1
Introduction to three-dimensional fibrous assemblies

Abstract: Three-dimensional (3-D) textiles are those materials that have a system or systems in all three axes of plane. These materials offer particular properties, such as interlaminar shearing force, mechanical and thermal stability along all three axes of space, that are not achievable with other reinforcements. The development of three-dimensional textiles has taken place rapidly over the past two decades. It can be credited largely to the growth of another technology: composite materials, which combine fibres and a matrix. An understanding of the production methods and structures of these 3-D fibrous assemblies would go a long way in design, process control, process optimization, quality control, clothing manufacture and development of new techniques for specific end uses. This chapter introduces various 3-D woven, knitted, non-woven, braided and stitched fabrics with their brief description and advantages.

Key words: three-dimensional (3-D) textiles, 3-D woven fabrics, 3-D knitted fabrics, 3-D non-woven fabrics, 3-D braided fabrics.

1.1 Introduction: concepts of three-dimensional fibrous assemblies

Textile structures such as in woven, knitted, non-woven and braided fabrics are being widely used in advanced structures in the aerospace, automobile, geotechnical and marine industries. In addition, they are finding wide application as medical implants such as scaffolds, artificial arteries, nerve conduits, heart valves, bones, sutures, etc. This is because they possess outstanding physical, thermal and favourable mechanical properties, particularly light weight, high stiffness and strength, good fatigue resistance, excellent corrosion resistance and dimensional stability. In addition, they act as attractive reinforcing materials in various composite applications with low fabrication cost and easy handling (Tan *et al.*, 1997). With high-end applications such as in aerospace, the orientation of the fibrous reinforcement is becoming more and more important from a load-bearing point of view, as is the need for placing the reinforcement oriented in the third dimension (Alagirusamy *et al.*, 2006).

Textile fabrics, termed preforms in composites and other applications, consist of various reinforcing fabrics such as wovens, knits, braids and non-wovens. Two-dimensional fabrics have allowed us to drape bed, board and body in a profusion of texture, pattern and colour over the centuries. The development of advanced fibres has led engineers to consider textiles for high-performance applications such as in construction and aeronautics. These fabrics have been relatively well developed in terms of production, analysis and application and some of them have long been used in structural composite fields (Chou and Ko, 1989; Mohamed, 1990). However, the strength of these traditional fabrics is anisotropic, manifesting itself primarily in the direction of the fibre orientations. Most of these 2-D textile structures retain the inherent weakness of laminated composites that are susceptible to delamination.

To extend the use and value of textiles into industrial and engineering applications, which typically require strength in more than two directions, textile designers have bound together layers of textiles and exploited the chemical properties of fibres and binders to create novel non-woven textiles whose fibres are not restricted to two-dimensional arrangements. More recently, they have taken the next step: finding ways to manufacture true three-dimensional (3-D) textiles. Hence, 3-D fabrics have been introduced to respond to the needs of a number of industrial requirements such as composites capable of withstanding multidirectional stresses.

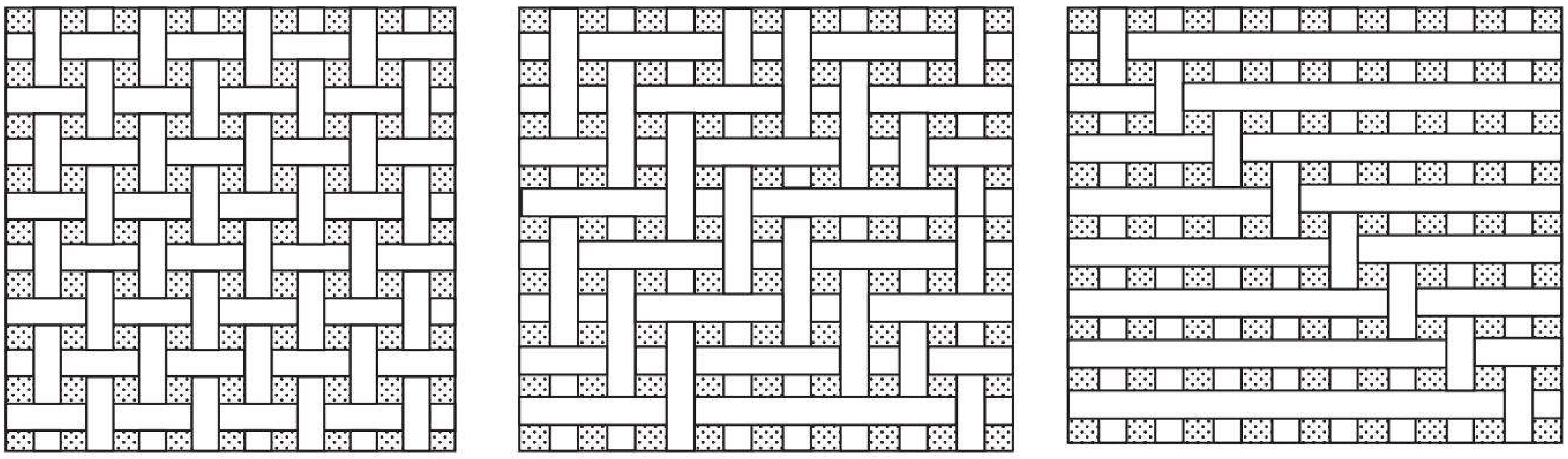
The development of 3-D textiles has taken place rapidly over the past two decades. It can be credited largely to the growth of another technology: composite materials, which combine fibres and a matrix. Textile engineers have been challenged to develop strong fibre architectures and new manufacturing processes for building textile structures in three dimensions, as these 3-D fabrics hold great promise for use in industry, construction, transportation and even military and space applications. They are often made into a near net shape so that the overall manufacturing cost can be very low for certain applications (Mohamed, 1990).

An understanding of the production methods and structures of these 3-D fibrous assemblies would go a long way in the design, process control, process optimization, quality control, clothing fabrication and the development of new techniques for specific end uses. The interrelationship between their structure and various properties may be of great help in designing new types of 3-D structures for the construction, medical, sports and aerospace industries.

1.2 Two-dimensional structures (two-dimensional fabrics)

1.2.1 Two-dimensional wovens

Weaving is the most widely used textile manufacturing technique and accounts for the majority of the two-dimensional (2-D) fabric produced

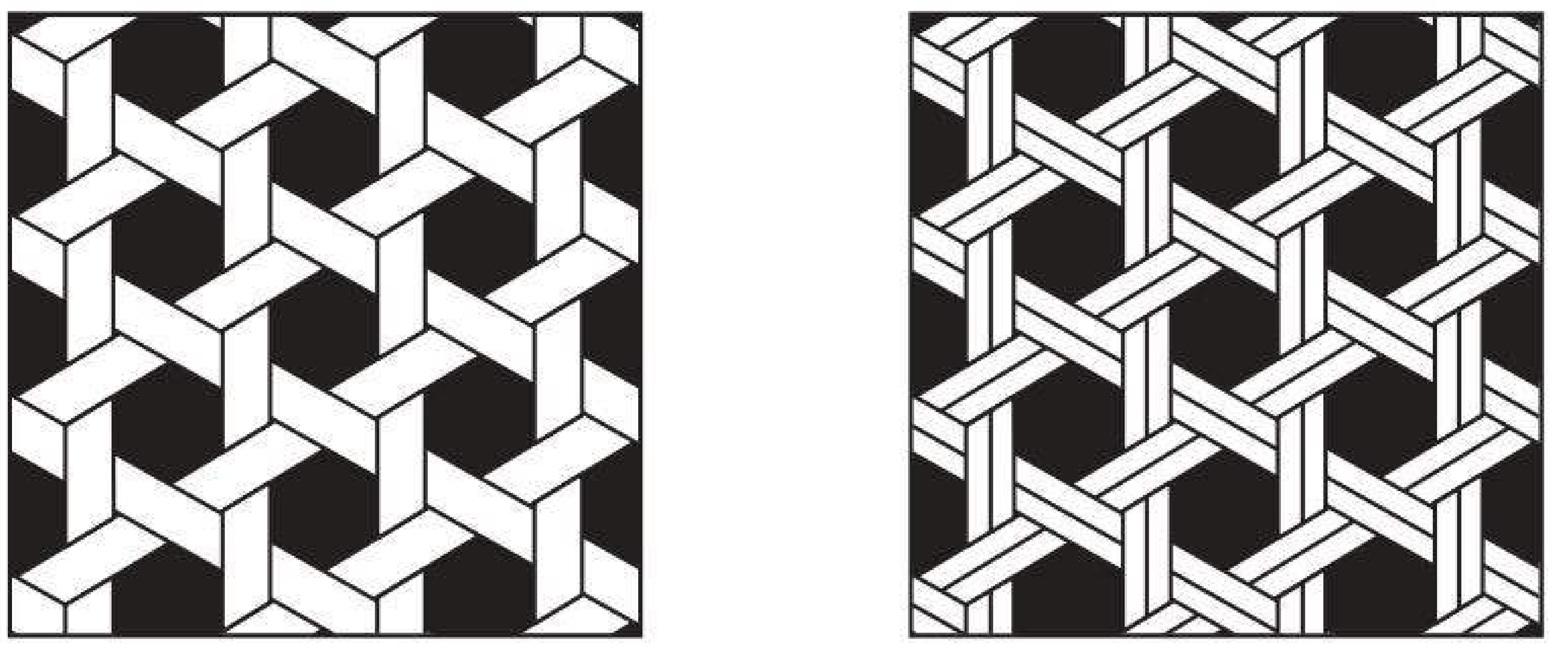

(a) Plain weave (b) Twill weave (c) 8-end satin weave

1.1 Basic weaves.

(Stobbe and Mohamed, 2003). Woven structures have the greatest history of application in textile manufacturing. Conventional woven fabrics consist of two sets of yarns mutually interlaced into a textile fabric structure. The threads that run along the length of the fabric are called warp or ends, while the threads that run along the width of the fabric from selvedge to selvedge are referred to as weft or picks. Warp and weft yarns are mutually positioned at an angle of 90°. The number of warp and weft yarns per unit length is called the warp and weft density. The warp and weft yarns in a woven fabric can be interlaced in various ways, called a weave structure. The structure in which warp yarns alternately lift and go over across one weft yarn and vice versa is the simplest woven structure, called plain weave (Fig. 1.1(a)). Other common structures are twill and satin weave. Twill is a weave that produces diagonal lines on the face of a fabric (Fig. 1.1(b)). The direction of the diagonal lines viewed along the warp direction can be from upwards to the right or to the left, making Z or S twill respectively. Compared to plain weave of the same cloth parameters, twills have longer floats, fewer intersections and a more open construction. A weave in which the binding places are arranged to produce a smooth fabric surface free from twill lines is called satin (Fig. 1.1(c)). The distribution of interlacing points must be as random as possible to avoid twill lines. The smallest repeat of satin weave is 5, while the most popular weaves are satins of 5 and 8 repeats. The 5-ends satin is most frequently used for technical applications for providing firm fabric, although having a moderate cover factor.

Triaxial woven fabrics

A triaxial woven structure consists of three systems of threads: one system for weft and two systems for warp. This fabric has three layers of material at any point, and is thus stronger than a rectangular woven fabric made using the same elements. Warp threads in a basic triaxial fabric are interlaced at 60° and the structure is fairly open with a diamond-shaped centre (Fig. 1.2(a)). A modification of basic triaxial fabric is basket weave, which forms a closer structure with different characteristics (Fig. 1.2(b)).



(a) Basic triaxial weave (b) Basket weave

1.2 Triaxial fabrics.

Triaxial fabrics possess exceptional mechanical properties in several directions. Since the interlacing points are fixed into the fabric structure, these fabrics exhibit high shear resistance (Lee *et al.*, 2002).

1.2.2 Two-dimensional knits

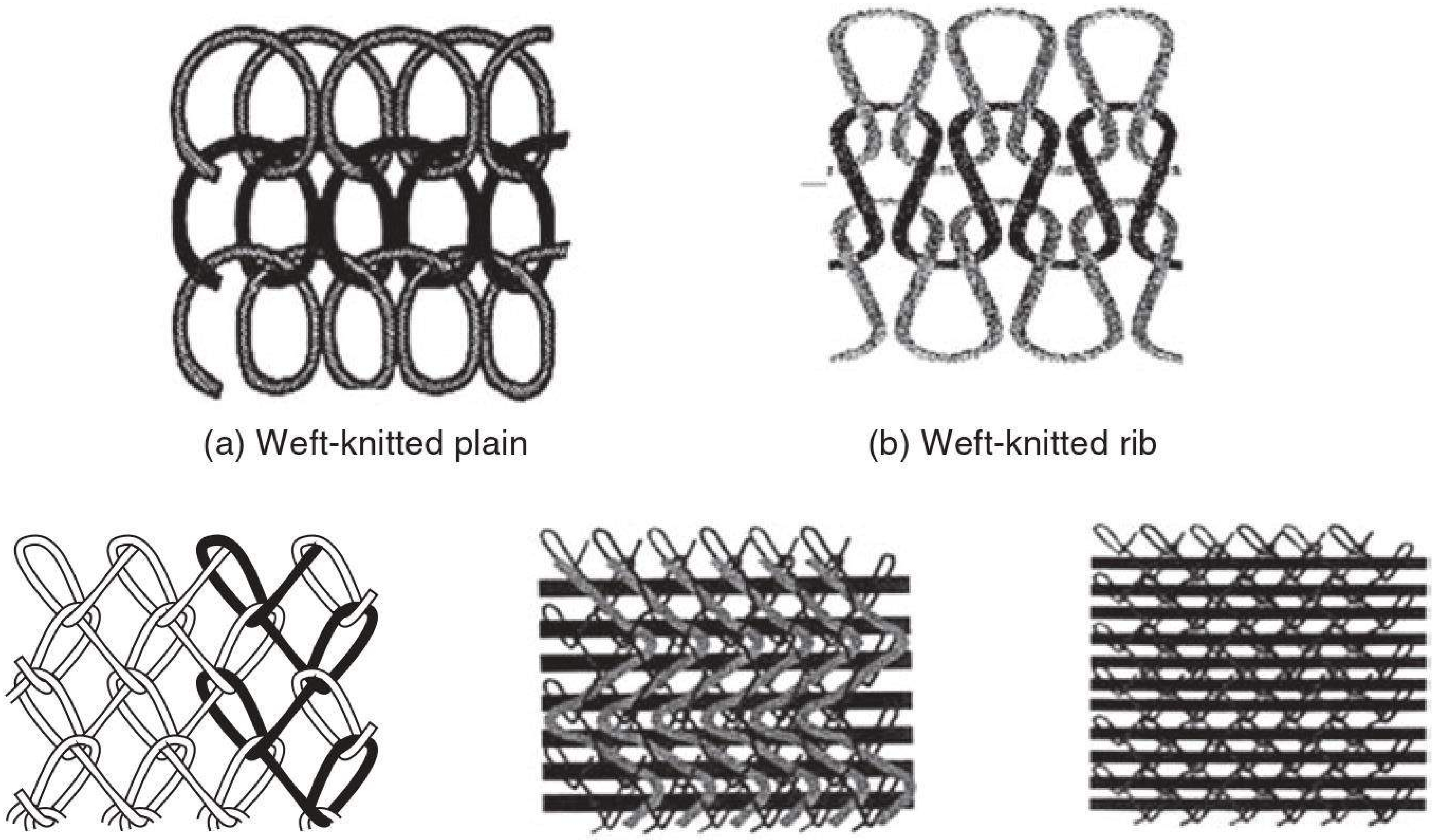
Knitted fabrics are textile structures assembled from basic construction units called loops. There exist two basic technologies for manufacturing knitted structures: weft and warp-knitted technology.

Weft-knitted fabric

The repeating unit of the knitted fabric is called the loop. The feature of weft-knitted fabric is that the loops of one row of fabric are formed from the same yarn. A horizontal row of loops in a knitted fabric is called a course, and a vertical row of loops is called a wale. In weft-knitted fabrics the loops are formed successively along the fabric width. The feature of weft-knitted fabric is that the neighbouring loops of one course are created of the same yarn. The simplest weft knit structure produced by the needles of one needle-bed machine is called plain knit or jersey knit (Fig. 1.3(a)). Plain knit has a different appearance on each side of the fabric. A structure produced by the needles of both needle beds is called a rib structure or double jersey (Fig. 1.3(b)) and has the same appearance on both sides of the fabric.

Warp-knitted fabric

In warp-knitted technology every loop in the fabric structure is formed from a separate yarn called the warp, introduced mainly in the longitudinal fabric direction. The most characteristic feature of warp-knitted fabric (Fig. 1.3(c)) is that neighbouring loops of one course are not created from



(a) Weft-knitted plain (b) Weft-knitted rib

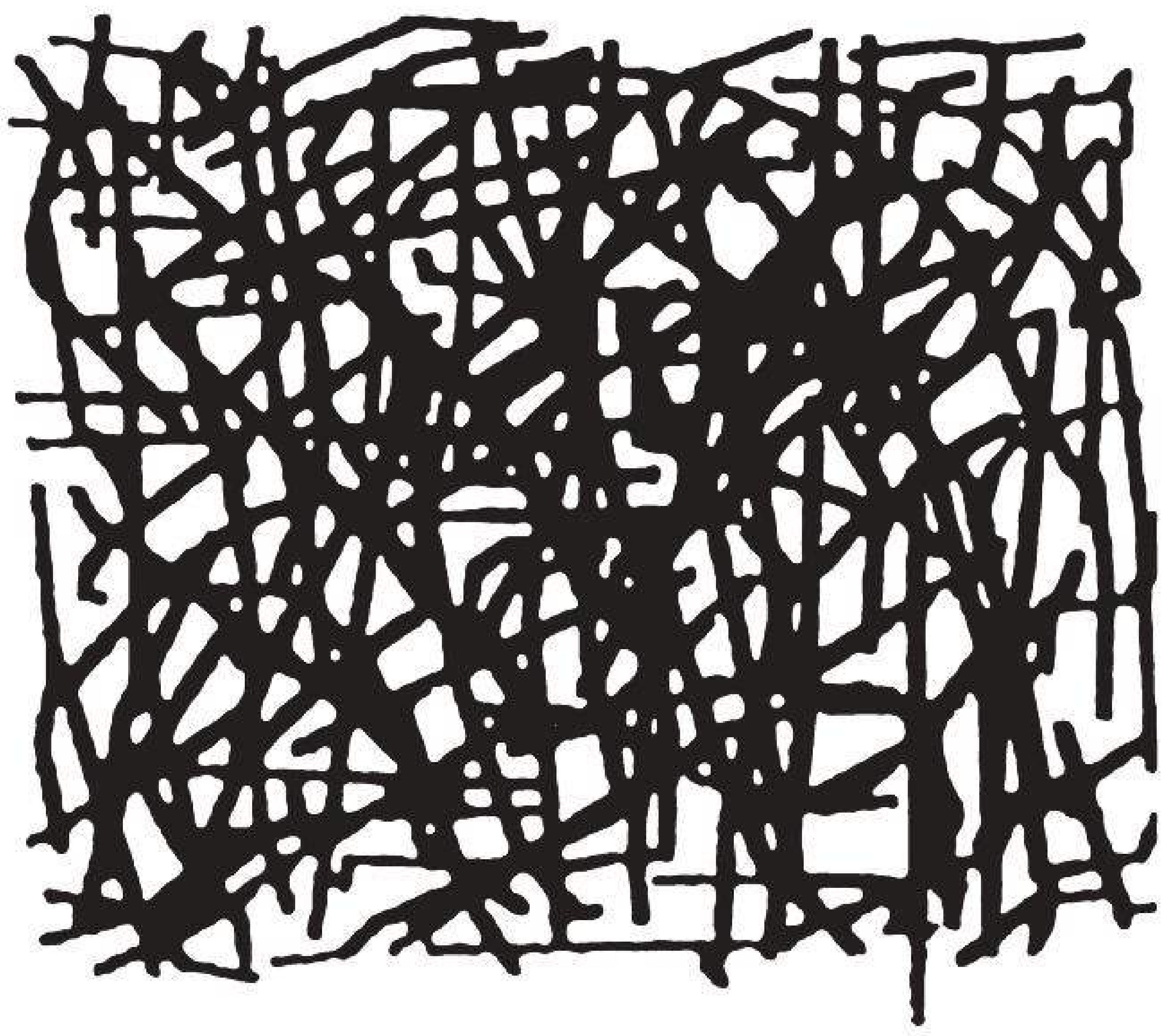
(c) Basic warp-knit structure (d) Weft-inserted warp-knit (e) Multibar weft-inserted warp-knit

1.3 Schematic representations of weft- and warp-knitted structures.

the same yarn. While weft-knitted technology is most commonly used in clothing manufacture, warp-knitted technology is substantially engaged in manufacturing structures for technical applications. Of special interest for technical applications are structures with inserted weft yarns, called weft-inserted warp-knitted fabric (Fig. 1.3(d)), and a multibar weft-knitted fabric (Fig. 1.3(e)).

1.2.3 Two-dimensional non-wovens

Non-woven fabrics are broadly defined as a sheet or web structure bonded together by entangling fibre or filaments either mechanically, thermally or chemically. They form a sheet, web or batt of directionally or randomly oriented fibres, bonded by friction and/or cohesion and/or adhesion, excluding paper and products, that is woven, knitted, tufted, stitch-bonded (incorporating bonding yarns or filaments) or felted by wet milling, whether or not additionally needled. The fibres may be of natural or artificial origin. They may form staple or continuous filaments. They are engineered to provide specific properties such as absorbency, liquid repellency, resilience, stretch, softness, strength, flame retardancy, washability, cushioning, filtering, bacterial barrier and sterility. A basic non-woven structure is shown in Fig. 1.4.



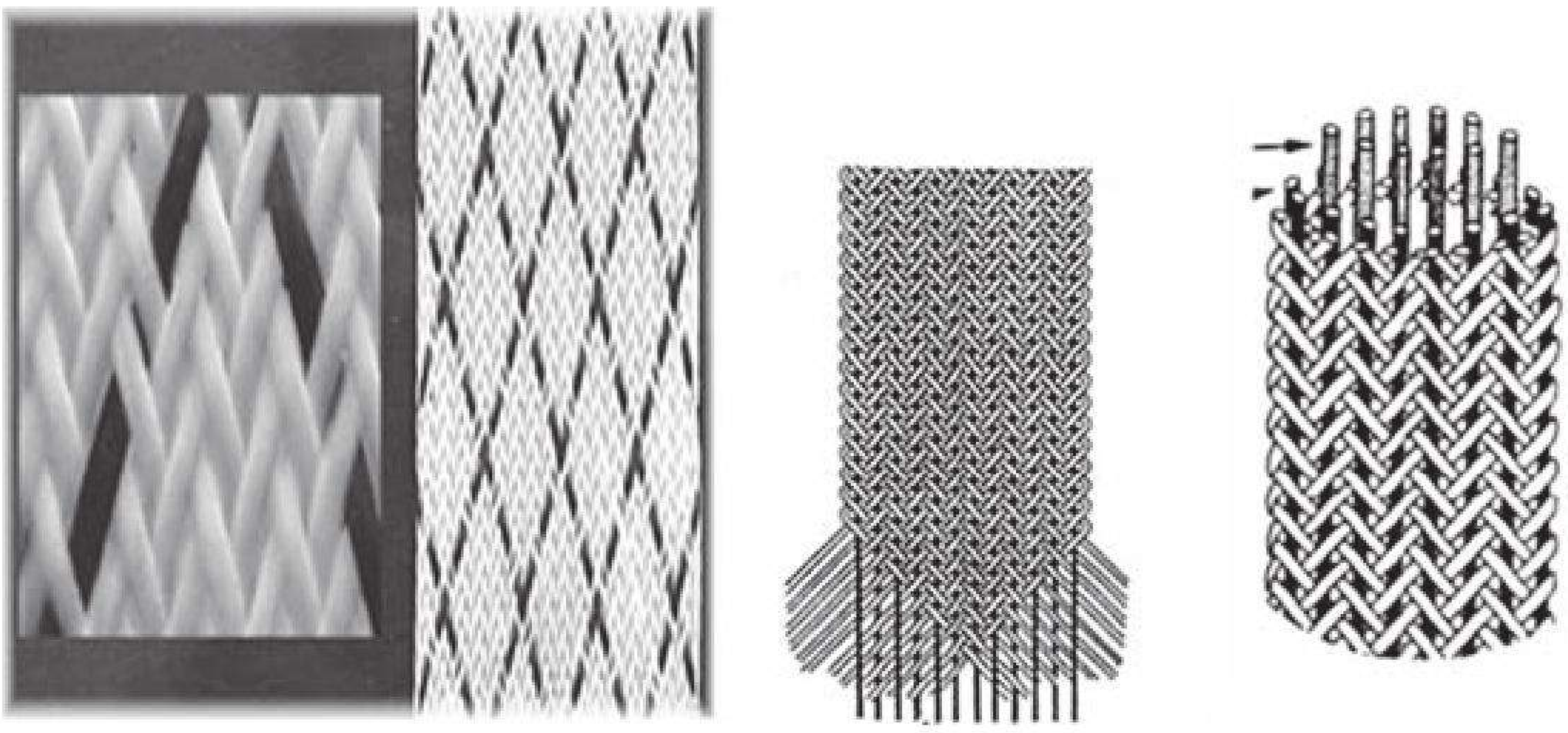
1.4 Basic non-woven fabric.

1.2.4 Two-dimensional braids

A braid is a textile structure formed by interlacing two or more sets of yarns resulting from the carriers rotating in clockwise and counter-clockwise directions (Brunnschweiler, 1953). Braiding has been conventionally used for applications such as shoelaces, ropes, etc. However, in recent years, fibre-reinforced composites and medical implants have become interesting applications for braiding. This has been achieved by employing 3-D preforms for such applications (Zhang *et al.*, 1997).

Braided textile structures are manufactured by intertwining or orthogonally interlacing two (or more) sets of yarns to form an integral structure in a tubular form. One set of yarns is called the axial yarns while the other is called the braided yarns. Hence, the structures of braided fabrics consist of parallel axial yarns, interconnected with braided yarns that are placed along complex spatial orientations. There are three typical braid structures: diamond, regular and hercules. A regular diamond structure is shown in Fig. 1.5(a). It is obtained when the yarns cross alternately over and under the yarns running in the opposite direction. The repeat notation is 1/1. Using this notation, the regular braid structure has notation 2/2 and hercules 3/3.

Braids are mostly produced in a regular structure, generally in a tubular form of biaxial yarn direction. By inserting longitudinally oriented yarns (middle-end-fibre) into the structure, triaxial braid is obtained (Fig. 1.5(b)). Moreover, in the centre of the tubular braid, additional fibres called axial fibres can be inserted. When the number of braiding fibre bundles is the same, the tubular braid increases the fibre volume fraction more than the flat braid (Fig. 1.5(c)). The main feature of the braid is the angle of intertwining, which can vary between 10° and 80° and depends on the yarn



(a) Regular diamond (b) Triaxial braid (c) Triaxial braid with axial fibres

1.5 Typical braided structures.

fineness, the type of structure (biaxial or triaxial), the cover factor (tightness of the structure) and the volume ratio of the longitudinal yarns.

1.3 Limitations of two-dimensional textile structures

Polymer laminates reinforced with a 2-D layer fibre structure have been used with outstanding success for over 50 years in maritime craft, for about 30 years in aircraft and for nearly 20 years in high-performance automobiles and civil infrastructure such as buildings and bridges. Despite the use of 2-D laminates over a long period, their use in many structural applications has been limited by manufacturing problems and some inferior mechanical properties. The manufacture of laminates can be expensive because of the high labour requirement in the manual lay-up of piles (Mouritz *et al.*, 1999).

The application of 2-D laminates in some critical structures in aircraft and automobiles has also been restricted by their inferior impact damage resistance and low through-thickness mechanical properties when compared to traditional aerospace and automotive materials such as aluminium alloys and steel. The low through-thickness properties, such as stiffness and fatigue resistance, have impeded the use of 2-D laminates in thick structures subjected to high through-thickness and interlaminar shear stresses. An additional problem is that many 2-D laminates have low resistance to delamination cracking under impact loading because of their poor interlaminar fracture toughness. As a consequence of this, their post-impact in-plane mechanical properties can be severely degraded, particularly their compression strength and fatigue performance. While these properties can be improved to a certain extent by the use of toughened resins of fibre interleaves, these solutions are usually expensive and do not overcome many of the problems associated with the manufacture of laminates (Mouritz *et al.*, 1999).

1.4 Three-dimensional structures (three-dimensional fabrics)

1.4.1 Definition of three-dimensional fibrous assemblies

Three-dimensional woven, braided or stitched fibrous assemblies are textile architectures having fibres oriented so that both the in-plane and transverse yarns are interlocked to form an integrated structure that has a unit cell with comparable dimensions in all three orthogonal directions, i.e., the 3-D structure basically consists of in-plane yarns for stiffness and strength and z-binder yarns for through-thickness reinforcement (Yang *et al.*, 2004). In other words, 3-D textiles are those materials that have a system or systems in all three orthogonal planes.

These materials offer particular properties, such as interlaminar shear force, mechanical and thermal stability along all three spatial axes, that are not achievable with other reinforcements. This integrated architecture provides improved stiffness and strength in the transverse direction and impedes the separation of in-plane layers in comparison to traditional 2-D fabrics. Because of their high transverse strength, high shear stiffness, low delamination tendency and near-net-shape manufacture, textile composites from weaving, knitting and braiding have received tremendous attention recently (Xuekum Sun and Changjie Sun, 2004). Recent automated manufacturing techniques have substantially reduced costs and significantly improved the potential for large-scale production.

Optimal orientations, fibre combinations and distributions of yarns have yet to be fully developed and perfected for 3-D fabrics subjected to impact loading conditions. For example, current body armour relies on ceramic plates to defeat penetrators. The rigidity and brittleness of these materials limit their use to military fighting applications. In addition, over time, environmental degradation and accidental mechanical impact damage the ceramic and render it ineffective. Hence, there are ample opportunities for substitute materials, and innovative concepts that combine hybrid 3-D fabrics with other materials such as ceramic and possibly new nano-scale materials are needed. The optimal combinations of these materials need to be determined along with new methodologies to ascertain how to utilize the inherent mechanisms (friction, micro-cracking, fibre breakage, fibre bridging, etc.) of these systems for energy dissipation and strengthening.

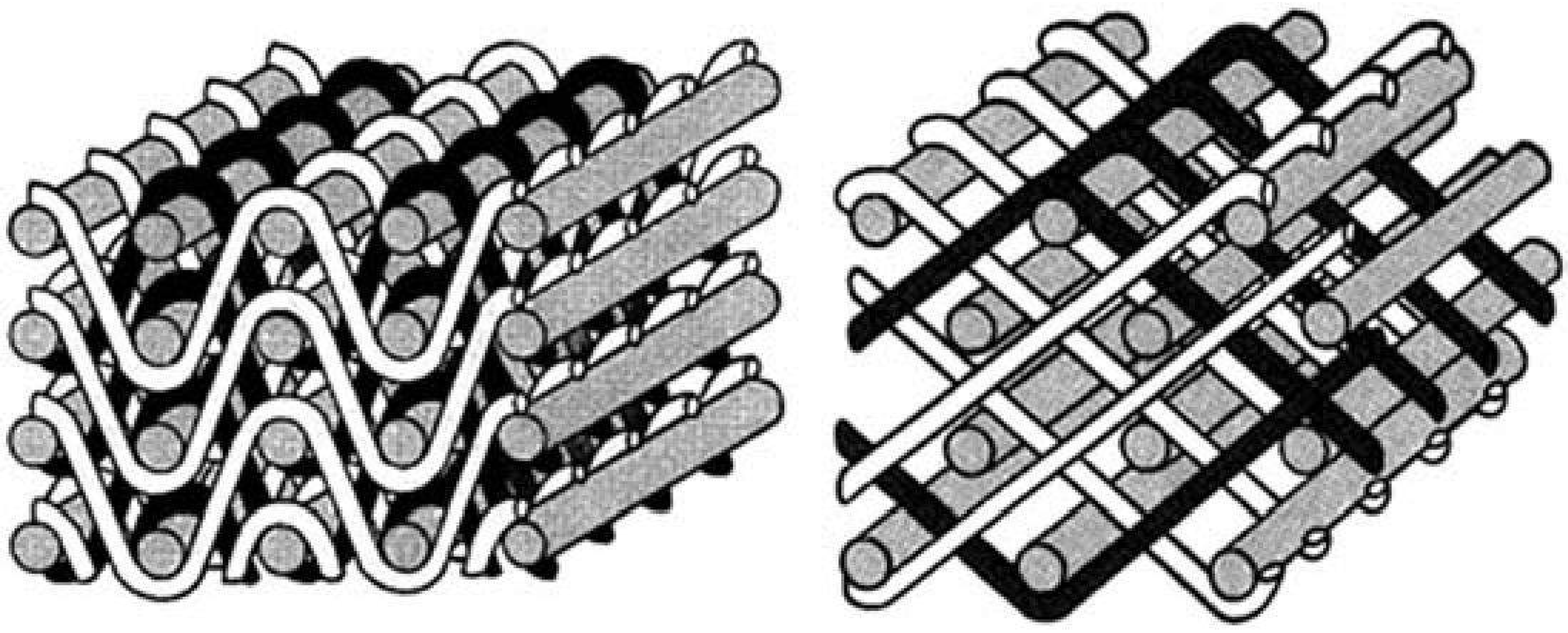
1.4.2 Comparison of three-dimensional with two-dimensional fabrics

- The absence of interlacing between the warp and filling yarns allows 3-D fabrics to bend and internally shear rather easily, without buckling within the in-plane reinforcement, which is not the case in 2-D fabrics.
- The presence of z-direction reinforcement in 3-D fabrics is an obvious advantage, as the dramatic improvement in composite transverse strength and impact damage tolerance is well documented. For example, tests of laminates made from these preforms have shown a 10–30% increase in short-beam shear strength over 2-D textile laminates.
- Three-dimensional fabrics exhibit improved compression after impact strength, reduced delamination area, and increased number of sub-perforation energy blows required to penetrate the panel.
- Composites made from 3-D preforms exhibit high fibre content (per cent by weight). Although somewhat lower percentages can be expected, the fibre content is still higher than in composites made from 2-D fabrics (Malik and Parmar, 2006).

1.4.3 Three-dimensional woven fabrics

Most woven fabrics are 2-D biaxial woven structures wherein two sets of yarns, warp and weft (fill), intersect and interlace at right-angles with one another. The biaxial fabrics can provide fairly balanced properties and good stability in the warp and weft directions. However, they exhibit a relatively low modulus or resistance to extension when deformed on the bias (45° to warp and weft) as compared with deformation in the warp or weft directions. There are many weave patterns for 2-D biaxial woven fabrics; the three most common weave structures are plain weave, twill weave and satin weave.

The use of 3-D woven fabrics as the reinforcing medium for composites, termed woven preforms, is becoming a popular choice. Because of the 3-D integrated fibre assemblage, such structures are less prone to delamination and can offer high impact resistance. They have emerged as a new class of lightweight material that has potential applications in the aerospace, maritime, infrastructure and medical fields. Three-dimensional woven fabrics are formed to near net shape with substantial thickness and additional yarns in the through-thickness direction. This distinguishes them from 2-D fabrics which possess a high width to thickness ratio and are typically layered to form a thick structure. They have been found to have better delamination resistance and damage resistance than 2-D woven laminates. The fibre structure of a 3-D woven composite consists of in-plane warp and weft yarn



1.6 Typical 3-D woven structure.

layers interlaced in the through-thickness direction by *z*-binder yarns. A typical 3-D woven structure is shown in Fig. 1.6 (Mohamed, 1990).

In a 3-D woven fabric, the warp and weft yarns are bound together by a series of warp binder yarns. Various arrangements of yarn placement are used to produce a wide range of multilayer 3-D reinforcements for composite applications (Yi and Ding, 2004). These are broadly categorized under two distinct headings:

- integrated structures, in which binder yarns link one layer to any other layer within the textile structure;
- interlinked structures, in which the binder yarns link the outer two layers, top to bottom.

In 3-D weaving, a number of the warp (or 0° direction) yarns provide through-the-thickness reinforcement to consolidate the preform. The through-thickness yarns are arranged in different areas and levels of the reinforcement according to the net shape and mechanical properties required. These through-thickness tows have been shown to provide increases in interlaminar shear strength of composite components (Quinn *et al.*, 2001). In general, 3-D weaving refers to the following:

- making of fabrics with substantial thickness by layering
- enabling shedding and weft insertion both horizontally and vertically
- creating 3-D woven shapes, e.g., a dome shape.

Classification of three-dimensional woven fabrics

Three-dimensional woven fabrics are produced principally by the multiple-warp weaving method, which has long been used for the manufacture of double and triple cloths for bags, waddings and carpets. The 3-D woven fabrics produced by using either multiwarp weaving technology or conventional weaving technology can be broadly classified as follows:

- 3-D solid
  - multilayer
  - orthogonal
  - angle interlock
- 3-D hollow
  - flat surface
  - uneven surface
- 3-D shell
  - by weave combination
  - by differential take-up
  - by moulding
- 3-D nodal.

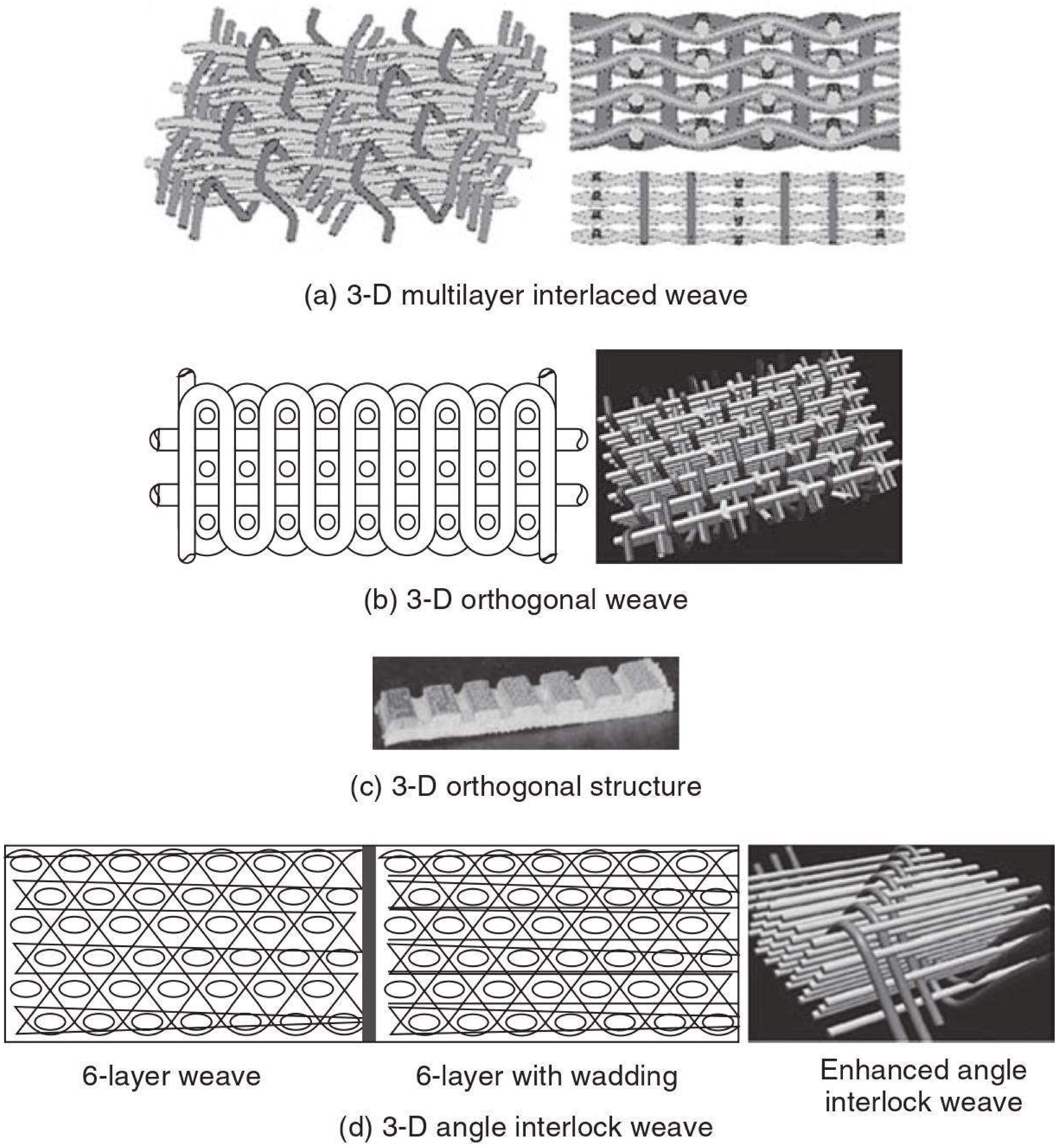
Three-dimensional woven solid fabrics produced by the multilayer principle are characterized by the presence of several layers of yarns woven together by using different interlacing techniques. The layers can also be stitched together and the stitching arrangement may have either a self-stitching or a central stitching arrangement. Wadding yarns may also be incorporated into the structure for specific applications. It is important to control the yarn ratio in the fabric to obtain specific properties (Xiaogang Chen, 2006).

Three-dimensional solid orthogonal fabrics feature straight warp, weft and vertical yarns in their design. The number of layers of straight weft yarn is always one more than that of warp yarn, and the amount of vertical yarn depends on the binding weave. Two options are possible: ordinary and enhanced. It is possible to have a variable interlinking depth.

The 3-D solid angle interlock principle involves the binding of straight warp yarns by interlocking warp yarns. Warp yarns can be bound to different depth. As in orthogonal fabrics, wadding yarns may be used in the structure. The structures of various 3-D solid woven fabrics are presented in Fig. 1.7 (Xiaogang Chen, 2006).

Three-dimensional hollow structures are of two types: one with a flat surface and the other with an uneven surface. The hollow structures with a flat surface are based on the multilayer principle but with different fabric section lengths. Such structures should be self-opening under the right conditions. It is possible to have multilevel cells in their structure. The hollow fabrics with uneven surface structures are based on the multilayer principle and are created by joining and separating adjacent layers. Such structures need opening. The cells created in the structure are generally of hexagonal shape. Different 3-D hollow structures are shown in Fig. 1.8 (Xiaogang Chen, 2006).

Three-dimensional shell structures can be created either by using different weave patterns or by employing a discrete take-up in the loom to

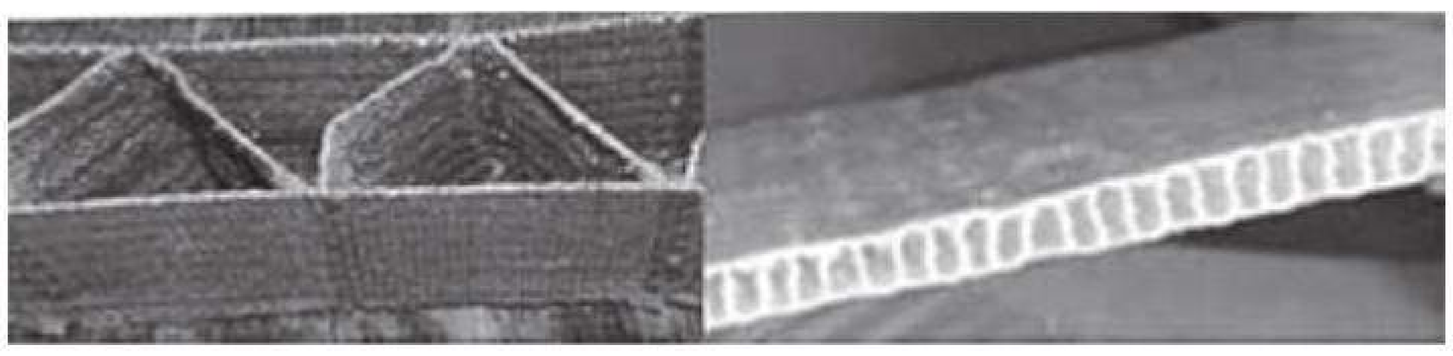


1.7 3-D solid woven structures (adapted from Xiaogang Chen, 2006).

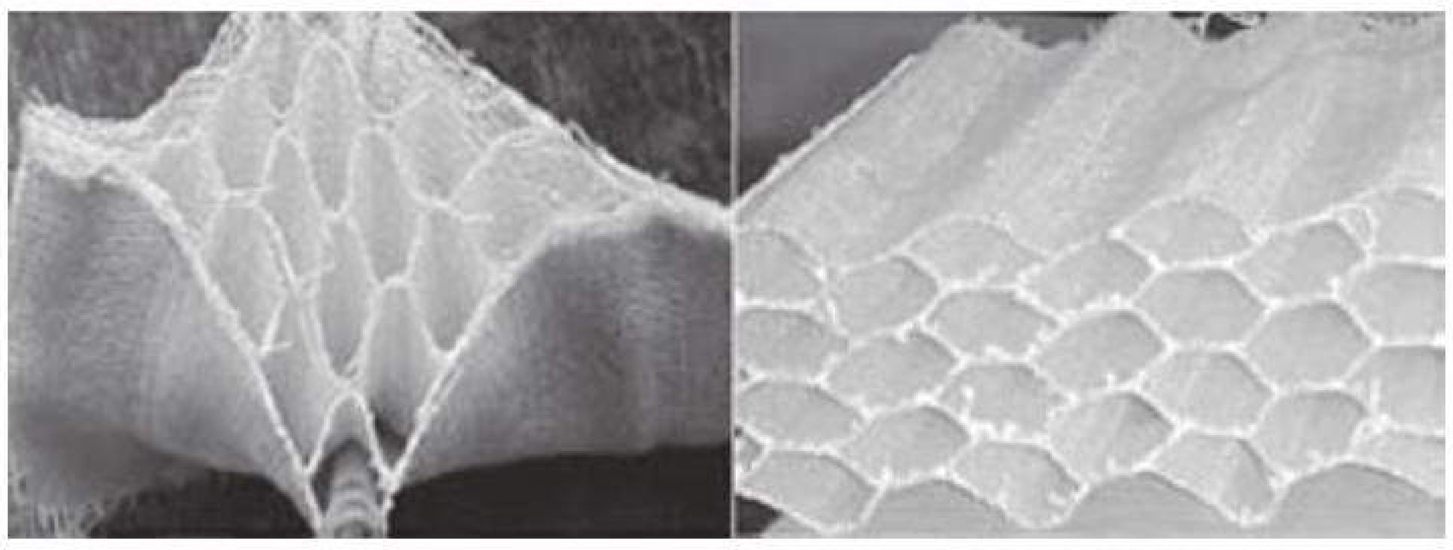
modify their structure to have a hollow-type surface. Sometimes it is possible to mould these fabrics to obtain a special moulded structure for technical or industrial applications. Three different types of hollow structures are shown in Fig. 1.9.

