ACI), 251

Air gripper system (AGS), 254–255

Air-jet looms, 201–203, 202*f*

- air design tank per weaving channel, 228
- AIRMASTER, 231, 232*f*
- air pressure, 229, 229*f*
- ARVD II Plus, 230–231, 231*f*
- auto speed and speed adjustment, 231–232, 232*f*
- dedicated sley cam, 228
- electronic pressure regulators, 229
- filling detector, 233–234, 234*f*
- fixed and movable main channel, 229
- leno fabrics, 257–259, 258–259*f*
- Picanol BlueBox, 228, 228*f*
- Picanol OMNIplus Summum, 227
- PRA II Plus system, 233, 233*f*

robust structure, 228

Sumo main motor, 233, 234*f*

twin stretch nozzle, 230

unique Picanol relay nozzle design, 230, 230*f*

unique triple air tank configuration, 230

Air-jet spun yarns, 22

AIRMASTER, 231, 232*f*

Air splicer, 75

Air-textured yarn, 402–404, 402*f*

Albany Engineered Composites (AEC), 355

Antifrictional bowls, 173–174

Apparel market, 31–33

Arahne, 277

Aramid filaments, 12

Artificial neural network (ANN), 312–315

- applications, 316–317, 317*f*

Artistic design

- vs. engineering design, 295–296, 295*t*
- ‘pencil-paper’ sketching, 296

ARVD II Plus, 230–231, 231*f*

Assembly winding machines, 42*f*, 43

Auto bobbin centring function, 59–60, 61*f*

Autolytic debridement, 443

Automatic brake system (ABS), 253, 256*f*

Automatic defective pick remover (APR-III), 249, 249*f*

Automatic doffer (AD), 63, 65*f*

Automatic insertion system (AIC), 256

Automatic shuttle changing looms, 190–191, 190*f*

Automatic Winder PROCESS CONER II QPRO, 58, 59*f*

Automotive applications

bilaminates, 396

cars, 396

test requirements, for interior fabrics

abrasion, 397

dimensional stability, 399

fabric strength, 399

flammability, 398–399

Automotive applications (*Continued*)

light fastness and degradation, 397–398, 398*f*

pilling, 397

trilaminates, 396

Autotenser, 38, 40*f*

Auxiliary loom mechanisms, 170–171

warp stop motion, 171–172, 171*f*

weft stop motion, 172

Azadirachta indica, 461–464

B

Baghouse, 476–477, 478–479*f*

Bally Ribbon Mills (BRM), 385

Banana fabrics, 14

Bandages, 444

compression properties, 450–451, 450*t*

modern, 450

purposes, 450

spandex, 451

Barrathea fabric, 432

Basalt filament, 12

Beaming off, 86

Beam warping, 84–86

Beat-up, 169, 170*f*

Bedford cord, 434

Bicomponent fibres, 12

Bifurcated woven endovascular prosthesis (BWEP), 454

Bifurcate woven graft, 332, 332*f*

Bioactive-treated fabric (BTF), 464

Bio-debridement, 443

Biodegradable/medical fibres, 13

Biteam, 274–275

Bottom closed shed, 185–187

Brocade, 431

BS3119, 420

C

CAD. *See* Computer-aided design (CAD)

Calico, 429

Cam traversing mechanism, 45, 45*f*

Canvas, 212, 438

Car interiors, 399–400

nylon fabrics, 400

one-way stretch solutions, 407

polyvinyl chloride (PVC), 400

properties, of fibres, 400, 401*t*

stretch, 404–405, 405*f*

two-way stretch solutions, 405–407, 406*t*, 406*f*

yarn development

air-textured yarn, 402, 402*f*

core and effect yarns, 402, 403*f*

false twist yarn, 402, 403*f*

‘fancy’ yarns, 404

flock yarns, 404

polyester, 402

staple spun yarns, 404

Taslan process, 402

Casual wear, 433

Catch cord-less (CCL), 248, 248*f*

Cavalry twill fabric, 433, 434*f*

Cellulose acetate, 4–5

Centre closed shed, 187

Centrifugal bags, 471–473, 472*f*

Ceramic filament, 12

Chemical debridement, 443

Chenille yarns, 404, 410*f*

Chino cotton, 433

ChitoGauze, 446–447

Chitosan treated polyester woven fabric, 461–464, 464*f*

Clearing yarn defects, winding, 36, 37*f*

electronic clearers, 38–41, 41*f*

mechanical clearers, 38, 39–40*f*

Clear shedding, 244–245

Cloqué, 431, 432*f*

CombatGauze, 446–447

Compound Annual Growth Rate (CAGR), 442

Compression, 30

bandages, 451

defined, 30

Computer-aided design and manufacture (CAD/CAM), 296

features

design archive and product data management, 279–280, 279*f*

design transfer, 279

domestic and commercial textiles, 277

heavy industrial/technical textiles, 278–279

future trends, 285–287

issues

communication, 283

costs, 285

design, 283
 expertise and skills, 283–284, 284*t*
 new products/markets, 285–287
 principles, 275–276
 role of, 281–282, 282*f*
 textiles industry and innovation
 scope and size, 273–274
 technical textiles, 274–275
 3D weave, 274–275
 Computer aided tension (CAT), 77, 78*f*
 Computer simulation models, 298–299
 COMSAT sectional warper UNI-EVO,
 109*f*
 automatic beam tension control, 110
 automatic warp section control, 109
 features, 110
 minimum loss of yarns, 110
 optional devices, 110–111, 110*f*
 Conductive Fibre Manufacturing Council
 (CFMC), 346
 Conductive fibres, 346–347
 Conductive tape, 348, 348*f*
 Conductive webbing
 interlinking, 349, 350*f*
 three strands, 352, 352*f*
 Conductive woven fabrics, 33
 Cone and cheese winding machines, 41, 43
 Continuous fibres, 3
 Continuous filament yarns, 6–7, 20, 127
 Contour weaving, 331–332
 Controlled Cut System (CCS), 72–73, 73*f*
 Cooking, 133–134
 Corduroy fabric, 434
 Core spun yarns, 23
 Cotton fibres, 10, 430
 chemical modification, 4
 length, 4
 linear density, 4
 U-shaped cross section, 9
 Cotton/polyester fabric, 433
 Cotton staple, 7
 Crank shedding, 178–179, 179*f*
 Crêpe, 429
 Cylinder drying, 143