Three-dimensional nodal fabrics (Fig. 1.10) refer to joining tubes to obtain certain special types of structures for industrial applications. The walls of the tubes may be 3-D solid structures themselves. All tubes must be in the same plane (x–y). The design procedure involves creating a nodal design in 2-D space, flattening, area segmentation and assignment of weaves for different sections (Xiaogang Chen, 2006).

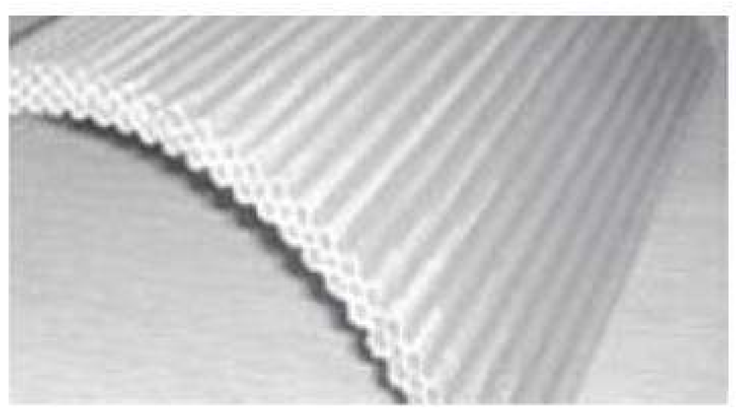
A 3-D weave contains multiple planes of nominally straight warp and weft yarns that are connected together by warp weavers to form an integral structure. The most common classes are shown in Fig. 1.11. Within each class, there are several parameters that can be varied.



(a) 3-D hollow flat surface



(b) 3-D hollow with hexagonal cells

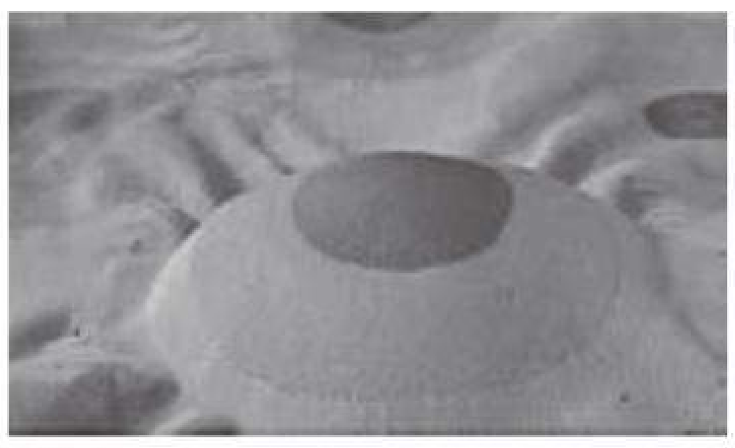


(c) 3-D hollow uneven surface

1.8 3-D woven hollow structures (adapted from Xiaogang Chen, 2006).

The angle interlock type of structure is a variation of 2-D weaving wherein more than two yarns are in the thickness direction. The angle interlock structure allows the preform to be up to 10 cm in thickness. In this fabric, warp yarns are used to bind several layers of weft yarns together. Weft yarns could be used for binding as well. In place of warp or weft yarns, an additional third yarn may also be used as binder. Stuffer yarns, which are straight, can be used to increase fibre volume fraction and in-plane strength.

Angle interlock weaves can be categorized by the number of layers that the warp weavers penetrate. Figure 1.11(a) shows a through-thickness interlock fabric, in which the warp weavers pass though the entire thickness. Figure 1.11(c) and (d) show layer-to-layer interlock patterns, where a given weaver connects only two planes of weft yarns but the weavers collectively bind the entire thickness. Various intermediate combinations can be fabricated, with the weavers penetrating a specified number of layers, with the warp weavers passing through the thickness orthogonal to both in-plane directions, as shown in Fig. 1.11(b). Interlock weaves are sometimes manufactured without straight warp yarns (stuffers) to produce a composite reinforced predominantly in one direction. They may also be fabricated with weft rather than warp yarns used for interlock. A major limitation of 3-D weaves is the difficulty of introducing bias-direction yarns to achieve in-plane isotropy. One solution is to stitch additional 2-D fabric plies oriented at 45° onto the woven preform.

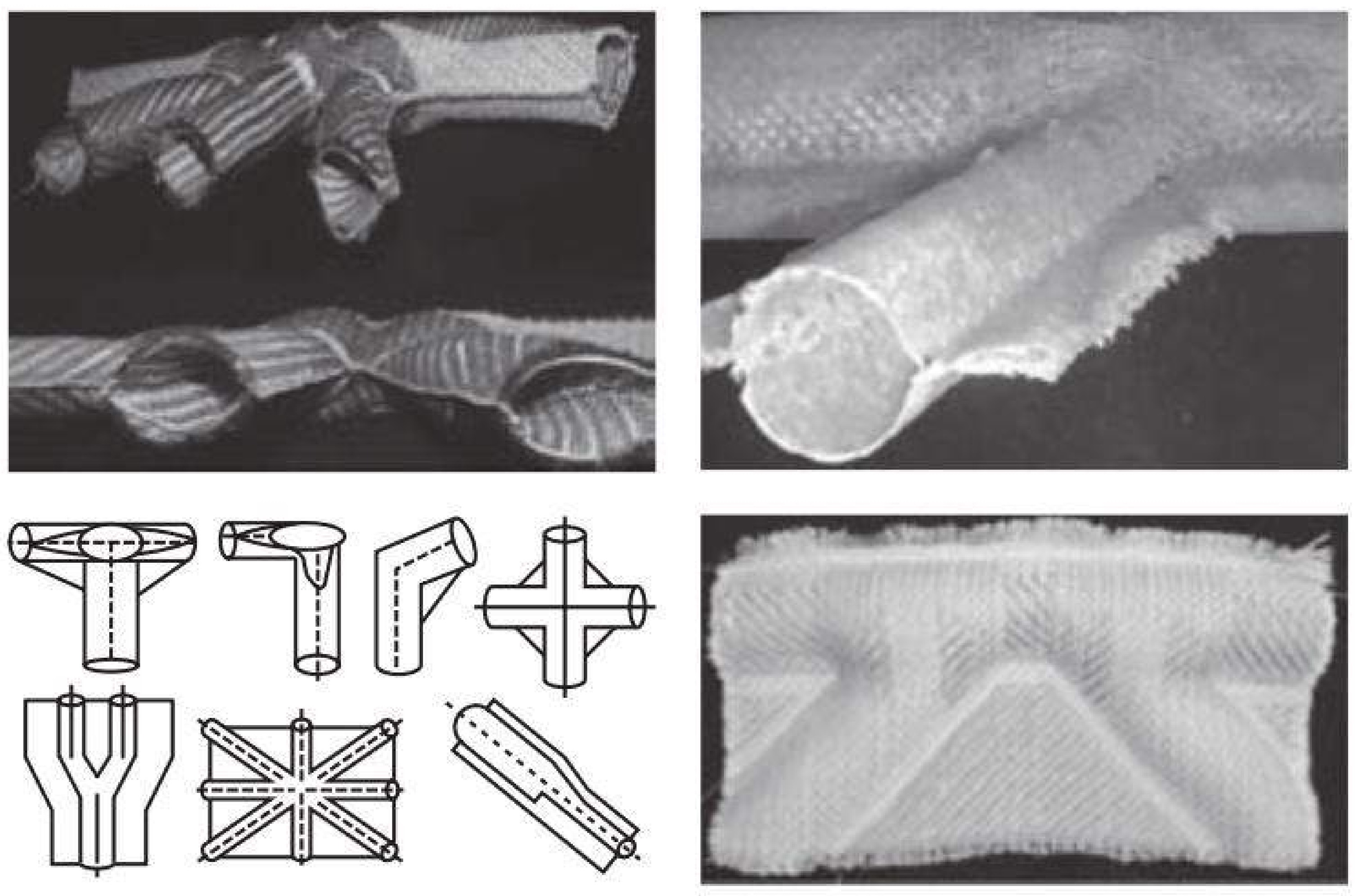


(a) 3-D shell by using different weaves

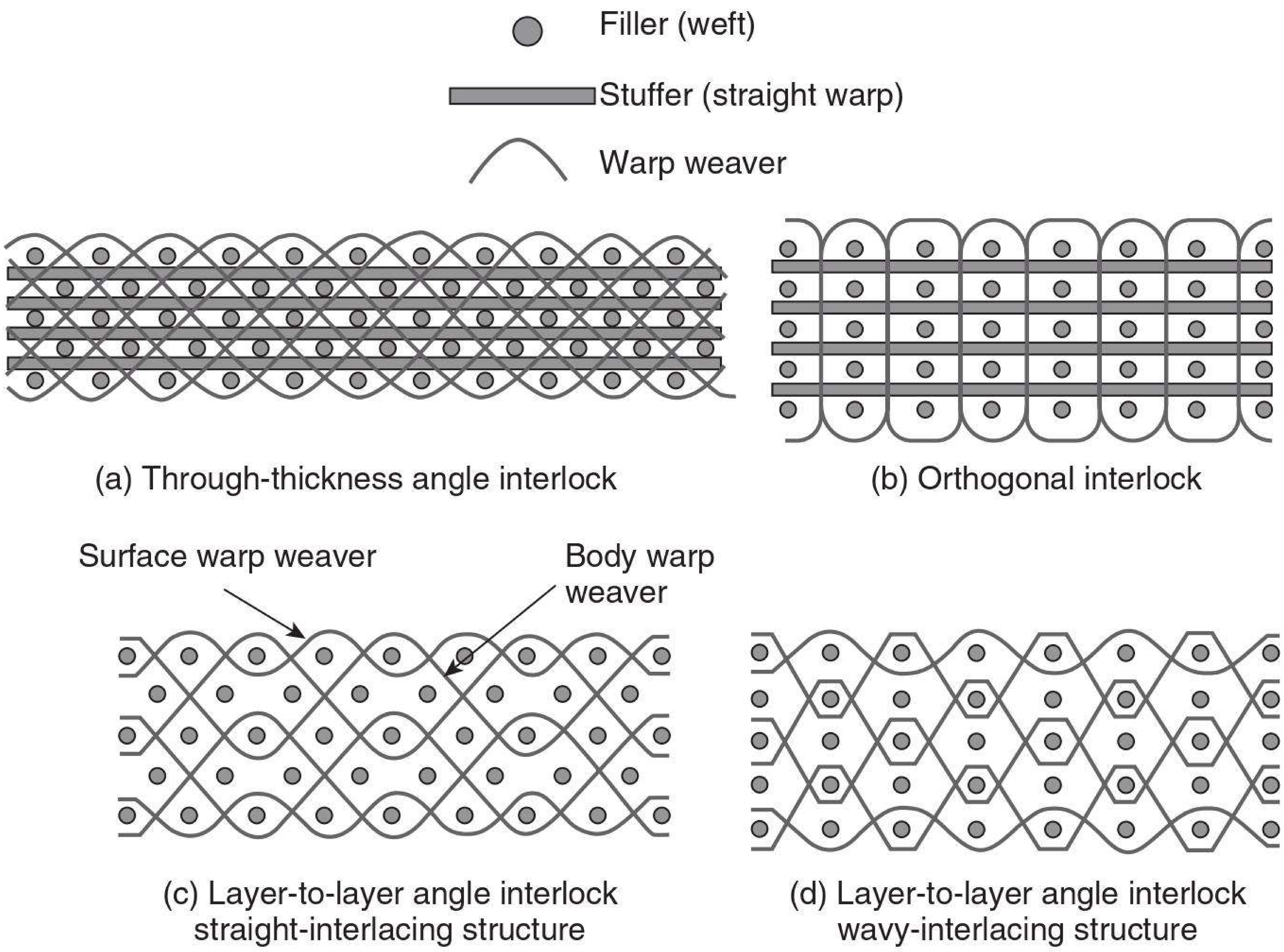
(b) 3-D shell by discrete take-up

(c) 3-D shell by moulding

1.9 3-D woven shell structures.



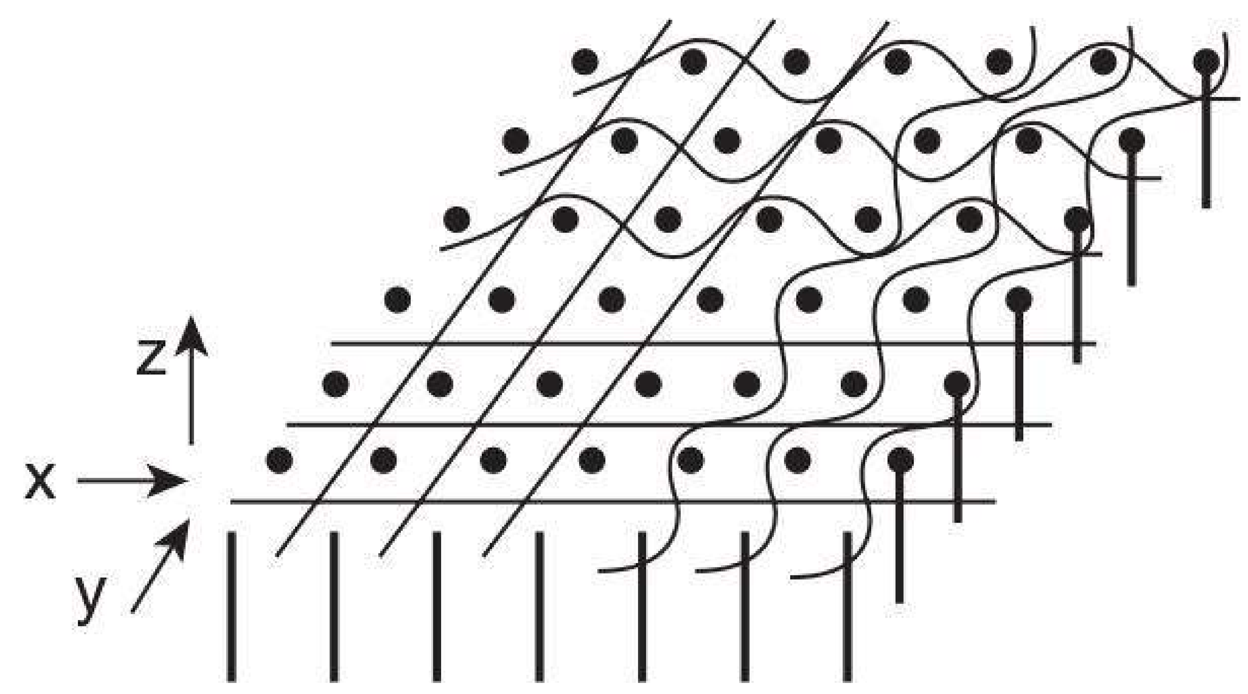
1.10 3-D woven nodal structures (adapted from Xiaogang Chen, 2006).



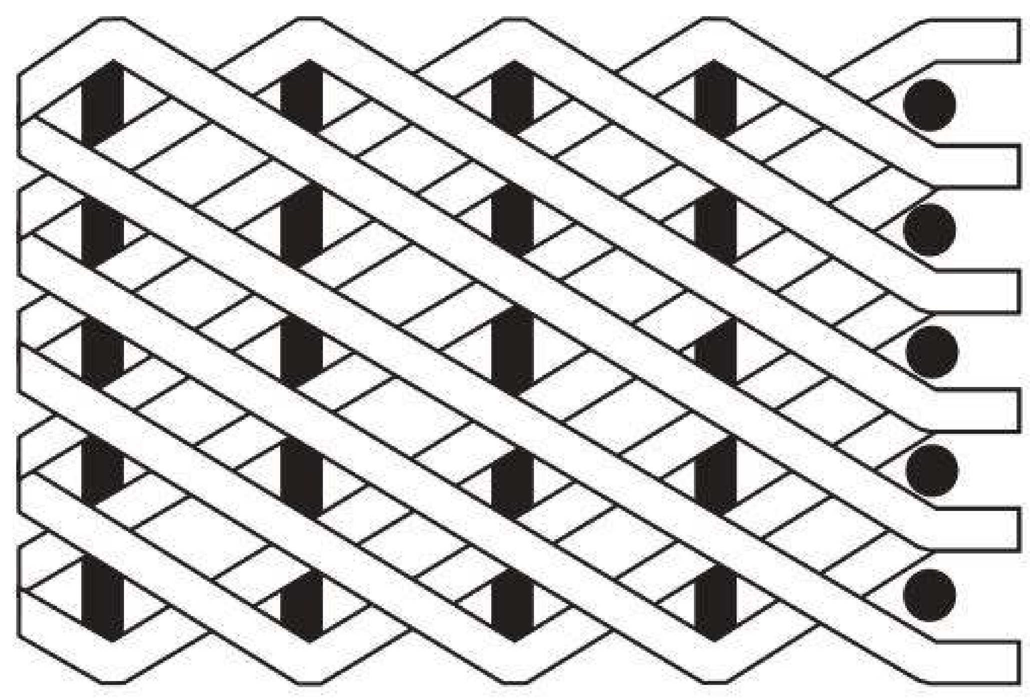
1.11 3-D weave patterns.

Textile technology has been involved in the construction of 3-D shells, but these are rather flexible structures for clothing and similar purposes. For production of strong 3-D fabrics, cutting, sewing and joints should be avoided as much as possible. True 3-D weaving can be accomplished on special machines as already developed. The simplest case of such a structure, in which the warp is crossed by two sets of wefts, is shown in Fig. 1.12(a). A woven structure in which the multilayer warp moves between the top and bottom of the material, thus providing *x* and *y* directions at an angle of 45°, and with weft yarns crossing between the warp providing the *z* direction, is shown in Fig. 1.12(b).

In general, a variety of 3-D structures can be accomplished. For example, the warp yarns can go only part-way across the whole material (Fig. 1.13(a)), or one set of warp yarns can be introduced in the axial direction and one set angled, thus providing yarns in four different directions (Fig. 1.13(b)). The latter structure gives higher control of the directional properties of the material. Shaping of 3-D weaves can be accomplished by varying the width of the warp layers, thus creating the required cross-section, for example in the form of a T-beam (Fig. 1.13(c)) (Demoski and Bogoeva-Gaceva, 2005).

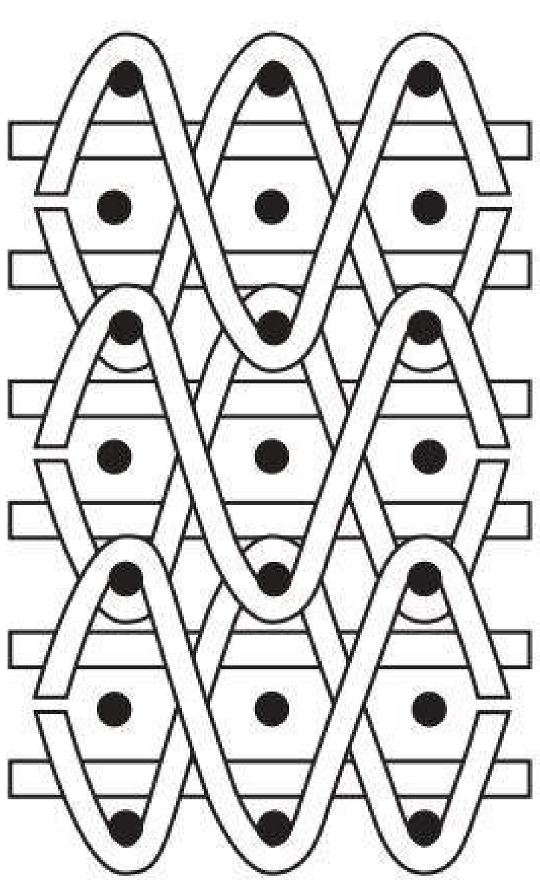


(a) Multilayer 3-D weave with warps in *x* and *y* directions

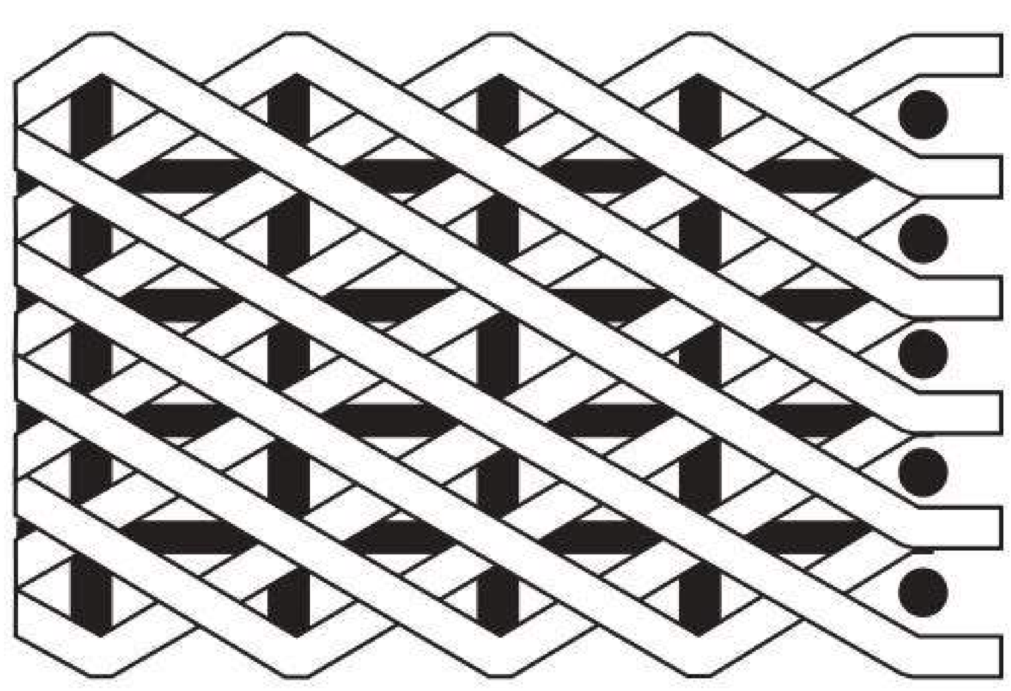


(b) Weft in *z* direction

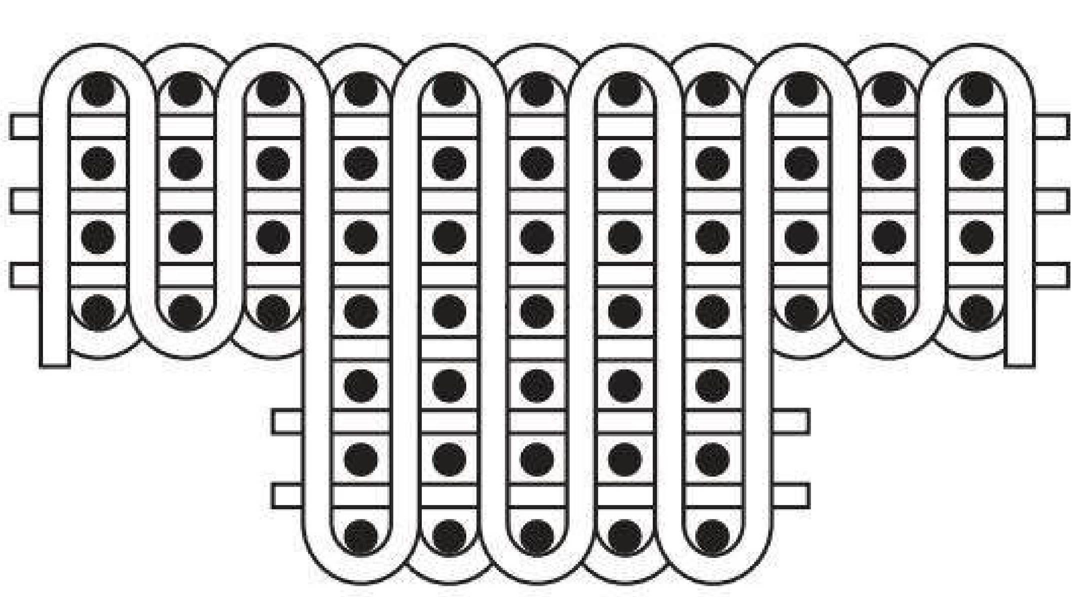
1.12 Two types of multilayer 3-D woven fabric (a) warp in the *z* direction and wefts inserted in the *x* and *y* directions, (b) warps at 45° in the *x* and *y* directions and weft in the *z* direction.



(a) Partial interlocking of layers



(b) Two sets of warp yarns



(c) Shaping of 3-D weaving by varying warp layers

1.13 Variants of 3-D multilayer weaving.

Advantages of three-dimensional woven structures

- 3-D weaving can produce complex near-net shaped preforms.
- 3-D woven composites with a complex geometry can be less expensive to produce.
- 3-D weaving allows the tailoring of properties for specific applications.
- 3-D woven composites show better delamination resistance and damage tolerance.

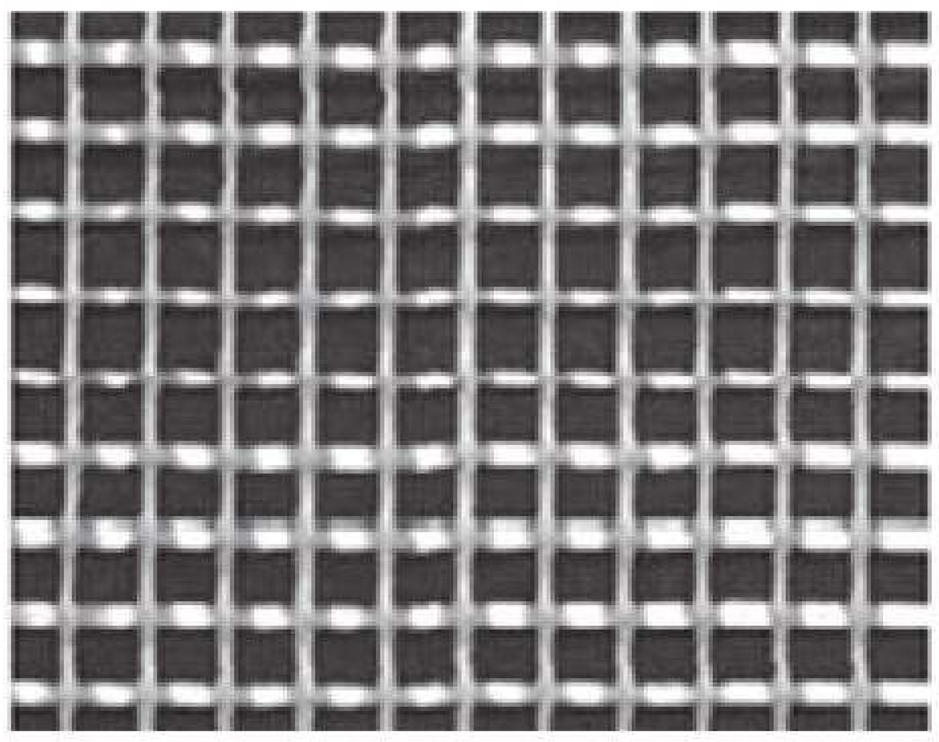
- 3-D woven composites show higher tensile strain-to-failure values.
- 3-D woven composites exhibit higher interlaminar fracture toughness properties.

1.4.4 Three-dimensional knitted fabrics

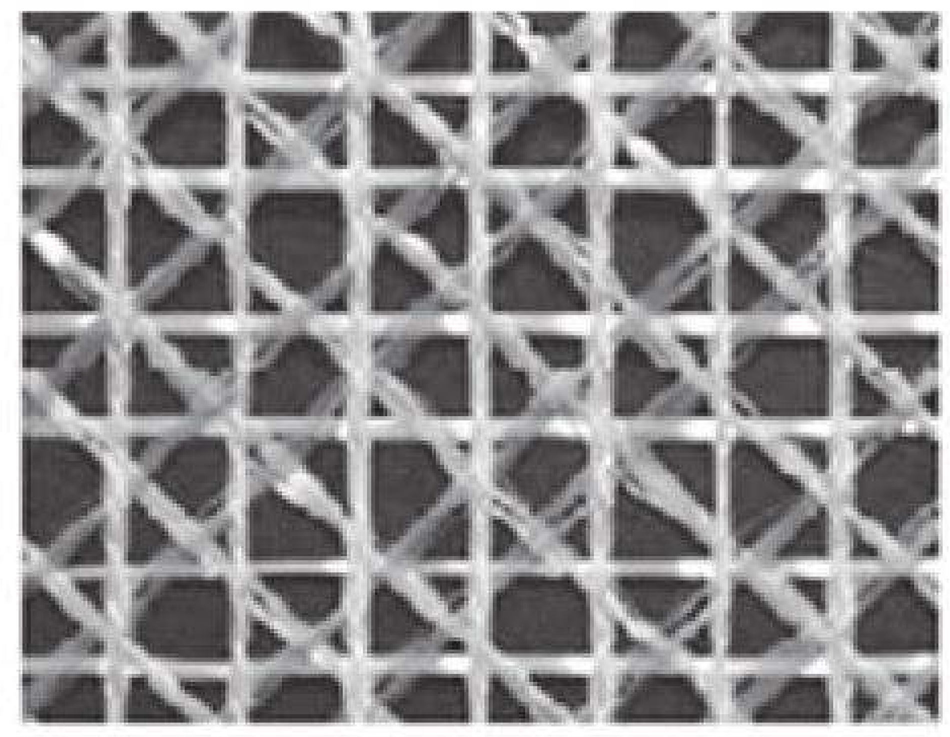
In the search for methods to reduce composite manufacturing costs, textile preforms, including knitted structures, are receiving increasing interest in the composites industry. While conformability and productivity are obvious attributes for knitted preforms, the availability of a broad range of micro- and macrostructural geometries has only recently been recognized. The non-linearity of knitting loops, severe bending of yarns during the knitting process and limited fibre packing density, resulting in the formation of resin pockets within a knitting loop, prevent knits from being considered for structural applications.

Knitting is the interlocking of one or more yarns through a series of loops (also called stitches). Knitted fabrics are considered 3-D due to their non-planar configuration of the loops in the structure. They are also known as multiaxial–multilayer structures and are fabrics bonded by a loop system, consisting of one or several yarn layers stretched in parallel. Multilayers of linear yarns are assembled in warp (0°), weft (90°) and bias ($\pm\theta$) directions to provide structural integrity and through-thickness reinforcement (Du and Ko, 1996).

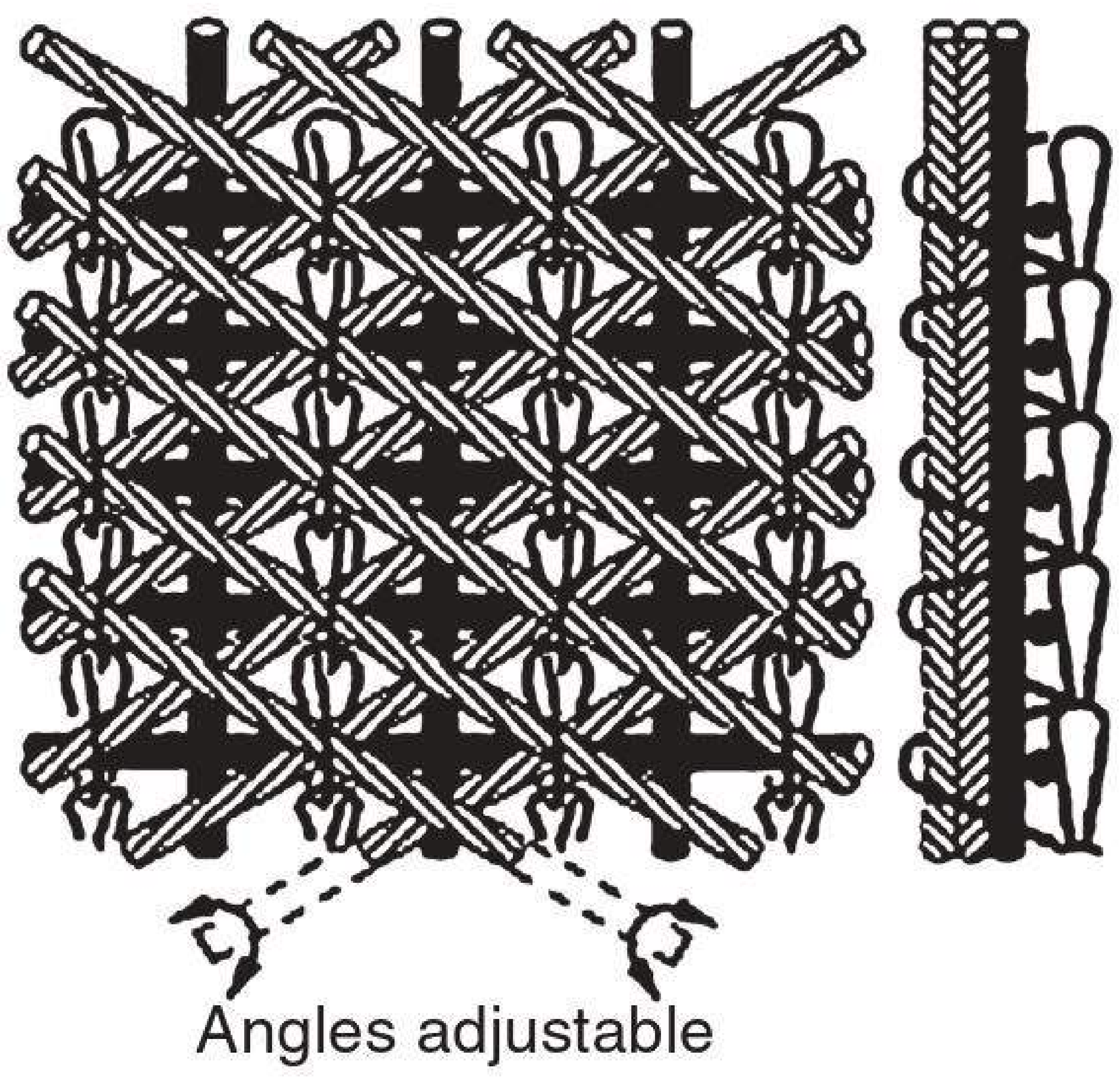
Three-dimensional knitted fabrics are produced by weft or warp knitting. An example of a weft knit is the near-net-shape structure knitted under computer control by the pressure foot process. In a collapsed form this preform has been used for carbon–carbon aircraft brakes. While weft-knitted structures have applications in limited areas, multiaxial warp knit (MWK) 3-D structures are more promising and have undergone a great deal of development in recent years. MWK fabrics generally possess up to four different load-bearing yarn systems arranged so that each can take on stress and strain virtually in all directions. Since these load-bearing yarns lie straight in the fabric, with no crimp, the physical parameters of the individual yarn system are fully utilized (Kaufmann, 1991). Multiaxial–multilayer warp knits (MWK) are also termed non-crimp structures since the presence of knitted loops is to perform the function of holding layers of uncrimped inlay yarns. These yarn layers may have different orientation and different yarn densities of single ends. MWK fabrics are used to reinforce different matrices, since the combination of multidirectional fibre layers and matrices has proved capable of absorbing and distributing extraordinarily high strain forces (Padaki *et al.*, 2006). Some of the 3-D knit structures are shown in Fig. 1.14.



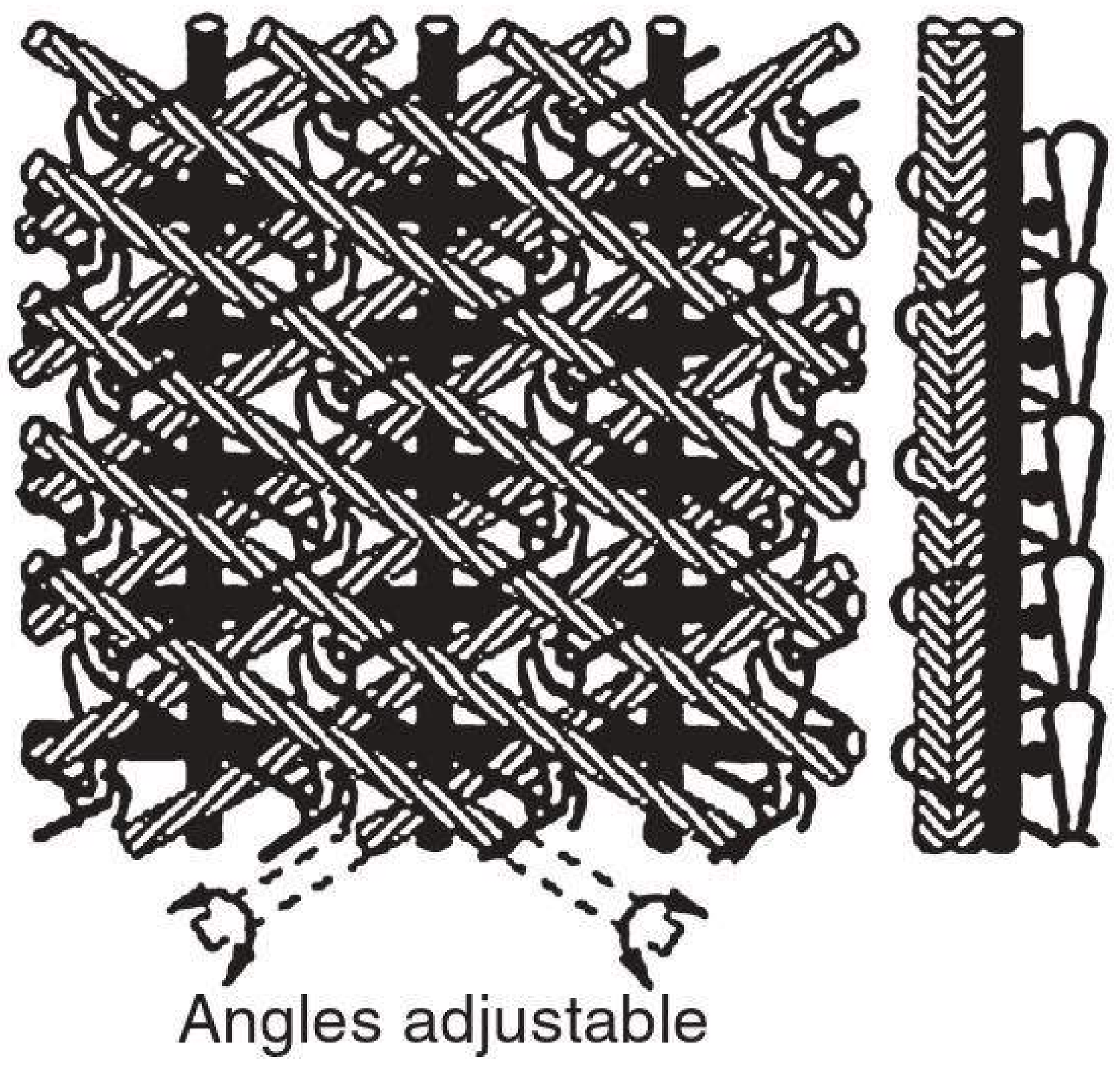
(a) Biaxial warp knit fabric



(b) Multiaxial reinforced warp

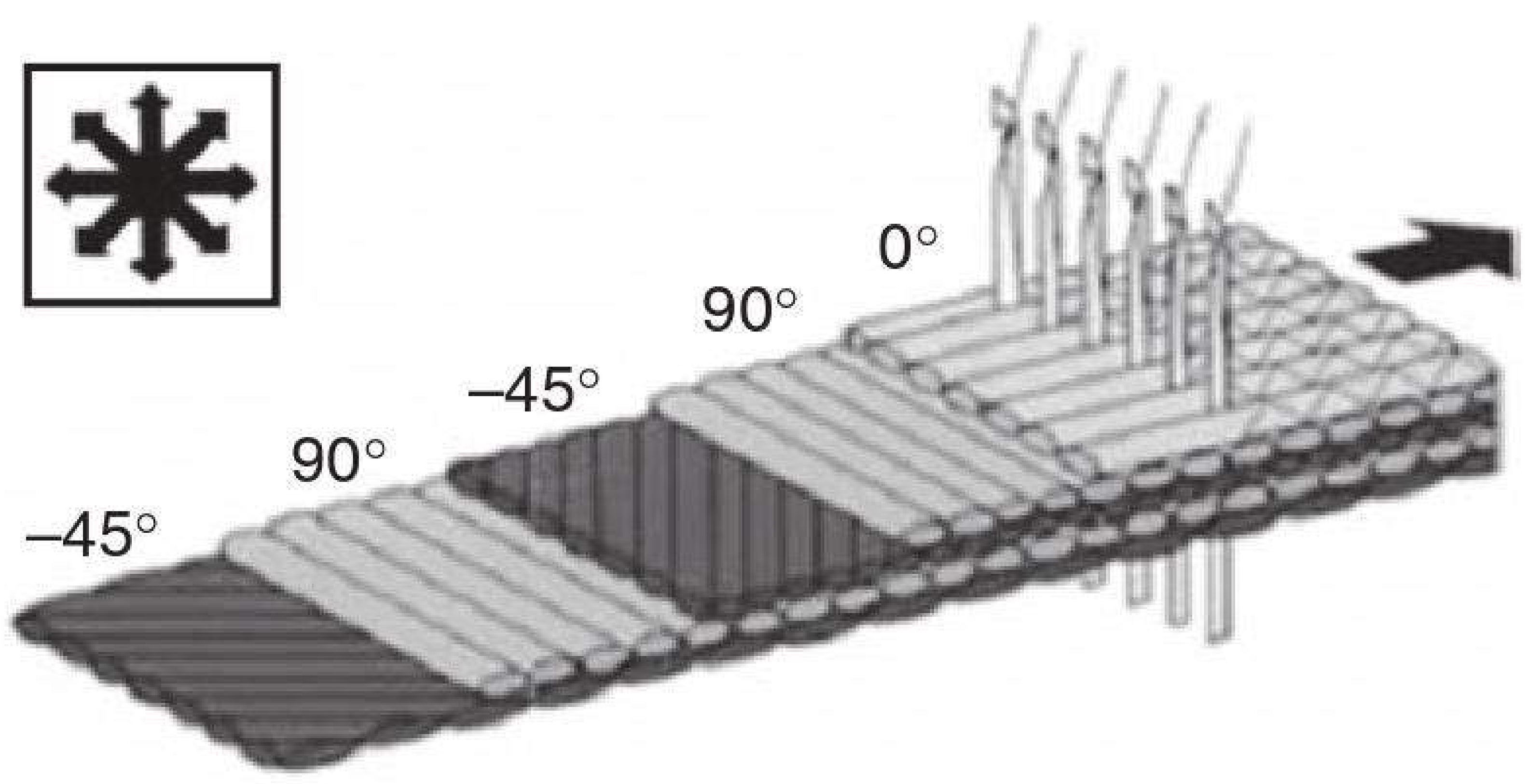


(c) MWK, chain stitch



(d) MWK, tricot stitch

1.14 Knit structures.



1.15 Multiaxial warp-knit system.

The MWK fabric system consists of warp (0°), weft (90°) and bias ($\pm\theta$) yarns held together by a chain or tricot stitch through the thickness of the fabric, as illustrated in Fig. 1.15. Theoretically, the MWK can be made to as many layers of multiaxial yarns as needed, but current commercially available machines allow four layers (the Mayer system) of 0°, 90°, $\pm\theta$ for insertion yarns, or at most eight layers (the LIBA system) of 0°, 90°, three ($\pm\theta$) insertion yarns, to be stitched together. All layers of insertion yarns are placed in perfect order each on top of the other in the knitting process. Each layer shows the uniformity of the uncrimped parallel yarns. The insertion yarns usually possess a much higher linear density than the stitch yarns and are therefore the major load-bearing component of the fabric.