D

Damask jacquard fabric, 431
 Denim, 433, 439

Densely woven waterproof breathable fabrics,
 32
 Designbase Victor, 280
 Design engineering
 mathematical modelling, 297–298
 model, 296–297
 nonconventional methods
 expert system (ES), 323–324, 324*f*
 knowledge-based systems, 323
 restrictions, 293–294
 scientific methods, 297–298
 textile products, 295–296, 295*t*
 theoretical modelling, 297
 traditional designing method, 294–295,
 294*f*
 structural mechanics approach, 295
 Deterministic models, 298–299
 empirical modelling, 311
 finite element modelling (FEM), 311–312
 geometrical model, 299–310
 mathematical models, 310–311
 Dimethylol-5,5-dimethylhydantoin
 (DMDMH), 460, 460*t*
 DIN 53906, 420
 Direct warping, 104
 beam warping, 84–86
 developments, 111*f*
 consistent optimal yarn
 arrangement, 112, 112*f*
 indirect pressure, active kickback,
 112–113, 112*f*
 full beam taken out and new one
 put in, 82–83, 84*f*
 head stock, 81, 82*f*
 sizing, 81
 V-shaped expandable comb, 82–83, 83*f*
 warper's beams, 83, 85*f*
 warping creel, 81, 82*f*
 weaver's beam, 82
 Discontinuous fibres, 3, 20–21
 Dobby looms, 423
 Dobby shedding, 179–180, 180–182*f*
 Dobby wovens, 413
 Doffing, 50
 Dornier air-jet loom
 application spectrum, 235
 complex yarns, 238
 developments, 242–244
 DORNIER Ergo Weave, 239

Dornier air-jet loom (*Continued*)

- Dornier MotoEco, 241, 242*f*
- DORNIER PIC, 235–236, 236*f*
- DORNIER ServoControl-2, 236, 237*f*
- dynamic warp guide (DWG) unit, 241, 241*f*
- efficient, 236, 237*f*
 - nozzle and valve technology, 238
- gentle filling yarn handling, 238
- new temple profile, 242, 243*f*
- performance boosters, 238
- robust construction, 239
- simple fabric width changes, 238
- slim throughlight sensor (STS), 239, 239*f*
- solid reed drive, 239
- sturdy basic framework, 241
- USB and ethernet interface, 240–241, 240*f*
- valve technology, 236–238
- DORNIER Ergo Weave, 239
- Dornier MotoEco, 241, 242*f*
- DORNIER PIC, 235–236, 236*f*
- Dornier rapier weaving machine
 - DORNIER-specific filling insertion system, 218–219, 219*f*
 - electronic selector motor (ECS), 221, 221*f*
 - open reed weave (ORW) technology, 222–223, 224*f*
 - precision control transfer, 220, 220*f*
 - unique torsion-free double filling insertion, 223, 225*f*
 - weft yarn tension level, 221–222, 223*f*
 - wide application yarn range, 219, 220*f*
- DORNIER ServoControl-2, 235–236, 237*f*
- DORNIER SyncroDrive, 235
- Double cylinder double-lift jacquard, 184–185, 185–186*f*
- Double rigid rapier looms, 194
- Drawing-in, 167
- Drawn filament yarn, 5
- Dressings. *See* Woven wound dressings
- Drill fabric, 433
- Drop box looms, 191, 191*t*, 191*f*
- Drum winding machines, 42–44, 44*f*
 - cam traversing mechanism, 45
- Dry-spun acrylic fibres, 6
- Duchesse satin, 429
- Duplicate creel, 91
- Dyneema, 12–13, 332

E

- Eco-Drum-Drive-System, 68
- Eco-friendly, 13–14, 424–425
- Efficiency resource planning (ERP), 280
- Elastic webbing, 352, 353*f*
- Electrically conductive pattern, 347–348
- Electro-conductive fibres, 13
- Electronic clearers, 38–41, 41*f*
- Electronic data interchange (EDI), 276
- Electronic filling tensioner (EFT), 217, 217*f*
- Electronic right hand gripper opener (ERGO), 211, 212*f*
- Electronic selector motor (ECS), 221, 221*f*
- Electronic selvage system (ELSY), 213, 215*f*
- Electronic textiles (E-textiles), 33
 - applications, 345
 - conductive fibres and yarns, 346–347
 - defined, 345
 - electrical conductivity, 345–346
 - electrically conductive pattern, 347–348
 - sensors, 345
 - tapes, 348–353, 348*f*
 - 3D preforms, 348–353
 - webbings, 348–353, 349*f*
- Electrostatic splicing, 55–56
- Empirical modelling
 - coefficient of multiple determination, 311
 - limitations, 311
- Enterprise resource planning (ERP), 276
- Erectile dysfunction (ED), 332
- Error
 - defined, 320–321
 - random, 320–321
 - systematic, 320–321
- Escherichia coli*, 446–447
- E-textile antenna, 349, 350–351*f*
- European wound care market, 442
- Expert system (ES)
 - components, 323–324
 - performance, 324
 - structure, 323–324, 324*f*

F

- Fabric constructions/finishing processes
 - cloth and yarn structures, 407–414, 408*t*
 - dobby wovens, 413
 - jacquard flat woven cloths, 412–413

- preferred yarn and fibre types, 408–411, 410*f*
- woven fabric structures, 411, 412*f*
- yarn and fabric colouration, 413–414
- finishing processes
 - automotive trilaminate fabric, 415, 416*f*
 - flame retardancy (FR), 415
 - knife over air foam coating, 415, 415*f*
- Fabric parameters, 25, 130, 299
- Fabric properties, 25, 29, 299, 426
- Fabric specification, 458*t*
 - product lifecycle management (PLM), 425
 - selection, 425
 - weave properties and characteristics, 426
- Fabric types, 397, 423
- Factory management system (FACT), 257
- False twist yarn, 402, 403*f*
- Fancy yarns, 23–24, 404
- FEM. *See* Finite element modelling (FEM)
- Fibre-optic tape, 349, 349*f*
- Fibres
 - characteristics, 7
 - comparative properties, 10, 10*t*
 - continuous, 3
 - cotton, 4
 - crimp, 9
 - cross section, 9
 - discontinuous, 3
 - flexibility and fineness, 9
 - length, 8
 - linear density, 9
 - moisture regain for, 7, 8*t*
 - natural (*see* Natural fibres)
 - new types, 11–14
 - properties, 31–33
 - abrasion, 31
 - comfort, 31
 - compression, 30
 - creasing, 29–30
 - shear behaviour, 30
 - wrinkling, 29–30
 - rigidity and cohesion, 9
 - tenacity/elongation for, 7, 8*t*
 - torsional resistance, 9
 - uniformity, 9
- Fibre tows, 329
- Filament sizing machine TSE30F, 159*f*
 - advanced roll structure, 162, 162*f*
 - automatic size supply, 164
 - beam cooling device, 161, 161*f*
 - flocked roll, 163, 163*f*
 - fluorine resin-coated tension roll, 164
 - gas burner-type drying chamber, 163, 163*f*
 - humidifying system, 162, 162*f*
 - low tension control, 161, 161*f*
 - multi-point taper control, 164
 - multisection drive system, 159–160, 160*f*
 - size level control, 164
 - size pump inverter, 164
 - stretch/tension control changeable device, 164
 - supply stand
 - pulling-out direction switchable function, 165
 - stable tension control, 165, 165*f*
 - tension setting and control, 165
 - uniform squeeze, 160, 160*f*
 - yarn speed, 164
- Filament yarns, 19–20, 127, 159–160
- FILGARD, 98–99, 101*f*
- Fillets (noodles)
 - carbon bifurcate fillet, 340, 341*f*
 - carbon fillet, 340, 341*f*
 - solid model of a fillet, 340, 341*f*
- Fill fibres, 329, 342, 359, 381
- Filling, 167
- Filter fabrics, 305
 - centrifugal bags, 471–473, 472*f*
 - ETP panel filters, 476, 477*f*
 - fluid bed dryer (FBD) bags, 473, 474–475*f*
 - forms, 471, 472*f*
 - nutsche filter bags, 473–474, 475*f*
 - structures, 471, 472*f*
 - vacuum filter bags, 475–476, 476*f*
- Filtration, 379–380
 - filter fabrics, 471–476
 - industries
 - automobiles, 478–479
 - baghouse, 476–477, 478–479*f*
 - electronic devices, 479–480
 - food industries, 480–481
 - medical field, 480
 - paint industries, 480
 - paper and pulp industries, 480
- Fine-denier filaments, 6–7
- Finite element modelling (FEM)
 - application, 311
 - compressional behaviour, 312

Fisherman's knot, 52–53
 Fixed creel inside (FCI), 90
 Fixed creel outside (FCO), 90
 Flame retardancy (FR), 415
 Flammability test, 398–399
 Flannel, 432
 Flannelette, 429
 Flat filament yarns, 20
 Flat rectangular filaments, 5–6
 Flax yarns, 119
 Flexible insertion system (FIS), 256
 Flexible rapier looms, 194, 194–195*f*
 Flock yarns, 404, 410*f*
 Fluid bed dryer (FBD) bags, 474*f*
 features, 473
 machine, 473, 474*f*
 working position, 473, 475*f*
 Foulard, 428
 Free flight system (FF), 210, 211*f*
 Friction spun yarns, 22
 Full-width temples, 172
 Fully automatic winding machines, 52, 53*f*
 Fully orientated yarn (FOY), 407
 Future Launchers Preparatory Program (FLPP), 356
 Fuzzy computing, 312–313
 Fuzzy logic, 319–320
 applications, 314
 crisp set, 313
 membership function, 313
 objective modelling, 314
 subjective modelling, 314

G

Gaberdine, 432, 433*f*
 Gauze, 428
 Genetic algorithms (GAs)
 applications, 319
 issues, 318
 procedure, 318–319
 Geometrical model, 286, 291–292
 applications, 304–305
 fabric design and engineering, 305
 fabric parameters, 299–301
 fabric shape and structure, 305
 jammed fabrics, 299–301, 303*f*
 fabric cover factor and fabric mass, 303–304, 304*f*

 fraction warp-and-weft crimp, 301–302, 302*f*
 warp-and-weft cover factor, 302–303, 303*f*
 warp-and-weft thread spacing, 301–302, 301*f*
 maximum sett, 305
 nonjammed structure, 299–301, 304
 numerical application
 areal density and fabric cover, 308
 fabric thickness, 306–307
 jamming condition, 306
 maximum cover factor, 306–307
 maximum threads density, 305–306
 weavability limit, 305
 thread spacing vs. crimp height, 299–301, 300*f*
 warp-and-weft cover, 299–301
 weavability, 305
 Glass filament, 12
 Gluing, 57
 Glycerine, 128–129
 Good sized yarn, 129
 Goretex fabric, 436
 Grosgrain fabrics, 429, 430*f*
 Guided gripper system, 209, 210*f*
 Guided positive grippers (GPG), 209–210, 210*f*

H

Habutai, 428
 Hank winding machines, 42
 Harris Tweed, 435
 Heald-on-yarn abrasion, 122–123
 Healthcare market, 441–442
 Heat shield for Extreme Entry Environment Technology (HEEET) Program, 333
 Heavy goods vehicles (HGVs), 417
 Hemostasis phase, 443
 High-modulus, high-tenacity (HM-HT)
 fibres, 12–13
 High-tenacity rayons, 4
 Hook fastner test, 397
 Hopsack, 426
 Hospital Acquired Infections (HAIs), 459
 Hot-air drying, 143
 Huckaback cotton wound dressing, 445, 445*t*
 Hybrid modelling, 319–320, 320*f*

I

Image processing analysis, 316
 Indian healthcare market, 441–442
 Indirect/sectional warping, 87–88^f
 beaming off, 86
 conditions, 86
 units, 86
 waxing of warp, 87–88
 Inflammatory phase, 443
 Intelligent textiles, 471
 Interfibre adhesion, 28
 Interlacements, 3, 291, 426, 471
 International Wool Secretariat (IWS), 420
 In Vitro Diagnostics Directive (IVDD), 442
 ISOWARP, 105, 105^f

J

Jacketing fabrics, 432, 433^f
 Jacquard flat woven cloths, 412–413
 Jacquard loom, 423
 Jacquard shedding, 371
 double cylinder double-lift jacquard,
 184–185, 185–186^f
 single cylinder double-lift jacquard, 184,
 184^f
 single cylinder single-lift jacquard,
 181–183, 183^f
 Vaupel weaving, 180–181, 182^f
 JAT810
 air gripper system (AGS), 254–255
 ALPIN, 253, 256^f
 automatic brake system (ABS), 253,
 256^f
 automatic insertion system (AIC), 256
 E-shed, 253
 factory management system (FACT), 257
 flexible insertion system (FIS), 256
 JAT e-REEDs, 253, 255^f
 power consumption, 253, 254^f
 Toyota automatic pick operator (TAPO),
 254, 257^f
 weave assist system (WAS), 257
 JAT e-REEDs, 253, 255^f
 Jute fibre, 9

K

Kapok fabric, 14
 Kevlar, 12–13, 395

Knitting, 41

 genetic algorithms (GAs), 319

Knowledge-based systems, 323

L

Lasertronic Plus sectional warper, 106^f
 adjustable waxing device, 108, 109^f
 kick back feeler roller, for compact beam,
 106, 107^f
 programmable leasing device, 106, 107^f
 reverse drum rotation, 108, 108^f
 section tension control, 106–107, 108^f
 Leno, 428
 Less hairiness, 61, 61^f
 Lightweight fabrics, 428
 6-Link crank shedding, 245, 245^f
 Load-bearing joints
 cruciform structure, 337, 338^f
 double blade joint without tapering, 336,
 338^f
 fillets (noodles), 340
 I-beam structure, 338, 339^f
 intersecting Pi structure, 339–340, 340^f
 Pi structure, 338, 339^f
 single blade joint structure without
 tapering, 336, 337^f
 T-bar profile, 335–336, 337^f
 T structure, 335–336, 336^f
 Loden, 435
 Long staple spinning
 core spun yarns, 23
 fancy yarns, 23–24
 ply yarns, 23
 self-twist spun yarns, 22
 twistless spun yarns, 23
 wrap spun yarns, 22
 Loom connection, 280
 LoomNet Victor, 280
 Lotus fibre, 13–14
 Lubricants, 128–129
 Lutan single-end warping machine, 100–101,
 102^f
 Lycra, 405, 437