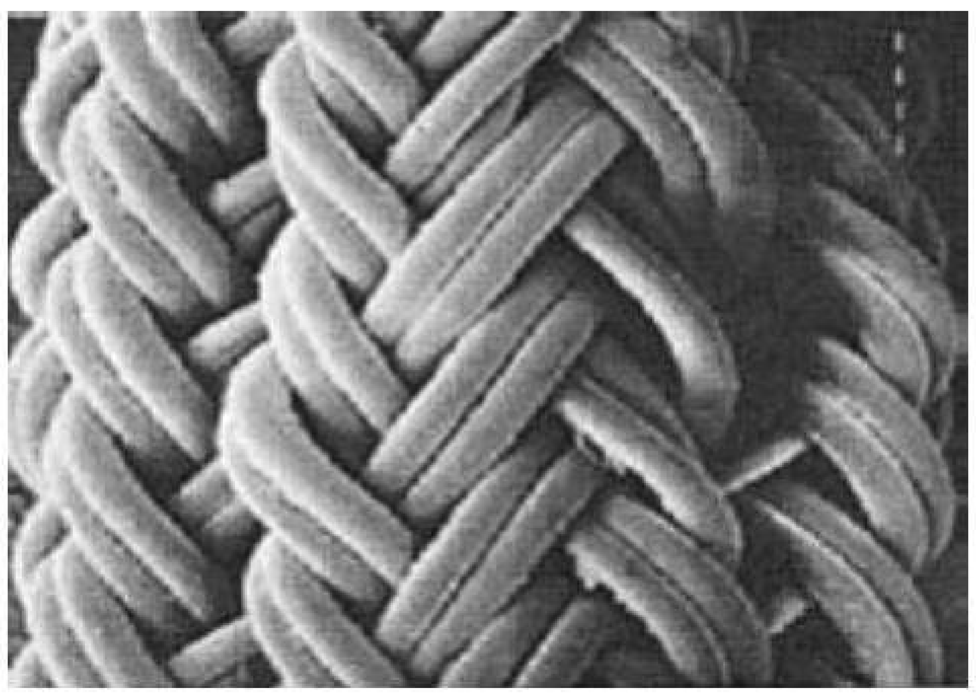
Advantages of three-dimensional knitted structures

- 3-D knitted preforms have better formability because they are more drapable.
- 3-D knitting can produce more complex near-net-shape preforms.
- Some types of 3-D knitting can be done on existing automatic machines with little modification.
- 3-D knitted sandwich composites have a lower specific density.
- Some types of 3-D knitted composites have higher impact damage tolerance and energy absorption (crash) properties.

1.4.5 Three-dimensional braided fabrics

Braiding is a textile process that is known for its simplicity and versatility. It is an old technique but experiencing resurgence in interest because of its diverse applications. The conventional 2-D braiding (or Maypole braiding) is a simple textile process. It is composed of two sets of yarn carriers rotating on a circular track. One set rotates in the clockwise direction while the other set rotates in the counter-clockwise direction and interlaces with the first one to form a tubular preform. The yarn carriers move through two sinusoidal slots in the track plate by means of horn gears. Several layers each with a specified braiding angle can be serially superimposed in order to form a multilayer braid. But the problem of these multilayer braids consists in the interlaminar weakness or in other words in its sensitivity to delamination. Three-dimensional braiding overcomes this problem by introducing reinforcing yarns of materials that transversely connect the different layers during the process.

Three-dimensional braiding technology is an extension of the well-established 2-D braiding technology wherein the fabric is constructed by intertwining or orthogonal interlacing of two or more yarn systems to form an integral structure. This extension of 2-D to 3-D braiding has opened up new opportunities in the near-net-shape manufacture of high-damage-resistant structures. At present most composite manufacture uses 2-D textiles in the form of simple 2-D braids, fabrics and unidirectional plies as basic reinforcement. Additional steps such as cutting, stacking of plies and stitching are then needed to complete the final textile reinforcement. These secondary operations are expensive and could be eliminated if suitable 3-D textile preforms could be produced using cost-sensitive mass production. Three-dimensional rotary braiding is an automated production method that could provide an attractive solution for the manufacture of certain



1.16 Braid structure.

net-shaped 3-D-textile preforms (Bigaud *et al.*, 2005). A typical 3-D braided structure is shown in Fig. 1.16.

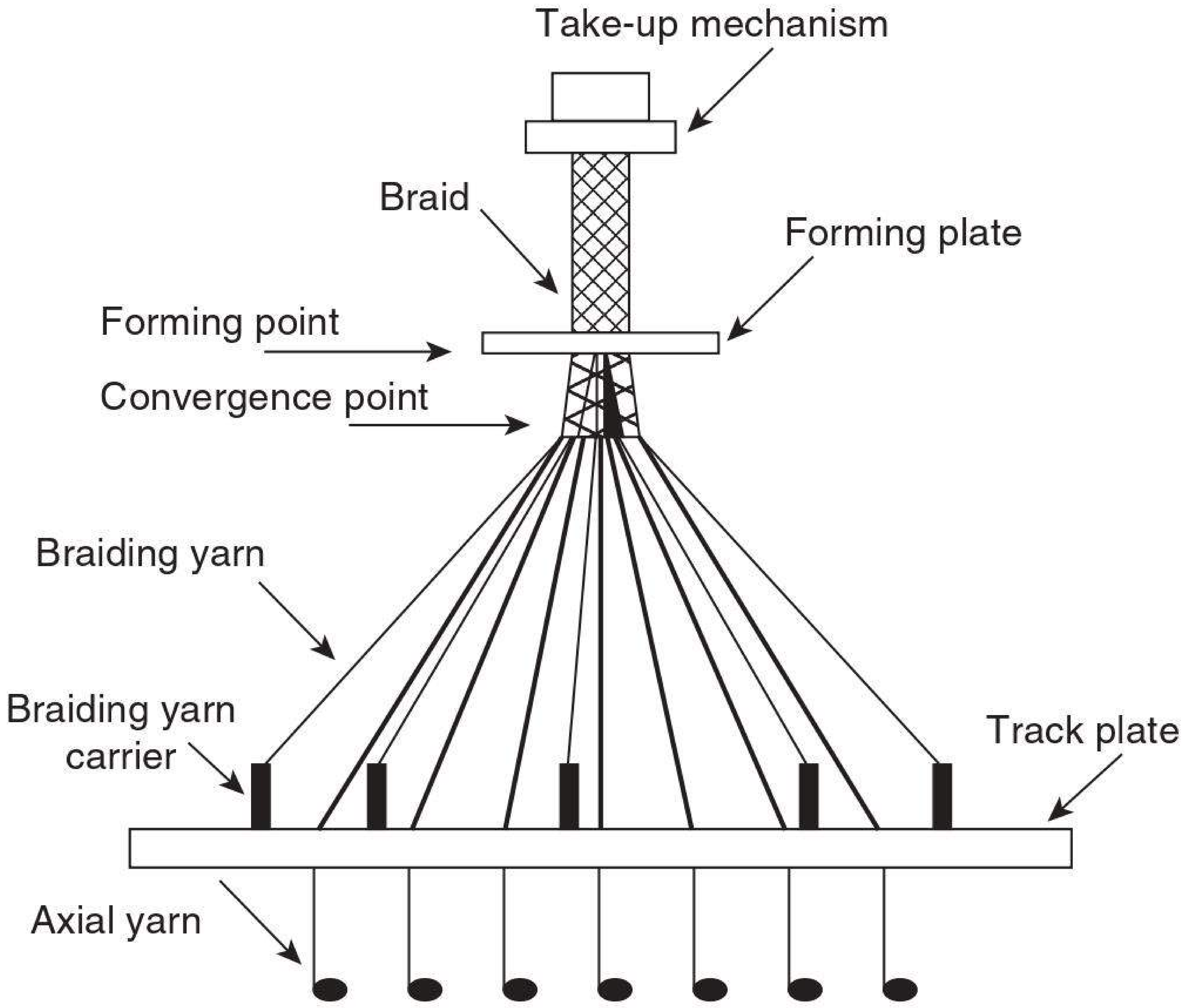
Three-dimensional braiding is one of the textile processes in which a wide variety of complex structural shapes can be produced in an integrated manner, resulting in highly damage-resistant structural preforms, as these preforms can withstand axial, flexural and torsional loads (Rawal *et al.*, 2005).

Principle of three-dimensional braiding

The 3-D braids are produced by a number of processes including the track and column (3-D circular loom) method (Brown and Ashton, 1989), the two-step braiding method (Popper and McConnell, 1987), and a variety of displacement braiding techniques. The basic braiding motion includes the alternate x and y displacement of yarn carriers followed by a compacting motion. The proper positioning of the carriers and the joining of various rectangular groups through selected carrier movements accomplish shape formation.

A generalized schematic of a 3-D braiding process is shown in Fig. 1.17. Axial yarns, if present in a particular braid, are fed directly into the structure from packages located below the track plate. Braiding yarns are fed from bobbins mounted on carriers that move on the track plate. The pattern produced by the motion of the braiders relative to each other and the axial yarns establishes the type of braid being termed, as well as the microstructure.

Three-dimensional rotary braiding is based on the well-known 2-D rotary braiding concept but now uses the horn gears arranged in a flat array as shown in Fig. 1.18(a). Each horn gear is equipped with a special clutch–brake mechanism, which allows a controlled stop or rotation of each single horn gear and the attached bobbins. Grooves in the machine working plate guide the bobbins driven by the horn gears. Switches, however, located between each pair of horn gears, can be activated to transfer the bobbin to an adjacent horn gear or to be kept. According to the status of the clutch–brake mechanism and switches, any arbitrary movement of the bobbins is



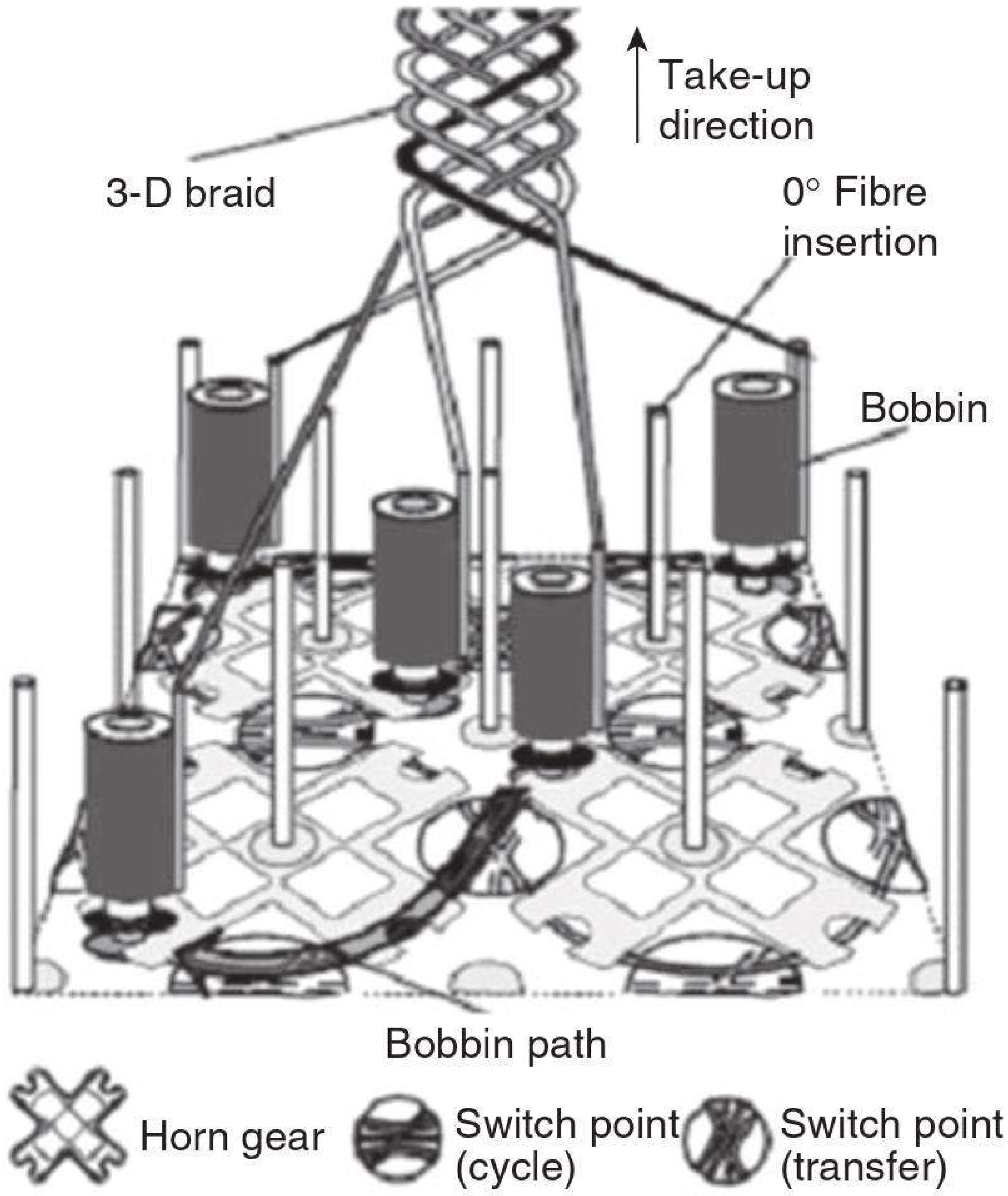
1.17 Schematic drawing of a generalized 3-D braider.

possible. The principle of formation of 3-D braided fabrics is shown in Fig. 1.18(b).

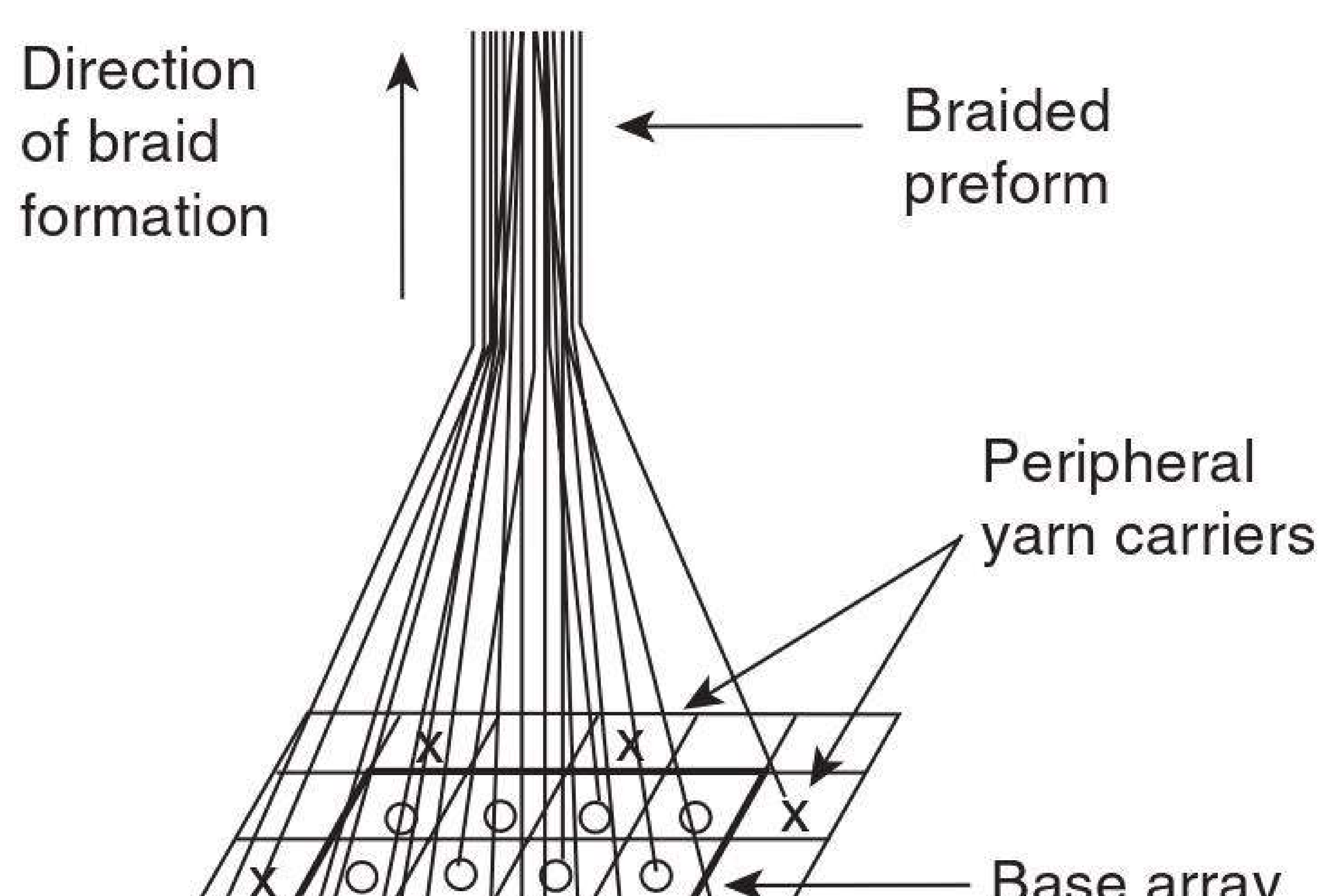
For the insertion of standing ends into the braid, those yarns are led through input tubes positioned between the horn gears or through the horn gear axles (Fig. 1.18(a)). In this way it is possible with this technique to produce braids with almost any fibre orientations and cross-section geometry in near net shape with minimum waste. Due to the possibility of changing the number of 'active' bobbins, the cross-sectional area and with that the geometry of the braid can be varied online (Schneider *et al.*, 2000). Another 3-D braider consisting of star-shaped rotors arranged in a matrix of multiple rows and columns was presented by Tsuzuki *et al.* (1991). In this machine (Fig. 1.19), four yarn carriers can surround a rotor and can move in four diagonal directions which are determined by the rotation of the rotors. The addition of axial yarns and the addition and subtraction of braider yarns allows for changes in fabric geometry and the ability to braid complex shapes.

Advantages of three-dimensional braided structures

- 3-D braiding has the ability to produce complex near-net-shape preforms.
- 3-D braiding processes can be automatically controlled, which increases production and preform quality.
- 3-D braided composites with a complex shape can be inexpensive and simple to manufacture.



(a) 3-D rotary braiding machine



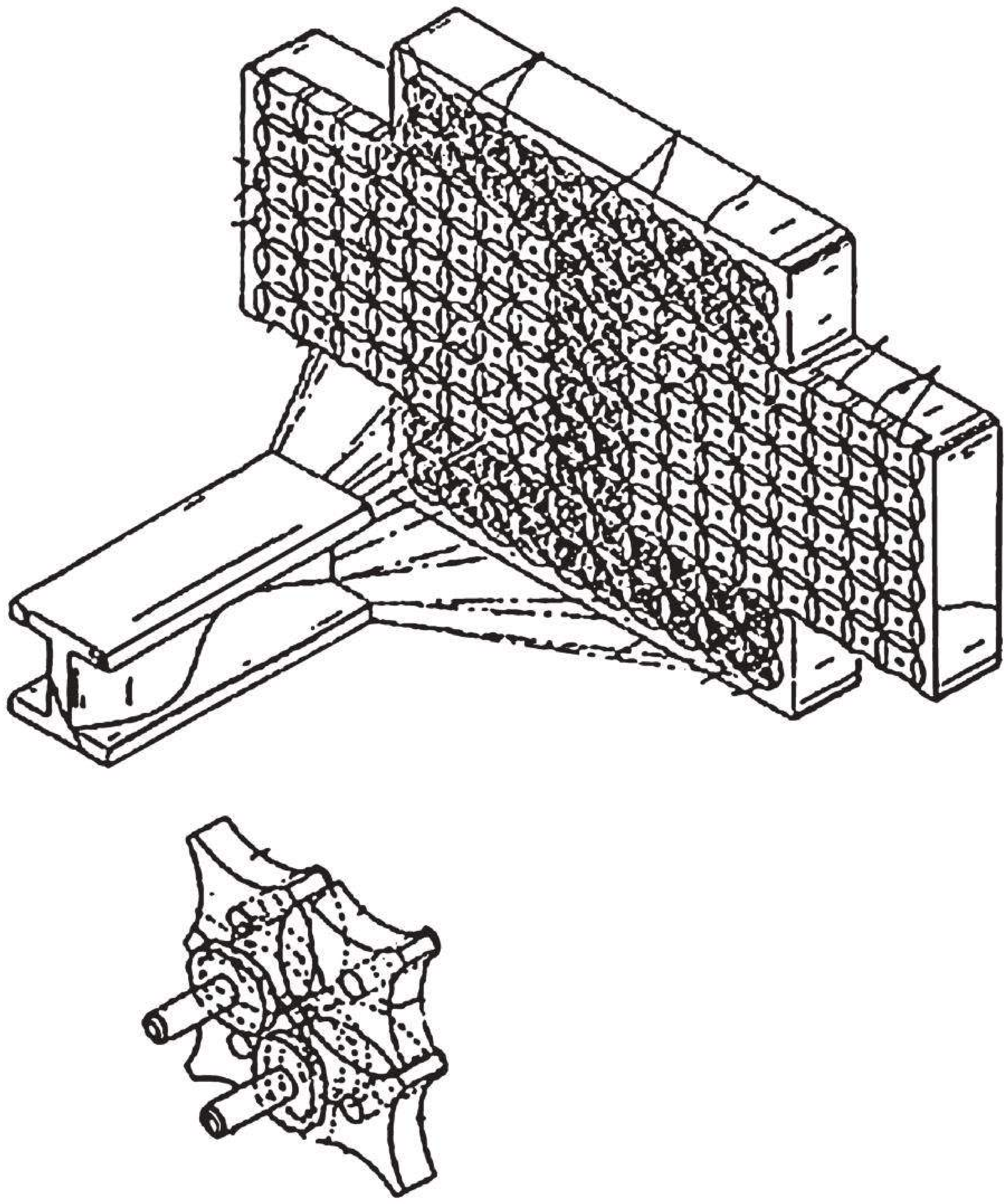
(b) 3-D braid formation

1.18 Principle of 3-D rotary braiding.

- 3-D braided composites have better delamination resistance and impact damage tolerance.
- 3-D braided composites are less sensitive to notches.

1.4.6 Three-dimensional stitched fabrics

The development of stitch-bonded, multiaxial fabrics has allowed for faster fabrication of parts with better physical and mechanical properties. Parts



1.19 Solid braiding apparatus of Tsuzuki *et al.* (1991).

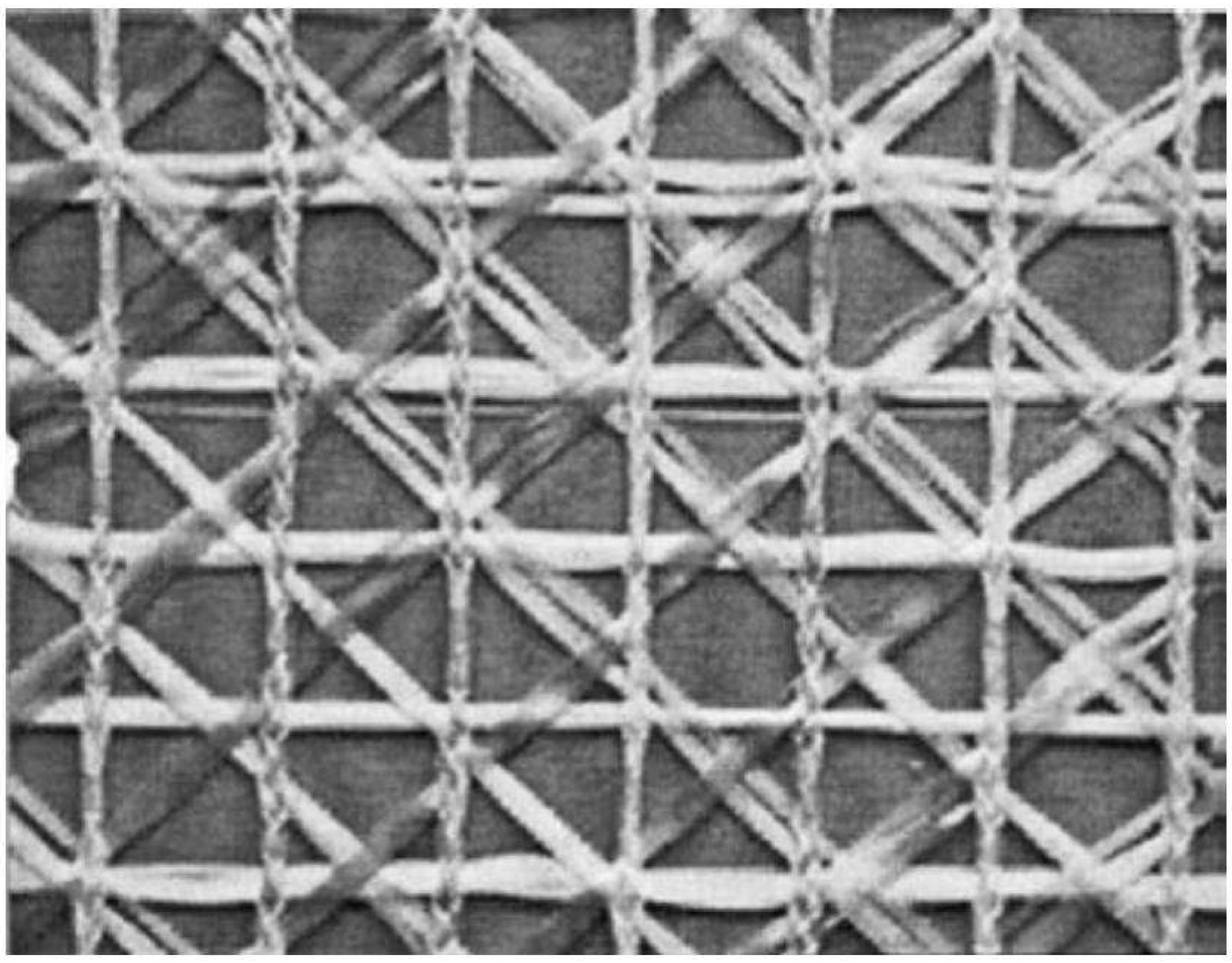
made from these structures have led to cost-effective solutions for a variety of applications including marine, transportation, infrastructure, sports and recreation, and aerospace. The cost-effective solution begins with engineering the laminate requirements at the point of fabric manufacture. Stitch-bonding of fabric is essentially an automated process and is highly efficient compared to a shop-fabricated laminate using unidirectional or woven fabrics.

Conventional fabrics are made by weaving fibres in two perpendicular directions (warp and weft). Weaving bends the fibres, reducing the maximum strength and stiffness that can be attained. When cut, fabrics also tend to fray, making them difficult to handle. Stitched fabrics offer several advantages over conventional woven fabrics. In the simplest case, woven fabrics can be replaced by stitched fabrics, maintaining the same fibre count and orientation.

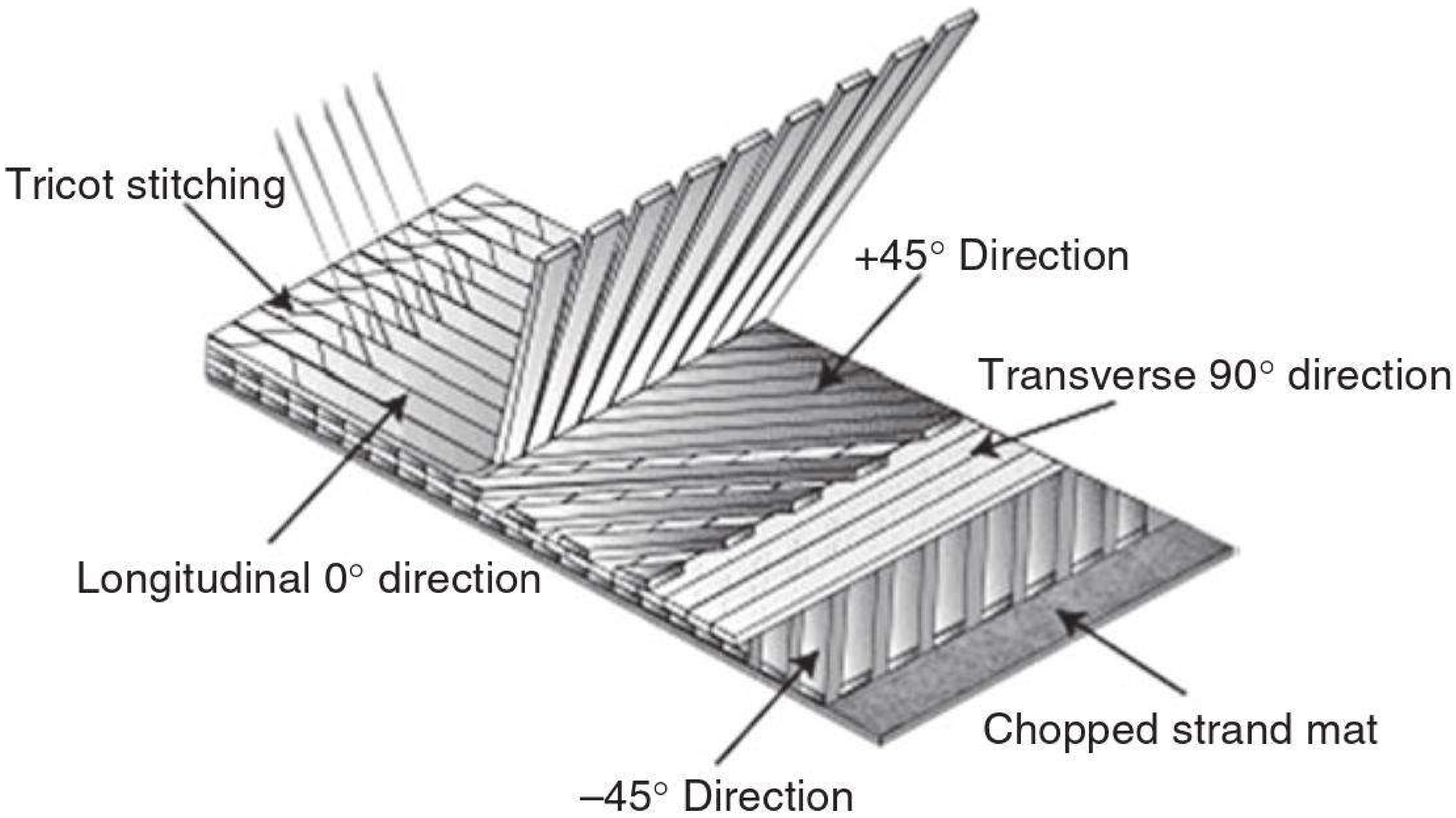
Stitch-bonded multi-plies

Multi-plies are fabrics consisting of one or more parallel and drawn layers of threads that can have different orientations. Stitch-bonded, multiaxial fabrics or, simply, stitched fabrics consist of several layers of unidirectional fibre bundles held together by a non-structural stitching thread, usually polyester. The fibres in each layer can be input at almost any angle between 0° and 90°. The entire fabric may be made of a single material, or different materials can be used in each layer for a hybrid fabric. A typical stitch-bonded fabric structure is shown in Fig. 1.20.

Multiaxial multi-plies have versatile properties such as drawn thread orientation, different angles between the layers, manifold layer composition and arbitrary mass. A stitch-bonded multiaxial multi-ply consists of several layers of reinforcing threads and a mesh structure – the warp knit. Up to eight layers can be combined with the orientation of the layers arranged as necessary (for example 0°, 90°, +45°, –45°: Fig. 1.21).



1.20 Stitch-bonded multiaxial multi-ply.



1.21 Stitch-bonded quadraxial fabric.

A typical quadraxial ply stack includes 0°, 90°, +45° and –45° plies. They are often made balanced (equal weight on all axes) but can also be tailored to suit a particular load case, such as for a typical boat-bottom panel where bending occurs mostly in the transverse direction. In this case quads are designed with more 90° fibre than the other axis. The 0° orientation is called the warp system and corresponds to the work direction. The other layers are called weft systems (Potluri *et al.*, 2003).

Stitch-bonded fabrics offer greater range and flexibility compared to woven fabrics, especially in the field of multiaxial (three plies or more). Multiaxial reinforcements can be engineered to meet specific requirements and perform multiple tasks such as providing good surface finish, impact and abrasion resistance, and structural integrity, all in one fabric (Hausding *et al.*, 2006).

Advantages of three-dimensional stitched fabrics

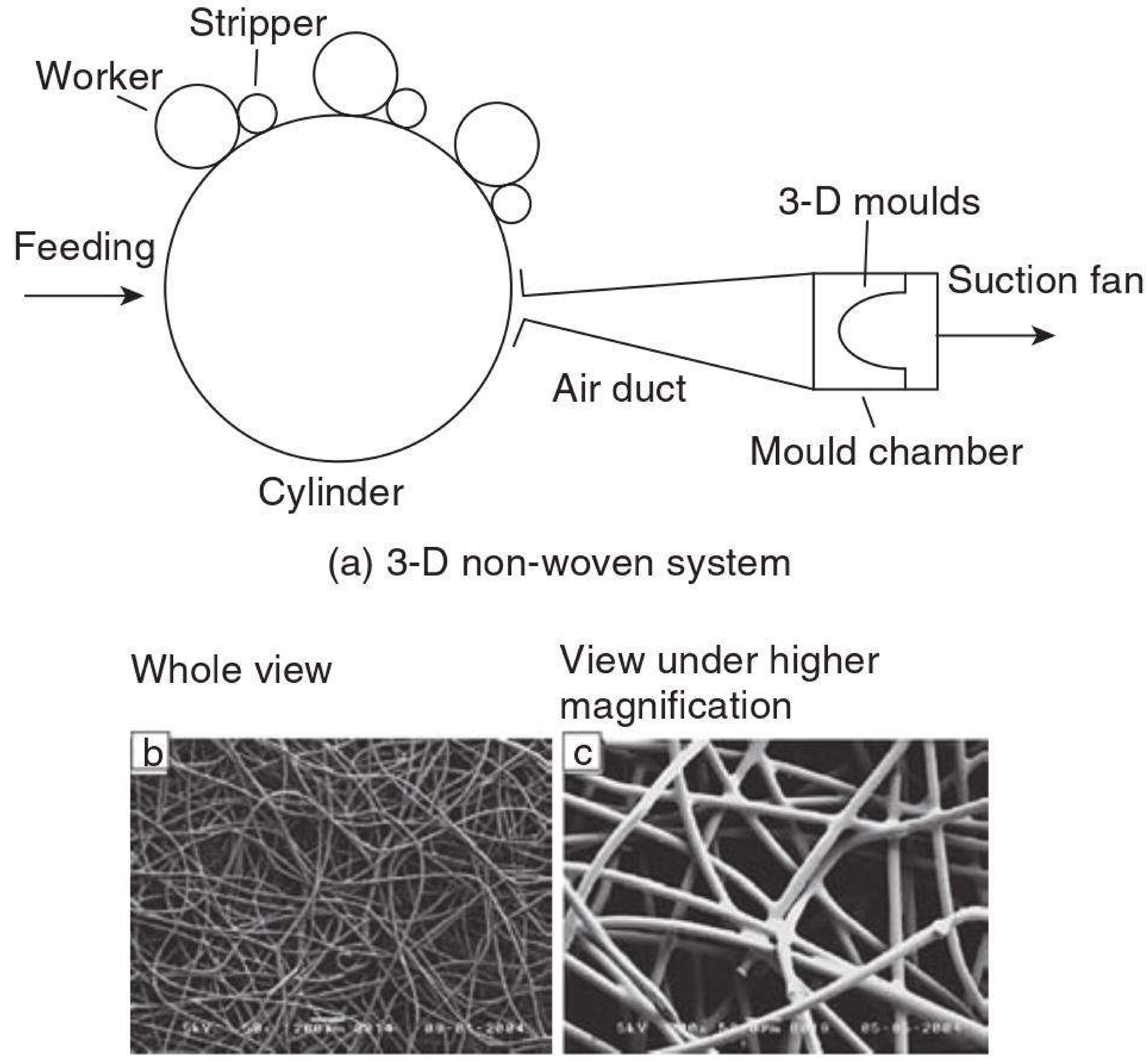
- inexpensive and simple to manufacture
- handling preforms (plies prevented from moving)
- better impact damage tolerance
- improved delamination resistance to ballistic impact and blast loading
- better interlaminar fatigue resistance
- improved joint strength under monotonic and cyclic loading.

1.4.7 Three-dimensional non-woven fabrics

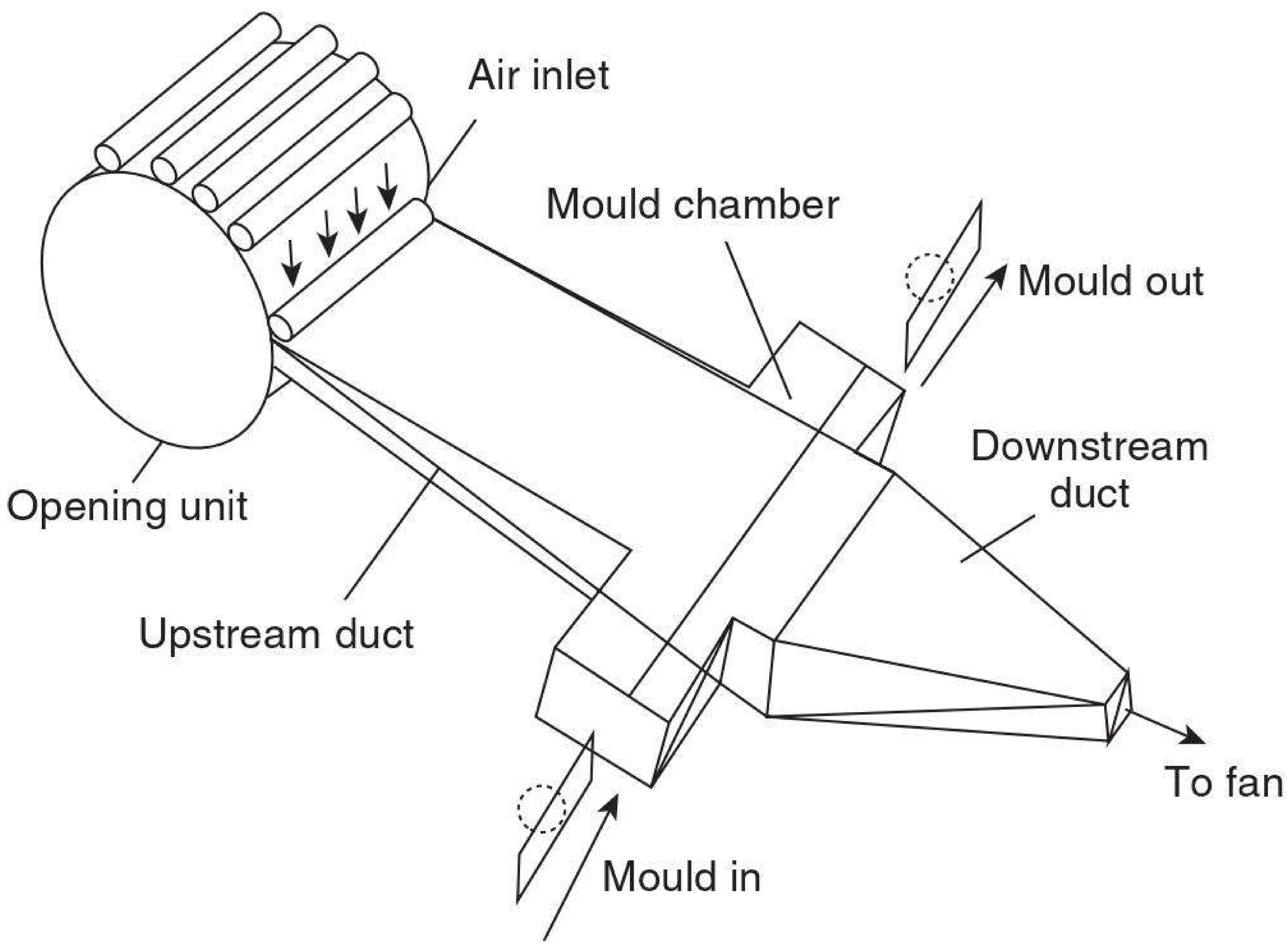
Non-wovens are widely used in technical applications such as fitted filters, preforms for composites and geotechnical equipment. Three-dimensional shaped non-woven products are currently constructed from flat webs. In addition to the high cost of the conversion processes, irregularity is inevitably introduced into the final product because of joints. There is a long history of 3-D non-woven reinforcements, primarily in carbon–carbon composites. Orthogonal 3-D materials are fabricated by fixing a series of yarns in one direction (or rods which will later be withdrawn and replaced by yarns) and then inserting planar yarns in the two orthogonal directions around the fixed yarns.

Most of the processes described in the literature are based on production of 3-D non-wovens using the regular manufacturing processes, i.e. needle punching, spun bonding, melt blowing, air laying, etc. Needle felts in 3-D form are a type of substrate that acquires its dimension or shape after fabric/web formation is complete (i.e. it is an additional process) via a moulding or thermoforming process. Air-laid technologies also exist that utilize air streams to blow or lay fibres on screens or moulds, thus providing a 3-D form during fabric/web formation. Melt blowing has similar capabilities. Molten polymer is extruded between two high-velocity laminar sheets of air, and fibre is collected on a drum (Wang *et al.*, 2007).

Gong *et al.* (2003) have described a method for producing 3-D non-wovens directly from fibres, thus eliminating the conversion processes required for many applications. The 3-D fibrous web is formed by air-laying and is then consolidated by heat through-air bonding. The process was based on the air-laying principle for web formation of thermal through-air bonding for web consolidation (Fig. 1.22(a)). The fibre-opening unit was modified from a roller card with a 1 m working width. Opened fibres were stripped off the main cylinder of the opening unit by and dispersed in airflow, then carried by the airflow through a transport duct to perforated 3-D moulds, which move across the machine during web formation. After moving out of the web-forming area, the 3-D web, carried on the mould surface, was moved into the bonding section for consolidation. After evaluating numerous bonding techniques, it was found that the thermal through-air method was the most appropriate because it could be readily adapted to suit different shapes and is very economical. In the bonding section, the 3-D web was stationary and hot air was drawn through it by a suction fan to bond the fibres. The time for which the 3-D web stays in the bonding chamber (the dwell time) is an important parameter that influences the bonding effect and also the cycle time. A minimum time was needed in order for the hot airflow to stabilize and for the temperature around the 3-D web to reach the desired level. Because the web-forming process was con-



1.22 Examples of 3-D non-woven structures.



1.23 3-D non-woven web forming by air-laying principle.

tinuous while the bonding is intermittent, fibre feed, mould movement and the bonding process had to be closely coordinated so that the area weight of web and the effects of bonding meet the preset requirements. Examples of 3-D non-woven structures are presented in Fig. 1.22(b) and (c).

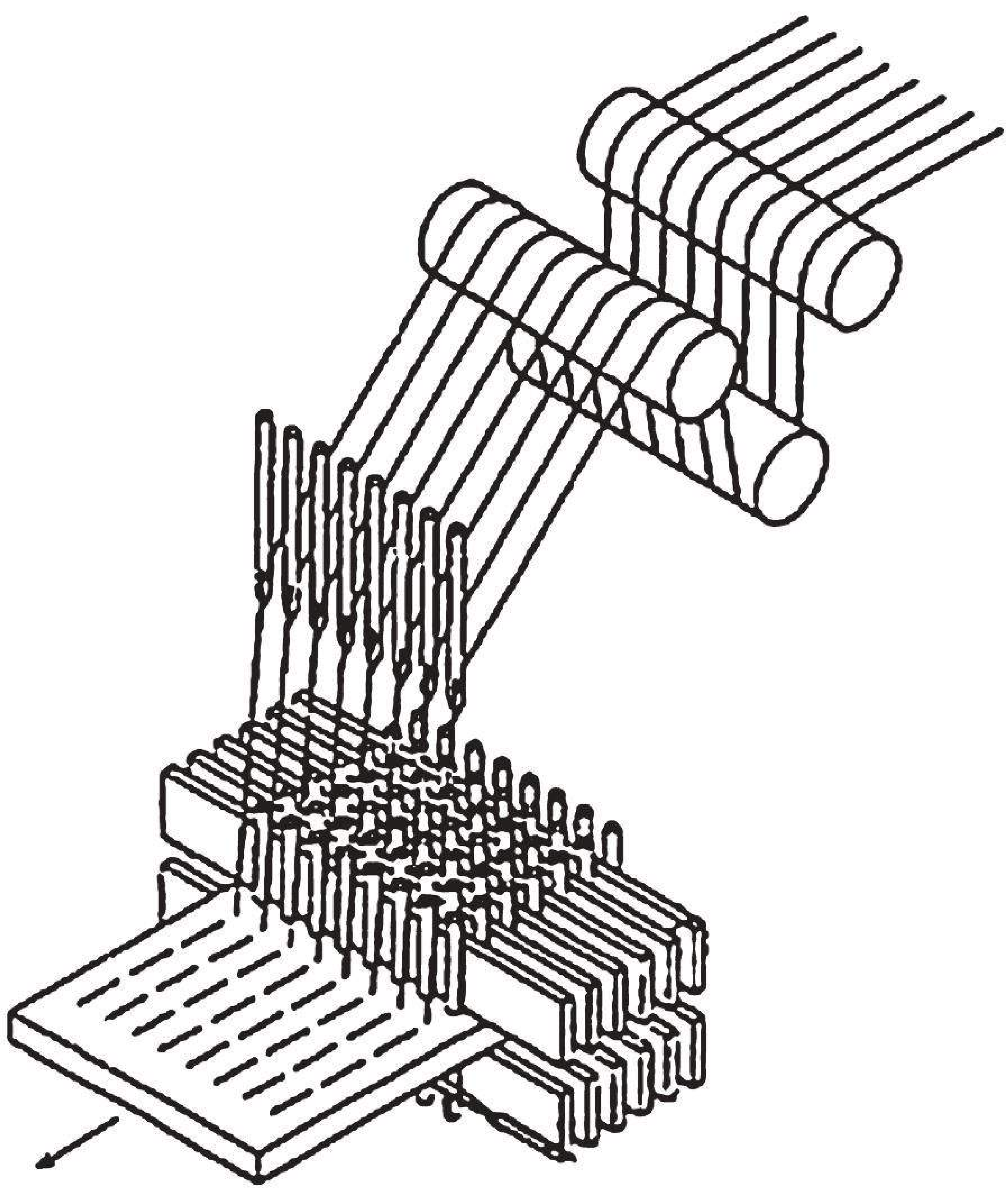
Production of 3-D non-wovens by the air-laying principle has been described by Ravirala and Gong (2003). In this process the 3-D non-woven products were produced directly from staple fibres using the air-laying principle. The fibres were deposited onto 3-D porous moulds before the fibrous web was consolidated to produce the final product. The web-forming process is schematically shown in Fig. 1.23.

The machine width was 1245 mm and the length of the upstream air duct was 1600 mm from the opening unit to the mould chamber. The fibres opened by the opening unit were transported by airflow through the upstream duct to the mould chamber, which had a vertical depth of 300 mm. The fibres were then deposited on the 3-D porous moulds as they moved across the machine in the mould chamber. As in flat webs, the distribution of fibres in the 3-D web is a key factor in determining the performance of the final product. However, in the process of forming flat webs, the angle between the airflow and the deposition surface is broadly the same over the web formation zone, while this angle varies greatly at different points of the 3-D mould surface. Because of flow angle variations, even when the airflow distribution is perfectly uniform, fibre deposition will be uneven around the 3-D mould. In order to produce an even product, the airflow must be regulated according to the shape of the mould.

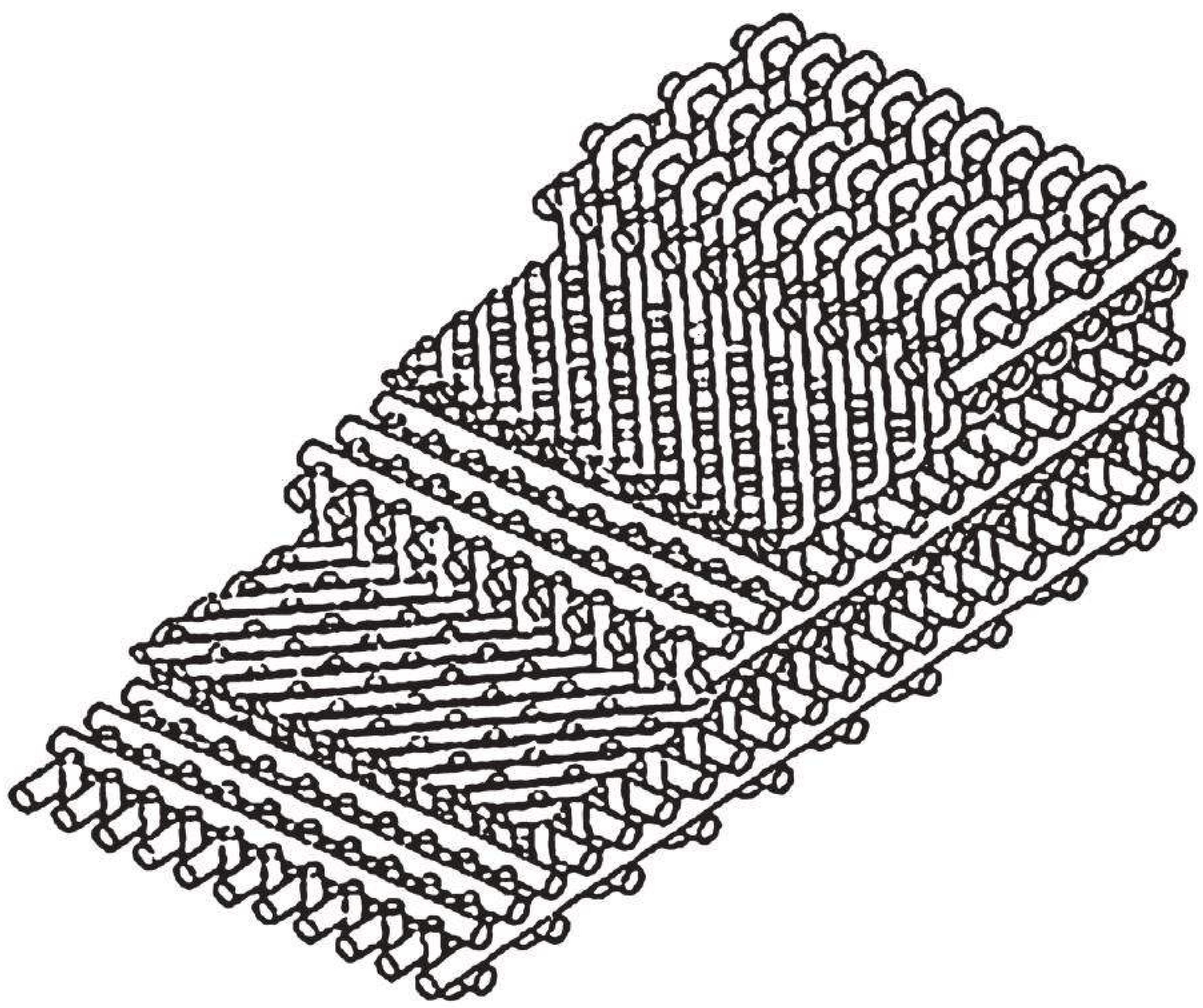
Production of 3-D fabrics by non-woven technology introduces through-thickness reinforcement without causing significant in-plane fibre damage

(Kamiya *et al.*, 2000). In an extensive review on recent advances in the fabrication and design of 3-D textile preforms, the above authors have presented different techniques of production of 3-D non-woven fabrics. A technique presented by Yasui *et al.* (1994) is shown in Fig. 1.24. In this technique, an array of pipes is arranged with predetermined spacing on a base plate. A line of yarn is then looped back and forth widthwise through the array of pipes. A second layer can then be formed by looping the yarn in a biased direction. In this manner, many layers of various orientations can be produced. The through-thickness yarns can then be introduced by stitching (or knitting) needles which are inserted into each pipe and pushed through the thickness of the fibre bed. As shown in Fig. 1.25, the yarns are looped over a selvedge yarn at the bottom of the fibre array, which effectively binds the preform together. By changing the base plate, various 3-D shapes can be formed.

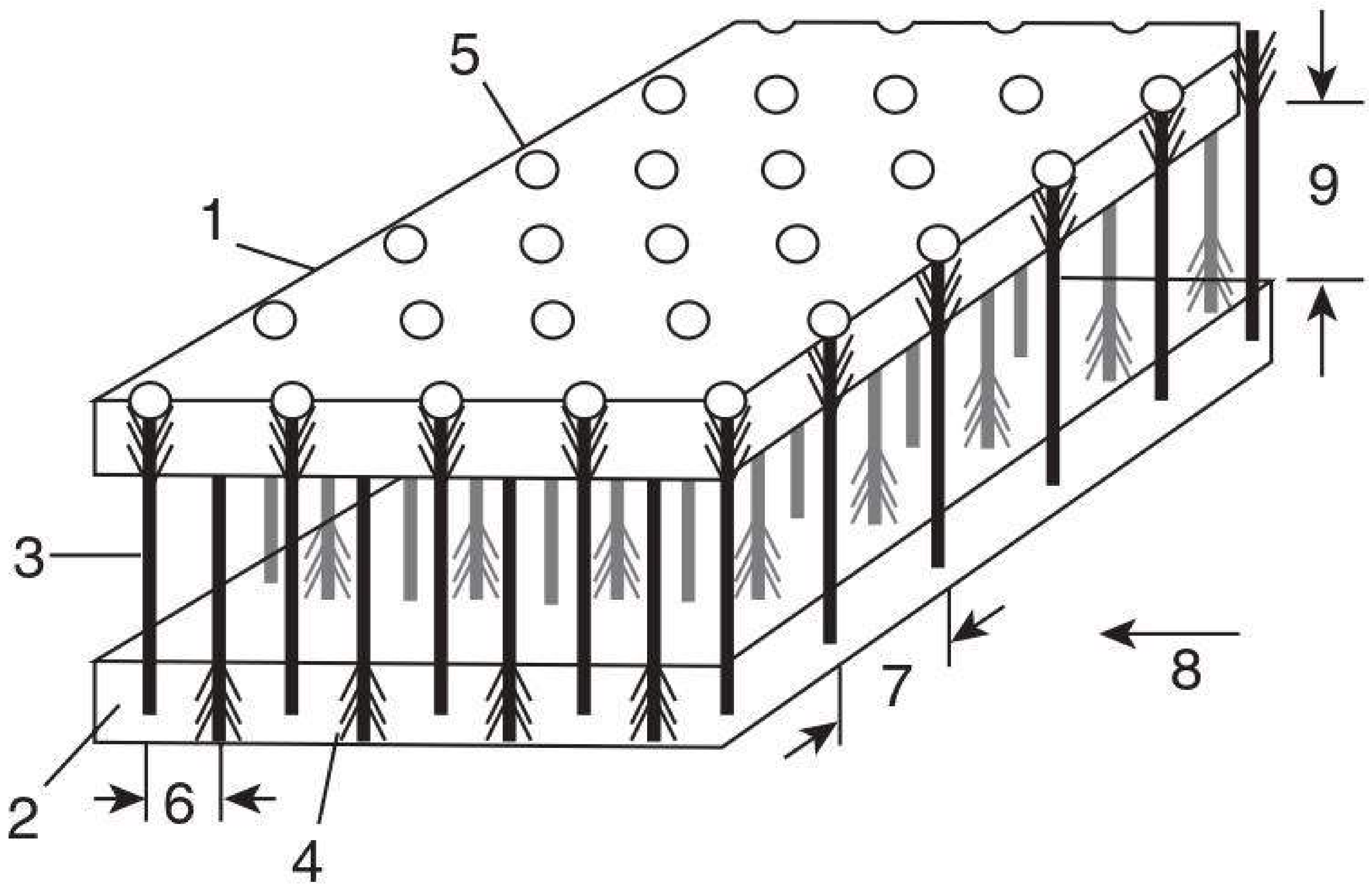
Three-dimensional non-woven structures can also be obtained by means of needle-punching two pre-needled non-woven layers with a defined space between, realized by mean of a spacer (Vasile *et al.*, 2006). Napco® is a technology that enables the manufacture of a 3-D spacer non-woven fabric with large hollow spaces, using 3-D Web Linker®, a special machine devel-



1.24 Non-woven apparatus (Yasui *et al.*, 1994).

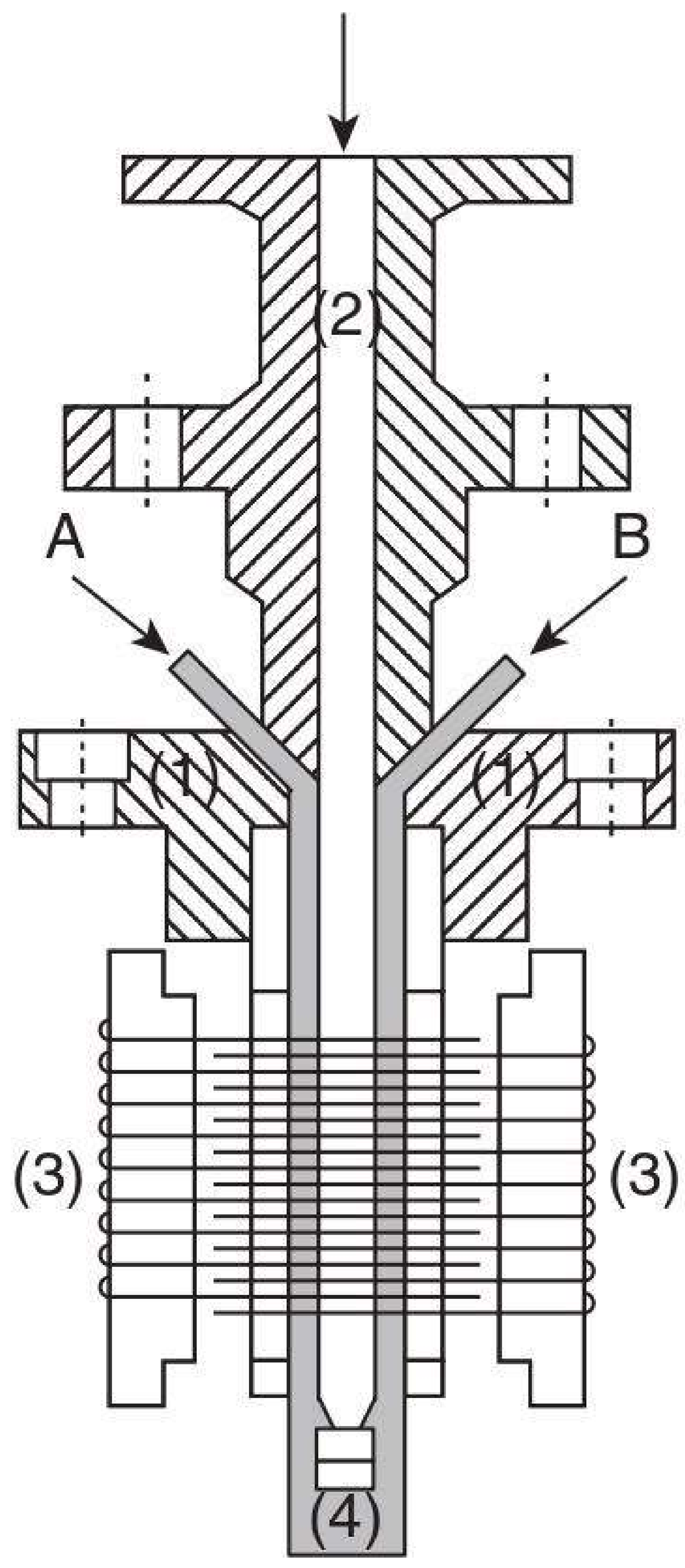


1.25 Non-woven fibre architecture.



1.26 Structure of Napco® 3-D non-woven fabric: 1 – top layer; 2 – bottom layer; 3 – connecting layer (bridge fibres from 1); 4 – bridge fibres from 2; 5 – needle stitch; 6 – distance between bridge fibres depending on stitch depth; 7 – distance between bridge fibres depending on needle density; 8 – take-out direction; 9 – product thickness depending on the spacer's width.

oped by Laroche. In this process, special barb or fork needles arranged in rows penetrate simultaneously from both sides of the two pre-needled non-wovens, creating fibre bridges formed by fibre bundles, and so the structure of the layers should contain enough unbounded fibres of sufficiently great fibre length. In Fig. 1.26, a schematic representation of a Napco® structure is shown, and a cross-section of the working zone of a 3-D Web Linker® machine that produces 3-D structures starting from two pre-needled mono-layers A and B can be seen in Fig. 1.27. This technology allows the production of unfilled 3-D non-wovens, as well as filled products (e.g. granulates, powders, tubes, paste, foam, textile wastes, etc.) for composites.



1.27 Machine cross-section: A and B – pre-needled non-woven monolayers; 1 – stripper plate; 2 – spacer tables; 3 – needle area; 4 – fibre bridges.

1.5 Conclusions

Three-dimensional fibrous assemblies constitute a whole family of textile structures manufactured using weaving, knitting, braiding and non-woven methods. They comprise structural preforms, which are fully integrated continuous fibre assemblies having multiaxial in-plane and out-of-plane fibre orientation. More specifically, a 3-D fabric is one that is fabricated by a textile process resulting in three or more yarn diameters in the thickness direction, with fibres oriented in three orthogonal planes. Among the large family of textile structures, 3-D fibrous assemblies have attracted the most serious interest in the aerospace industry and served as a catalyst in stimulating the revival of interest in textile composites. The engineering applications of 3-D composites originate from the use of carbon–carbon composites in aerospace. With the experience gained from 3-D carbon–carbon composites and the recent progress in fibre technology, the class of 3-D fabric structures is increasingly being recognized as a serious candidate for structural composites.

The ability to take complexity and labour out of manual composites fabrication processes through the innovative automation of engineered preforms is a key to more widespread use of composites. The trend is towards more control over fibre orientation and architecture while increasing productivity. This trend continues with the 3-D fibre assemblies discussed in this chapter. The 3-D weaving, knitting, braiding and non-woven processes and resulting preforms offer many advantages in both performance and economics. These 3-D fabrics will continue to gain acceptance as more companies recognize the value these materials offer. Technocrats using 3-D preforms could efficiently and accurately design totally new materials, novel manufacturing processes and new fabric structures to accelerate the fabric development process and foster innovation.

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2
Applications of three-dimensional textiles

Abstract: In an attempt to overcome many of the problems with the manufacture and mechanical properties of laminates, considerable attention has been given over the past 30 years to the development of advanced structures reinforced with 3-D fibre architectures. Among the large family of textile structures, 3-D fabrics have attracted the most serious interest in the aerospace industry and served as a catalyst in stimulating the revival of interest in textile composites. Considering the importance of 3-D fabrics, in this chapter some of the applications of 3-D woven, knitted, non-woven and braided fabrics to advanced composites, medical textiles, sports, geotextiles, space and protective garments are presented.

Key words: textile composites, multiaxial warp-knitted (MWK) fabrics, 3-D woven fabrics, applications of 3-D fabrics, geotextiles, automotives, sports, aerospace industry.

2.1 Introduction

Textile reinforcements have received widespread use as preforms in composites due to their flexibility to accommodate various reinforcing requirements. With the developments that have taken place in the aerospace industry, geotechnical fields, the composites industry and implantable medical devices, the use of high-performance textiles as reinforcements is increasing rapidly (Alagirusamy *et al.*, 2006). Developments in the field of preforming have led to the production of preforms with fibres oriented in different directions by weaving, knitting and braiding individually or in combination. Since reinforcements play a major role in dominating the mechanical properties of composites, the continuity and integrity of the architecture of fibre preforms becomes a main concern in advanced composites. Polymer laminates reinforced with a two-dimensional (2-D) layered fibre structure have been used with outstanding success for over 50 years in maritime craft, for about 30 years in aircraft and for nearly 20 years in high-performance automobiles and civil infrastructure laminates such as buildings and bridges.

Despite the use of 2-D laminates over a long period, their use in many structural applications has been limited by manufacturing problems and by some inferior mechanical properties. The manufacture of laminates can be expensive because of the high labour requirement in the manual lay-up of piles. As a result, many complex components need to be built from a number of machined laminate parts that must then be joined by co-curing, adhesive bonding or mechanical fastening. This is a major problem in the aircraft industry, where structures such as wings need to be made from a large number of smaller composite parts such as skin panels, stiffeners and stringers rather than being fabricated as a single integrated structure. Hence the use of 2-D structures in aircraft and automobiles has been restricted because of their inferior impact damage resistance and low through-thickness mechanical properties. In addition, these structures have low resistance to delamination cracking under impact loading because of their poor interlaminar fracture toughness.

In an attempt to overcome many of the problems with the manufacturing and mechanical properties of laminates, considerable attention has been given over the past 30 years to the development of advanced structures reinforced with 3-D fibre architectures. The development of advanced 3-D textile composites for specialized aircraft components began in the late 1960s, and since then these materials have attracted increasing attention because of their potential uses in aircraft, marine vessels, civil infrastructure and medical fields (Mouritz *et al.*, 1999). Considering the importance of 3-D fabrics, this chapter will present some of the applications of 3-D woven, knitted, non-woven and braided fabrics to advanced composites, medical textiles, sports, geotextiles, space and protective garments.

2.2 Application of three-dimensional fabrics to composites

Three-dimensional fabrics for structural composites are fully integrated continuous fibre assemblies having multiaxial in-plane and out-of-plane fibre orientation. More specifically, a 3-D fabric is one that is fabricated by a textile process resulting in three or more yarn diameters in the thickness direction with fibres oriented in three orthogonal planes. Among the large family of textile structures, 3-D fabrics have attracted the most serious interest in the aerospace industry and have served as a catalyst in stimulating the revival of interest in textile composites. The engineering applications of 3-D fabrics for composites date back to the late 1960s, and have their origin in aerospace carbon–carbon composites. Since most of these early applications were for high-temperature and ablative environments, carbon–carbon composites were the principal materials (Ko, 1989). In recent years, composites fabricated using reinforcements made with textile preforming processes, combined with cost-effective composite fabrication such as resin infusion, are being researched and developed at an ever-increasing pace. The increasing interest and use of textile composites, particularly 3-D textile composites, is attributed to improved performance due to controlled fibre distributions and lower cost through the use of automated textile processing equipment (Stobbe and Mohamed, 2003).

The expansion of the interest in 3-D fabrics for resin, metal and ceramic matrix composites is a direct result of the current trend in the expansion of the use of composites from secondary to primary load-bearing applications in automobiles, building infrastructures, surgical implants, aircraft and space structures (Chou and Ko, 1989). This requires a substantial improvement in the damage tolerance and reliability of composites. In addition, it is also desirable to reduce the cost and broaden the usage of composites from aerospace to automotive applications. This calls for the development of capability for quantity production and the direct formation of structural shapes. In order to improve the damage tolerance of composites, a high level of through-thickness and interlaminar strength is required. The reliability of a composite depends on the uniform distribution of the materials and consistency of interfacial properties. The structural integrity and handleability of the reinforcing materials for the composite is critical for large-scale, automated production. A method for direct formation of the structural shapes would therefore greatly simplify the laborious hand lay-up composite formation process. With the experience gained in 3-D carbon–carbon composites and the recent progress in fibre technology, the class of 3-D fabric structures such as woven, knitted, non-woven and braided forms is increasingly being recognized as important materials for advanced structural composites.

The attractions of advanced composites include their high ratio of strength to weight, their resistance to elongation under strain and their low coefficient of thermal expansion. These properties derive from the qualities of the reinforcement fibre and matrix material and of the interface between them and from the reinforcement provided by the fibre architecture (Mohamed, 1990). With the proper selection of materials and manufacturing technology, composites can be designed to outperform metals in any application.

The degree of a composite structural component dictates which fibre preform manufacturing technique should be employed. Knowledge of the load-carrying structural shape and fibre orientation determines which textile manufacturing technique is best suited for preform fabrication. It is obvious that an integrated, systematic approach, ranging from microstructural design, preform processing to performance characterization, is indispensable in the utilization of textile composites (Kamiya *et al.*, 2000).

2.2.1 Classification of textile preforms

There is a large family of textile preforming methods suitable for composite manufacturing (Ko, 1989). The key criteria for the selection of textile pre-

Table 2.1 Fibre architecture for composites

Level	Reinforcement system	Textile construction	Fibre length	Fibre orientation	Fibre entanglement
I	Discrete	Chopped fibre	Discontinuous	Uncontrolled	None
II	Linear	Filament yarn	Continuous	Linear	None
III	Laminar	Simple fabric	Continuous	Planar	Planar
IV	Integrated	Advanced fabric	Continuous	3-D	3-D

forms for structural composites are (a) the capability for in-plane multiaxial reinforcement, (b) through-thickness reinforcement and (c) the capability for formed shape and/or net shape manufacturing. Depending on the processing and end-use requirements, some or all of these features are required.

On the basis of structural integrity and fibre linearity and continuity, fibre architecture can be classified into four categories: discrete, continuous, planar interlaced (2-D) and fully integrated (3-D) structures. In Table 2.1 the nature of the various levels of fibre architecture is summarized (Scardino, 1989).

A discrete fibre system such as a whisker or fibre mat has no material continuity; the orientation of the fibres is difficult to control precisely, although some aligned discrete fibre systems have recently been introduced. The structural integrity of the fibrous preform is derived mainly from interfibre friction. The strength translation efficiency, or the fraction of fibre strength translated to the non-aligned fibrous assembly of the reinforcement system, is quite low.

The second category of fibre architecture is the continuous filament, or unidirectional (0°) system. This architecture has the highest level of fibre continuity and linearity, and consequently has the highest level of property translation efficiency and is very suitable for filament-wound and angle ply tape lay-up structures. The drawback of this fibre architecture is its intra- and interlaminar weakness owing to the lack of in-plane and out-of-plane yarn interlacings.

A third category of fibre reinforcement is the planar interlaced and interloped system. Although the intralaminar failure problem associated with the continuous filament system is addressed with this fibre architecture, the interlaminar strength is limited by the matrix strength owing to the lack of through-thickness fibre reinforcement.

The fully integrated system forms the fourth category of fibre architecture wherein the fibres are oriented in various in-plane and out-of-plane directions. With the continuous filament yarn, a 3-D network of yarn bundles is formed in an integral manner. The most attractive feature of the integrated structure is the additional reinforcement in the through-thickness direction which makes the composite virtually delamination-free. Another interesting aspect of many of the fully integrated structures such as 3-D woven, knits, braids and non-wovens is their ability to assume complex structural shapes.

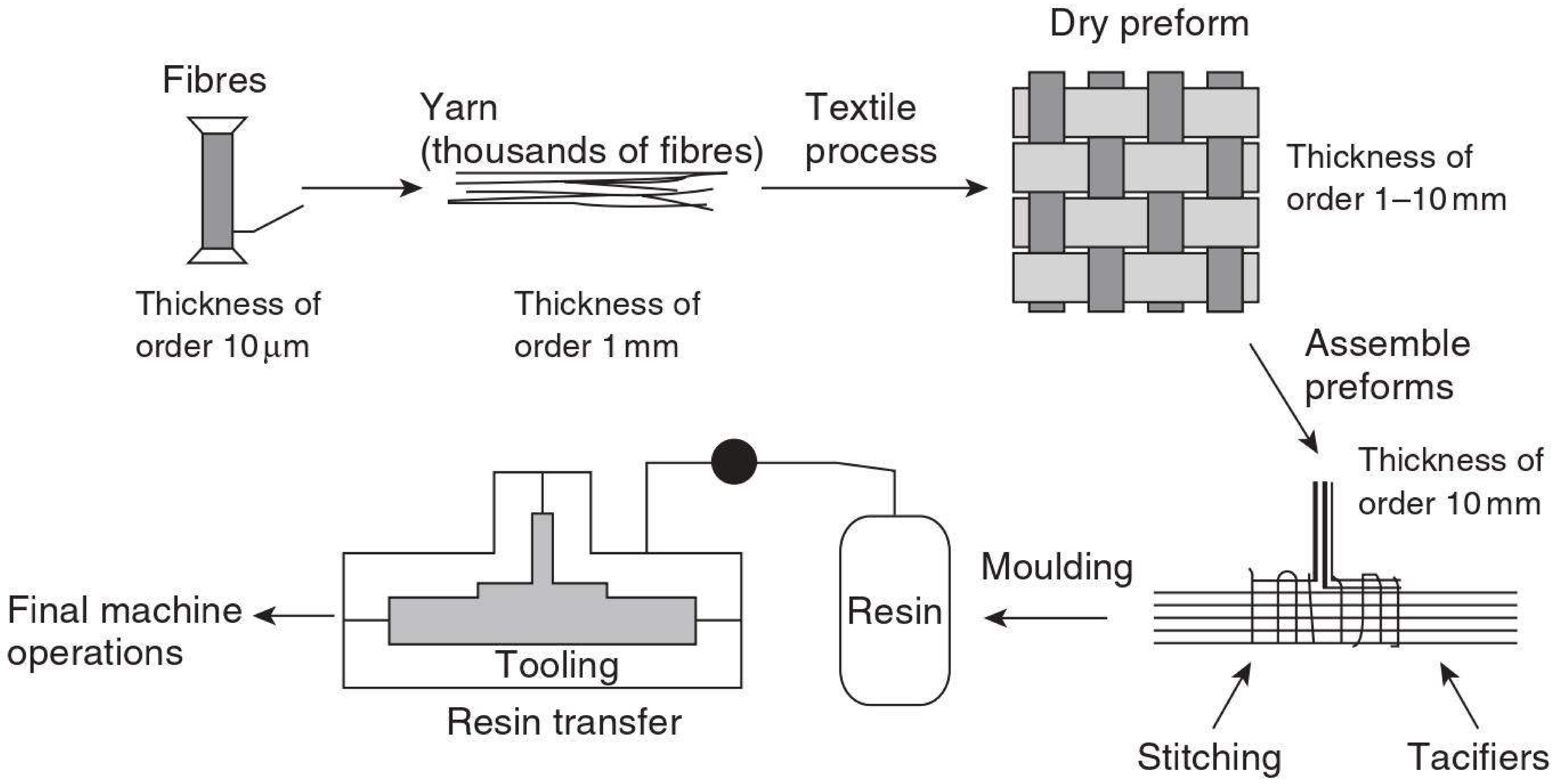
From the point of view of preform fabrication and the macrostructural geometry of the textile preforms, textile structural reinforcements can be classified according to the axis of fibre or yarn introduction and geometric dimension (Fukuta *et al.*, 1984). As shown in Table 2.2, the axis, or the direction of yarn introduction, is divided into 0 (or 'non-axial'), monoaxial, biaxial, triaxial and multiaxial systems for reinforcements; in the last case, yarns are introduced from four or more directions.

2.2.2 Processing of textile composites

The first processing step is the formation of yarns from fibres. Figure 2.1 illustrates scales in one textile process. The part shown is an integrally

Table 2.2 Types of reinforcement

Dimension \ Axis		0 Non-axial	1 Monoaxial	2 Biaxial	3 Triaxial	4~ Multiaxial
1-D			Roving yarn			
2-D		Chopped strand mat	Pre-impregnation sheet	Plain weave	Triaxial weave	Multiaxial weave, knit
3-D	Linear element		3-D braiding	Multi-ply weave	Triaxial 3-D weave	Multiaxial 3-D weave
	Plane element		Laminate type	H or I Beam	Honeycomb type	



2.1 Production process of a textile composite.

formed skin/stiffener assembly. In the second step, the yarns are woven into plain woven cloth. The cloths are then laid up in the shape of the skin and stiffener and stitched together to create an integral preform. Finally, the composite part is consolidated by the infiltration of resin and curing in a mould.

There are many techniques available today for manufacturing thermoset composite parts. Some are still very low-tech and labour intensive, while some involve very sophisticated tooling and computer controls. However, all of these processes share some of the same challenges and requirements. They all consist of a tool to hold the fabric in the correct position while the resin is curing, and require some means of forcing the resin into the fabric. The major differences in the processes are the resulting part quality, limitations in size and geometry, cost of tooling, and process time.

The most basic and labour-intensive process is known as hand lay-up. In hand lay-up fabric is placed onto a tool where resin is applied by hand using rollers and squeegees. Each ply must be saturated as it is applied to the tool to ensure that no bubbles are left between plies. This makes hand lay-up very time consuming, but it does have its advantages. Carefully applying resin to each ply can ensure a part without dry spots. Unfortunately, the process is not performed under vacuum so micro-porosity is possible. Hand lay-up is very attractive due to the low cost of the tooling required. Since there is no pressure applied to the tool, it does not have to be very robust, and can be made out of a variety of materials. In many cases, the tool will have only one side to produce a nice finish on the outside of the part. Hand lay-up can also be used to produce very large parts. As long as there are enough people to apply the resin to the fabric before it cures, there are really no limitations on the size of the part. Hand lay-up is currently the most utilized method of manufacture for large wind turbine blades. Unfortunately, there are also many disadvantages to hand lay-up. The most obvious is the labour cost. In addition, the application of the resin in an open environment allows very volatile emissions to escape from the resin that can be harmful to humans and to the environment (Skramstad, 1999). It is anticipated that the use of hand lay-up for wind turbines will eventually be restricted due to the high volume of emissions. Other disadvantages are lower dimensional tolerances, poor fatigue performance, and less aerodynamic surfaces. Even with these considered, hand lay-up is still the fastest and cheapest way to produce a small number of composite parts with few defects, but the process is limited.

Beginning in the 1950s, more industrialized processes began to evolve for use on aircraft. These processes are generally referred to as resin transfer moulding processes, or RTM. In RTM the fabric is laid into a tool where the resin is forced into the fabric under pressure. These processes have several advantages over the hand lay-up process. The process has the potential to be more repeatable and consistent since the human involvement is reduced. This reduction in human involvement also reduces labour costs. In addition, the amount of volatile emissions is reduced. Much higher fibre contents can also be achieved, since the tool can clamp down on the fibre preform. Dimensional tolerances can also be increased if the tool is two-sided (Gebart, 1992). The disadvantages are the cost of the mould and the difficulty in forcing the resin through the fabric.

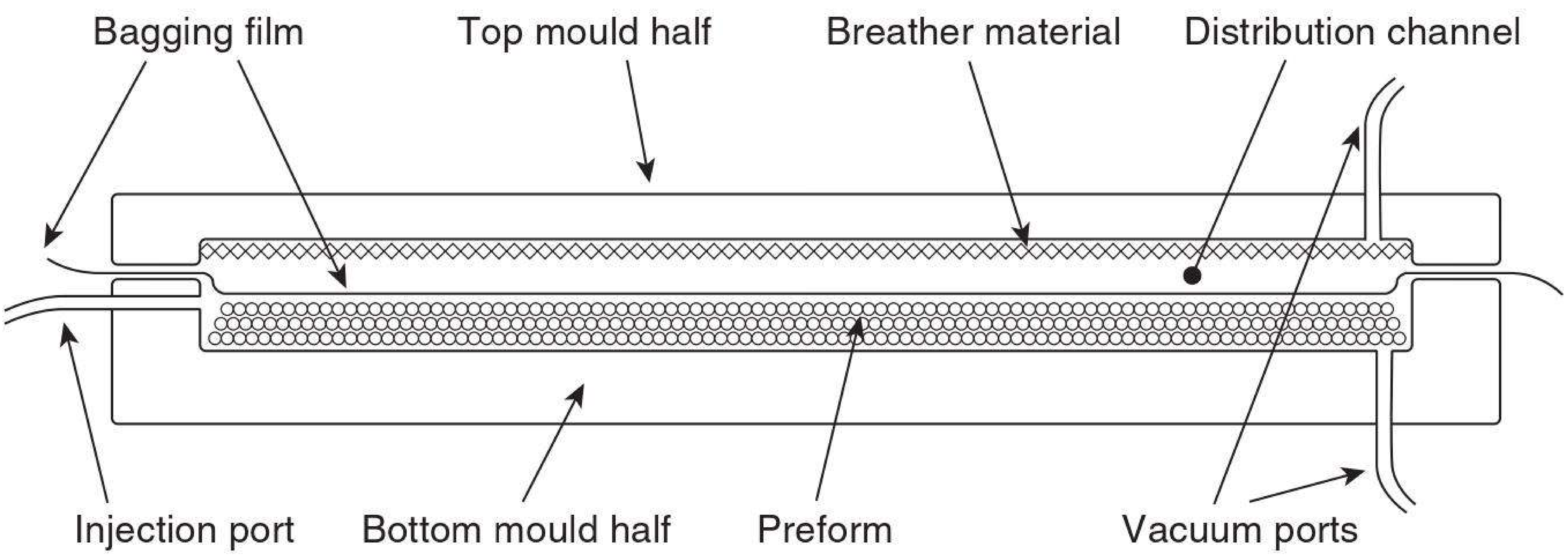
Modifications of the RTM process have been developed recently that reduce these disadvantages. Although there are many variants being used today, they all deal with these problems in a similar manner. Lower tool costs are achieved with the use of one-sided moulds. In these processes a vacuum is drawn on the fabric, while a flexible bagging is forced against the preform by atmospheric pressure. To deal with the problem of getting the resin to flow large distances through the fabric, a distribution network is used. This distribution network allows the resin to flow through high-permeability channels or layers to disperse it throughout the mould. The resin must then flow a much shorter distance in the plane or though the thickness of the part. Several variants of these processes are described in detail by Larson (2004) and will be discussed briefly here.

One process that has been successfully used on large structures is the Seemanns Composite Resin Infusion Molding Process (SCRIMP™). This process has been used since the 1980s and its use continues to increase. There are several variations of SCRIMP. One uses a series of channels above the fabric for resin distribution, and the resin is then forced to flow in the plane of the fabric between the channels. In other variants, a high-permeability layer may be placed over the fabric for resin distribution. The resin is then forced to flow though the thickness of the fabric. This layer is then peeled off after the process is complete. SCRIMP is capable of producing large parts very quickly, cheaply, and with high fibre volume fractions (Han, *et al.*, 2000).

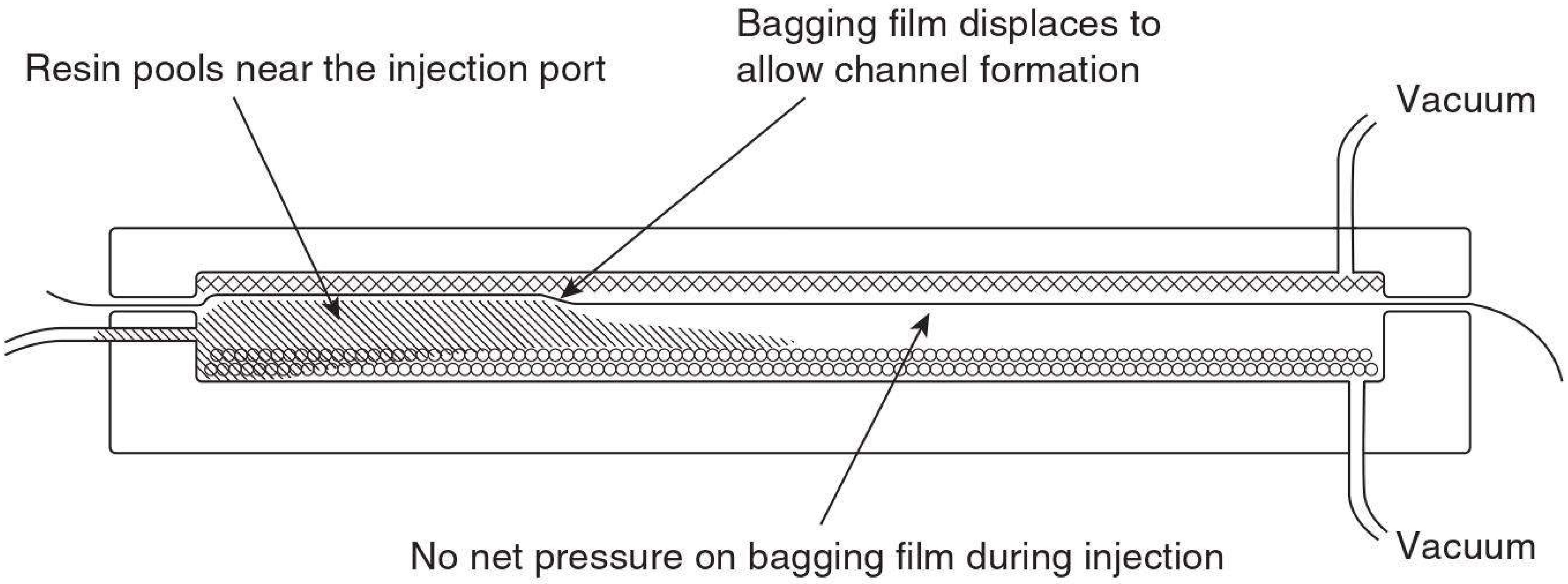
A very similar process known as the Fast Remotely Actuated Channeling process (FASTRAC) is a more recent variation of this general principle. The main difference in the FASTRAC process compared to SCRIMP is a more refined distribution strategy. The distribution network is created by a 'FASTRAC layer' which is a flexible membrane with tightly spaced channels formed into it. The major difference is that these channels can be collapsed to force the extra resin though the fabric or out of the mould, rather than leaving them attached to the part as in SCRIMP. The FASTRAC layer also allows a positive pressure to be applied to the fabric to achieve even higher fibre volume fractions.

A process very similar to FASTRAC was developed by Larson which will be referred to as pressure bag moulding. In pressure bag moulding the distribution system is a channel that covers the whole surface of the fabric. Once the resin fills the channel, pressure is applied to a flexible film to force the resin into the fabric as in FASTRAC. In order to apply a positive pressure to the bagging, a second tool half is required. Although this adds an additional cost in the tooling, the second mould half would not require the surface finish and dimensional tolerance that the first half would. The mould for this process is illustrated in Figs 2.2 and 2.3. In these figures the flow channel is just empty space; however, it could also represent a highly permeable layer as in SCRIMP or FASTRAC.

Of the processes examined, the FASTRAC and pressure bag moulding process have been identified as having the largest injected volume per port. This is due to the fact that the distribution system covers the whole part.



2.2 Schematic for pressure bag moulding.



2.3 Pressure bag moulding during stage one.

For this reason, these processes are the most viable for large wind turbine blades, and will be the focus of this study. For future modelling this process will be described in two stages. Stage one consists of injecting the resin into the mould, and stage two is when pressure is applied to the bagging to force the resin through the thickness.

A summary of several of the processes described is presented in Table 2.3. Due to their similarity, the FASTRAC and pressure bag moulding processes are presented together.

2.2.3 Three-dimensional woven fabrics

Woven fabrics are probably by far the most commonly used form of textile composites in structural applications (Laroche and Vu-Khanh, 1994). Very good drapability, complex shape formation with no gap and reduced manufacturing cost are the main features of woven fabrics. They generally exhibit good dimensional stability in the warp and weft directions, offer highest cover or yarn packing density, and provide higher out-of-plane strength which can carry the secondary loads due to load path eccentricity, local buckling, etc. In addition, woven fabrics generally have a very low shear rigidity which gives a very good formability. However, they offer anisotropy, and relatively less extensibility for deep draw moulding compared to knitted and braided fabrics, and they are poor in resisting in-plane shear (Tan *et al.*, 1997). Most of the pure and hybrid woven fabrics used in textile composites are simple 2-D fundamental weaves, i.e., plain, twill and satin weaves.

The process of weaving is suited for the production of flat panels, and woven fabrics have been used for a number of years in 2-D laminated composites. However, these composites exhibited poor impact resistance, delamination strength and reduced in-plane shear properties, since typical

Table 2.3 Summary of manufacturing process details

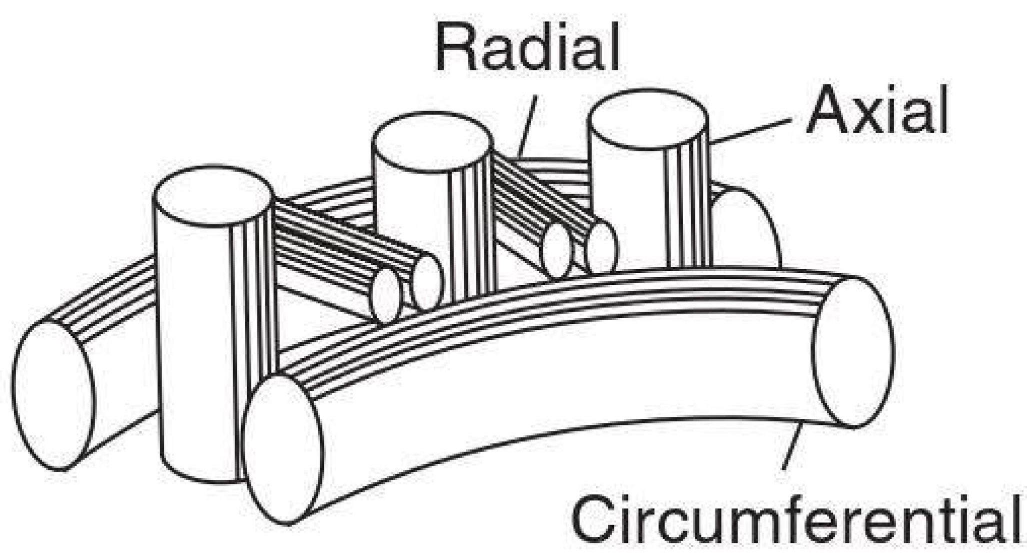
Process	Basic principles	Advantages	Disadvantages
Hand lay-up	Open mould Manual infusion One-sided mould	Low cost Fastest implementation	Volatile emissions Health risks Inconsistent results Less efficient material usage
RTM	Closed mould In-plane resin flow Two-sided mould	Higher dimensional consistency Less volatile emissions Both sides finished	Higher mould cost Resin flow pattern critical Costly equipment required Lowest volume per port
VARTM	Closed mould In-plane resin flow Two-sided mould Evaluated mould	Higher dimensional consistency Less volatile emissions Both sides finished Higher quality products than RTM	Higher mould cost Resin flow behaviour critical Costly equipment required Complexity of vacuum porting
SCRIMP™	Closed mould In-plane resin flow One-sided mould Evaluated mould	Higher dimensional consistency Less volatile emissions Higher quality products than RTM	Proprietary process One side finished
FASTRAC + pressure bag	Closed mould Channel flow One side critical Evaluated mould	High quality High dimensional consistency Less volatile emissions Largest injection volume per port	Added cost of FASTRAC layer or top mould half Highest complexity Possible artefacts from bag Costly equipment required

2-D weaves possess fibres only in the 0° (warp) and 90° (weft) directions. To improve the impact and interlaminar properties, through-thickness reinforcement was required. This was accomplished by the use of multilayer 3-D weaving by angle-interlock weaves which use fibres to either weave together adjacent fabric layers (layer-to-layer interlock) or weave together all fabric layers (through-thickness interlock) (Kamiya *et al.*, 2000). These fabrics are produced principally by the multiple warp weaving method, which has long been used for the manufacture of double cloth and triple cloths for bags, webbings and carpets. The bending and friction resulting from the shedding motion and beat-up motion inherent to this weaving process tend to damage the high modulus yarns for the 3-D fabrics (Ko, 1989). The woven fibre architectures commonly used in 3-D woven composites are composed of several series of warp and weft yarns that form distinct layers, one above the other. The fabrics can be woven with a space between layers (core fabrics) or woven as thick, dense structures. The layers can be bound together by interlacing warp ends in the structure with the weft of adjacent layers (angle interlock) or by having the ends interlaced between the face and back layers (warp interlock). The binding yarns may also interlace vertically between the layers, producing an orthogonal weave (Mohamed, 1990).