M

Machine directional fibres, 329
 Machine intelligence quotient (MIQ),
 324–325

- Madras, 428
 Magazine creel, 91, 91f
 Man-made filaments, 3
 Manual design, 294–295, 294f
 Manual winding machines, 50–51
 Martindale test, 397
 Material design, 296
 Mathematical modelling, 296–297, 310–311
 limitations, 311
 philosophy of, 297–298, 298f
 Maturation phase, 443
 Mechanical clearers, 38, 39–40f
 Mechanical debridement, 443
 Mechanical self-compensating tensioner, 95, 96f
 Mechanical splicing, 55
 Medical applications
 acute and chronic wounds, 442–452
 woven structures, 459–466
 woven vascular prostheses and meshes, 452–459
 Medical Devices Directive (MDD), 442
 Medicines and Healthcare Products Agency (MHRA), 442–443
 MEDWATCH programme, 442–443
 Methicillin susceptible *Staphylococcus aureus* (MRSSA), 459
 Microfibres, 11
 Modelling methodologies
 deterministic models, 298–312
 nondeterministic models, 312–320
 Modified starches, 126
 Moistair splicer, 75
 Moleskin, 433
 Monofilament yarns, 19–20
 MultiJet system, 67, 68f
 Multilayer perceptron (MLP), 315
 Multiphase weaving
 principle, 205–206, 205f
 sheds, 205
 single-phase shuttle-less looms, 205
 Sulzer *Textil* multiphase loom M8300, 206–207, 207f
 Muslin, 428
- N**
- Nanochitosan treated polyester woven fabric, 461–464, 464f
 Nano silver-chitosan treated polyester woven fabric, 461–464, 464f
 National Health Service (NHS), 441–442
 Natural fibres, 409, 421, 429
 physical and mechanical properties, 3
 types of, 3–5
 Natural polymer, 4, 127, 461–464
 NedGraphics, 277, 280
 Negative cam (tappet) shedding, 174–175, 175–177f
 Neural networks (NN)
 actual values, 321–322, 322f
 artificial neural network (ANN), 314–315
 applications, 316–317, 317f
 back propagation algorithm, 315–316
 multilayer perceptron (MLP), 315
 prediction performance, 320–321, 321t
 types, 315
 ‘90 Degrees fibres’, 329
 Nitanol wires, 332
 Noncrimp fabric (NCF), 364–365
 Nondeterministic models, 298–299
 artificial neural network (ANN), 312–313, 315
 fuzzy computing, 312–313
 fuzzy logic
 applications, 314
 crisp set, 313
 membership function, 313
 objective modelling, 314
 subjective modelling, 314
 genetic algorithms (GAs), 317–319
 hybrid modelling, 319–320, 320f
 neural networks (NN), 314–317
 Nutsche filter bags, 473–474, 475f
 Nylon fibres, 5–6, 400
- O**
- Octalobal yarns, 5–6
 Open reed weave (ORW) technology, 222–223, 224f
 Open shed, 187
 OptiLeno, 212, 213f
 Organza fabric, 428
 Orion multipurpose crew vehicle, 333, 334f
 Outlet guide vane (OGV), 355, 356f
 Oxford, 428

P

Package doffing, 70, 71*f*
 Packing coefficient, 17–18, 18*t*
 Partially orientated yarn (POY), 407
 PBT. *See* Polybutylene terephthalate (PBT)
 PC Bal-Con, 58, 60*f*
 Peirce model, of plain weave, 291–292, 292*f*
 ‘Pencil-paper’ sketching, 296
 Percalé, 430
 Perfect Length counter, 62, 63*f*
 PET. *See* Polyethylene terephthalate (PET)
 Picanol BlueBox, 227–228, 228*f*
 Picanol OMNIplus Summum, 227
 Picanol rapier loom OptiMax-*i*, 209
 guided positive grippers (GPG), 209–210, 210*f*
 Picking, 169
 Picking shaft, 192–193
 Picking-tappet, 192–193
 Pile woven fabrics, 423
 Pilling, 397
 Pirn changing automatic loom, 188–190, 188–189*f*
 Plain nonautomatic shuttle loom, 188, 188*f*
 Ply yarns, 23
 Pneumatic splicing, 54
 Polyacrylic acid, 128
 Polyamides, 6, 127
 Polybutylene terephthalate (PBT), 11, 405–407
 Polyester, 5–6, 127, 332
 properties, 402
 Polyethylene terephthalate (PET), 5, 12, 452
 Polylactic acid fibre (PLA), 13
 Polynosic rayon fibres, 4
 Polypropylene, 7
 Poly-tetra-fluoro-ethylene (PTFE), 332
 Polytrimethylene terephthalate (PTT), 11
 Polyvinyl alcohol (PVA), 126, 128
 Polyvinyl chloride (PVC), 210
 stickiness, 400
 Poplin, 430
 Positive cam (tappet) shedding, 176–178, 178*f*
 PRA II Plus system, 233, 233*f*
 Precision winding machines, 45–46, 45–46*f*
 Predictive modelling methodologies, 297
 Premier Vision, 436

Prewet sizing, 157, 158*f*
 Primary loom mechanisms
 beat-up, 169, 170*f*
 picking, 169
 shedding, 169
 Production planning and control (PPC), 280
 Product lifecycle management (PLM), 280, 425
 Programmable leasing device, 106, 107*f*
 Programmable speed control (PSC), 248, 249*f*
 Projectile looms
 advantage, 196
 picking mechanism, 197, 198*f*
 Sulzer package and gripper, 196–197, 197*f*
 weft insertion system, 197, 199–200*f*
 stages, 198–200
 Proliferation period, 443
 Propagation network (BPN), 316
 PROWARP, 104*f*, 105

Q

Quick dry cotton fabrics, 436

R

Radial basis function neural network (RBFN), 316
 Random error, 320–321
 Rapier looms, 330
 active filling tensioners, 211, 211*f*
 double rapier, 193
 double rigid rapier looms, 194
 electronic filling tensioner (EFT), 217, 217*f*
 electronic right hand gripper opener (ERGO), 211, 212*f*
 electronic selvedge system (ELSY), 213, 215*f*
 electronic setting of shed crossing (AKM), 215–216, 216*f*
 flexible rapier looms, 194, 194–195*f*
 free flight system (FF), 210, 211*f*
 guided gripper system, 209, 210*f*
 OptiLeno, 212, 213*f*
 optimized harness frames and connections, 215, 216*f*
 Picanol rapier loom OptiMax-*i*, 209
 guided positive grippers (GPG), 209–210, 210*f*
 rigid construction, 212