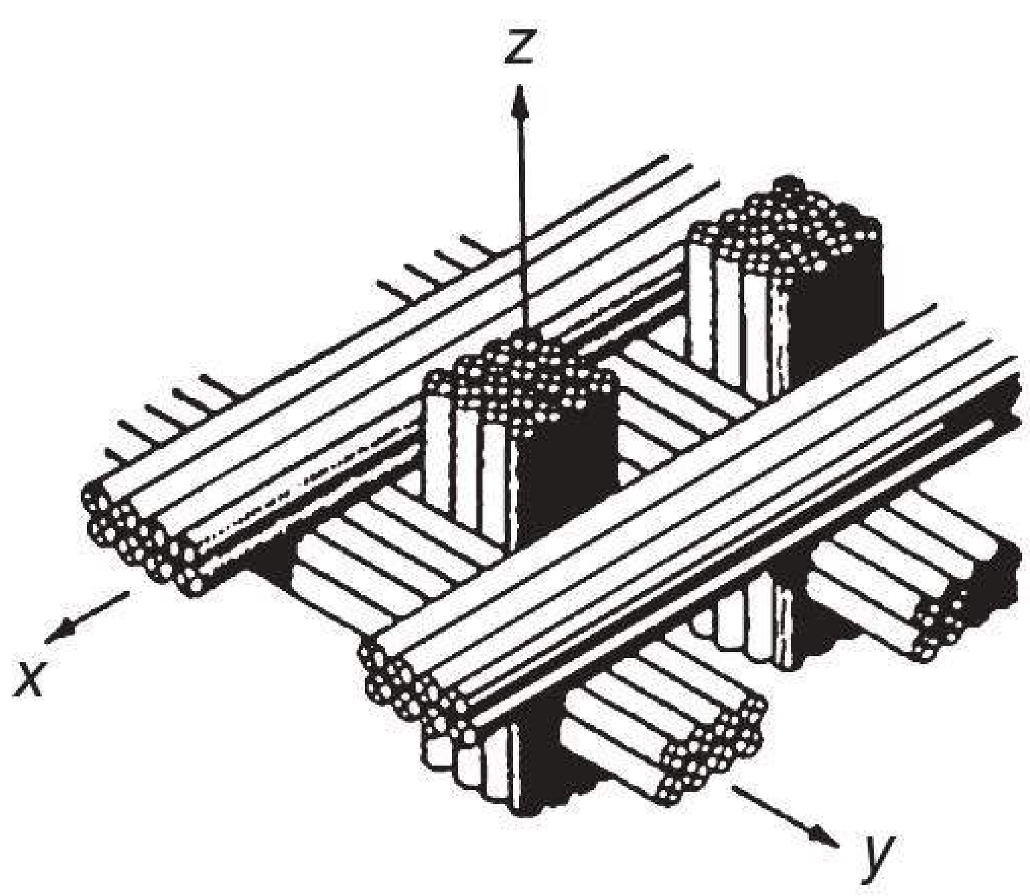
The angle-interlock woven fabrics consist of three sets of yarns. The stuffers (warp yarns) and warp weavers are oriented along the longitudinal direction, i.e., along the loom feed direction. The fillers (weft yarns) are oriented transverse to the loom feed direction, and are inserted between layers of stuffers. The stuffers and fillers form an orthogonal array. The warp weavers traverse through the thickness of the weave, and interlock with filler layers. The warp weavers crisscross the weave thickness at off-axis angles. Different weave geometrical parameters are yarn size, yarn spacing, yarn distribution, interlock lengths and depths. There are two main types of angle-interlock preforms: through-thickness angle interlock weave (TTAW) and layer-to-layer angle interlock weave (LLAW). The TTAW is a multi-layered preform in which warp weavers travel from one surface of the preform to the other, holding together all the layers of the preform. The LLAW is a multilayered preform in which warp weavers travel from one layer to the adjacent layer, and back. A set of warp weaves together hold all the layers of the preform (Naik *et al.*, 2002).

Angle-interlock or multilayer fabrics for flat panel reinforcement can be woven on traditional looms, mostly on shuttle looms. The warp yarns are usually taken directly from a creel. This allows mixing of different yarns in the warp direction. Other, more complex 3-D fabrics such as polar and orthogonal weaves require specialized weaving machines.

In polar weave structure, fibres or yarns are placed equally in circumferential, radial and axial directions. The fibre volume fraction is around 50%. Polar weaves are suitable for making cylindrical walls, cylinders, cones and convergent–divergent sections. To form such a shape, prepreg yarns are inserted into a mandrel in the radial direction. Circumferential yarns are wound in a helix and axial yarns are laid parallel to the mandrel axis. Since the preform lacks structural integrity, the rest of the yarns are impregnated with resin and the structure is cured on the mandrel. Polar weaves can be woven into near-net shapes. A near-net shape is a structure that does not



2.4 Polar weave.



2.5 Orthogonal weave.

require much machining to reach the final product size and shape. A polar weave structure is shown in Fig. 2.4 (Adanur, 1995).

In orthogonal weave, reinforcement yarns are arranged perpendicular to each other in the *x*, *y* and *z* directions. No interlacing or crimp exists between yarns. The fibre volume fraction is between 45% and 55%. By arranging the amount of yarn in each direction, isotropic or anisotropic preforms can be obtained. Except for the components that are fundamentally Cartesian in nature, orthogonal weaves are usually less suitable for net shape manufacturing than the polar weaves. The unit cell size can be smaller than in polar weaves, which results in superior mechanical properties. Since no yarn interlacing takes place in polar and orthogonal structures, they are also referred to as 'non-woven' 3-D structures in the composites industry. However, it is more proper to label these structures as woven structures with zero level of crimp. A typical orthogonal weave structure is shown in Fig. 2.5 (Adanur 1995).

One of the most promising, recently developed textile processes is a new form of 3-D weaving (Brandt *et al.*, 1992; Dickinson *et al.*, 1999) being commercialized under the trademark 3WEAVE™ by 3TEX, Inc. With completely controlled and tailorable fibre orientations in the *x*, *y* and *z* directions, the ability to weave aramid, carbon, glass, polyethylene, steel fibres, etc. and any hybrid combination, at thicknesses up to one inch (2.54 cm) and widths up to 72 inches (183 cm), and the ability to make net shapes, an almost infinite number of 3WEAVE materials are possible with a tremendously wide range of performance (Mohamed *et al.*, 2001). Although these materials are typically more expensive than 2-D fabrics and mats, reduction of labour, higher performance and improved process efficiency result in overall cost savings in a variety of applications. When compared on a cost per square foot of finished composite structure, 3WEAVE reinforcements consistently outperform traditional 2-D materials.

Preforms made by the 3WEAVE process provide several important advantages in composites fabrication. The most obvious advantage of this material shows in manufacturing thick composites, owed to a dramatically reduced labour time, when multiple layers of 2-D fabric plies are replaced by one or a few 3WEAVE plies to obtain the required thickness in a composite structure. In many cases, a single 3WEAVE layer can replace multiple 2-D layers (Singletary and Bogdanovich, 2001).

It is natural to expect that the processing advantages of thick 3WEAVE preforms come at the expense of reduced conformability. In fact, it has been demonstrated that these preforms conform as well as or better than the most conformable 2-D fabrics. The absence of interlacing between warp and filling yarns allows the fabric to bend and internally shear rather easily, without buckling within the in-plane reinforcement (Mohamed *et al.*, 2003).

A fully automated 3-D weaving process with simultaneous multiple filling insertions has been developed at the North Carolina State University College of Textiles (Dickinson and Mohamed, 2000). This process is inherently 3-D from the onset, and does not involve the building up of layers one layer at a time. Rather, a single unit of thick fabric is formed during each weaving cycle. The essence of the innovation/patent centres around this simultaneous multiple insertion from one or both sides of the fabric.

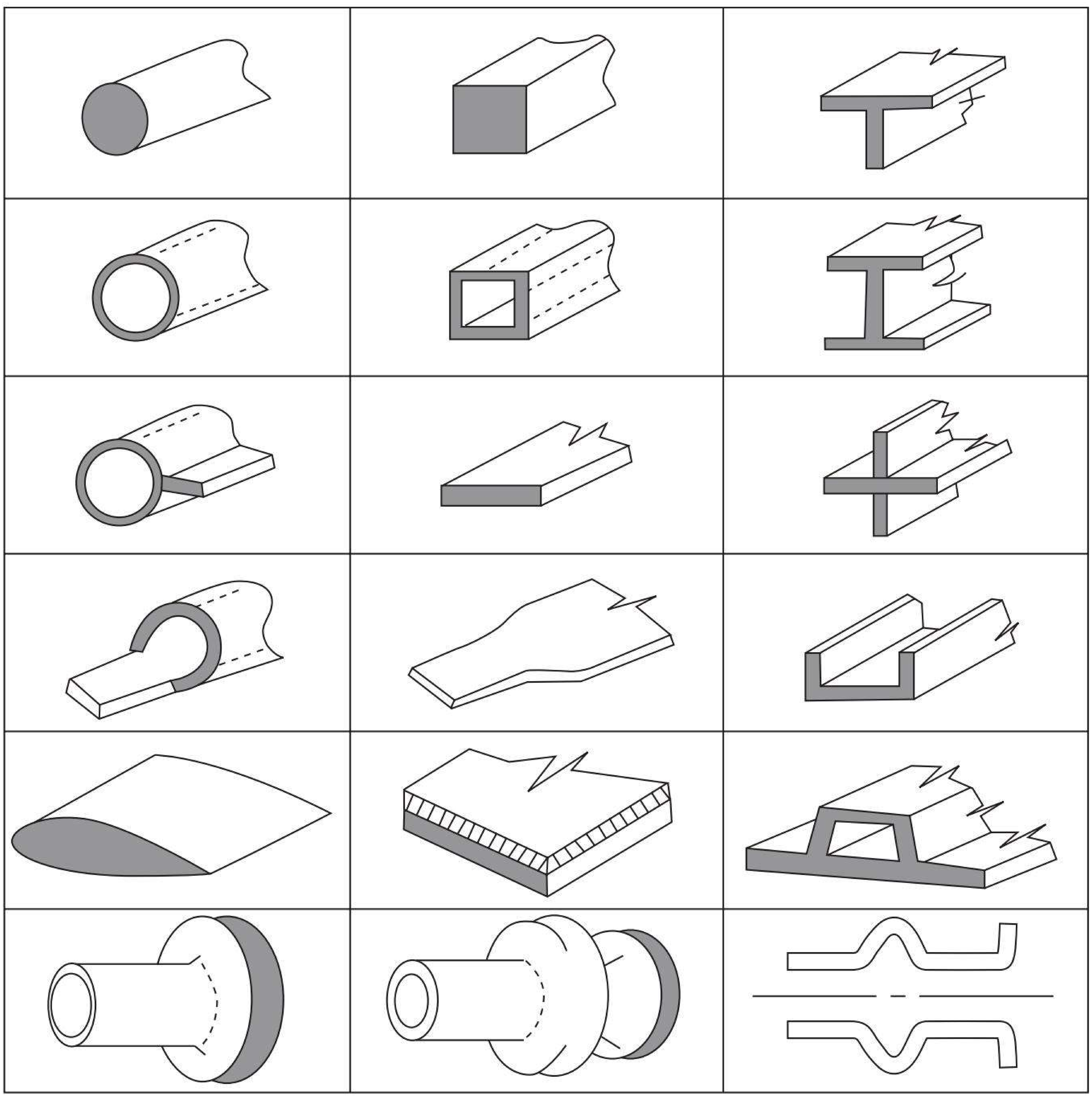
2.2.4 Three-dimensional braided fabrics

Braiding was the first process used to manufacture a 3-D fibre preform for a composite. This process was developed in the late 1960s to produce 3-D carbon–carbon composites to replace high-temperature metal alloys in rocket motor components in order to achieve weight savings of 30–50%. Textile composites with braided fabric preforms are under consideration for aircraft applications that can be used at a lower cost and provide higher impact resistant/tolerant materials (Tan *et al.*, 1997).

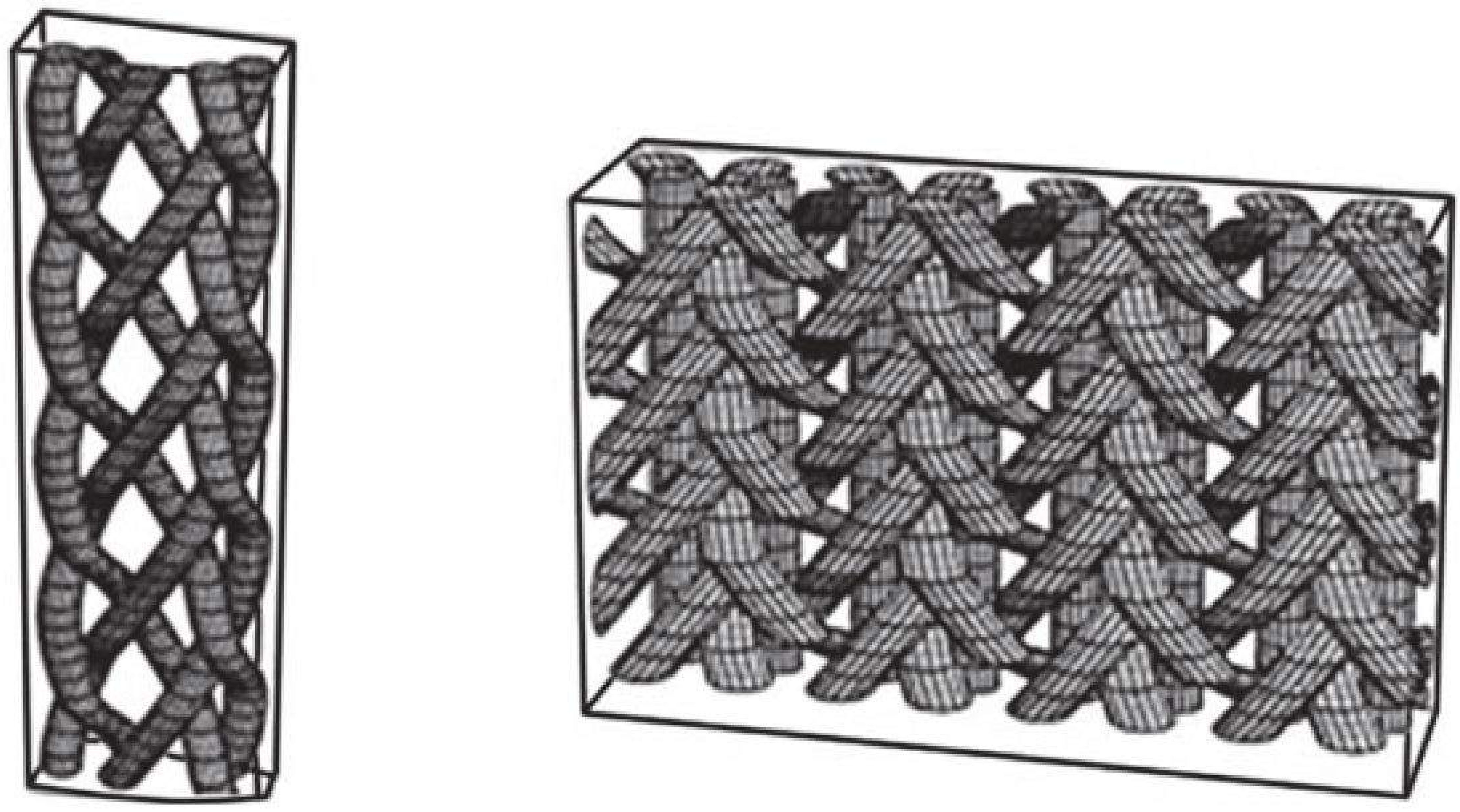
The 3-D braiding technology is an extension of the well-established 2-D braiding technology wherein the intertwining or orthogonal interlacing of two or more yarn systems to form an integral structure constructs the fabric. It is one of the textile processes in which a wide variety of solid complex structural shapes can be produced integrally, resulting in a highly damage-resistant structural preform.

The 3-D braids are produced by a number of processes including the track and column (3-D circular loom) method (Brown and Ashton, 1989), the two-step braiding method (Popper and McConnell, 1987), and a variety of displacement braiding techniques. The basic braiding motion includes the alternate *x* and *y* displacement of yarn carriers followed by a compacting motion. The proper positioning of the carriers and the joining of various rectangular groups through selected carrier movements accomplish shape formation. Examples of the structural shapes successfully demonstrated as shown in Fig. 2.6.

3-D braided fabrics formed by the intertwining of yarn systems can be obtained in a variety of forms with laid-in yarns. At any time one half of the yarns are travelling in one direction at some angle to the axis down the fabric, while the other half are travelling in the opposite direction, passing over and under the strands of the first group. Figure 2.7(a)



2.6 Examples of 3-D braid net-shaped structures.



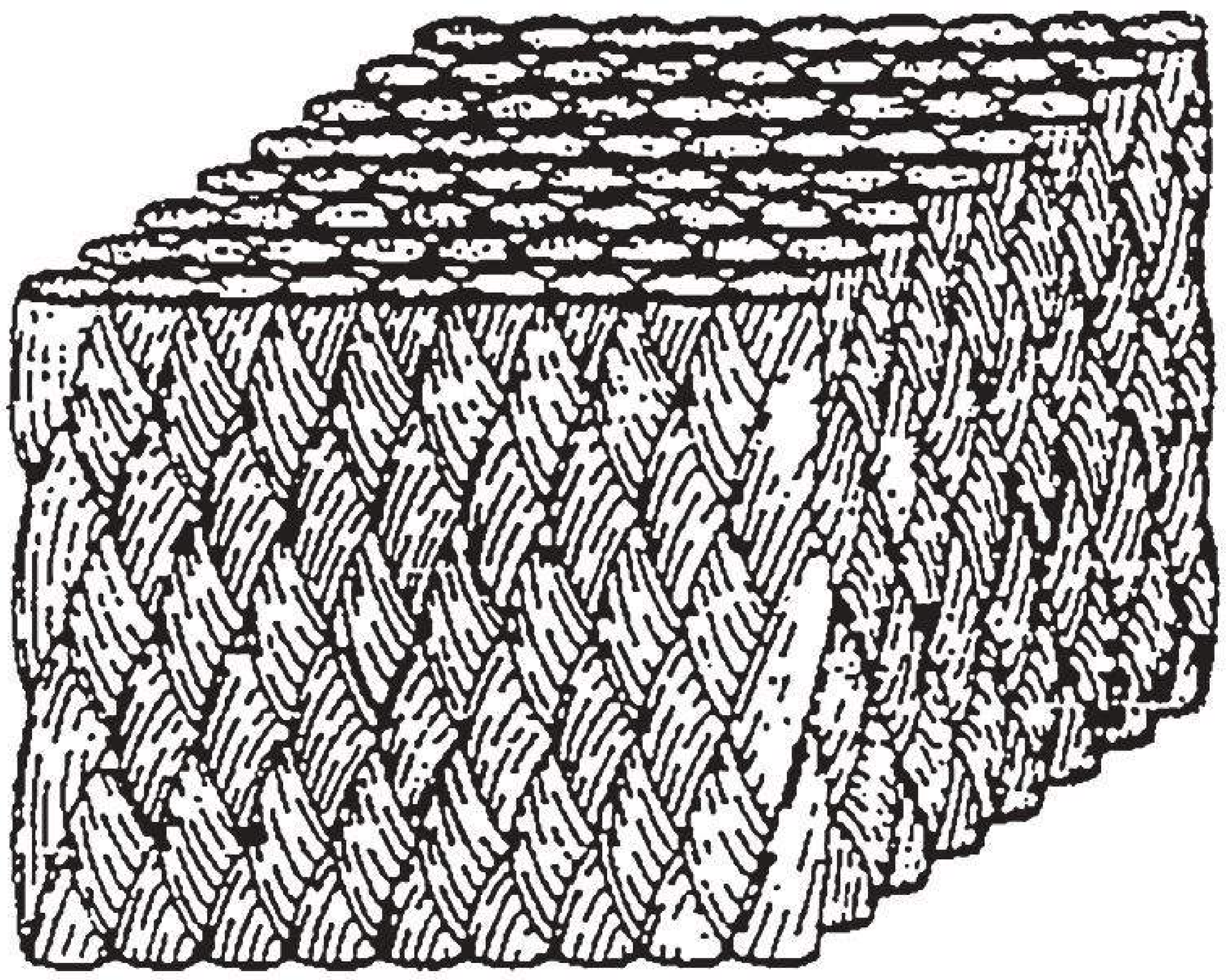
(a) Flat braided fabric (b) Circular braided fabric

2.7 3-D models for braided fabrics.

shows a braid fabric plaited by five strands. Braided fabrics have yarns interlacing at angles other than 0° and 90°. For a yarn orientation of ±45° interlacing is half that for the plain weave. This results in better adoption of fibre properties by the composite fabric due to reduced crimp. Therefore, braiding is one of the major manufacturing processes for textile composite preforms, although it is not a major manufacturing process for traditional textiles relative to weaving and knitting.

Figure 2.7(b) shows the local yarn structure in a circular braid consisting of three yarn systems. Two groups of yarns, one having an angle of 45° and the other having an angle of 90° to the mandrel axis, interlock to form a biaxial fabric. As an option, a third group of yarns mounted on the back side of the track ring of a braiding machine can be inserted through the centre of each horn gear. These yarns are deposited onto the mandrel in the axial direction. Clearly, the angle made by this group of yarns is 0° to the mandrel axis. All three groups, namely $\pm\theta$ and 0°, form a biaxially interlocked braid as shown in Fig. 2.7(b).

In the four-step braiding method, yarns are intertwined to form a multilayer 3-D structure (Fig. 2.8). Some of the braiding yarns traverse the internal layers and bind the two exterior layers together. Some sort of a beat-up is needed to push the yarns into the fabric structure after each round of braiding. In a two-step system to make 3-D braids, axial yarns and braider yarns are used. The braider yarns move around axial yarns which are fixed parallel to each other. The resultant tubular structure has good reinforcement in the axial direction but is weak in the circumferential direction. The multilayer interlock braiding method, which is similar to two-step braiding, allows greater circumferential reinforcement. In this method, yarns from adjacent layers are interlocked together.



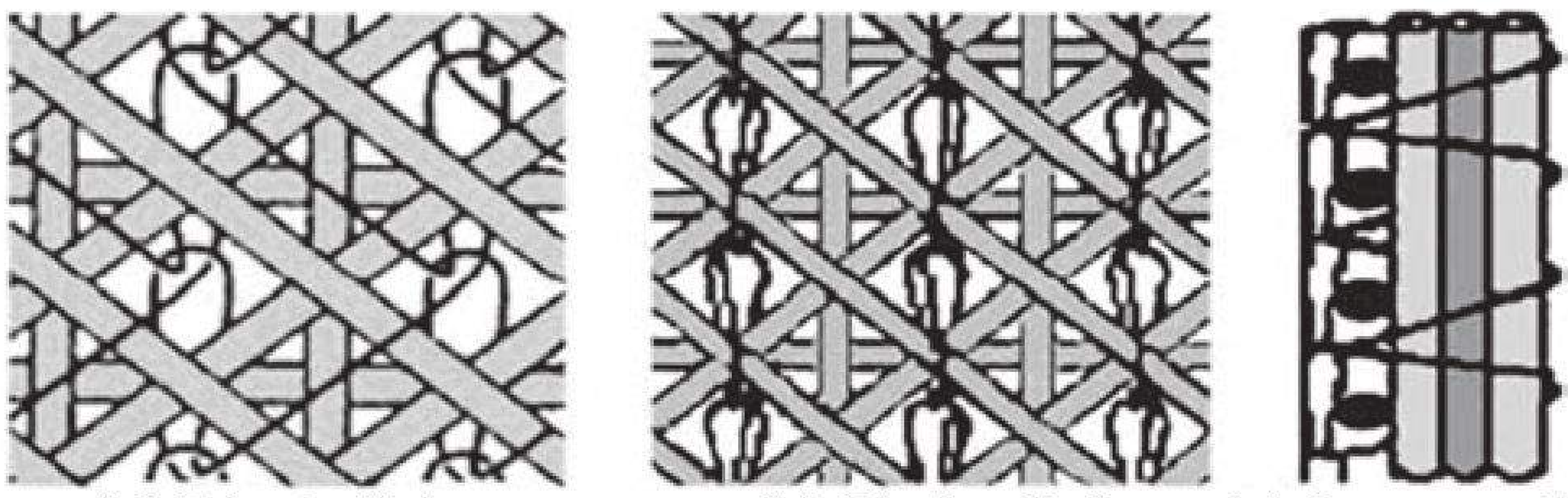
2.8 3-D braid produced by intertwining of multi-yarns.

In comparison to woven structures, due to the lack of beat-up during braid formation, braided fabric structure usually has low shear resistance and therefore is highly deferrable in the axial and radial directions. This characteristic of braided structures makes them particularly suitable to conform to surfaces of varying cross-sectional shapes such as cones and nozzles, and allows the production of near-net-shape structures. Hence, interest in braiding for composite manufacture has grown in recent years.

2.2.5 Three-dimensional knitted fabrics

Knitted fabrics are interlooped structures wherein the knitting loops are produced by the introduction of the knitting yarn either in the cross-machine direction (weft knit) or along the machine direction (warp knit). The most undesirable feature of weft-knitted structures is their bulkiness, which leads to the lowest packing density, or lowest level of maximum fibre volume fraction, compared to the other fabric preforms. While weft-knitted structures have applications in limited areas, multiaxial warp knit (MWK) 3-D structures are more promising and have undergone a great deal of development in recent years. Three-dimensional knitted fabrics are produced by either the weft-knitting or the warp-knitting process.

Multiaxial–multilayer structures are fabrics bonded by a loop system, consisting of one or several yarn layers stretched in parallel. Multiaxial–multilayer warp knits (MWK) are also termed non-crimp structures since the presence of knitted loops is to perform the function of holding layers of uncrimped inlay yarns. These yarn layers may have different orientation and different yarn densities of single ends. Multiaxial–multilayer fabrics are used to reinforce different matrices, since a combination of multidirectional fibre layers and matrices has proved capable of absorbing and distributing



2.9 Multiaxial–multilayer warp-knitted structures.

extraordinarily high strain forces. Among three basic types of these structures, Karl Mayer structures (Raz, 2000) are those in which, along with the ground tricot structure, inlaid yarns in warp, weft and both diagonal directions (30–60°) are incorporated in the fabric. Two other types, the LIBA and Malimo systems, along with layers of knits can also incorporate fibre/non-woven fleece between the layers to produce multiaxial–multilayer structures (Anand, 1996), which are predominantly applied to composite reinforcements.

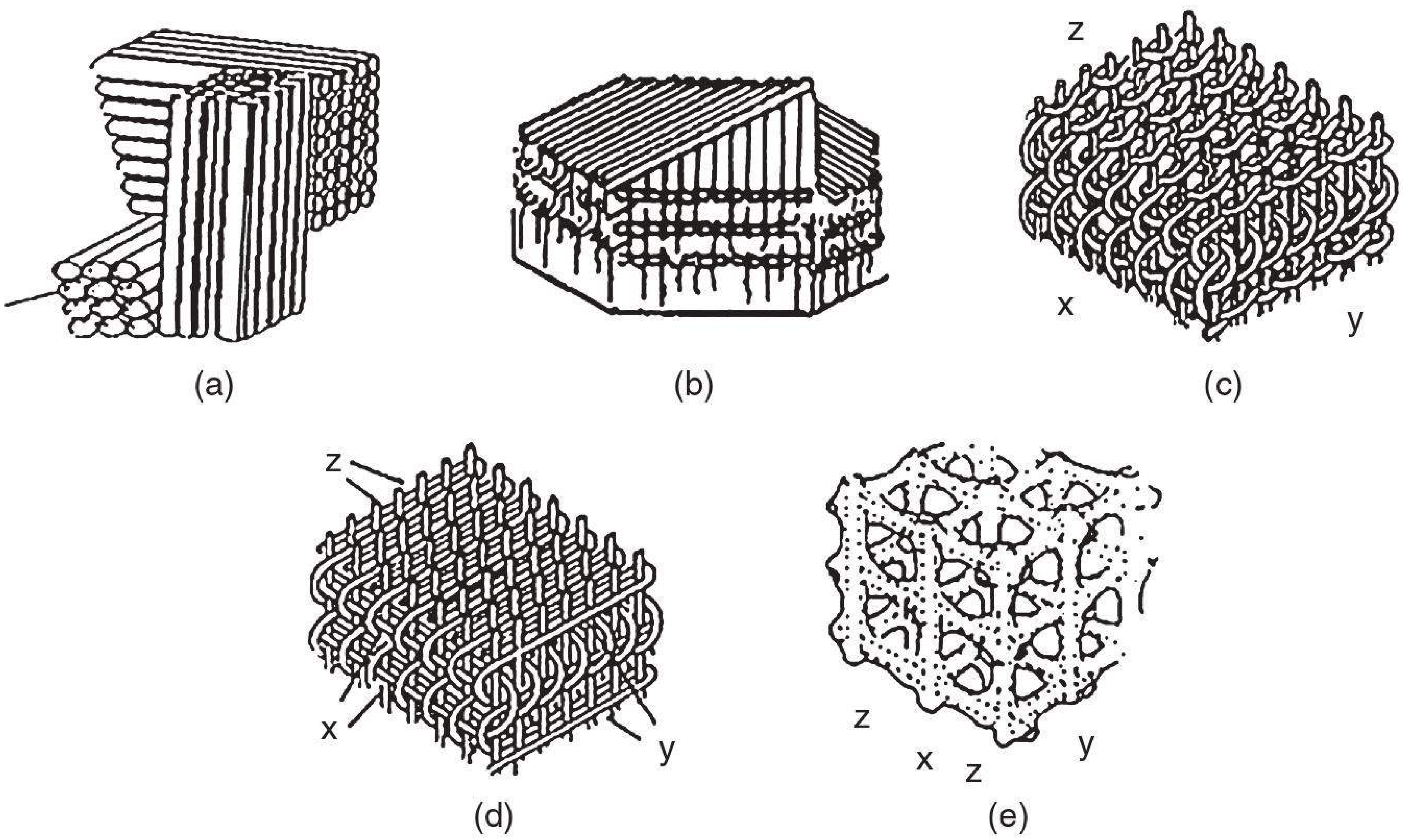
Figure 2.9 illustrates tricot and chain-stitched multiaxial–multilayer knitted structures along with their cross-sectional view. Structural and mechanical studies on these knit preforms based on unit cell modelling have shown superior performance of these preforms for composite applications (Ko *et al.*, 1985; Dexter and Hasko, 1996; Du and Ko, 1996; Franzke *et al.*, 1997).

2.2.6 Three-dimensional non-woven fabrics

Use of 3-D non-woven surfaces in the composites industry is not so long established as that of woven and diagonal knit structures. Production of these structures is simple and quick. Needling and assembling by sewing (Malimo) are the most common methods. In addition to these, some uncurled structures can be defined as non-woven surfaces. Since there is no connection between the yarns in non-woven structures, they have weaker mechanical features compared to woven or knitted fabrics.

There is a long history of 3-D non-woven reinforcements, primarily in carbon–carbon composites. Orthogonal 3-D materials are fabricated by fixing a series of yarns in one direction (or rods which will later be withdrawn and replaced by yarns), and then inserting planar yarns in the two orthogonal directions around the fixed yarns.

Pioneered by aerospace companies such as General Electric, the non-woven 3-D fabric technology was developed further by Fiber Materials Incorporated. Recent progress in automation of the non-woven 3-D fabric manufacturing process has been achieved in France by Aérospatiale



2.10 Orthogonal non-woven 3-D fabrics.

(Pastenbaugh, 1988; Geoghegan, 1988) and Bruno (Bruno *et al.*, 1986) and in Japan by Fukuta and co-workers (Fukuta *et al.*, 1982; Fukuta and Aoki, 1986).

The structural geometries resulting from the various processing techniques are shown in Fig. 2.10. Figure 2.10(a) and (b) show the single-bundle *xyz* fabrics in a rectangular and cylindrical shape. In Fig. 2.10(b), the multidirectional reinforcement in the plane of the 3-D structure is shown. Although most of the orthogonal non-woven 3-D structures consist of linear yarns in a non-linear manner, as shown in Fig. 2.10(c), (d) and (e) these structures can result in an open lattice or a flexible and conformable structure.

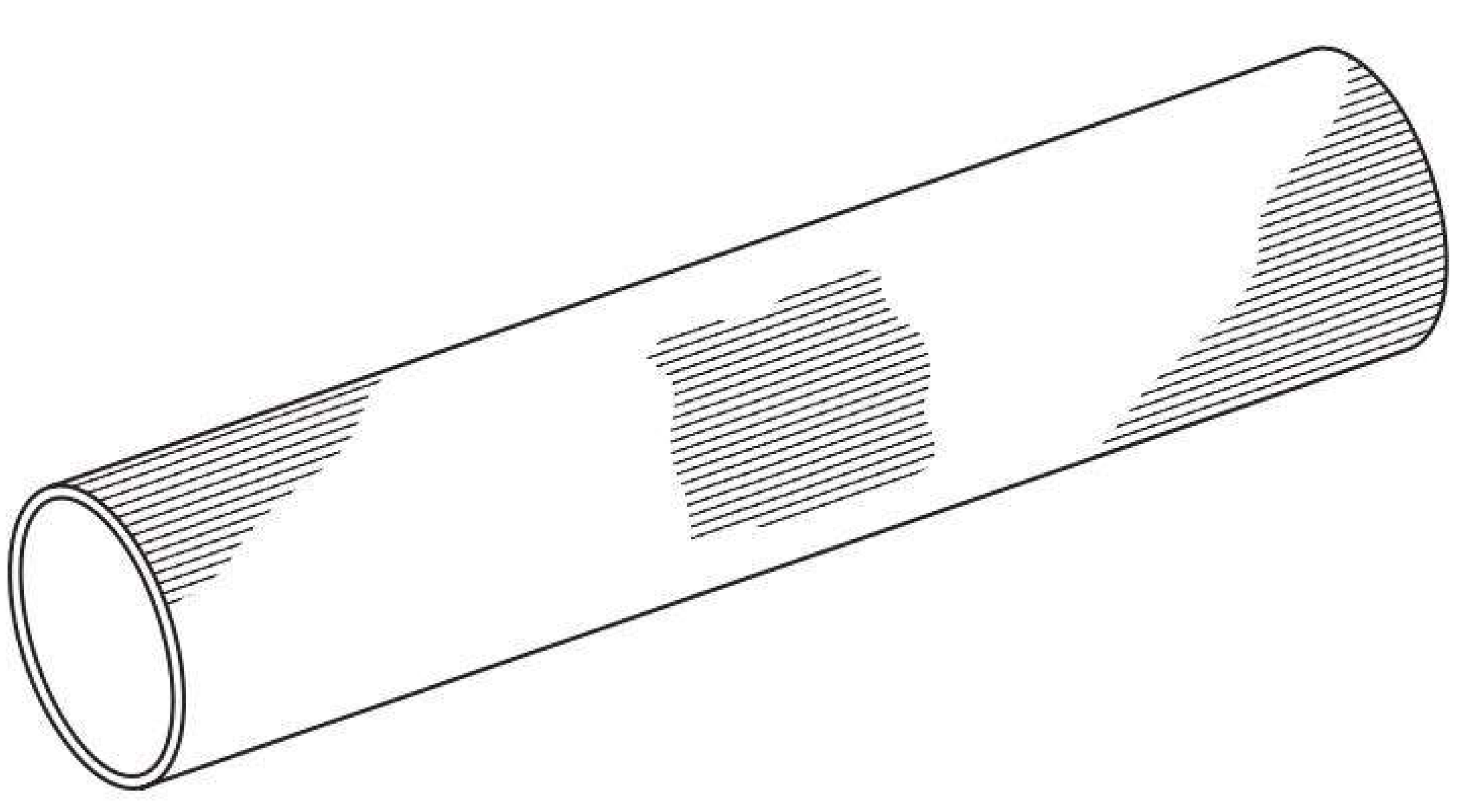
2.3 Application of three-dimensional fabrics to medical textiles

Textile materials in the medical field gradually have taken on more important roles. As more research has been completed, textiles have found their way into a variety of medical applications. In addition to protective medical apparel, textiles in fibre and fabric form are used for implants, blood filters and surgical dressings. Woven and knitted materials in both synthetic and natural form play a part in the biotextile field, but non-woven materials also have proven to be effective and cost-efficient. Textile structures in implantation are identified by structure, material composition, and behaviour of fibre surface and degradation. A major concern with artificial implants is the reaction that the body will have towards the implant. A biotextile in implantation must meet mechanical requirements and it must be biocompatible. Biocompatibility testing evaluates the response of the host system to the medical textile. Results of this testing must be viewed along with the risks and benefits of the device.

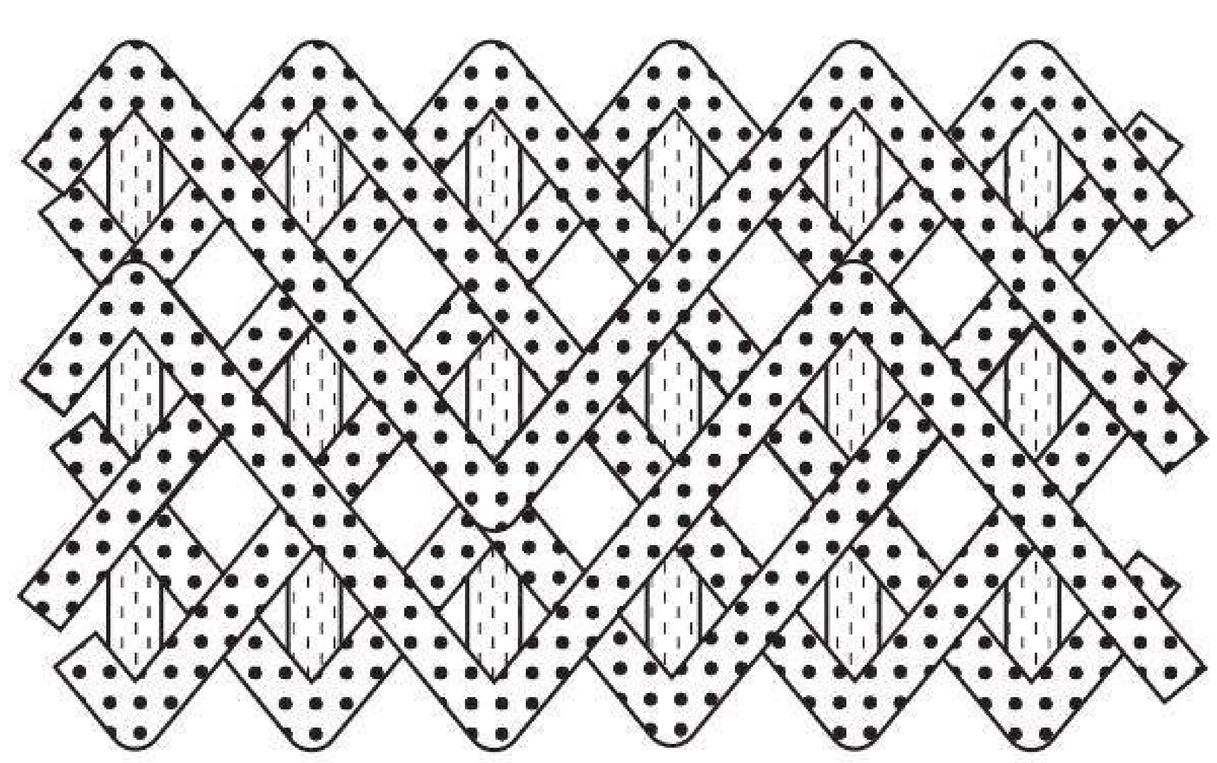
The use of 3-D fabrics in medical textiles is relatively new. Compared to 2-D woven fabrics, 3-D fabrics are dimensionally stable and find wide applications as vascular grafts, wound dressings, plasters, tissue engineering scaffolds, hospital bedding and uniforms and surgical gowns. Three-dimensional warp-knitted structures tend to be more stable and versatile and find applications as vascular implants, artificial tendons and ligaments, stents, compression bandages, surgical hosiery, etc. The applications of braided 3-D structures include artificial ligaments, tendons and absorbable and non-absorbable sutures. The non-woven 3-D fabrics have their applications as artificial implants and tissue engineering scaffolds.

In a study on woven prosthesis, a solid 3-D woven tubular prosthesis has been developed (Schmitt, 1999). This prosthesis has sufficient inherent wall stiffness so as to be radially self-supporting. This solid woven prosthesis (Fig. 2.11) is capable of being formed with a smooth, continuous inner wall that improves the hemodynamic flow compared with conventional 2-D woven structures, thereby facilitating the flow-through of fluid. The wall is believed to provide the prosthesis with sufficient radial stiffness to maintain an open lumen. The crimping additionally provides a degree of longitudinal compliance to the prosthesis. These devices may be used in a variety of locations in the body, such as in intraluminal applications in the vascular system, pulmonary system or gastrointestinal tract.

A biocompatible implant material made of a 3-D woven/knitted fabric has been reported by Yasuo Shikinami (Shikinami and Kawarada, 1998). This implant material has high mechanical strength and durability in all three orthogonal directions and synchronizes with the deformation characteristics of the surrounding biological tissues. It is developed using a



(a)



(b)

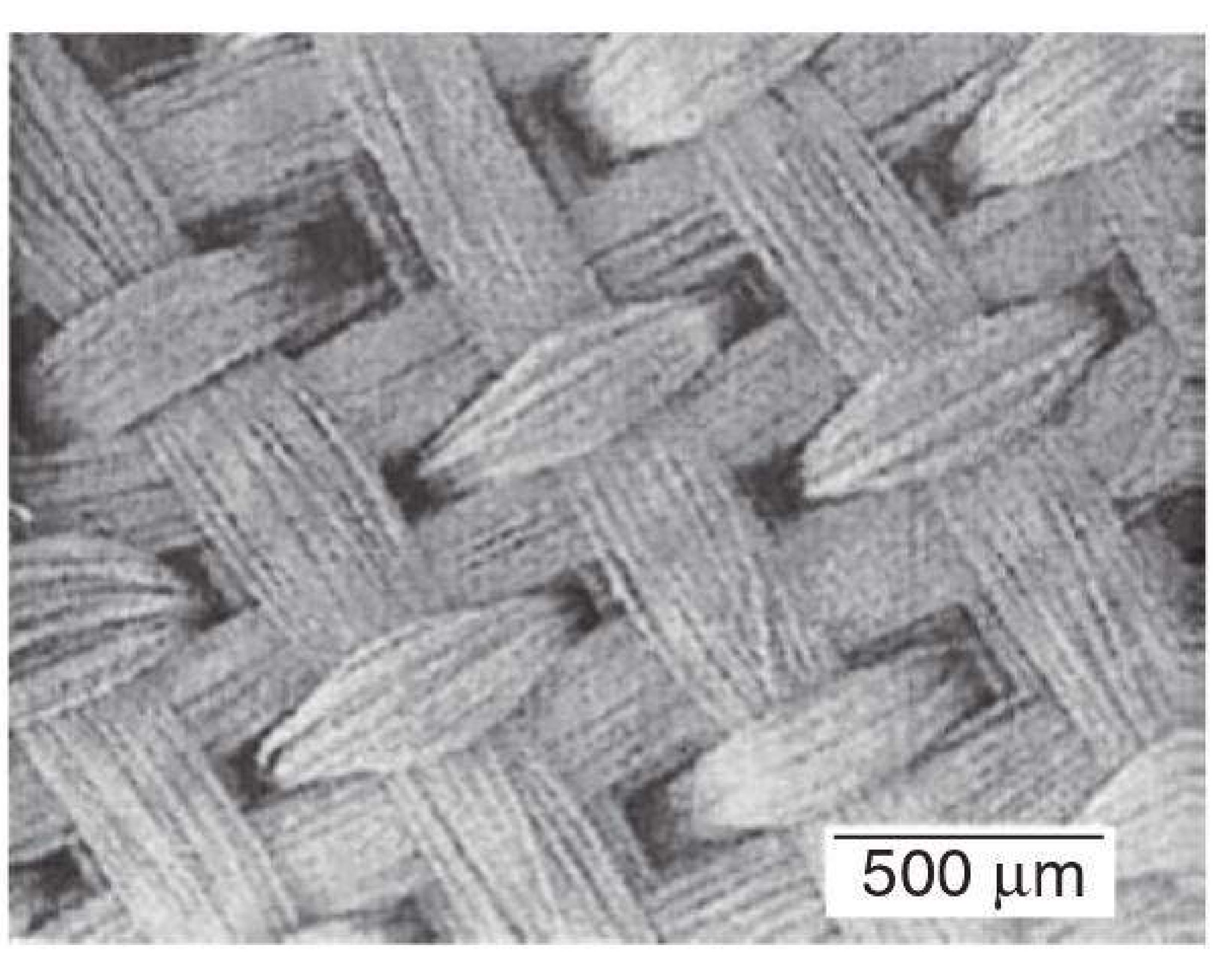
2.11 Prosthesis made of 3-D woven fabric.

biocompatible bulk structure of a 3-D woven or knitted fabric of organic fibres. This implant material can be used to make artificial bones, cartilages, menisci and finger joints, bone fillers and materials for osteosynthesis and prosthesis.

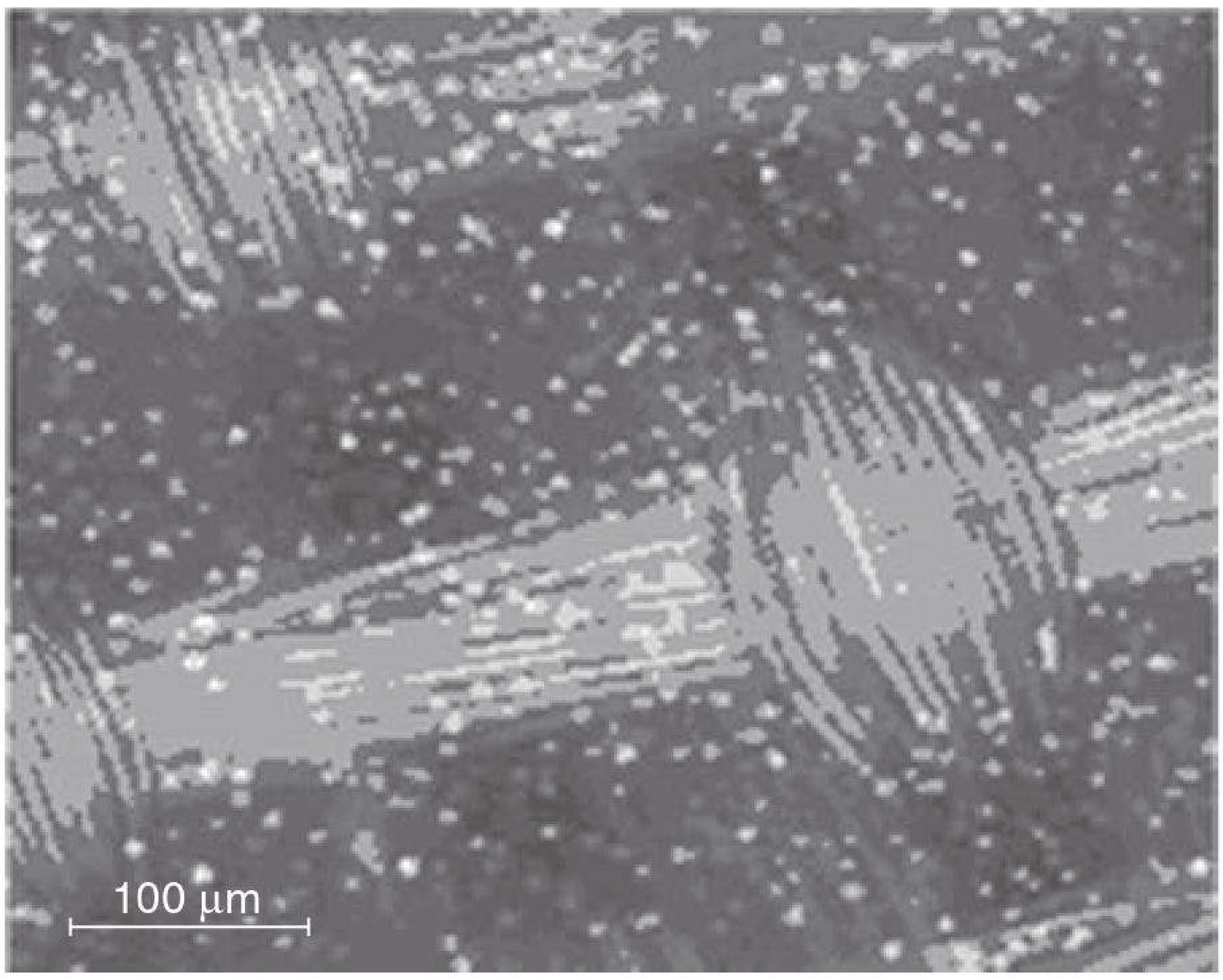
Tissue engineering seeks to repair or regenerate tissues through combinations of implanted cells, biomaterial scaffolds and biologically active molecules. Three-dimensional woven, knitted and non-woven structures are finding application in tissue engineering for the manufacture of highly porous 3-D scaffolds, which can be produced by 3-D weaving techniques. A novel scaffold, mimicking the multidirectional biomechanical behaviour and the anisotropy of native cartilage, has been developed by Moutos *et al.* (2007). The porous structure was produced using 104-μm-diameter continuous multifilament polyglycolic acid yarn. The yarn was woven into two different 3-D structures containing a total of 11 in-plane fibre layers, five layers being oriented in the warp direction (0° or lengthwise in the loom) and six layers in the weft direction (90° to the lengthwise fibres) (Figs 2.12 and 2.13).

Non-woven fabrics are widely used as scaffolds in tissue engineering applications. However, non-woven fibrous matrices currently used in tissue engineering have a relatively large porosity, and a pore size in the range of several hundred micrometres, and have not been structurally optimized for specific applications. A non-woven 3-D scaffold produced by an electrospinning technique has been reported by Bhattarai *et al.* (2004). The study reports that the novel biodegradable block copolymer scaffold produced by the electrospinning process (Fig. 2.14) is a non-woven, 3-D, porous, nanoscale fibre-based matrix. The structure is suitable for soft tissue, such as skin and cartilage Fig. 2.15(a).

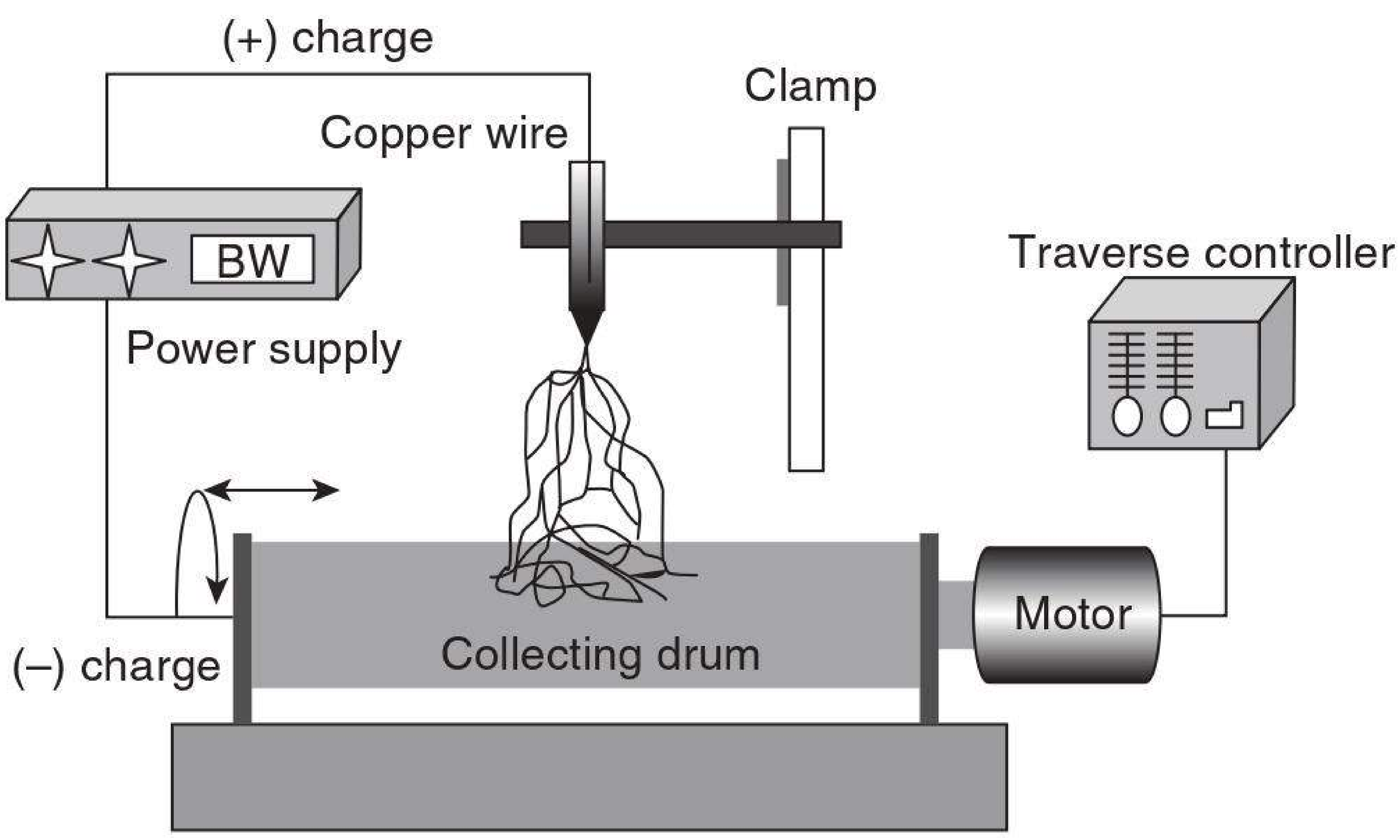
A tubular vascular prosthesis (Fig. 2.15(b)) with a complex triple-layered woven structure has been outlined by Latvian researchers (US Patent 6,863,696, 2005). The graft will find application in reconstructive surgery,



2.12 3-D woven structure for making porous scaffolds.



2.13 Cell growth on the freshly seeded scaffold.

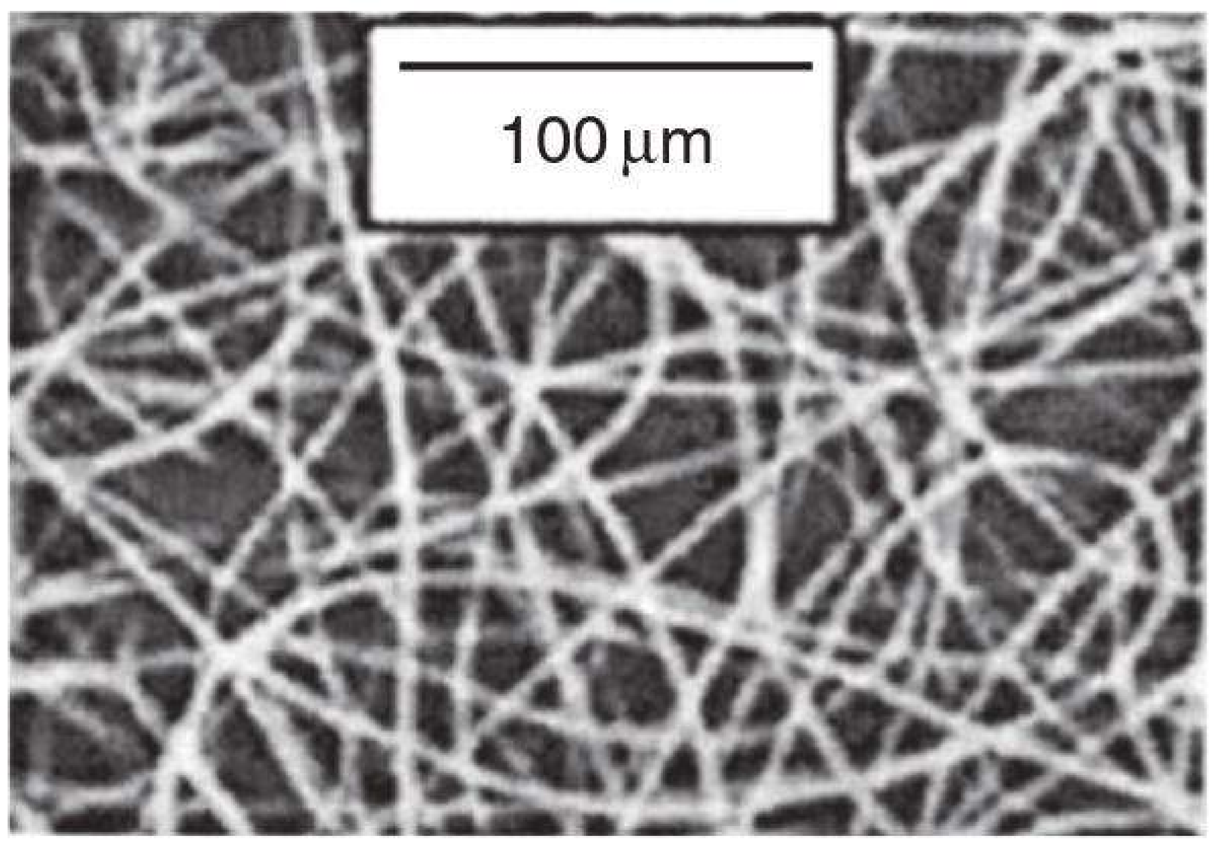


2.14 Electrospinning apparatus to produce 3-D porous non-woven structure.

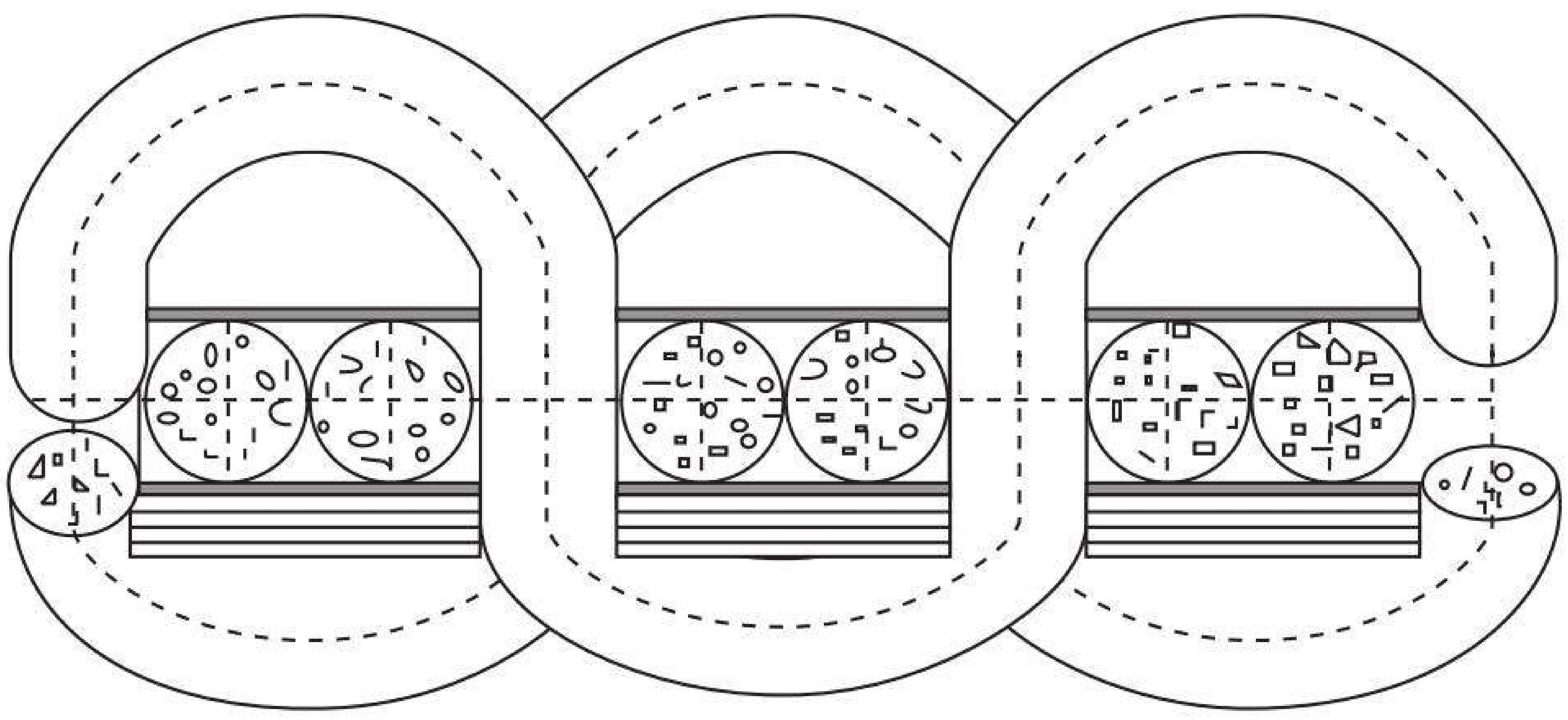
such as for inborn vessel anomaly or for arterosclerotic damage or injury. The vascular prosthesis outlined in the patent is claimed to have good mechanical characteristics, non-ravelling ends, low permeability for blood, and good acceptance for ingrowth of tissue to seal the prosthesis walls.

2.4 Application of three-dimensional fabrics to sports

In the last decade tremendous progress has been made in the development of fibres and fabrics for sports end-uses. Textile materials are used in virtu-



(a) 3-D porous non-woven structure



(b) Multilayer fabric for vascular prosthesis

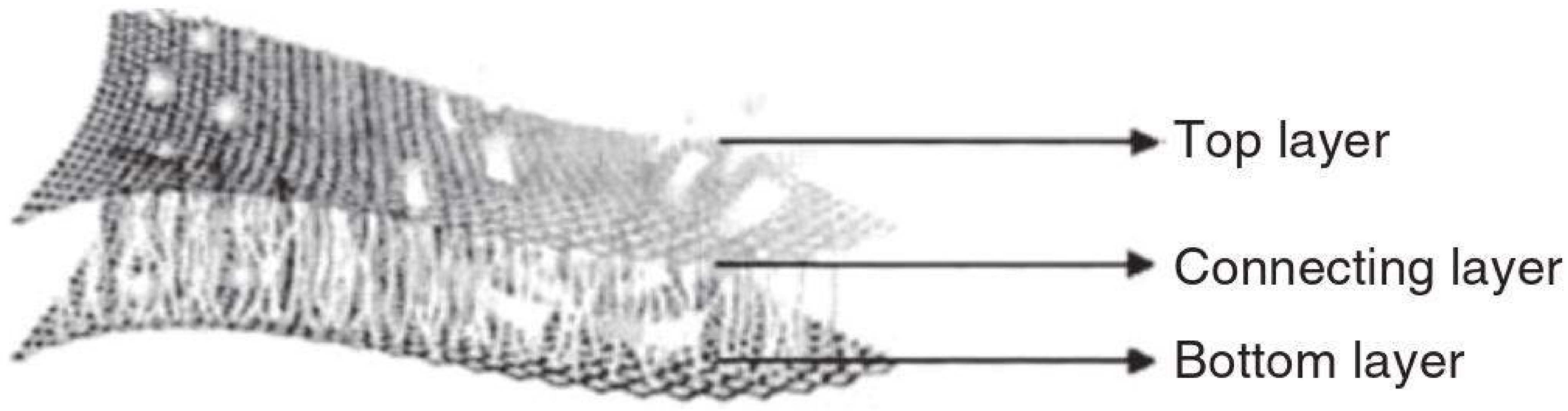
2.15 3-D non-woven fabrics in medical application.

ally every sport from exercising and camping to football. High-performance textile fibres and fabrics are used in uniforms, equipment and sports facilities. The use of textile structural composites in sporting goods is increasing. Their applications include composite roller blades, bike frames, golf clubs, tennis rackets, ski and surf equipment, etc. Sports such as golf, baseball and tennis rely heavily on composites for their essential equipment. These sports would be drastically different if composite materials were not used. Due to their high strength and durability, composites have won favour in the sporting industry.

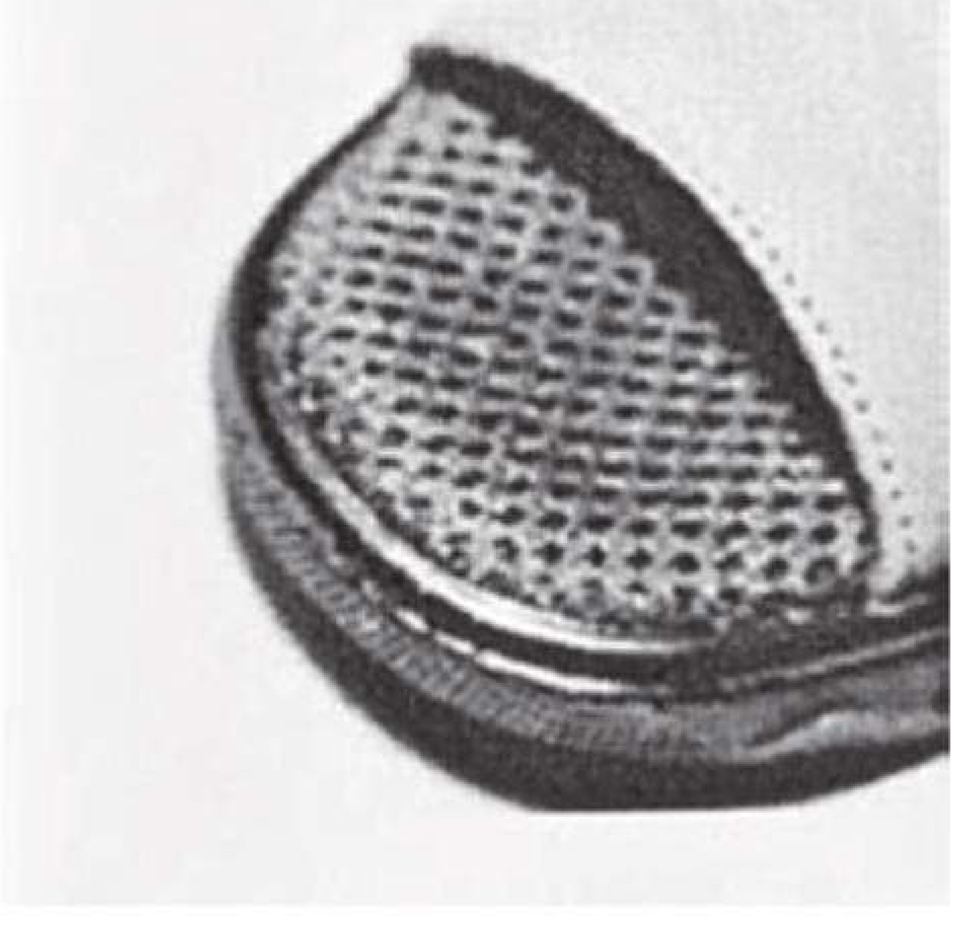
The application of 3-D textile fabrics is increasing in areas such as footwear, heavier fabrics such as for track suits and jogging suits, and shorts and shirts. Footwear, especially training/jogging shoes, is an area in which 3-D fabrics are now very widely used (Hill, 1985) to the almost total exclusion of leather in the construction of the main part of the upper. The fabrics in footwear are generally made of three layers: woven nylon outside, foam in the middle and warp-knit fabric inside (Adanur, 1995). The main advantages of 3-D fabrics over others are their consistency of quality and specification compared with the irregularities of leather, and their lightness, easy care properties and dimensional stability.

Garments for foul weather have received a great deal of attention recently as they are very much needed for such recreations as sailing, golf, climbing and running. The main direction has been to seek waterproof fabrics which 'breathe', that is, allow transportation of water vapour (perspiration) from the inside out. Multilayer fabrics have been found to be very successful in this direction. Very closely woven 3-D fabrics, multiaxial warp-knitted fabrics which have been calendered to close up the structure, and blended fabrics with coatings such as silicone–elastomer, are becoming popular.

Three-dimensional knits, also called spacer fabrics (Fig. 2.16(a)), are also attracting the attention of sportswear manufacturers for their capacity to trap air and offer extremely lightweight high-performance thermoregulation. Initially developed for industrial uses for cushioning and filtering, these fabrics are now popular in both sports shoes and garments. Sports shoes are one of the big initial success stories for spacer fabrics, making use of their light weight, high bulk and springiness. Climate properties, washability and a superior substitute for laminated foam are other advantages. Spacer fabrics are much like a sandwich and feature two complementary slabs of fabric with a third layer tucked in between. The inner layer can take a variety of shapes including tubes, pleats or other engineering forms, which gives the entire three-layer fabric a wide and ever-expanding range of potential applications (Bruer *et al.*, 2005) (Fig. 2.16(b)). This has led to successful experimentations with outerwear applications, where those properties found in sports shoes can be transferred to sports and leisure apparel.



(a) 3-D knit spacer fabric



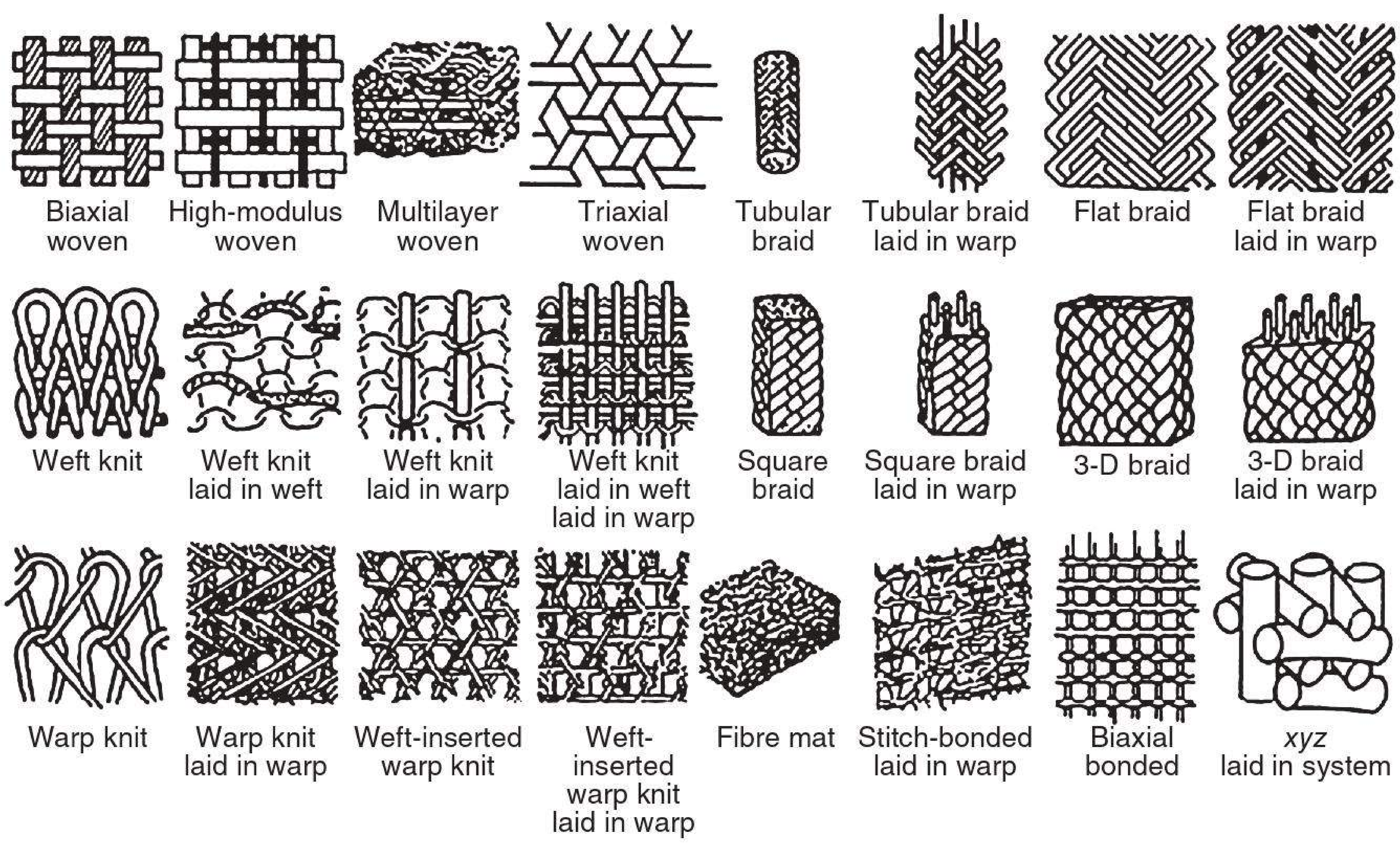
(b) Application in footwear

2.16 3-D knit fabric in sports. (Source: *Knitting International* (February 2002), Breathing Room, Knit Americas).

2.5 Application of three-dimensional fabrics to geotextiles

Geotextiles are permeable textile structures made of polymeric materials and are used mainly in civil engineering applications in conjunction with soil, rock or water. They are constructed as woven, non-woven, knitted, braided and combination materials. They are a member of a large family called geosynthetics. Other members of the family are geogrids, geonets, geomembranes and geocomposites. The first modern-day commercial geotextiles, also known as 'filter fabrics', were used for erosion control in the 1950s. The mechanical and hydraulic properties of the geotextile vary with the fabric type and can be adjusted to focus on five important performance functions: drainage, filtration, reinforcement, separation and armour. In addition, a geotextile composition must be selected to provide satisfactory placement and longevity for the design life of the structure. The first geotextiles were woven monofilament fabrics with a high percentage open area. Non-woven needle-punched fabrics were introduced in Europe in the late 1960s. The first non-woven (thermally bonded and needled) geotextiles were introduced in the United States in 1972 (Adanur, 1995).

There is a large family of textile structures available for geotextiles. Figure 2.17 illustrates examples of these structures. In the past two decades, apart from traditional woven fabrics, diversification into various forms including knits and speciality non-wovens has occurred. A particular class of textile structures that has been rediscovered and has undergone



2.17 Textile structures for geotechnical applications.

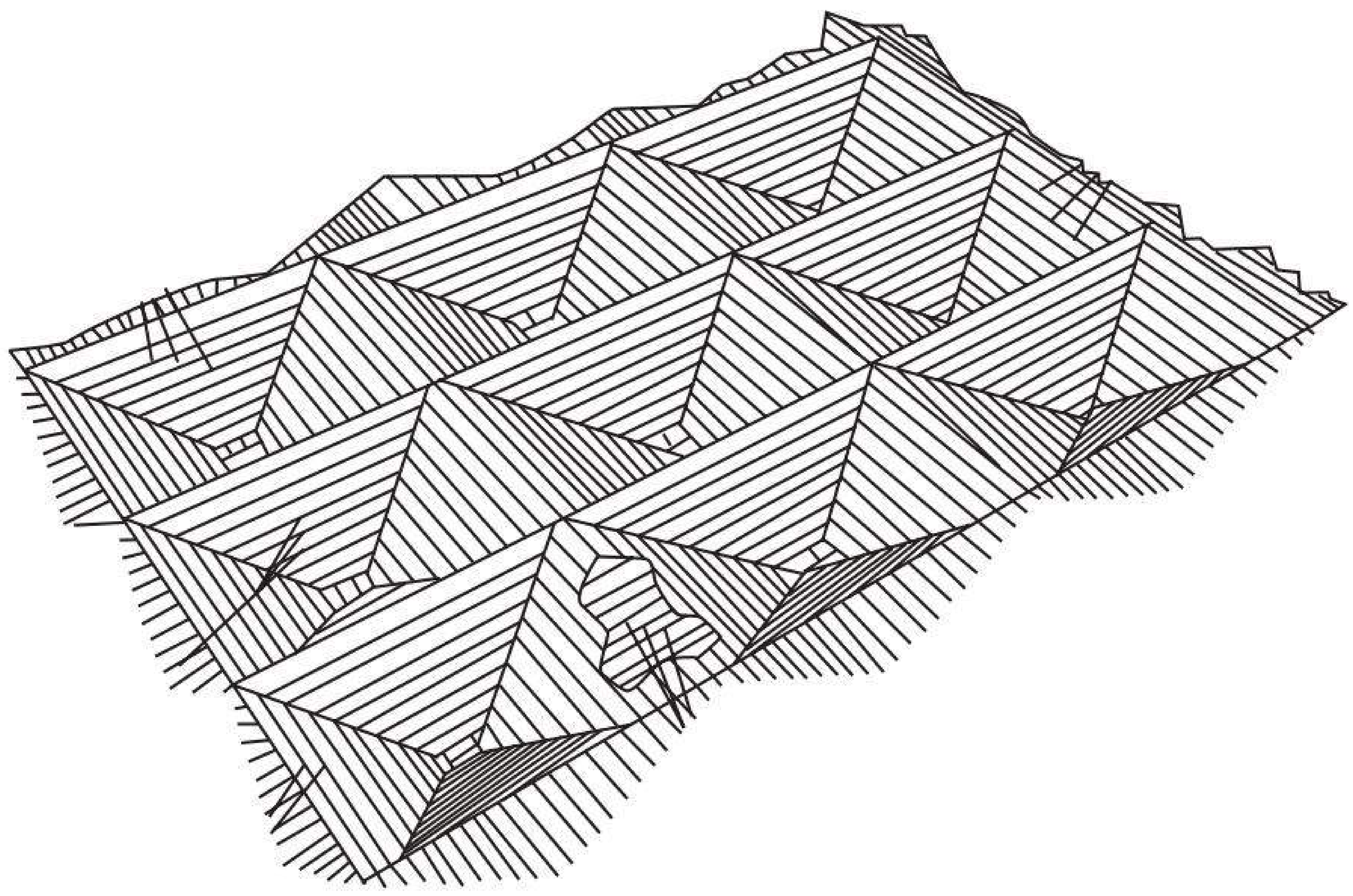
extensive development for advanced composites and many other industrial applications is the 3-D textile structure.

Of the large family of textile structures, both woven and non-woven fabrics have found extensive applications as geotextiles because of their broad availability and low cost. Recently, 3-D woven, knitted, braided and non-woven fabrics have also been making inroads into the geotextiles area, although with limited application. Two traditional but less widely known technologies – braiding and warp knitting – have been rediscovered recently and have found many applications in marine, automotive and aircraft applications. Taking advantage of their multidirectional reinforcement capability, multiaxial warp knits (MWK) have been adopted extensively for large area coverage/reinforcement applications by boat builders as well as aircraft manufacturers, whereas braids have found applications in which linear, tubular and complex structural shapes are required, ranging from sporting goods to automotive components to concrete reinforcement. These structures also lend themselves to easy sensor incorporation, thus opening up new design opportunities for multifunctional geotextiles (Ko, 2004).

As produced by the Karl Mayer Malimo warp knitting system, the MWK fabric consists of warp (0°), weft (90°) and bias ($\pm\theta$) yarns plus the option of a non-woven backing held together by a chain or tricot stitch through the thickness of the fabric. Apart from the multidirectional and multicomponent nature of the fibre architecture, the MWK is characterized by its high productivity, at over one metre per minute and in widths as great as three metres. Since MWK fabrics possess a high level of tensile strength due to their non-crimped nature (and tear resistance as a result of the bias reinforcement and stitching yarn integration), they can be engineered for a wide range of geotechnical applications, including filtration and soil reinforcement.

MWK fabric composites incorporating a non-woven structure are ideally suited for many high-strength geotextile applications for which isotropic strength, resistance to tear and tear propagation, good water permeability, low creep and good fabric/soil interaction are required (Kaufmann, 1991).

A method for stabilizing soil and reinforcing vegetation using a 3-D woven fabric has been reported by Theisen (1996). In this method, a single-layered, three-dimensional, high-profile woven geotextile fabric (Fig. 2.18) was placed into the soil. The single-layered, homogeneous fabric was woven from monofilament yarns with different heat shrinkage characteristics such that, when heated, the fabric forms a thick 3-D cuspated profile. The monofilament yarns had a relatively high tensile strength and a relatively high modulus at 10% elongation so as to provide a fabric that is stronger and more dimensionally stable than other geotextile structures. The geotextile



2.18 3-D woven fabric for soil reinforcement.

fabric thus produced was suitable for use on slopes, ditches and other embankments and surfaces where erosion control, soil stabilization and/or vegetative reinforcement may be necessary. The homogeneous, single-component nature of the fabric promotes easier handling and minimizes failure points, while offering a thick, strong and dimensionally stable product upon installation.

Braiding is a well-established technology which intertwines two or more systems of yarns to form a tubular structure. Longitudinal yarns can be laid in between the braiding yarns to form a triaxial braid and/or placed in the core of the braided tubular structure. Depending on the yarn diameter and the braiding angle, a continuous length of micron-diameter to metre-diameter structure can be produced. Taking advantage of the design flexibility and the wide availability of manufacturing capacity in the industry, braided structures can be employed as the foundation fibre architecture for the construction of ductile composite rebar systems as well as for seamless soil containment columns. By judicious selection of fibre materials and fibre architecture for the braid sleeve and the core structure, the load–deformation behaviour of the braided fibrous assembly can be tailored. The end product of this hybridization of material systems and fibre architecture is a composite rebar which has high initial resistance to tensile deformation followed by a graceful failure process manifested by a gradual reduction in the slope of the stress–strain curve before reaching a high level of ultimate strain (Ko, 2004).

Concrete structures (such as bridge decking) are frequently reinforced with steel bars (rebars) to prevent cracking during use. One of the major problems with steel rebars is corrosion due to salt from road deicing, environmental conditions and standing water on deck surfaces. Previously, attempts to replace steel with fibre-reinforced composites have been unsuccessful because of the brittle, sudden and catastrophic failure of these materials. In traditional metallic rebars, the steel will reach a yield point and lose modulus while extending. Current composite rebars (typically fibreglass-reinforced epoxy) rupture in two when the reinforcing element reaches a critical strain level. This type of catastrophic failure is unacceptable for civil constructions because there is no opportunity to avoid critical and catastrophic failure of the entire bridge structure. Replacement of steel rebars with non-corrosive braided hybrid composite rebars of equal strength and stiffness has been reported by Christopher (Pastore and Ko, 1999). This 3-D braided hybrid structure offers the opportunity for improved bridge durability and corrosion resistance. In addition, since composite rebars can be made to be lighter than steel, the designed capacity of the bridge increases and the labour cost of constructing and repairing the bridge decreases. The fibre-reinforced composite rebar consisting of a braided construction in a sheath–core combination has a core of high-modulus, low strain-to-failure material, whereas the sheath shows a high-extension, high-strength material. The structure uses a core of high-stiffness P-55 carbon fibre braided over by a sheath of Kevlar®49 aramid yarns, which provides high stiffness. The aramid fibres carry some load, resulting in a composite system that prevents structural system failure.

Non-woven geotextiles are complex 3-D structures formed by random arrangement of fibres. They are permeable and compressive textile materials and belong to the geosynthetic group which also includes geogrids, geonets, geomembranes and geocomposites. Three-dimensional needle-punched non-woven fabrics have been used as geotextiles for soil reinforcement, filtration and other civil engineering applications. Some of these applications require geotextiles to perform more than one function, including separation, drainage and filtration. The production processes for non-woven geotextiles involve fibre production, fibre preparation, web formation, web bonding and finishing. Thus, continuous filaments or short staple fibres are initially arranged in the form of a fibrous web in various orientations (random, cross, parallel or composite). Subsequently, these fibrous webs are bonded together by means of chemical, thermal or mechanical bonding processes. Mechanical bonding is generally carried out by a needle-punching process for producing geotextile structures. The needle-punched fabrics are produced by the penetrating action of barbed needles which reorientates and intermingles the fibres from a horizontal to a vertical direction. This forms a 3-D intermingled structure which fulfils the necessary requirements of geotextiles (Rawal and Anandjiwala, 2006).

2.6 Application of three-dimensional fabrics to automotives

The automotive industry is the largest user of technical textiles. Textiles provide a means of decoration and a warm soft touch to surfaces that are necessary features for human well-being and comfort, but textiles are also essential components of the more functional parts of all road vehicles, trains, aircraft and sea vessels.

Textiles in the automotive sector in the form of fibres, fabrics and composite structures are widely used because of the very high performance specifications and special properties required. Seat coverings, for example, are not easily removable for cleaning and indeed in automobiles they are fixed in place and must last for the lifetime of the car without ever being put in a washing machine. In trains, aircraft and passenger vessels they are exposed to much more rigorous use than domestic furniture. In addition they have to withstand much higher exposure to daylight and damaging ultraviolet radiation (UV) and because they are for public use they must satisfy stringent safety requirements such as flame retardancy.

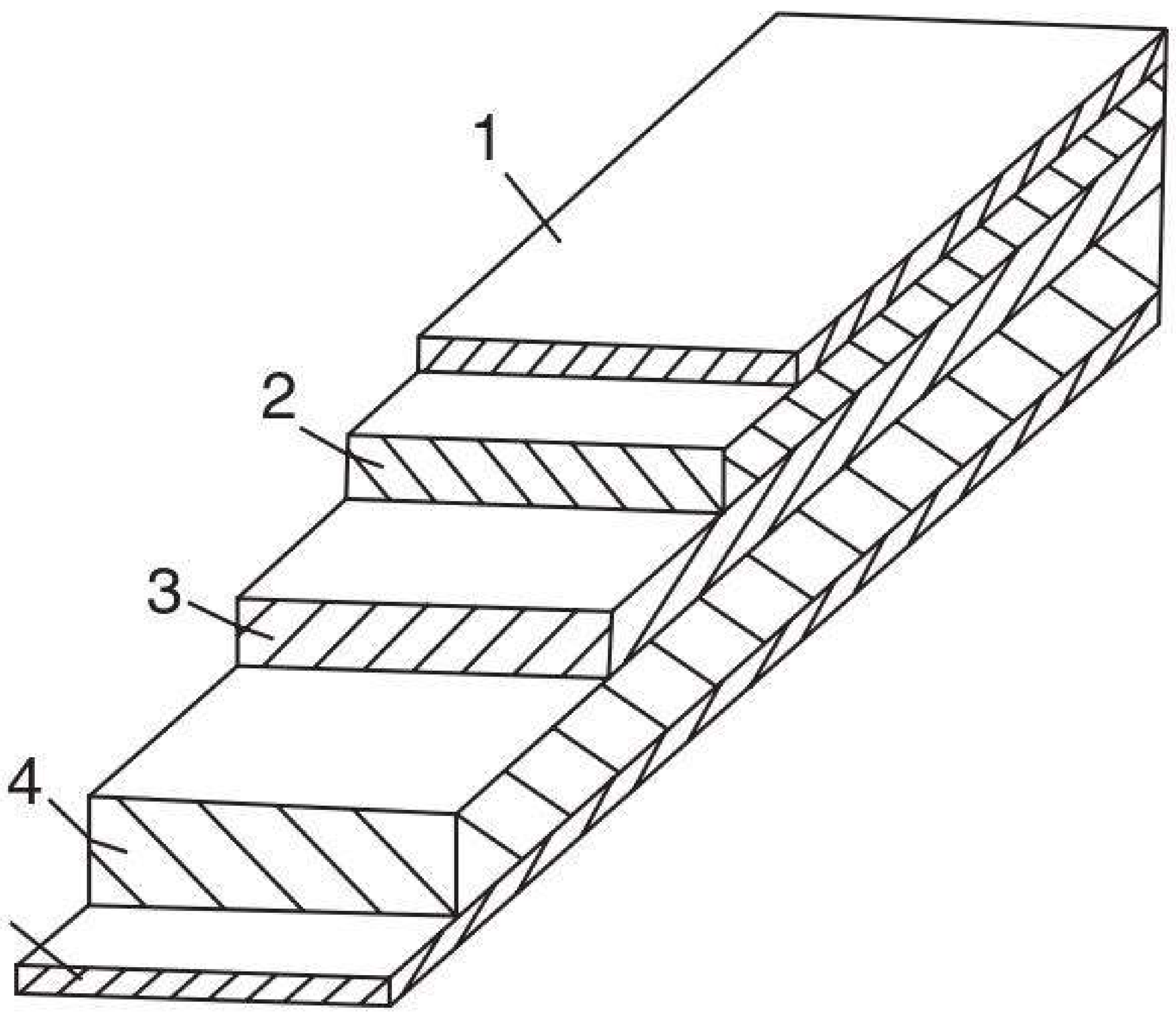
In more functional applications, textiles are used in articles as diverse as tyres, heater hoses, battery separators, brake and clutch linings, air filters, parts of the suspension, gears, drive belts, gaskets and crash helmets. The most significant growth area in transportation textiles is expected in composites that straddle the textile and plastics industries.

The most familiar technical textile in transportation is car seat fabric, which is among the largest in volume and is growing rapidly. Car seat fabric requires considerable technical input to produce both the aesthetic and also the very demanding durability requirements. The processes developed for car seat fabric and the technical specifications provide some indication of the requirements for seat materials in other transport applications.

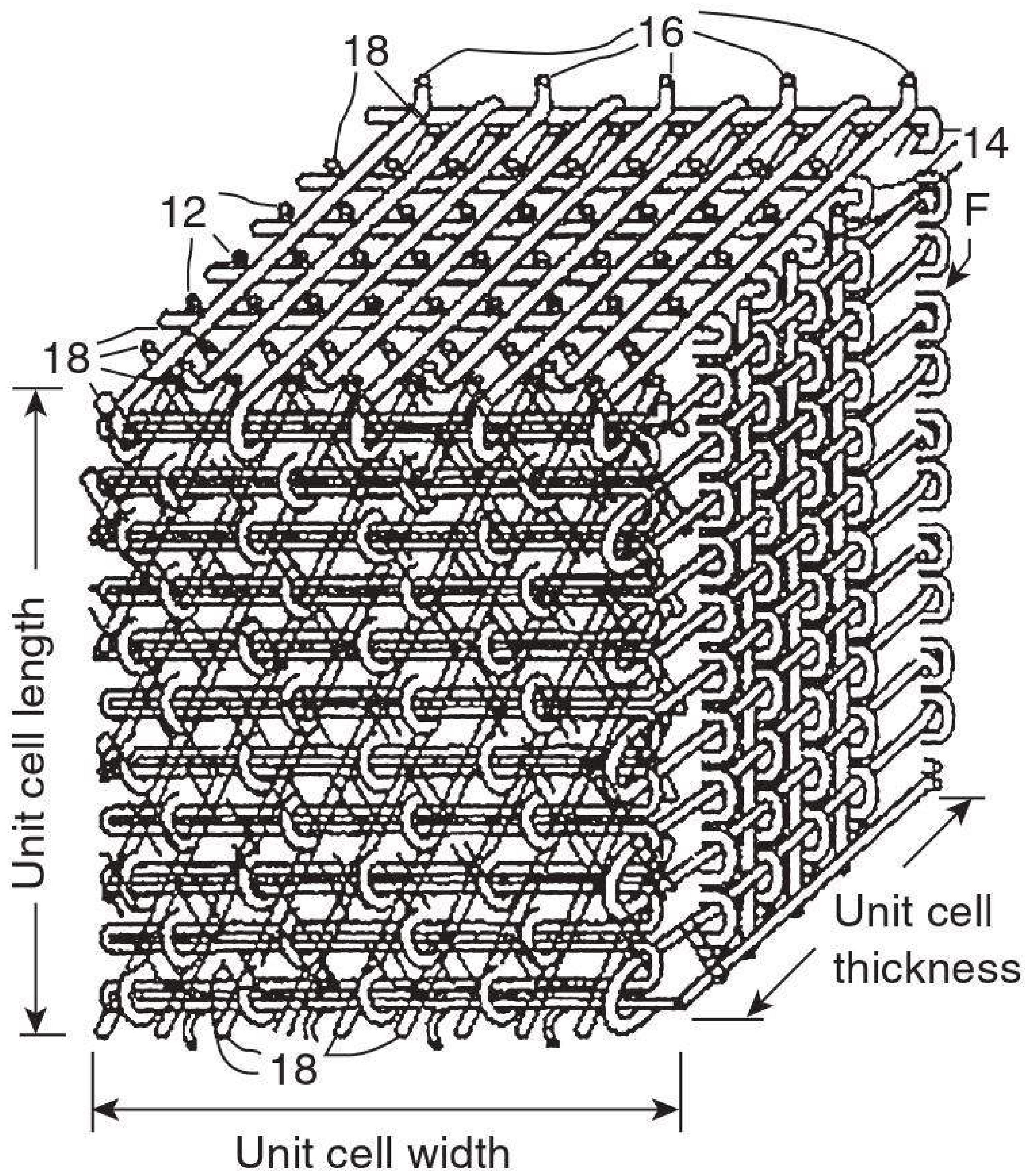
The application of 3-D textiles in the form of composites in the automotive sector is developing slowly. Because of their excellent dimensional stability and very high delamination resistance, these fabrics are finding their way into many applications in the automobile industry.