- Rapier looms (*Continued*)
 shed geometry, 214
 single rapier, 193
 SmartCut, 217, 218*f*
 tuckers, 213, 214*f*
 width adjustment, 213, 214*f*
- Rayons, 335
 cross-sectional shapes, 4
 high-tenacity, 4
 polynosic, 4
- Reed-on-yarn abrasion, 121, 123*f*
- Regenerated fibres
 acetate, 4
 rayon, 4
- Regenerated polymer, 127
- Removable bobbin trucks (RT), 92, 92*f*
- Resilient back propagation (RBP), 316–317
- Resin transfer moulding (RTM), 355
- Reverse engineering, 322
- Ring spun yarns, 21
- Ring temples, 172
- Rotary creel VMI 801, 103, 103*f*
- Rotor spun yarns, 21
- Rubber temples, 172
- S**
- Sateen, 429
- Satin, 429
- SAURER Autoconer 6
 eco-drum-drive system, 67
 maximum productive capacity, 68, 69*f*
 MultiJet system, 67, 68*f*
 new yarn tension control, 68–69, 69*f*
 package doffing, 70, 71*f*
 Speedster FX, 69–70, 70*f*
 yarn pick-up, new suction tube, 67, 68*f*
- Savio automatic winder Eco PulsarS, 72*f*
 computer aided tension (CAT), 77, 78*f*
 Controlled Cut System (CCS), 72–73, 73*f*
 end finder station, 77–78
 new tensioning system, 73–74, 74*f*
 Savio identification system (SIS), 78
 Suction on Demand System (SDS)
 energy saving, 76, 76*f*
 smart and flexible cycle, 76, 77*f*
 up graded splicing solutions, 75, 75*f*
- Savio identification system (SIS), 78
- Scientific methods, 297–298
- ScotWeave, 277
- Secondary loom mechanisms
 let-off, 170
 take-up, 170
- Sectional warping machines
 ISOWARP, 105, 105*f*
 PROWARP, 104*f*, 105
- Seersucker fabrics, 430, 431*f*
- Self-compensating tensioner-type data
 terminal ready, 94, 95*f*
- Self-twist spun yarns, 22
- Semiautomatic winding machines, 52
- Semiopen shed, 187–188
- Serge, 432
- Sharp-edged filaments, 5–6
- Shed, 187*f*, 205
 bottom closed shed, 185–187
 centre closed shed, 187
 open shed, 187
 semiopen shed, 187–188
- Shedding mechanism, 169
 characteristics, 173–174, 174*t*
 crank, 178–179
 dobby, 179–180, 180–182*f*
 jacquard shedding, 180–185
 negative cam (tappet), 174–175, 175–177*f*
 positive cam (tappet), 176–178
- Short staple spinning
 air-jet spun yarns, 22
 friction spun yarns, 22
 ring spun yarns, 21
 rotor spun yarns, 21
- Shuttle box, 192
- Shuttle-less weaving machines, 207–208
- Silk fibres, 4
- Singed unsized yarn, 123–125, 125*f*
- Single cylinder double-lift jacquard, 184, 184*f*
- Single cylinder single-lift jacquard, 181–183, 183*f*
- Single-end creel, 89
- Single-end warper VMI 601, 102*f*
 rotary creel VMI 801, 103, 103*f*
 stationary creel VMI 701, 103
 technical features, 103*t*
- Single-end warping machines, 99–101, 102*f*
- Size ingredients, for yarns
 lubricants, 128–129
 modified starches, 126
 polyacrylic acid, 128

- polyvinyl alcohol (PVA), 128
- size materials, Size materials for, 127, 128*t*
- sodium carboxymethyl cellulose (SCMC), 127–128
- softeners, 128–129
- starch adhesives, 126
- thin boiling starches, 126–127
- Sizing (slashing), 81
 - adhesion, 131–133, 132*f*, 133*t*
 - cooking, 133–134
 - filament sizing machine TSE30F, 159–165
 - good sized yarn, 129
 - machines, 135*f*
 - automation controls, 146
 - creel section, 134–135, 136–137*f*
 - drying section, 143–144, 144*t*
 - headstock, 145
 - ISOSIZE, 150–151
 - leasing section (splitting), 145
 - PROSIZE, 147–150
 - size box, 135–142, 138*f*, 140–142*f*
 - TTS10S, 151–159
 - process, 125
 - singeing, 123–125, 125*f*
 - single spun yarns
 - factors, 120
 - high tension, 120
 - yarn hairiness, 120, 120*f*
 - size mixtures
 - factors, 129–130
 - quantity, 130–131, 131*f*
 - warp sizing, 146–147
 - weaving trial, unsized warp yarns, 121–123, 122–124*f*
 - yarn stretch, 145–146
- Sizing machine ISOSIZE
 - dryer configurations, 151, 152*f*
 - special size boxes, 151, 151*f*
- Sizing machine PROSIZE, 148*f*
 - ergonomics layout, 150
 - size circulation system, 148–149, 149*f*
 - VSB and HSB, 147–148, 148–149*f*
 - working range, 150, 150*f*
- Sizing machine TTS10S, 152*f*
 - automatic size viscosity measuring device, 158, 158*f*
 - beam stand, 153
 - dip and twin squeeze, 154–155, 155*f*
 - drying, 154
 - easy access, 153, 153*f*
 - even drying, 156
 - even sizing and perfect fluff lay down, 153, 156
 - multisection drive, 154
 - nip and twin squeeze, 154, 155*f*
 - prewet sizing, 157, 158*f*
 - size concentration, 156, 156*f*
 - SPM size pickup monitor, 156, 157*f*
 - squeeze roll, 157, 157*f*
 - take-up, 154
 - T-MDS machine data station, 159
- Slim throughlight sensor (STS), 239, 239*f*
- Slough suppression, 59, 60*f*
- Slub catcher, 38
- Smart air grid, 252, 252*f*
- SmartCut, 217, 218*f*
- Smart fabric transducers (SFT), 348
- Smart fibres, 13
- Smit Textiles, 223–226, 225*f*
- Snecma (SN), 355
- Sodium carboxymethyl cellulose (SCMC), 127–128
- Soft computing methods, 312–313
- Softeners, 128–129
- Solid panels
 - fifty-millimetre thick 3D orthogonal carbon panel, 333–334, 335*f*
 - fifty-millimetre thick 3D orthogonal pitch panel, 335, 336*f*
 - Orion multipurpose crew vehicle, 333, 334*f*
 - seventy-five-millimetre thick 3D MAT Quartz panel, 333, 334*f*
 - thermal protection systems (TPS), 333
- South India Textile Research Association (SITRA), 454, 454*f*
- Spandex, 332, 451
- Spectra, 12–13, 332
- Speedster FX, 69–70, 70*f*
- Spinner's package, 35
- Splicer, 64, 66*f*
- Split-thickness skin graft (STSG), 446–447
- Sports textiles, 31–33
- Spun yarns, 20–21, 127
- Staphylococcus aureus*, 446–447, 461–464
- Staple spun yarns, 404
- Starches, 119
 - adhesives, 126

Starches (*Continued*)

modified, 126

thin boiling, 126–127

Static electricity, 348

Stationary creel VMI 701, 103

Steel roller temples, 172

Stent, 332, 333*f*

Suction on Demand System (SDS)

energy saving, 76, 76*f*smart and flexible cycle, 76, 77*f*

Suiting fabrics, 431–432

Sulzer *Textil* multiphase loom M8300,
206–207, 207*f*Sumo main motor, 233, 234*f*

Super-bugs, 460–461

Surgical debridement, 443

Surgical Site Infections (SSIs), 459

Swivelling frame creel, 92–93, 93*f*

Synthetic fibres, 9, 127, 347, 439

types of, 5

acrylics, 6–7

polyamides, 6

polyester, 5–6

polypropylene, 7

Synthetic polymer, 19, 127

Synthetic yarns, 127, 428

Systematic error, 320–321

T

Taber test, 397

Taffeta, 426, 429

Take-up tension control system

guide roll system, 117, 117*f*nip tension control system, 116, 116*f*roll tension control system, 116, 116*f*

Tallow, 128–129

Tape yarns, 20

Tappet looms, 423

Taslan process, 402

Technical/high-performance fibres,
12–13

Technical textiles, 274–275

Teflon, 332

Temples

full-width, 172

function, 172

ring, 172

rubber, 172

steel roller, 172

types, 172, 173*f*TENS CONTROL, 38, 40*f*, 43

Tensioning units, of creels

adjustable disc tensioner-type DT, 94

disc tension device, 93–94, 94*f*electronic tension units, 95, 97*f*mechanical self-compensating tensioner,
95, 96*f*self-compensating tensioner-type data
terminal ready, 94, 95*f*Tsudakoma new tensioner device, 96–97,
98*f*

types, 94

TensorFlex, 38, 40*f*

Terry, 430

3Tex, 274–275

TexEng, 278–279

TexGen, 278–279

Textile/Apparel Manufacturing

Communications (TAMCS), 276

Textile-based vascular grafts, 452

Textile industry, 424

Textile products, 295–296, 295*t*Textiles reinforced composite materials
(TRCM), 275

Textronic, 277

Theoretical modelling, 297

Thermal protection systems (TPS), 333

Thermotropic liquid crystalline polymers
(TLCP), 13

Thin boiling starches, 126–127

Thread stop motion, 97–99, 99–101*f*

Three dimensional (3D) fabrics

contour fabric, 330–331, 331*f*

contour weaving, 331–332

tubular fabrics, for medical applications,
332, 332–333*f*Three dimensional (3D) woven fabrics/
structures, 330–332

advantages, 358

applications, 357–358

complex structures

complex woven preform, 355, 357*f*composite ring, 356, 357*f*composite woven engine vane, 355, 356*f*integral multiple T stiffener, 356, 358*f*sine-wave structure, 355, 356*f*

definition, 329–330

- electronic textiles (E-textiles), 345–353
 - hollow structures, 353, 354–355*f*
 - industries, 329
 - load-bearing joints, 335–340
 - manufacturing technologies, 370–386
 - polar structures/spiral/arched structures, 340–344, 342–344*f*
 - solid panels, 333–335
 - 3D weaving calculations, 386–388
 - truss cores, 354, 355*f*
 - weaves, 359–370
 - Toyota automatic pick operator (TAPO), 254, 257*f*
 - Traditional designing method
 - fabric design cycle, 294–295, 294*f*
 - manual design, 294–295, 294*f*
 - structural mechanics approach, 295
 - Transportation market
 - aircraft, 395, 419–420
 - automotive, 395
 - buses and coaches, 395, 417–418
 - heavy goods vehicles (HGVs), 417
 - marine, 395, 420
 - railways, 395, 418–419, 419*f*
 - Trevira CS, 418
 - Triacetate textile fibres, 4–5
 - Triaxial fabrics, 3
 - Trilobal polyester yarns, 5–6
 - Trinca rapier loom, 226, 226*f*
 - Tsudakoma air-jet loom
 - air consumption indicator (ACI), 251
 - auto cruise, 252
 - automatic defective pick remover (APR-III), 249, 249*f*
 - catch cord-less (CCL), 248, 248*f*
 - clear shedding, 244–245
 - direct subnozzle system, 250, 251*f*
 - eight colour weft selection, 246, 247*f*
 - electronic independent selvedge (EIS) motion, 245, 247*f*
 - i-start, 250–251
 - i-Weave, 250
 - i-Weft brake system, 246–248
 - 6-link crank shedding, 245, 245*f*
 - needle-less tuck-in device, 245, 246*f*
 - programmable speed control (PSC), 248, 249*f*
 - reduced floor vibration, 244
 - self-navigation, 251
 - Smart air grid, 252, 252*f*
 - soft weft insertion, 244
 - switchable subnozzle block, 250, 250*f*
 - Tsudakoma loom monitoring (TLM), 252
 - tune navigation, 251
 - Weave Navigation System-II, 251
 - Tsudakoma loom monitoring (TLM), 252
 - Tsudakoma new tensioner device, 96–97, 98*f*
 - Tsudakoma water-jet loom, 260*f*
 - AIHWW free drum pooling device, 264–265
 - electric weft pull-back device, 263, 263*f*
 - electronic let-off (ELO), 267–268
 - electronic take-up (ETU), 267–268
 - exclusive positive cam shedding, 266, 267*f*
 - low warp line, 260, 261*f*
 - offset rocking shaft, 260–263, 262–263*f*
 - Programmable Start System (PSS-W), 259, 268
 - robust frame structure, 260, 261*f*
 - rotary drum pooling (RDP) device, 264, 265*f*
 - rush start motor, 266, 267*f*
 - short stroke beating, 260, 262*f*
 - stationary drum pool (SDP), 264, 265*f*
 - twin pump, 266, 266*f*
 - weft break system (WBS), 264, 264*f*
 - T-Tech, 115*f*
 - fixed-position stop system, fluff, 115, 115*f*
 - take-up tension control system, 115–117
 - Tuckers, 213, 214*f*
 - Tweed, 435, 435*f*
 - TW30F, 114–117
 - Twill weaves, 426
 - Twistless spun yarns, 23
 - Two-phase weaving machines, 194–196, 196*f*
- ## U
- Ultrahigh-molecular weight polyethylene (UHMWPE), 12–13
 - UNI-EVO DIRECT warping machine, 113, 113*f*
 - Untreated polyester woven fabric, 461–464, 464*f*
 - US Health Industry Manufacturers Association (HIMA), 441–442
- ## V
- Vacuum filter bags, 475–476, 476*f*
 - Vascular grafts, 332