A multilayer fabric construction that offers greater air permeability and is intended as a seating material for use in automobiles has been described by Lohmann GmbH & Co KG (US Patent 5,747,393, 1999). The multilayered structure also wicks moisture away from the seat's occupant. This fabric is made up of multilayered non-woven polyester needlefelt fabric bonded to a viscose rayon felt (Fig. 2.19).

In a world patent, Mansour Mohamed and Kadir Bilisik (1998) describe a prototype 3-D woven fabric for reinforcement in automobile seats and other applications. The preform consists of multiple warp layers or axial yarns, multiple weft yarns, multiple z-yarns and ± bias yarns (Fig. 2.20). This



2.19 3-D multilayer fabric for automobile seats.



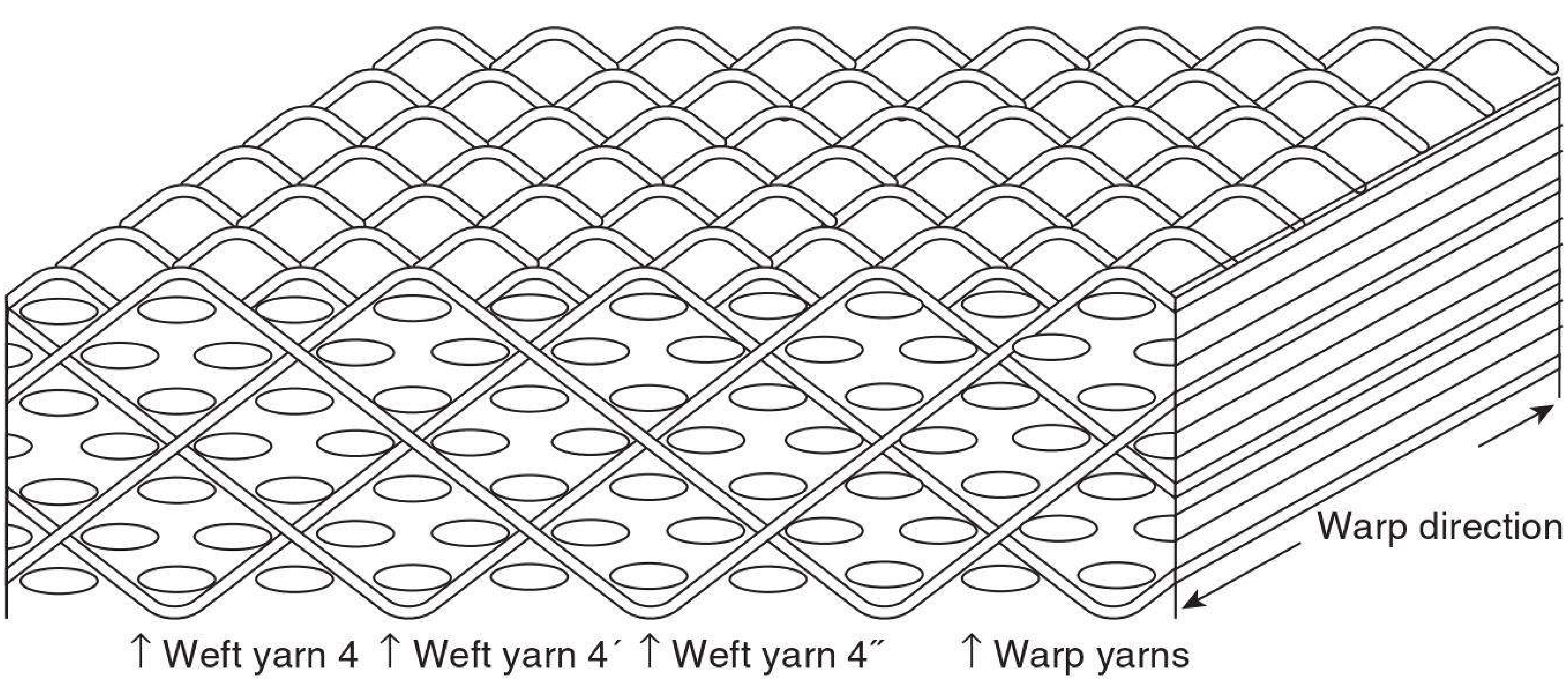
2.20 3-D woven fabric for automobile interiors.

3-D fabric could be used as a reinforcing fabric for automobile interiors such as seat coverings and other interiors.

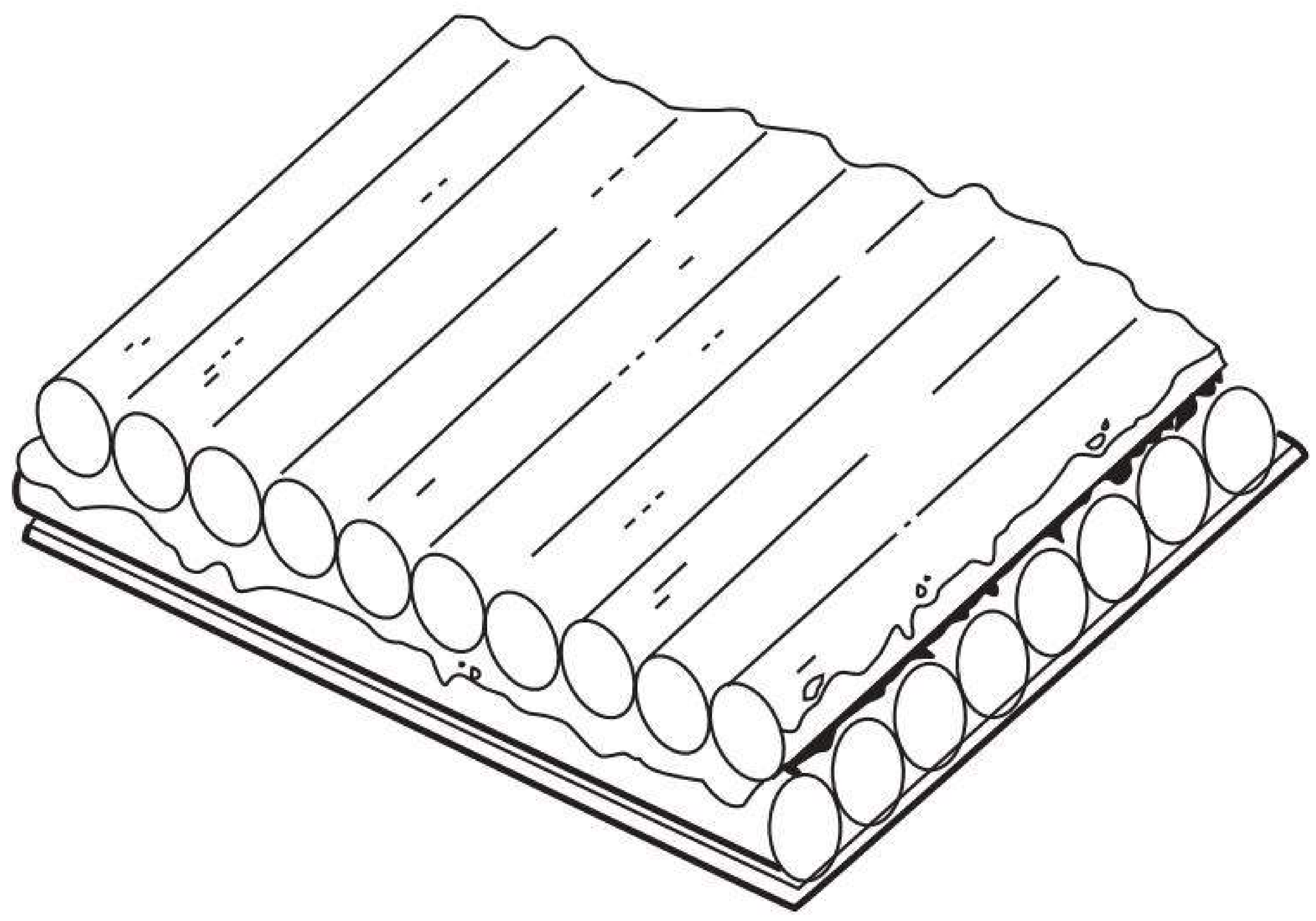
Apart from the above applications, 3-D fabrics are used in floor coverings, while tufted and needle-punched 3-D non-wovens are widely used as pre-assembled interior components such as for bootliners, seatbacks, door panels and various types of filter. In addition, 3-D fabrics find application in roof linings, door kick-panels, parcel shelves, insulation materials (for heat, sound, vibration, etc.), wheelhouse covers, etc. Coated or laminated needle-punched 3-D non-wovens and 3-D warp-knitted fabrics are the main materials for these pre-assembled interior components (Mukhopadhyay, 2000).

2.7 Application of three-dimensional fabrics to protective clothing and the aerospace industry

Protective textiles refer to garments and other fabric-related items designed to protect the wearer from harsh environmental effects that may result in injury or death. There has been a large increase in the hazards to which humans are exposed as a result of developments in technology in the workplace and on the battlefield, for example. The need to protect against these agencies is paralleled by the desire to increase protection against natural forces and elements. The dangers are often so specialised that no single type of clothing will be adequate for work outside the normal routine. Previous studies have indicated that a series of protective clothing ensembles is required for a variety of potential hazards. Woven, knitted and non-woven fabrics have been designed to suit specific requirements. Blast-proof vests are most frequently made from aramid fibres, such as Kevlar® (DuPont) and Twaron® (AKZO) and Dyneema® (DSM) high tenacity polyethylene fibre. Different fabric constructions are required for protection against low-velocity and high-velocity ammunition. Most traditional ballistic armour used for bullet-resistant vests relies on multiple layers of woven fabric. The number of layers dictates the degree of protection. Three-dimensional fabric structures are being used extensively for ballistic protection. By adopting a 3-D multilayer weave construction, inventors in the USA claim that thinner, more comfortable protective vests can be produced without reducing the level of protection afforded. The 3-D fabric developed by the US inventors (US patent 5,456,974, 1996) is said to offer improved ballistic resistance but can be thinner than the 2-D fabrics that have been used previously, because it uses a 3-D weave and incorporates at least two planes of high-modulus warp yarns (Fig. 2.21).



2.21 3-D woven fabric for improved ballistic protection.



2.22 3-D non-woven fabric for increased ballistic protection.

Three-dimensional non-woven fabrics have also been reported as fabrics for ballistic protection. It is claimed by an inventor in the USA (US Patents 5,443,882 and 5,443,883, 1996) that a non-woven construction can be used for improved ballistic protection. The construction is based on an array of high-performance fibre bundles of Kevlar with multilayer concept. This 3-D construction (Fig. 2.22) is said to provide increased ballistic protection, and suitable body armours can be produced with the fabric.

Protective textiles, specially produced for ballistic applications, consist of a number of fabric layers stitched or quilted together. An alternative and cost-effective method would be to weave all the layers together. Relatively thick fabrics consisting of a number of warp and weft layers can be produced on conventional and specialized 3-D weaving machines. The warp and weft yarns are held together with interlacing *z*-yarns: orthogonal and angle-interlaced are the two prominent structures used. In these structures, most of the yarns remain non-crimped and hence these structures have high in-plane modulus and high longitudinal wave velocity (Potluri and Needham, 2005). 3TEX have developed a number of orthogonal weaves for the ballistic protection market (Singletary and Bogdanovich, 2000). They can typically weave up to 14 warp layers with a corresponding number of weft layers. Potentially, 3-D weaves have a number of advantages over broad cloth:

- Fabrics can be woven with much higher cover factors, since there are only small percentages of interlacing yarns.
- Warp and weft yarns have very little or no crimp at all in 3-D weaves. Hence, coarser yarns can be used as opposed to the fine yarns that are required in 2-D fabrics to minimize the effect of crimp.
- Labour cost can be reduced as a result of using coarser yarns and eliminating subsequent stitching processes.

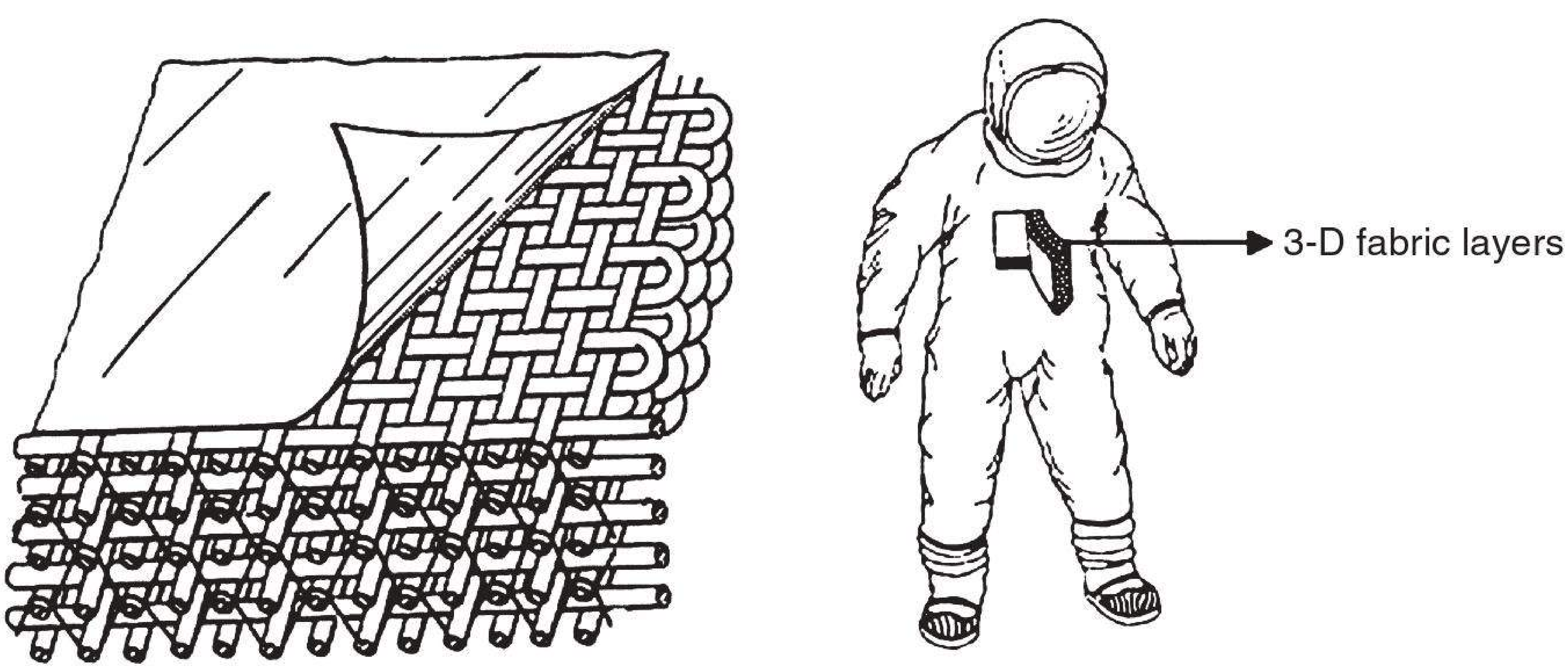
Orthogonal 3-D woven fabrics from 3TEX have very low-crimp warp and weft yarns held in place by binding yarns. It is expected that these 3-D fabrics will eventually replace conventional multilayer constructions in body armour.

Aerospace structures require materials of high specific modulus, and composite materials are gaining increased popularity nowadays for use in aerospace structures because of their advantages such as high specific strength in certain preferred directions and material tailoring (Brandt *et al.*, 1990). Three-dimensional woven fabrics nowadays are extensively used in aerospace applications. The potential applications include space suits for astronauts, space shuttle components, aircraft seat cushions, bags for gas-filled aircraft, etc.

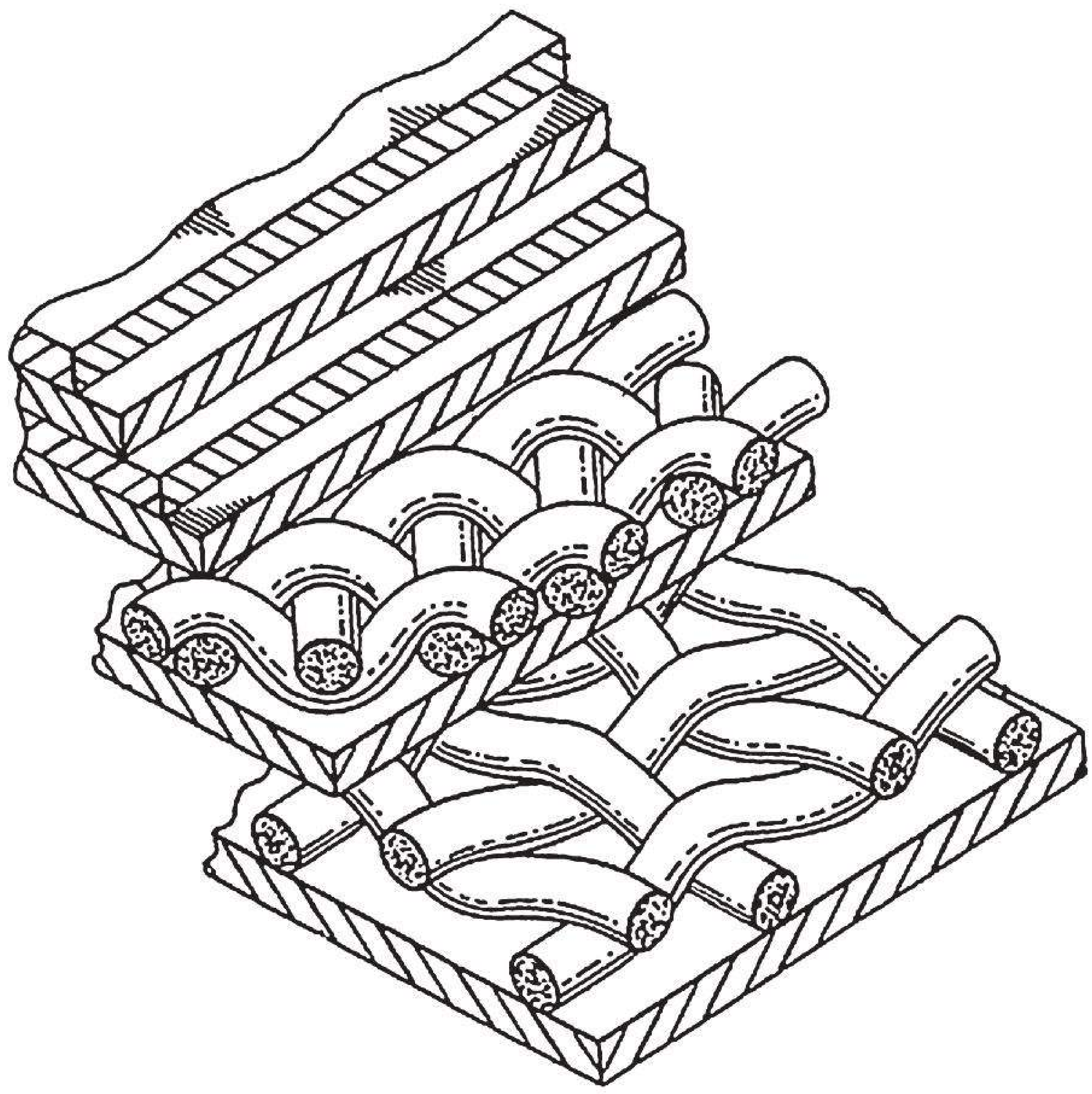
A multilayered 3-D fabric intended for making garments for astronauts has been developed by a German company. In the multilayer material patented by ERNO Raumfahrttechnik GmbH, the various layers of fabric are interconnected to create a 3-D structure. Different materials can be used in each layer to provide specific properties. The construction may be used to make space suits (Fig. 2.23).

A laminated multilayer fabric has been designed by Lockheed Corporation (World Patent WO 96/10666) for the bag of a gas-filled aircraft. The patent suggests that the fabric is woven from a strong fibre such as Vectran or Kevlar. The fabric (Fig. 2.24) is a 3-D multilayered structure and can be used to make bags for gas-filled aircraft.

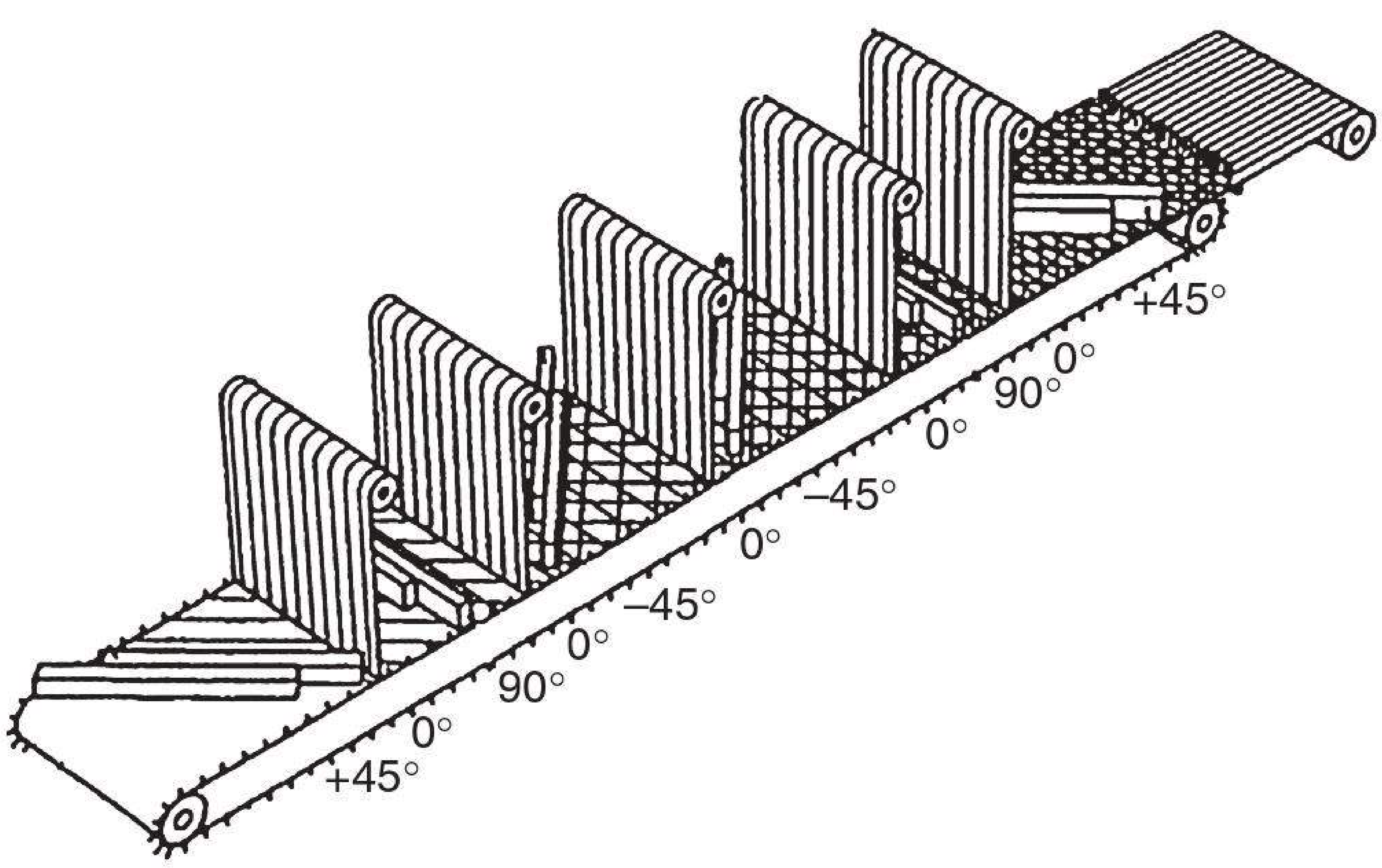
McDonnell-Douglas Corporation has introduced a new multiaxial and multi-ply warp-knitted fabric for structural applications. In World Patent WO 98/10128 (1999), the company disclosed a 3-D warp-knitted fabric to be used in structural applications including the components of a space shuttle. The fabric (Fig. 2.25) contains one or more plies oriented at 0°, and



2.23 3-D woven fabric for space suits.



2.24 3-D woven fabric for the bag of a gas-filled aircraft.



2.25 3-D multiaxial warp-knitted fabric for space shuttle.

provides localized reinforcement with better damage tolerance than 2-D structures. Using fibres of different moduli, it is possible to make fabrics in different weights and thicknesses for a variety of applications.

MWK fabric composites are being used more and more in the aerospace industry, which includes the military, aerospace and commercial aircraft industries. Relatively speaking, they are being used in this industry for many of the same reasons as in the marine industry, namely reduced weight and increased strength and integrity. Because of the flexibility and tailorability of mechanical and physical properties, MWK fabric composites can be customized for the application and specific properties can be emphasized to suit the particular need.

Currently, there are very few aircraft that use MWK fabric composites in critical structures such as the fuselage or wings. Most current applications centre around the skin of the aircraft. Other areas of use are in the top and side tail units, fuselage panelling, leading edges on side rudders, and engine panelling. MWK fabric composites are also being evaluated for rotor blades, outer skin and ballistic protection for helicopters. It is thought that the use of MWK composites is also being evaluated in the new military plane/helicopter, the V-22 Osprey, and the all-composite Beech Starship business plane (Kaufmann, 1991). The lower weight achieved through the use of MWK composite structures means that less fuel is consumed by the aircraft, which translates into significant energy savings for the user. Also, because of the improved structural integrity offered by the MWK fabric composite, it is believed that safety is enhanced.

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3
Multiaxial warp-knitted fabrics

Abstract: Over the past few years, multiaxial warp-knitted (MWK) fabrics have made significant inroads into the industrial composites arena. The use of MWK fabrics can lead to cost savings in the manufacture of composite components, and the uncrimped nature of the yarn can also produce improved mechanical performance when compared to traditional woven fabrics. MWK fabrics have a wide application scope ranging from geotextiles, pneumatic materials and construction to automobiles and aerospace-quality components as well as vessel-body parts due to their desired mechanical properties, and flexibility in design and low production cost. This chapter explains the structure, manufacturing methods, properties and advantages of multiaxial warp-knitted fabrics.

Key words: multiaxial warp-knitted (MWK) fabrics, manufacture of MWK fabrics, structure of MWK fabrics, shear of MWK fabrics, compression of MWK fabrics, applications of MWK fabrics.

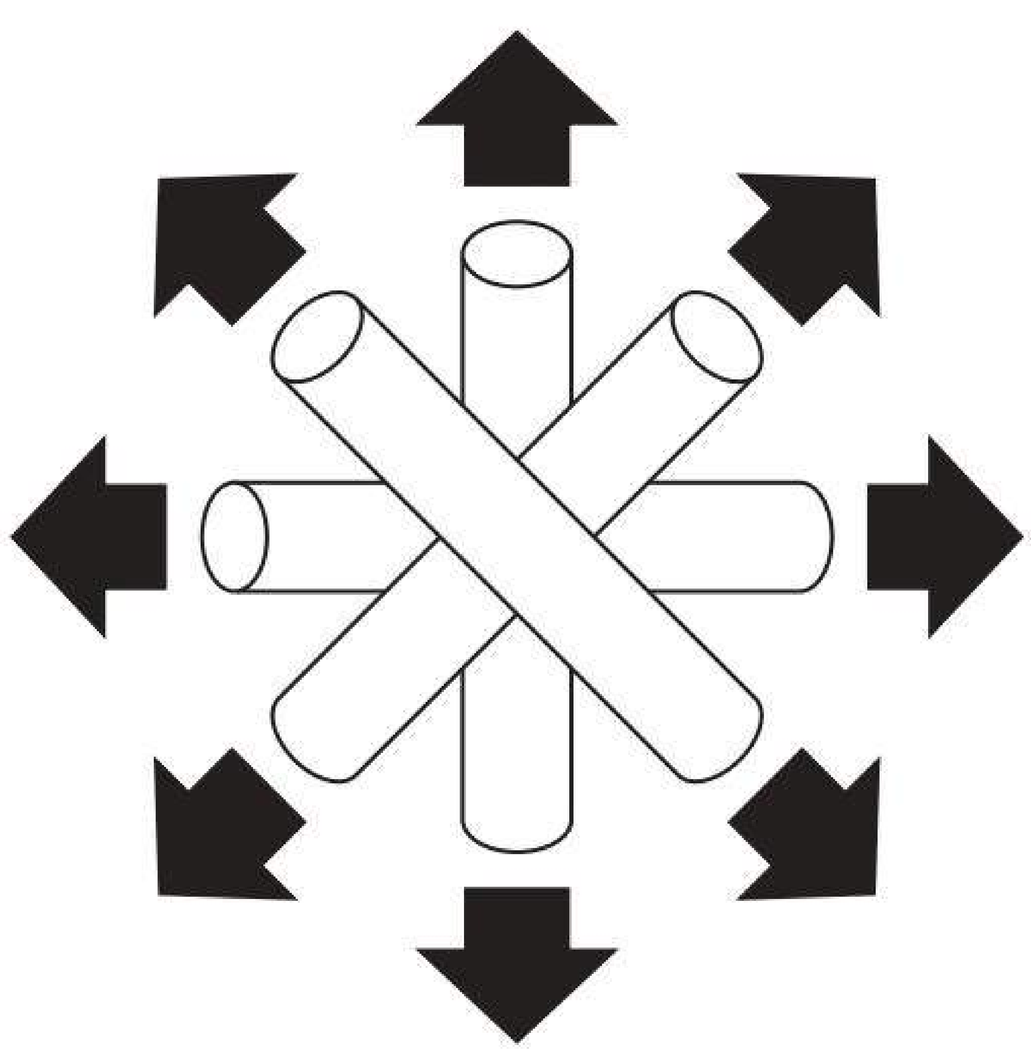
3.1 Introduction to multiaxial warp-knitted fabrics

Multiaxial multi-ply fabrics constitute one of the most efficient predesigned reinforcement techniques for the production of composite components and also offer improved product performance. Compared with the most widely used woven fabrics, a multiaxial multi-ply fabric offers better mechanical properties (strength and Young's modulus), and in addition the degree of drape can be adjusted in a wide range by the design of the knitting system. The production costs of composites can be reduced by the use of multiaxial multi-ply fabrics. This can be demonstrated in various special applications such as city bus body and motorcycle wheel rim production.

Over the past few years, multiaxial warp-knitted (MWK) fabrics have made significant inroads into the industrial composites arena. They are a family of high-performance technical fabrics, which was developed in the early 1980s and entered into the field of structural composites in the 1990s. MWK fabrics have a wide variety of applications ranging from geotextiles, pneumatic materials and construction to automobiles, aerospace-quality components and vessel body parts, due to their desired mechanical properties, flexibility in design and low production cost (Kaufmann, 1991b; Dexter, 1992). The current trend in textile structural composites is to extend their applications from secondary non-load-bearing structures to primary load-bearing structures. This requires a significant improvement in their damage tolerance and reliability. For thin to medium-thickness structures, multiaxial warp-knitted (MWK) structures form an attractive family of textile preforms, and have the potential to meet the demand for structural composites. All layers of the insertion yarns in an MWK structure are placed in perfect order and reveal the uniformity of the non-crimped parallel yarns (Du and Ko, 1996). While the insertion yarns play a principal role in plane reinforcement, the stitch yarns provide through-thickness reinforcement, thus significantly increasing the damage tolerance, structural integrity and out-of-plane strength of the reinforced structure (Zhou Rongxing *et al.*, 2005). Being lightweight and resistant to corrosion and chemicals, multiaxial fabrics have opened up new developments in the fuselage and wings of aircraft, fast-moving machine parts, tennis rackets, skis and snowboards, and rotor blades for wind turbines (*Textile Month*, 2006).

Advanced composite structures comprising high-strength materials combined with a resin system are being used in the most diverse sectors of the industrial arena. MWK fabrics are ideally suited for this type of end-use because of their flexibility and engineerability. MWK fabrics, produced in a one-step process, have properties similar to those of quasi-isotropic lay-up structures. Besides good handleability, MWK fabric preforms are extremely conformable. The four axes of an MWK fabric are shown in Fig. 3.1.

In a nutshell, the use of MWK fabrics can lead to cost savings in the manufacture of composite components and the uncrimped nature of the yarn can also produce improved mechanical performance when compared to traditional woven fabrics. Their tear strength is also found to be higher than that of woven fabrics and this may be due to the shifting of yarn layers under force which bunch together to resist tearing. Warp inlay multiaxial structures show higher elastic modulus than woven fabrics. These fabrics have excellent dimensional stability and are outstanding in plane shear resistance in all directions.



3.1 Four axes of an MWK fabric.

3.2 Advantages of multiaxial warp-knitted fabrics

The significant dominance of yarn layers against stitches in multiaxial structures leads to a fabric behaviour which has little to do with typical knitted structures.

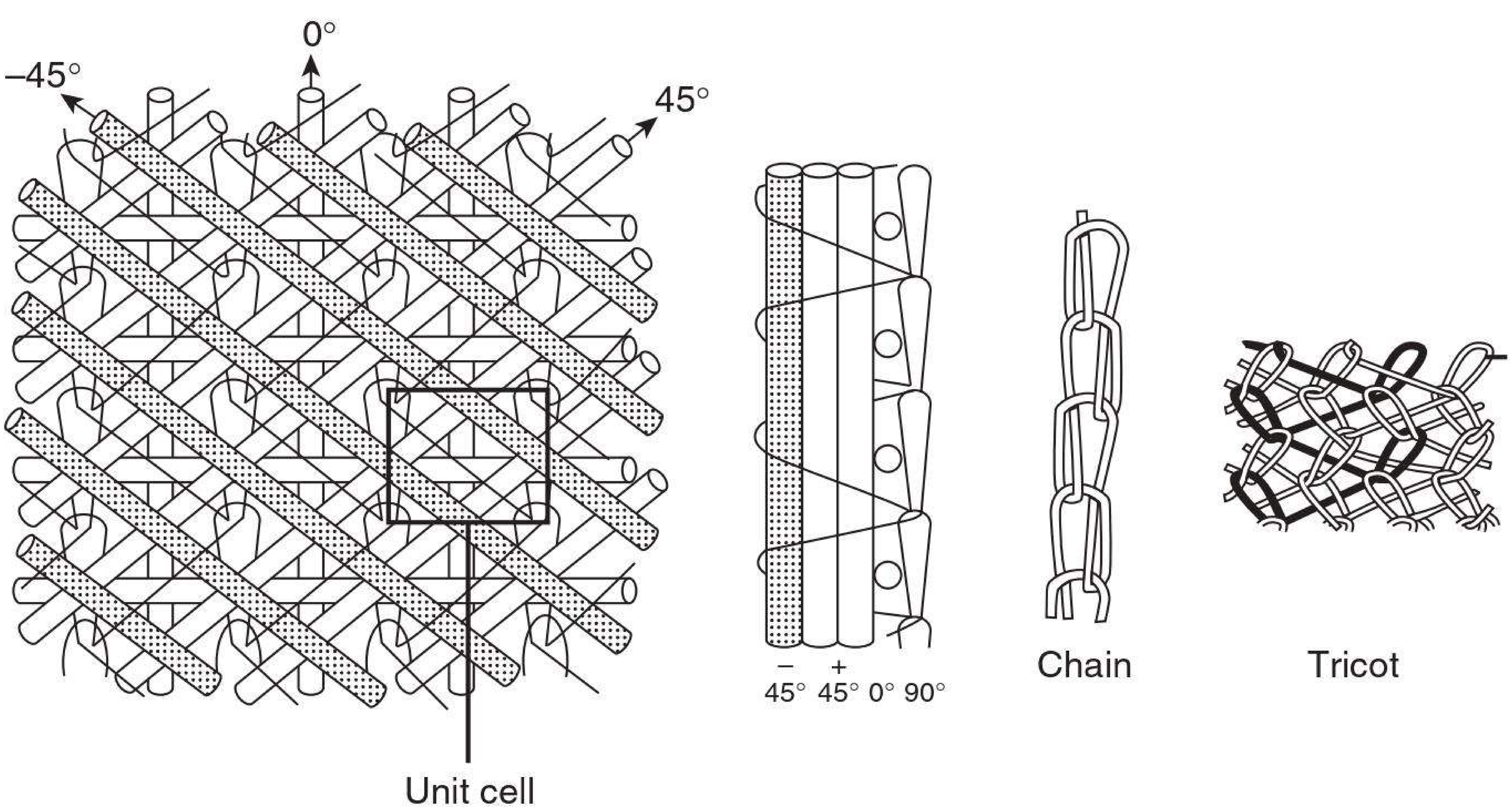
- MWK fabrics generally possess up to four different load-bearing yarn systems arranged so that each can take on stress and strain in virtually all directions. Since these load-bearing yarns lie straight in the fabric, with no crimp, the physical parameters of the individual yarn system are fully utilized.
- Unlike the crimp inserted into the yarn in woven fabrics during weaving, the load-bearing yarn in MWK fabrics lies straight and parallel to other yarns in its yarn system. This characteristic of MWK fabrics allows for the yarn properties to be more fully utilized in withstanding in-plane forces.
- Fabric design is made easier because the designer can more accurately calculate the tensile load of an MWK fabric with a much higher degree of confidence than had been previously attainable with woven fabrics.
- MWK fabrics are capable of withstanding stresses and strains in an optimum fashion. This is due largely to the parallel and straight arrangement of the load-bearing yarns in the MWK fabric. Because the load-bearing yarns lie straight in the fabric, their tensile properties are fully utilized and they are able to absorb tension without the elasticity that occurs when the yarns are crimped or in a wavelike form, such as in a woven fabric.
- Due to the parallel nature of the load-bearing yarns in the MWK fabric, excellent tear propagation resistance is achieved. This resistance to tear propagation becomes increasingly important when an MWK structure is damaged while in use (such as in a sail, inflatable structure or aircraft skin). The damage is minimized by the resistance to further tearing.
- Because the yarn systems are not interwoven, but rather lie directly on top of each other and are held together by the fifth yarn system, conformability of the fabric is greatly improved. This allows the MWK fabric preforms to conform to many complex geometrical shapes and still maximize the translation of fibre mechanical properties to the composite structure. The conformability of the uncured MWK fabric also provides good shape retention during the laying up and curing process.
- By combining a web or non-woven fabric (usually nylon, polyester or fibreglass) to the MWK fabric during the knitting process, it is possible to control many other physical aspects of the fabric structure. Both the MWK fabric and the web can demonstrate their specific advantages. Because the web is fed into the knitting machine during production of

the MWK fabric, it is linked to the load-bearing yarns by the stitch yarn, rather than being rigidly bonded. Adding a web to the MWK structure allows the designer even greater design flexibility.

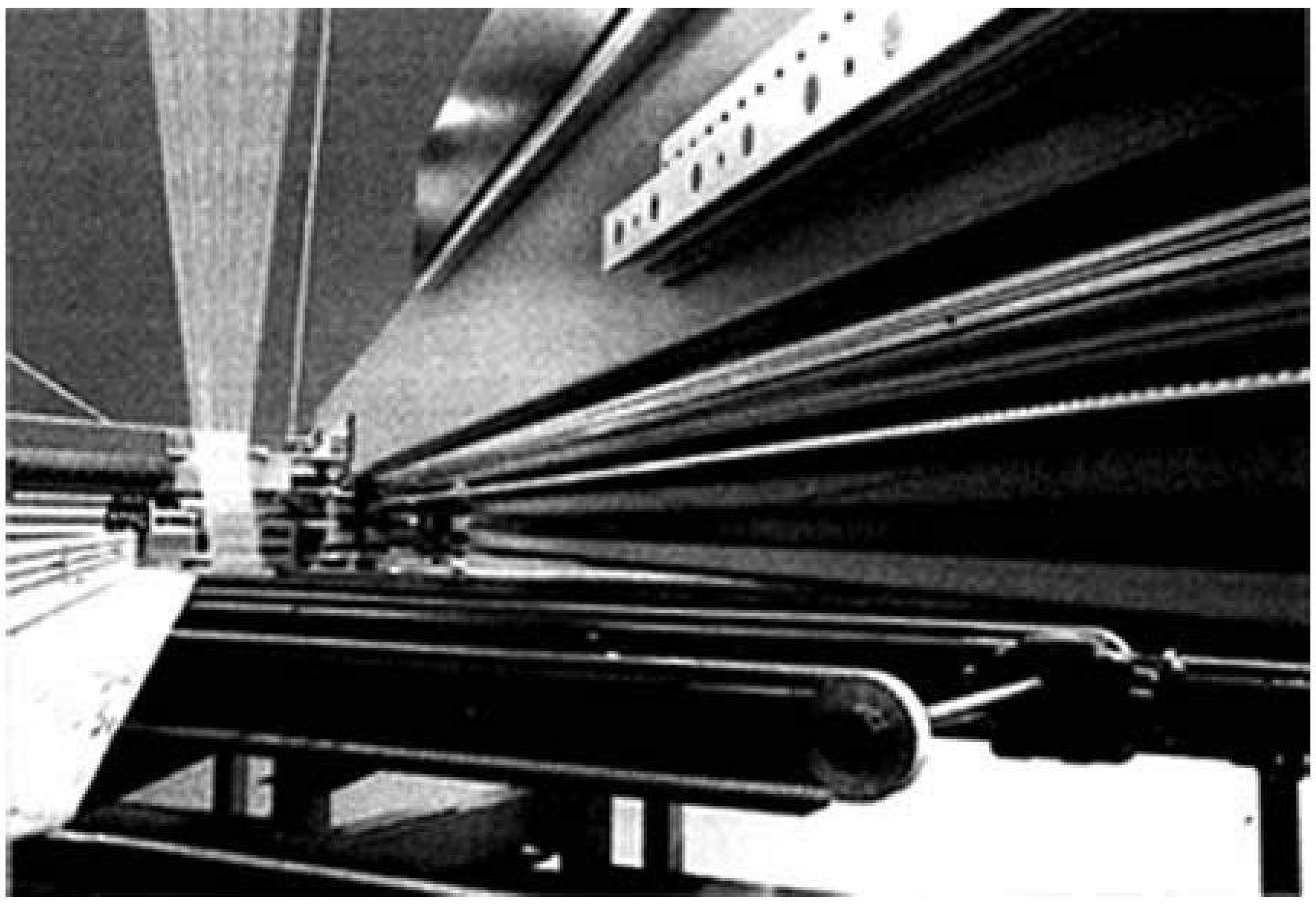
- Several advantages of multiaxial knits indicate clearly that a considerable reduction in yarn material (reaching up to around 30%) is justifiable. This is particularly important in lightweight composites, taking into account that multiaxial fabric production is more expensive than that of woven ones.
- One aim in composite production is to make maximum use of textile properties with a minimum of resin. Matrix ratio is the proportion of resin to fabric weight. In this connection multiaxial warp knits perform similar to woven fabrics. It is also claimed that wet resins are distributed better in a multiaxial fabric during impregnating, injecting or transfer moulding.
- Multiaxial knits could bear up to about 50% or more specific load capacity (breaking load per unit weight of fabric) in comparison to woven fabrics. This means that lighter warp knit constructions are possible for the same usage.