- Vectran, 13
 Velvet, 277, 418, 434
 Ventile, 32
- W**
- Warping, 48
 beam inertia compensator, 117
 COMSAT sectional warper UNI-EVO, 108–111
 direct warping, 81–86, 104
 indirect/sectional, 86–88
 Lasertronic Plus sectional warper, 106–108
 sectional warping machines, 104–105
 selvedge warper, 113–114, 114*f*
 single-end warper VMI 601, 102–103
 single-end warping machines, 99–101, 102*f*
 take-up tension indicator, 117
 tension setting and control, 117
 thread stop motion, 97–99, 99–101*f*
 T-Tech, 114–117
 UNI-EVO DIRECT warping machine, 113, 113*f*
- Warping creels, 89–93
 duplicate creel, 91
 fixed frame creels, 90*f*
 design, 89, 90*f*
 fixed creel inside (FCI), 90
 fixed creel outside (FCO), 90
 magazine creel, 91, 91*f*
 removable bobbin trucks (RT), 92, 92*f*
 single-end creel, 89
 swivelling frame creel, 92–93, 93*f*
 tensioning units, 93–97
- Warp sizing, 146–147
- Warp stop motion, 171–172, 171*f*
- Warp yarns, 35, 167, 168*f*, 291, 329
- Water-jet looms, 203
 drawbacks, 203–205
 principles, 203, 204*f*
 weft insertion rates, 203
- Water-soluble ethers, 126
- Waxing, 74, 74*f*
 device, 63, 66*f*
- Weatherometres, 397
- Weave assist system (WAS), 257
- Weave Navigation System-II, 251
- Weaver's beam, 35, 81–83, 85*f*
- Weaver's knot, 52–53
- Weaves, 291, 292*f*
 architecture, 367–368, 367–369*f*
 basic, 359–361, 359–361*f*
 3D weaves
 complex shapes, 366–367, 366*f*
 layers in various locations, complex shapes, 365–366, 366*f*
 layer-to-layer angle interlock weave
 either by warp/filling, 363, 364*f*
 layer-to-layer angle interlock with
 stuffer threads, 364, 365*f*
 layer-to-layer interlock weave based on
 satin weave, 363, 364*f*
 layer-to-layer interlock weaves either by
 warp/filling, 362, 362–363*f*
 layer-to-layer interlock weave with
 Z fibres, 362, 363*f*
 orthogonal weave, 364–365, 365*f*
 properties, 368–370
- Weaving technology, 441
 air-jet looms, 226–234
 leno fabrics, 257–259
 automatic shuttle changing looms, 190–191, 190*f*
 auxiliary loom mechanisms, 170–172
 conventional loom
 fibre damage, 372–378, 372–374*f*
 loom set up, 371–372
 narrow fabric loom, 378–380, 379–380*f*, 379*t*
 Dornier air-jet loom, 235–244
 Dornier rapier weaving machine, 218–223
 drop box looms, 191, 191*t*, 191*f*
 and finishing tensions, 405, 406*t*
 JAT810, 252–257
 maximum loom speeds and weft insertion
 rates, 268–269
 modified loom, 380, 381*f*
 multiphase weaving, 205–207
 pirn changing automatic loom, 188–190, 188–189*f*
 plain nonautomatic shuttle loom, 188, 188*f*
 preparation, 370–371
 primary loom mechanisms, 169
 rapier looms, 209–217
 secondary loom mechanisms, 170
 shed, 185–188
 shedding mechanisms, 173–185
 shuttle-less weaving machines, 207–208

- Smit Textiles, 223–226, 225*f*
- specially built machine, 385–386, 385–386*f*
- temples, 172
- 3D looms, 381–385, 382–384*f*
- Trinca rapier loom, 226, 226*f*
- Tsudakoma air-jet loom, 244–252
- Tsudakoma water-jet loom, 259–268
- weft insertion, shuttle-less looms, 193–205
- weft insertion, shuttle looms
 - overpicking mechanism, 192–193, 192*f*
 - underpicking mechanism, 193
- Weft break system (WBS), 264, 264*f*
- Weft insertion, shuttle-less looms
 - air-jet looms, 201–203, 202*f*
 - projectile looms, 196–199
 - rapier looms, 193–194
 - two-phase weaving machines, 194–196, 196*f*
 - water-jet looms, 203–205
 - weft insertion, jetlooms, 200–201, 201*f*
- Weft insertion, shuttle looms
 - overpicking mechanism, 192–193, 192*f*
 - underpicking mechanism, 193
- Weft stop motion, 172
- Weft thread, 3
- Weft yarns, 35, 119, 167, 291
- Welding, 57
- Winding process, 145, 170
 - assembly winding machines, 43
 - bobbins, 50, 51*f*
 - clearing yarn defects, 36, 37*f*, 38–41
 - cone and cheese winding machines, 43
 - cone types and build, 49–50
 - doffing, 50
 - drum winding machines, 42–44, 44*f*
 - cam traversing mechanism, 45
 - fully automatic winding machines, 52, 53*f*
 - hank winding machines, 42
 - knots, weaving and knitting processes, 52–54, 55*f*
 - manual winding machines, 50–51
 - mechanisms, 43
 - precision winding machines, 45–46, 45–46*f*
 - SAURER Autoconer 6, 67–70
 - Savio automatic winder Eco PulsarS, 70–78
 - semiautomatic winding machines, 52
 - spinner's packages, 36, 37*f*
 - terminology
 - angle of wind, 48
 - close wind, 49
 - open wind, 49
 - overend unwinding, 48, 48*f*
 - patterning (ribboning), 49
 - precision wound package, 47
 - random wound package, 47, 47*f*
 - wind, 47
 - wind ratio, 47
 - yarn preparatory processes, 57–66
 - yarn splicing, 54–57
- WiseTex, 278–279
- Wool staple, 7
- Work wear, 433
- Worsted fabrics, 431
- Wounds
 - classification, 443
 - management, 443
- Woven apparel fabrics, 5
 - application examples
 - Chanel and Linton Tweeds, 438–439
 - denim, 439
 - fabric specification
 - product lifecycle management (PLM), 425
 - selection, 425
 - weave properties and characteristics, 426
 - manufacturing process, 423–424
 - practical design applications
 - pattern, 437
 - Premier Vision, 436
 - stretch, 437
 - support fabrics, 438
 - surface interest–felted appearance, 436–437
 - surface interest–texture, 437
 - tailored garments, 438
 - transparency, 437
 - trends and design, 424–425
 - types of, 427*t*
 - heavy weight, 435–436
 - jacketing fabrics, 432, 433*f*
 - lightweight fabrics, 428
 - medium lightweight, 428–429
 - medium-weight patterned, 430–431
 - medium-weight plain, 429–430, 430–431*f*
 - performance apparel fabrics, 436

- Woven apparel fabrics (*Continued*)
 pile and texture, 434–435
 suiting fabrics, 431–432
 work wear and casual wear, 433
- Woven fabrics, 3, 273, 441, 471
 antimicrobial treated, 461, 462*f*
 automotive applications, 395–399
 car interiors, 399–407
 filtration, 476–481
 formal structure, 291–292
 mechanical properties of, 27–28
 physical properties
 cover, 24–25
 fabric mass, 25
 packing, 26–27
 specific volume, 25
 thickness, 25–26
 types, 167
 untreated, 461, 462*f*
 warp yarns, 291
 weft yarns, 291
- Woven structures, 291–293, 292*f*, 441
 hospitals
 antimicrobial activity, 459–464
 infection control, 459
 medical applications, 465–466, 466*f*
- Woven textile industry. *See* Computer-aided design and manufacture (CAD/CAM)
- Woven vascular prostheses/meshes
 bicomponent vascular fabrics, 456–459
 bifurcated woven endovascular prosthesis (BWEP), 454
 commercial vascular grafts, 452, 453*t*
 Dacron (Du Pont) graft, 453–454
 essential criteria, 453
 Gelweave Valsalva (Vascutek) woven polyester graft, 455, 456*f*
 knitted prostheses, 454–455
 polyethylene terephthalate (PET), 452
 South India Textile Research Association (SITRA), 454, 454*f*
 woven and knitted grafts, merits and demerits, 455–456, 457*t*
- Woven wound bandages, 450–452, 450*t*
- Woven wound dressings
 bandage, 444
 commercial gauze dressings, 446–447, 447–448*t*
 applications, 447–448, 448–449*t*
 concept, 447–448, 449*f*
 cotton gauze, 444
 absorbency, 445, 446*t*
 dry gauze dressings, 444
 gauze dressing, 444
 huckaback cotton wound dressing, 445, 445*t*
 moist gauze dressings, 444
 requirements, 446
 split-thickness skin graft (STSG), 446–447
- Wrapping, 9, 57
- Wrap spun yarns, 22
- X**
- X direction fibres, 329
- Y**
- Yarn clearing, 36
- Yarn hairiness, 120, 120*f*, 123
 and weavability, 123–125
- Yarn-on-yarn abrasion, 121–122, 125
- Yarn preparation, 370
 looms, 35, 36*f*
 sizing (*see* Sizing (slashing))
 spinner's package, 35
 warping (*see* Warping)
 warp yarn, 35
 weaver's beam, 35
 weft yarn, 35
 winding (*see* Winding process)
- Yarn preparatory processes, 57–58
 auto bobbin centring function, 59–60, 61*f*
 automatic doffer (AD), 63, 65*f*
 Automatic Winder PROCESS CONER II QPRO, 58, 59*f*
 clear package, 62, 62*f*
 less hairiness, 61, 61*f*
 multigrooved drum, 64–66, 67*f*
 PC Bal-Con, 58, 60*f*
 Perfect Length counter, 62, 63*f*
 power saving design, 63, 64*f*
 slough suppression, 59, 60*f*
 smart guide panel, 63, 65*f*
 splicer, 64, 66*f*
 stable winding, high speed, 58
 waxing device, 63, 66*f*

Yarns. See also *specific types*

acetate, 4–5

car interiors

air-textured yarn, 402, 402*f*core and effect yarns, 402, 403*f*false twist yarn, 402, 403*f*

‘fancy’ yarns, 404

flock yarns, 404

polyester, 402

staple spun yarns, 404

Taslan process, 402

and fabric colouration, 413–414

fibres, 3

filaments, 3

properties

characterization, 14, 14*t*

diameter, 16–17

linear density, 14–16, 15*t*packing, 17–18, 18*t*twist, 18–19, 19*t*

size ingredients, 126–129

types, 19–21, 20*t***Yarn splicing**

applications, 57

electrostatic, 55–56

gluing, 57

mechanical, 55

pneumatic, 54

techniques, 54, 56*f*

welding, 57

wrapping, 57

Yarn stretch, 95, 145–146, 437

Yarn tension, 38, 68–69, 73–74, 164

Y direction fibres, 329**Z**

ZAX9200i, 246

‘0 Degree’, 329

Woven Textiles

Principles, Technologies and Applications

Second Edition

Edited by Kim Gandhi

Woven Textiles: Principles, Technologies, and Applications, Second Edition is an essential guide to woven textiles. Traditionally used in apparel and interior fabrics, woven textiles have increasingly been employed in a variety of technical applications. This new edition is updated and expanded to include major new application areas, as well as the latest developments and innovations in terms of fibres, yarns, fabrics, machinery, and technology.

The first part of the book introduces fibres and yarns used for weaving, and then explores key preparatory techniques and the fundamentals of weaving technology. The characteristics of woven structures are then discussed in greater depth in part two, alongside investigation into the use of computer-assisted design (CAD) systems, techniques for modelling the structure of woven fabrics, and methods for the manufacture of three-dimensional (3D) woven structures. Part three focuses on the application of woven textiles in a wide range of technologies, including in automotive interiors and other transport applications, woven apparel fabrics, geotextiles, hollow woven fabrics, medical applications, sports and leisure, floor coverings and carpets, filtration, and composite structures.

This book is an invaluable companion for designers, engineers, and technicians involved in the design, manufacture and use of woven textiles and garments, and academics and researchers in textiles.

- Provides an extensive coverage of woven textiles, including preparation, manufacture, woven structures, and characteristics.
- Presents the latest technical applications of woven textiles, such as transportation, geotextiles, medical applications, sports and leisure, filtration, and composite structures.
- Enables the reader to understand the latest technological advances in the area of woven textiles.

Dr. Kim Gandhi is a chartered consultant based in the United Kingdom. He is a fellow of The Textile Institute (FTI), the Royal Society of Arts (FRSA), and the Textile Association of India (FTA). With 45 years of experience in textiles, he has an international reputation for his expertise in weaving technology. Dr. Gandhi currently runs a textile services company in Manchester, and conducts tailor-made courses for industry or institutions, in the areas of weaving, yarn preparation, woven structures / textile design, spinning, fibres, and fabric properties.

Related titles

Handbook of Sustainable Textile Production, Tobler-Rohr, 2011, 9780857091369, Woodhead



VP

JODHEAD
BLISHING

imprint of Elsevier • elsevier.com



ISBN 978-0-08-102497-3



9 780081 024973