3.3 Manufacture of multiaxial warp-knitted fabrics

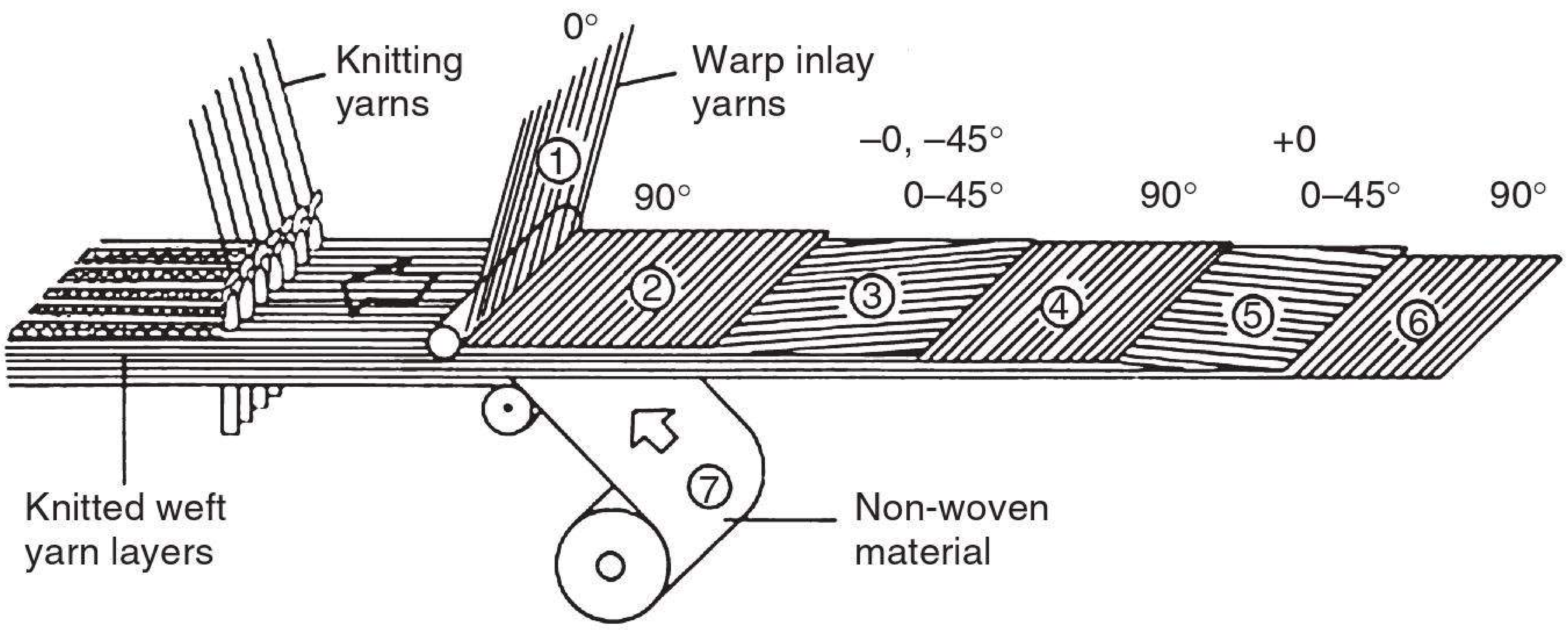
The MWK fabric system consists of warp (0°), weft (90°) and bias (±θ) yarns held together by a chain or tricot stitch through the thickness of the fabric, as illustrated in Fig. 3.2. Theoretically, the MWK can be made to as many layers of multiaxial yarns as needed, but current commercially available machines allow four layers (the Mayer system, Fig. 3.3) of 0°, 90°, ±θ



3.2 MWK fabric systems.



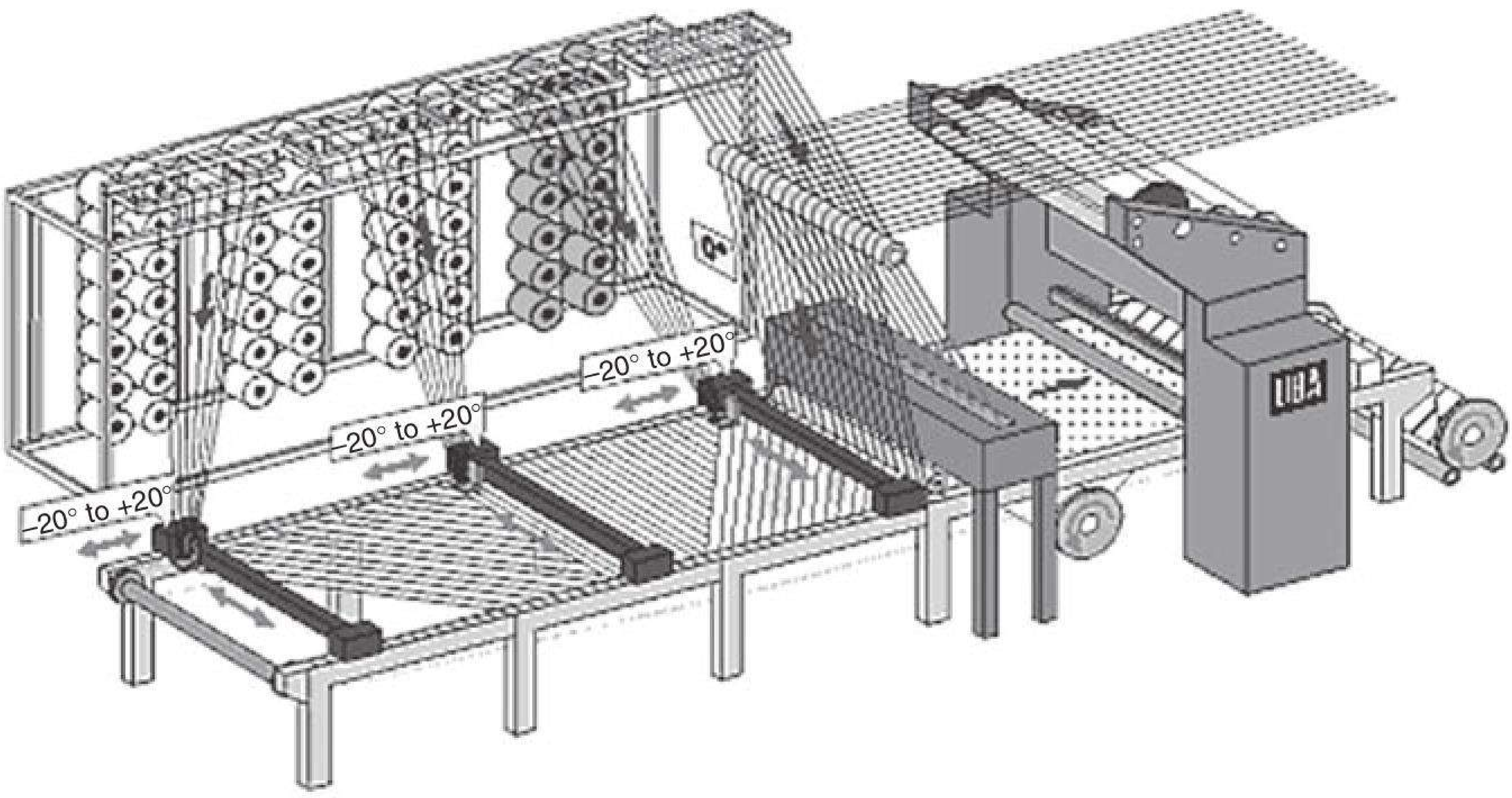
3.3 MWK fabric Karl Mayer system.



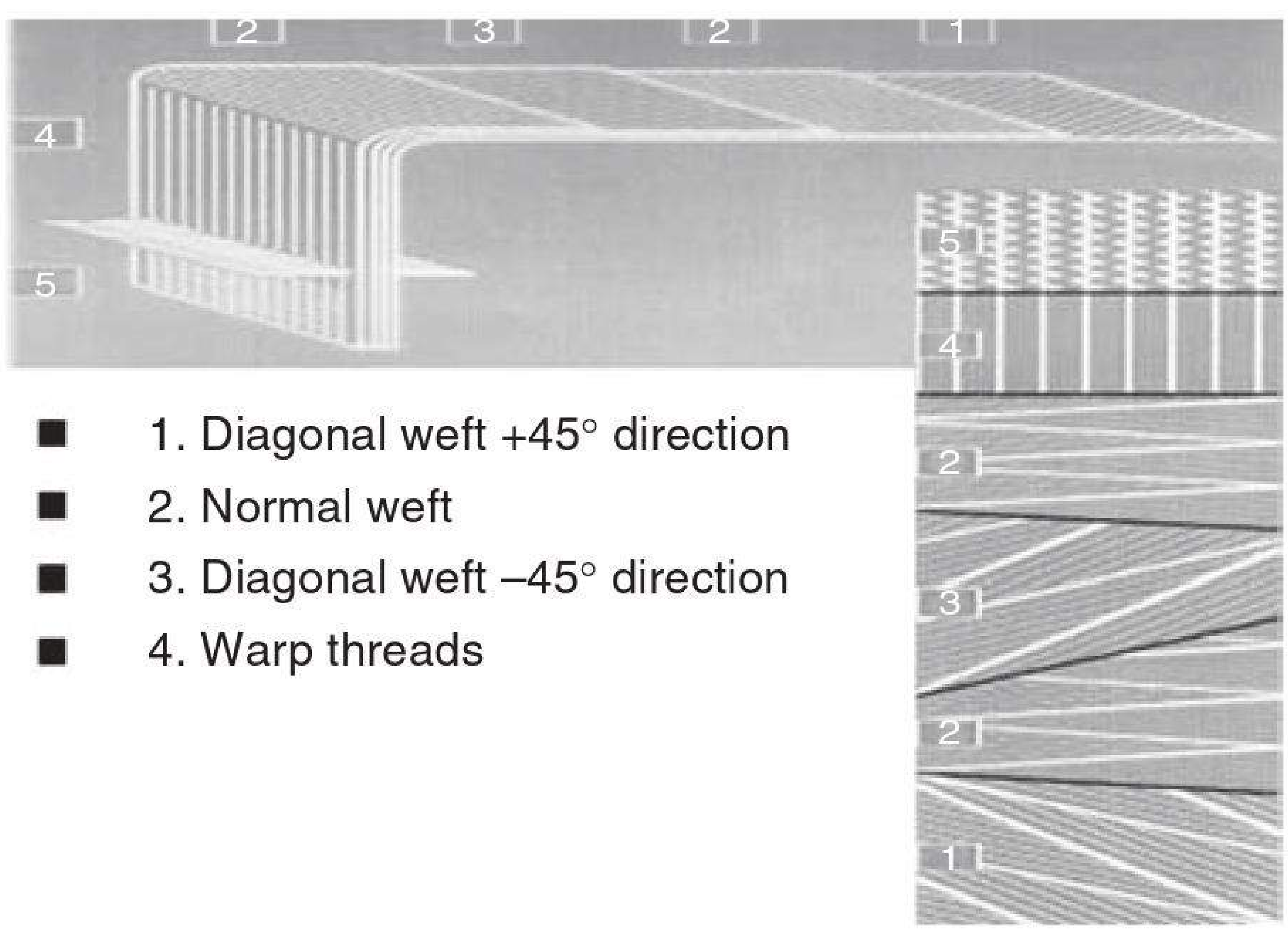
3.4 MWK fabric LIBA system.

for insertion yarns, or at most eight layers (the LIBA system, Figs 3.4 and 3.5) of 0°, 90°, three ($\pm\theta$) insertion yarns, to be stitched together. All layers of insertion yarns are placed in perfect order, each on top of the other, in the knitting process. Each layer shows the uniformity of the uncrimped parallel yarns. While the insertion yarns play a principal role in plane reinforcement, the stitch yarns provide through-thickness reinforcement, thus significantly increasing the damage tolerance, structural integrity and out-of-plane strength of the reinforced structure. To ensure the structural integrity, it is clear that the 0° yarns cannot be placed in either top or bottom layer. The insertion yarns usually possess a much higher linear density than the stitch yarns, and are, therefore, the major load-bearing components of the fabric (Du and Ko, 1996).

MWK fabrics are produced on a special Raschel machine and the structure consists of two diagonal weft layers, followed by a warp yarn and a horizontal weft yarn. The layers are held together by pillar stitches from



3.5 Schematic diagram of LIBA multiaxial warp-knitting machine.



3.6 Production of MWK fabrics.

both sides. The diagonal weft insertions ensure parallel placement of yarns at constant distance. Weft insertion makes it possible to arrange that the least part of the fibre is in stretched form. The diagonal angle of weft can be varied in the range of 30° to 60° by suitably altering the course density. A schematic diagram showing the production of MWK fabrics is shown in Fig. 3.6.

3.3.1 The LIBA technique

By using the LIBA technique (LIBA Maschinenfabrik GmbH), MWK fabrics can be produced on a special tricot machine so that an undesirable bending of the fabric immediately after leaving the knitting zone is avoided. The machine is offered in gauges between E6 and E12 (needles per inch) with working widths of 50 or 68. The linear production rate ranges roughly between 30 and 90 metres per hour. Five to seven weft-inlaid yarn layers and a warp-inlaid yarn layer are possible. At each weft station the yarn can be laid horizontally in the range 30° to 60° in positive and negative directions, so that layer positions can be easily interchanged. The standard version has five independent segments; this can be increased to seven segments. All weft yarns are withdrawn from bobbins mounted on a creel. Production economy can be raised by working with a relatively small number of bobbins. In each segment the yarns can be laid horizontally or diagonally. The yarns are traversed by a weft carriage between two transport chains, fixed on them and continuously transported into the knitting zone. The insertion sequence is electronically controlled and can be programmed for the required 'packing density'. A change in diagonal angle is independent of the course density (Iyer, 1992).

The LIBA technique gives quadraxial structures, where yarns are arranged at 0°, +45°, –45° and 90°. This system uses latch needles with a rounded hook to reduce the possibility of damage to the reinforcing yarns, a significant advantage over other systems for stitching and knitting through multiple layers (Mohamed, 1990). On the other hand, in the LIBA system, six layers of linear yarns can be assembled in various stacking sequences and stitched together by knitting needles piercing through the yarn layers. While this piercing action unavoidably damages the reinforcing fibre, the penetration of the knitting needles also permits the incorporation of a non-woven as a surface layer for the composite.

A maximum of 73 variations have been calculated for the standard machine version with five weft insertion systems. As mentioned earlier, this can be extended to seven systems. Besides this, it is also possible to produce yarn-reinforced, directionally oriented fleeces. Variations can be summed up as follows:

- The fleece can be laid on the top or bottom of the yarn layers.
- The diagonal angle can be altered at each weft insertion system independently and without changing the course density.
- Layers can be omitted as required.
- Weft yarn density can be freely changed in each system.

It is possible to use any kind of yarn in the layers for directional orientation. Thus use can be made of high-modulus filament yarns like aramid, glass, carbon or high-tensile polyester and polypropylene for the production of high-performance composites. Yarn counts can lie anywhere between about 100 and 1200 dtex. Short fibre yarns can also be utilized for corresponding composites like mats and fleeces. Stitches are normally produced by using 'conventional' synthetic polymer filament yarns like polyester. While producing resin-based composites one should bear in mind the compatibility between resin, the fibre used for stitches and the fibres used in the yarn layers.

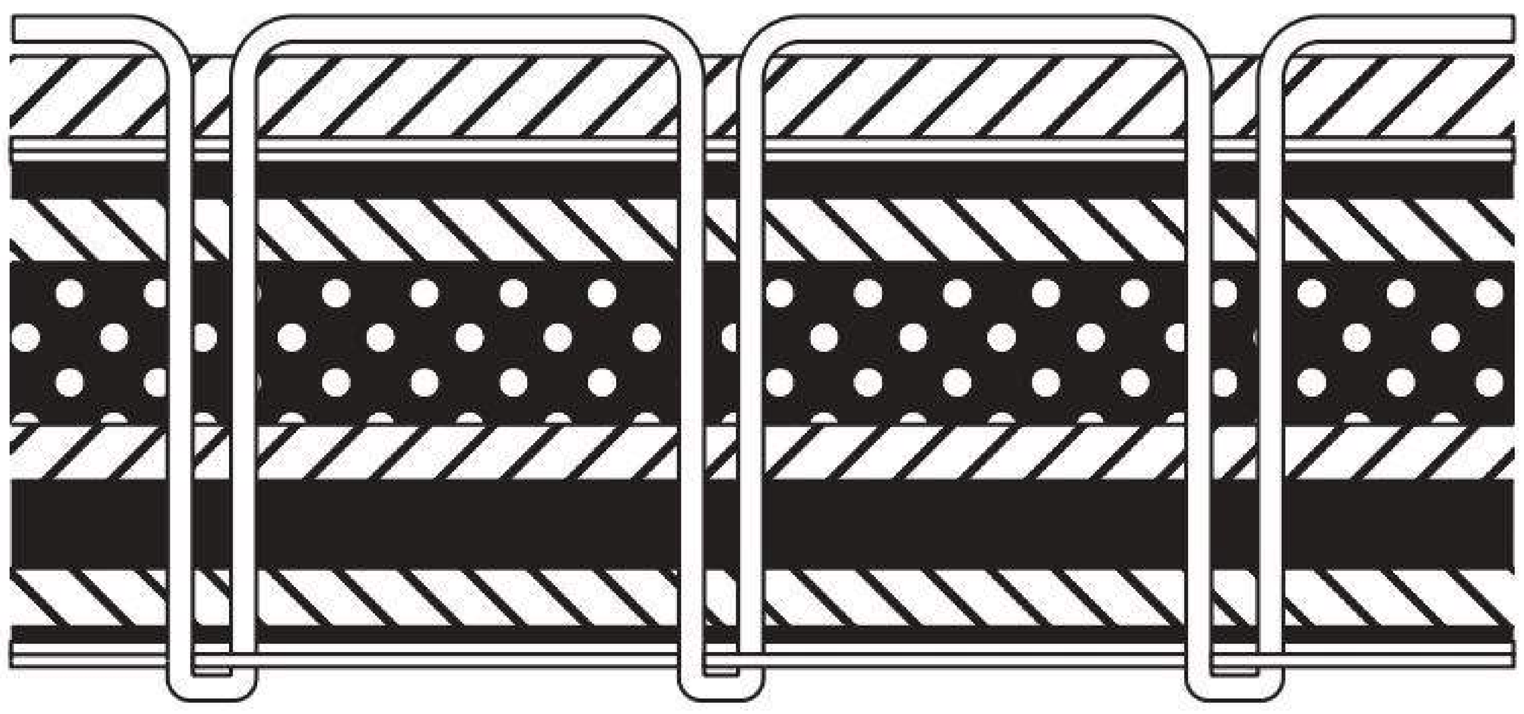
3.3.2 The Mayer technique

On a Raschel machine horizontal weft yarns are inserted by a magazine system. Guide bars are used for vertical warp yarns and stitches. With the help of special guides, rotating around the needle bar in one direction, diagonal weft yarns are laid exactly between two successive needles from one course to the next. Lateral guide movement and longitudinal fabric movement lead to a diagonal inclination of these yarns. The angle of inclination is determined by the course density. A multiaxial fabric contains two adjacent diagonal yarn layers, followed by vertical warp and horizontal weft yarns. This layer sequence cannot be altered. The production of yarn-reinforced fleeces is possible (Iyer, 1992).

The Malimo technique is another method to develop multiaxial stitch-bonded knitted structures by stitching several layers of yarns together at various angles or piles of skewed fabric on a modified stitch-bonding machine. This will improve mechanical properties and structural consistency (Iyer, 1994). In this machine, a parallel weft sheet is layered with the help of a weft layering apparatus. In the case of the weft threads the layering principle does not allow for a precise 90° orientation. The thread sheet is inserted into the transport system crossed at an angle of approximately 5° to the parallel weft layer due to the feed motion during the laying-up procedure. Finally the weft thread sheet and the warp threads (0° reinforcement) are fed into the knitting elements (Karlheinz and Burkhard, 1992).

In the production of MWK fabrics, the materials for inlays (knitting yarns) are normally high-modulus or high-temperature-resistant polymer filaments such as polyester, nylon and PEEK, whereas glass, aramid or carbon threads can be used as reinforcing fibre materials (Alagirusamy *et al.*, 2006).

The MWK fabric preforms, having four directional reinforcements similar to quasi-isotropic lay-up, can be produced in a single step. Besides good ease of handling and production economics, the MWK fabric preforms also provide the conformability to complex shapes, the flexibility in the principal yarn directions, and the improved through-thickness strength. The mechanical properties of MWK structural composites, especially out-of-plane strength and impact behaviour, are potentially superior to those of conventional woven laminated composites due to the elimination of fibre crimp in the insertion yarns and the presence of the through-thickness reinforcing stitch loops (Zhou Rongxing *et al.*, 2005). In addition to the above, Hearle



3.7 Knit-stitched structure.

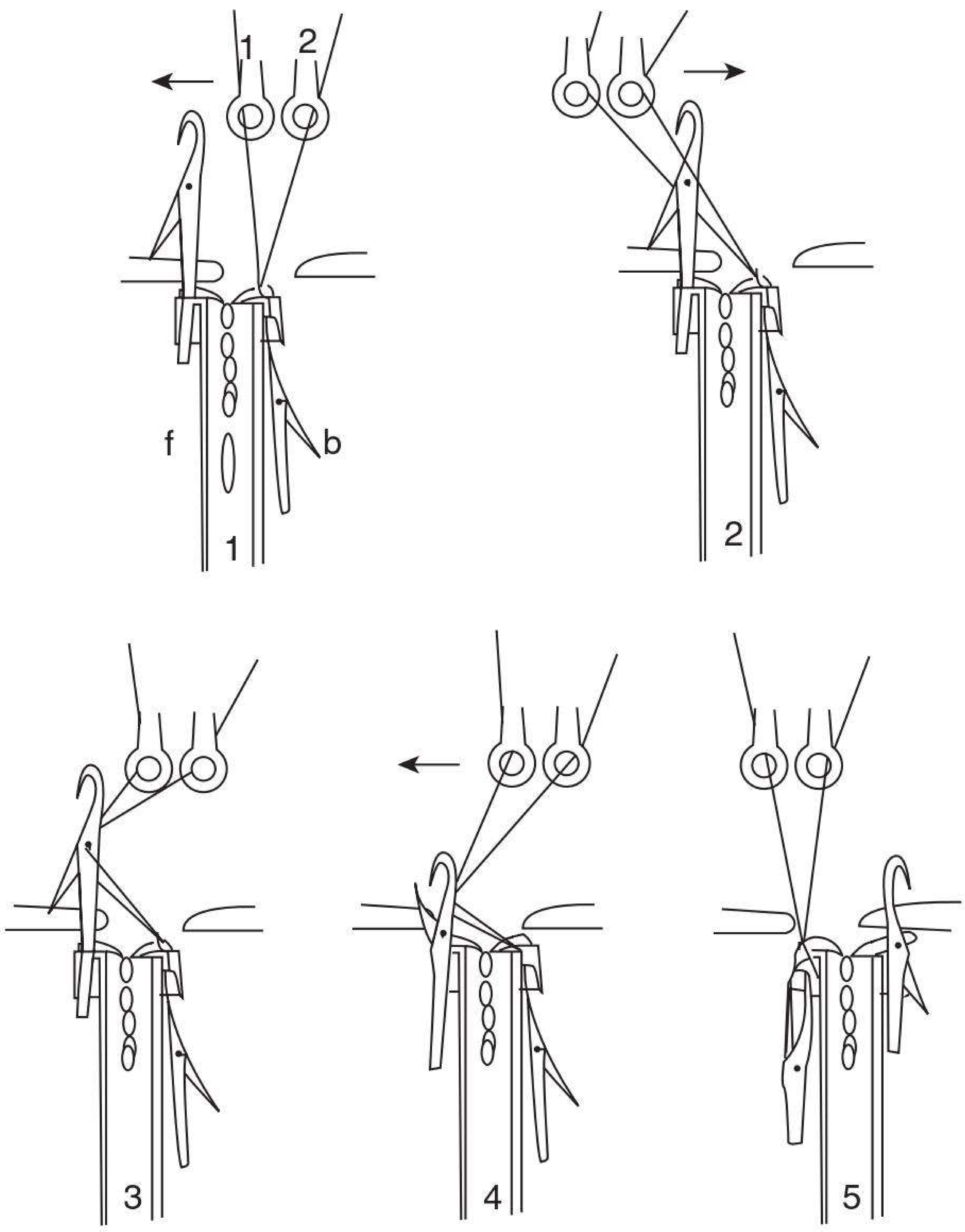
(1995) notes that the Mayer machine is capable of producing four-layer fabrics up to 1.6 m wide, while six-layer fabrics up to 2.5 m wide can be achieved with the LIBA machine at a rate of 45 m/h. Besides the oriented fibres, this process also allows the incorporation of non-woven fabric layers. The Mayer machine utilizes a multiaxial magazine weft insertion mechanism; the attractive feature of this system is the precision of yarn placement with four layers of linear or non-linear bias yarns arranged in a wide range of orientations. Furthermore, stitches are formed at over one metre per minute. The system creates loops that hold the reinforcing yarns in place in two directions.

The stitching-through principle of making warp-knitted multiaxial–multilayer structures (Fig. 3.7) for fibre-reinforced composites ensures isotropic behaviour through the uniform distribution of the yarn ends in multiple directions (Dow and Dexter, 1997). Due to the non-crimped and parallel yarn sheets in them, they are particularly suitable for fibre-reinforced composites with special characteristics such as low specific weight, adjustable stiffness (between extremely stiff and extremely stretchable) and highest mechanical load resistance (Wagener, 1993).

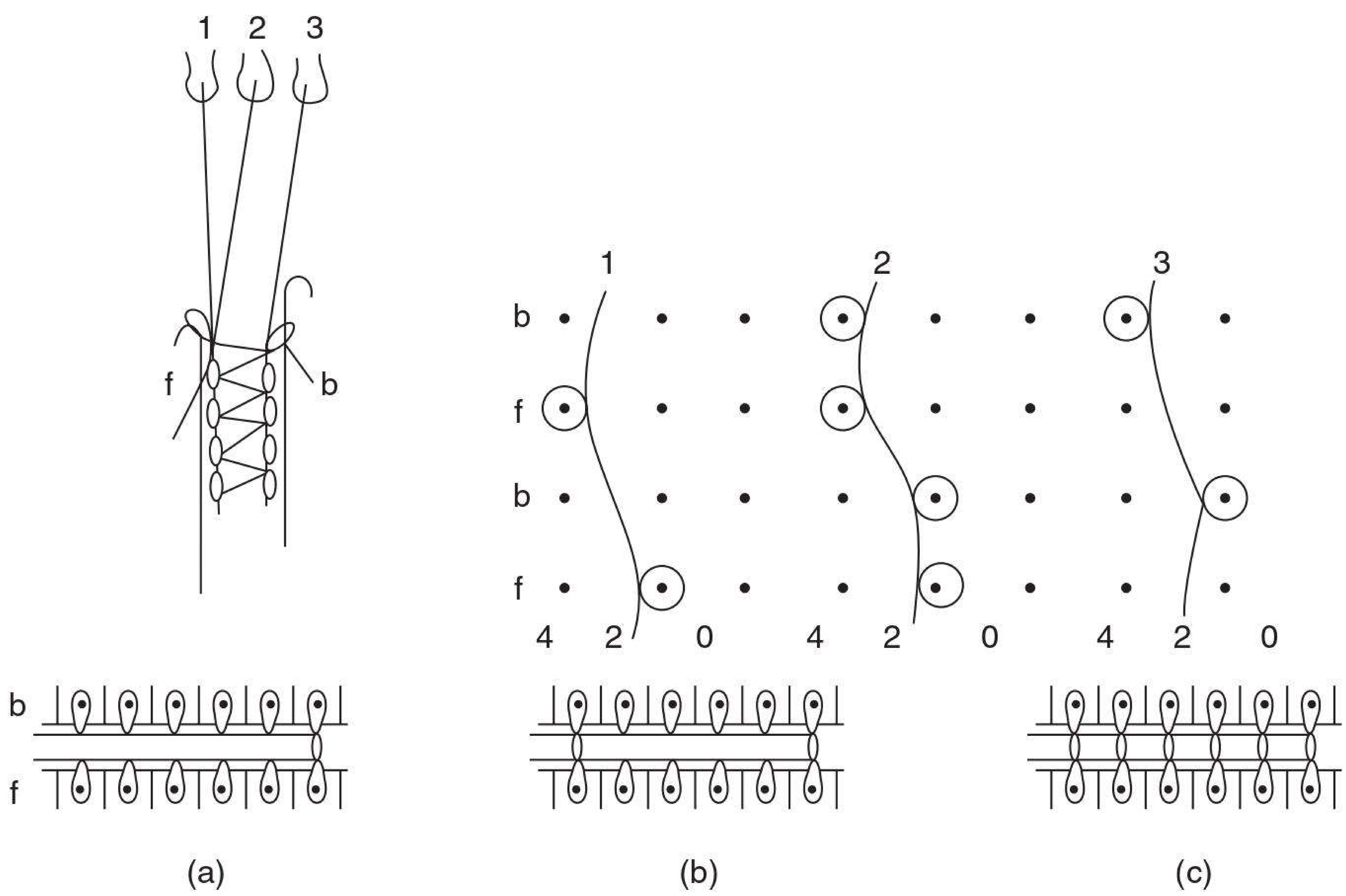
Stitch-bonding is considered to be a special case of stitching with the warp-knitting technique, while the loop formation cycle is similar to warp knitting but deviates with respect to constructive design of the stitch-bonding area (horizontal needle arrangement, fixed retaining, backing rail), the needle types applied (stitching needle), the reference size for the machine gauge (number of needles per 25 mm), and conversion of unbonded fibrous webs to purely mechanically stitch-bonded non-wovens (Padaki *et al.*, 2006).

A simplified knitting cycle in a two-needle-bar Raschel machine (spacer or tubular fabrics) for producing 3-D multiaxial warp-knitted (MWK) fabrics is represented in Fig. 3.8 and the knitting options are shown in Fig. 3.9. The use of two needle bars opened new horizons in warp knitting and different machine types are built for production of a wide variety of products ranging from packing sacks to artificial blood vessels.

1. The guide bars are positioned at the back of the machine, above the back needle bar. The front sinker bar is placed forward to secure the



3.8 Knitting action of a double-needle-bar Raschel machine (for description of shapes 1–5 see text).

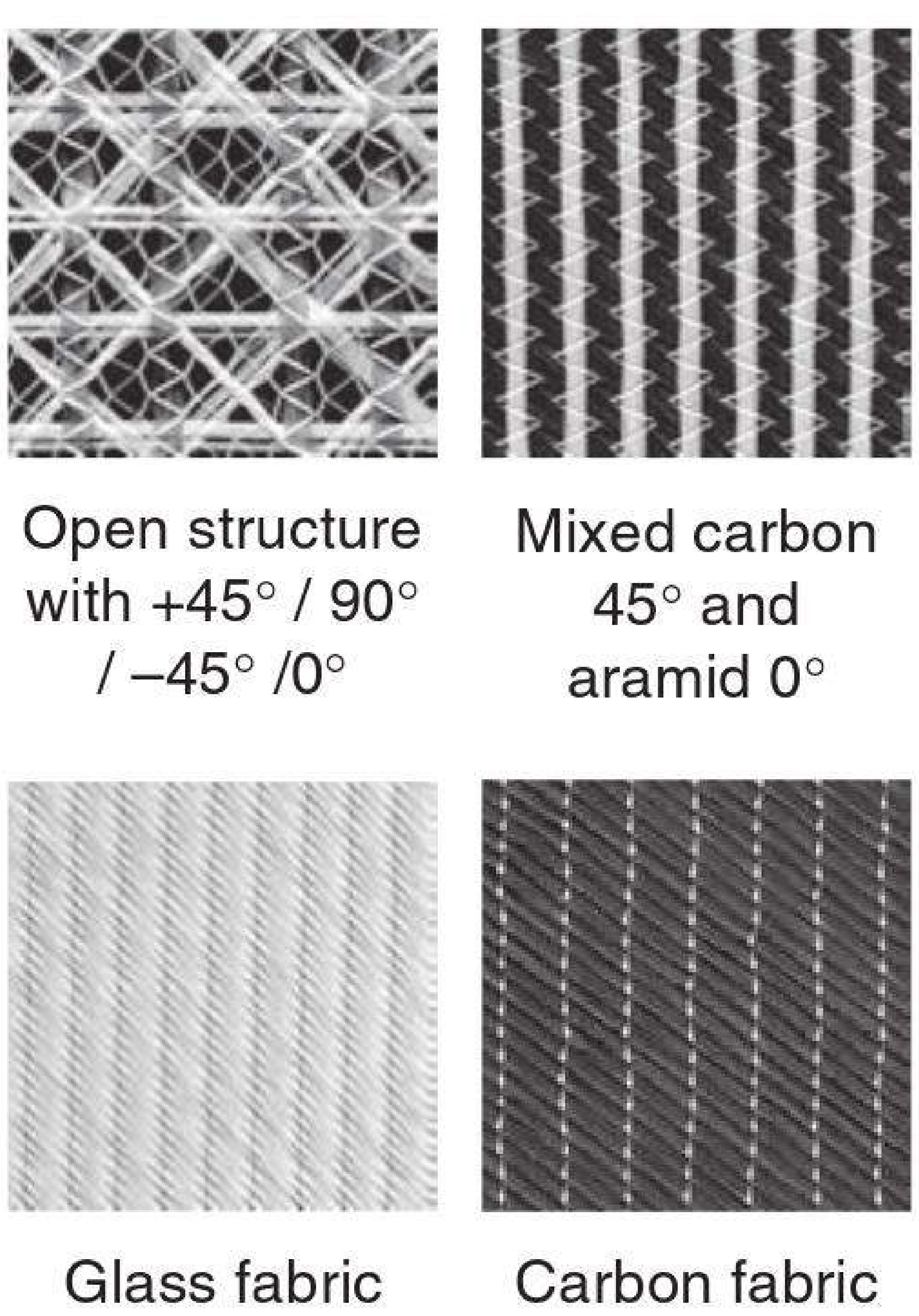


3.9 Knitting options with two needle bars and more than two guide bars (for description of shapes a–c see text).

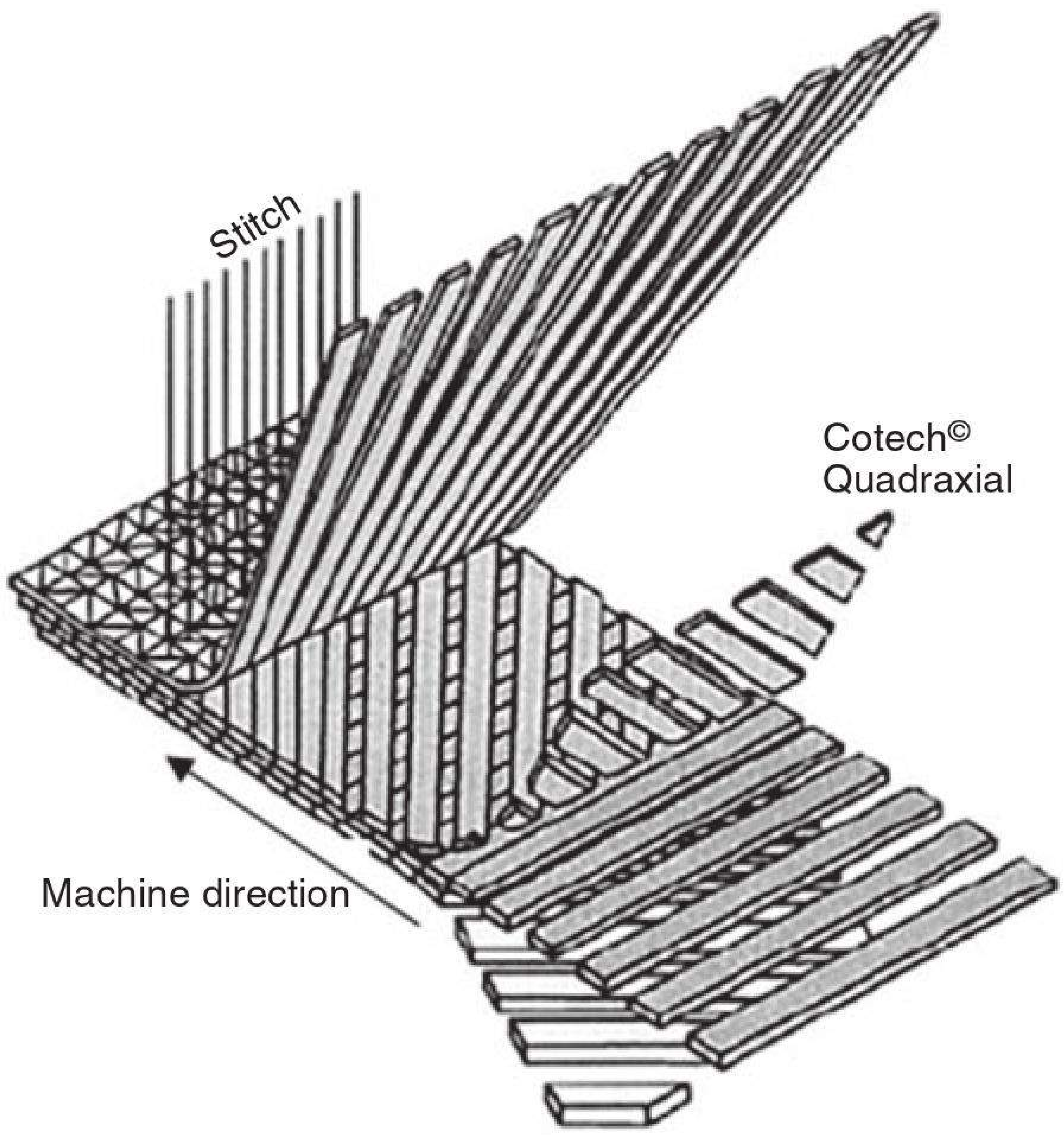
fabric while the front needle bar ascends to the clearing position. The guide bars perform the underlap shogging movement for the needle bar and then swing to the hook-side.

2. On the hook-side of the front needle bar, the guide bars shog an overlap according to the pattern mechanisms and then swing back.
3. The swing back is completed; the yarns are wrapped within the needle hooks so that the front needle bar can start to descend. The front sinker bar retreats while the back one moves forward.
4. The front needle bar descends the previously formed loops resting on the needle stems close to the latches. The front sinker bar continues to retreat and the back one is now above its needle bar. The guide bar swings for the third time, this time to the front in order to clear the way above the back needle bar. The underlap shogging movement for the back needle bar can start.
5. The front needle bar is at knockover position and the needles form new loops. The back needle bar, now with its fabric secured by the sinker bar, ascends to the clearing position.
   a. The third guide bar is only threaded through one guide finger on one side, resulting in two separate fabrics, produced by the fully threaded guide bars.
   b. By threading the middle guide bar through two guide fingers, one on each side, a tubular fabric is formed.
   c. A fully threaded middle bar is used to produce a sandwich of two fabrics connected by yarns.

Typical MWK structures produced by the LIBA system are shown in Fig. 3.10.



3.10 Types of MWK fabrics.



3.11 Yarn arrangement in MWK fabric.

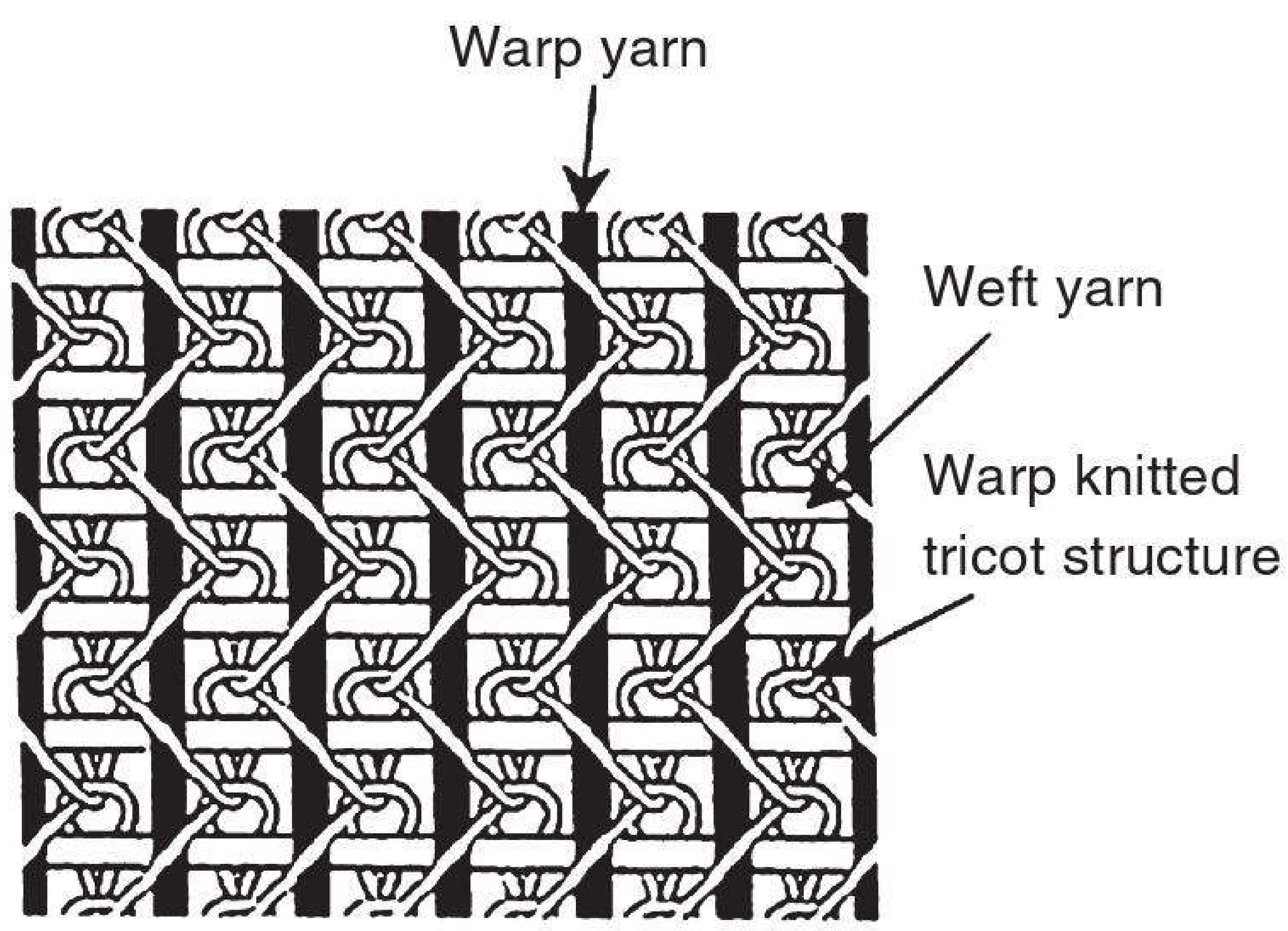
3.4 General structure and behaviour of multiaxial warp-knitted fabrics

3.4.1 Structure

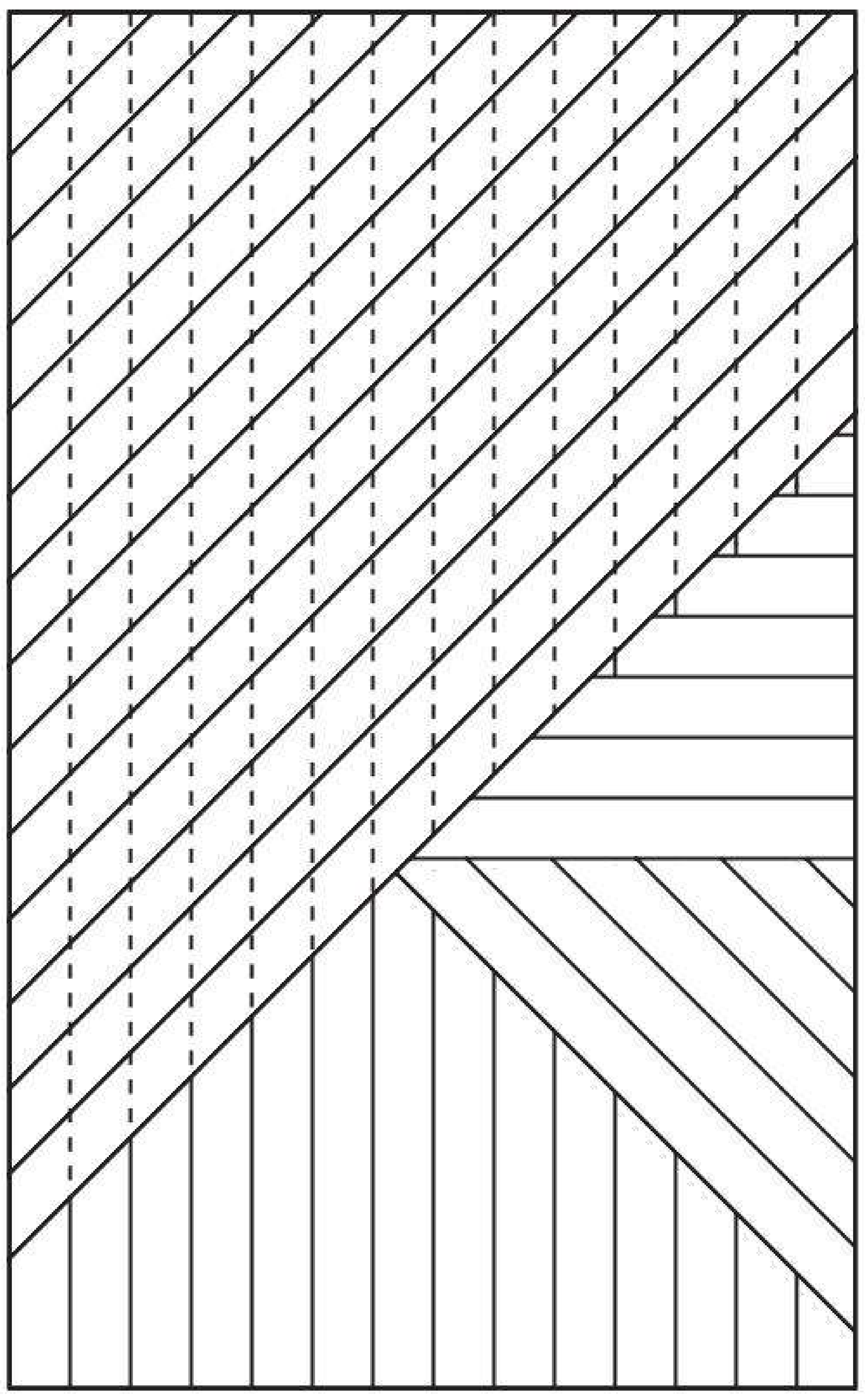
MWK fabrics are unique structures which are produced by warp-knitting techniques. With these techniques, straight ends of parallel and uncrimped yarns are inlaid into the knitted structure to give the ideal combination of mechanical properties at a favourable production cost. This produces MWK fabrics, with the combined advantages of design flexibility, performance, productivity and availability and the potential to become a major preform for industrial composites.

MWK fabrics have a structure where one or several yarn systems are held together by a binding yarn system. The interlacing yarn structure characterizing woven fabrics is not found in MWK fabrics. Instead, one or more layers of fibre tows are stacked on top of each other and held together by the binding yarn system (Fig. 3.11). Each layer consists of parallel fibre tows. Several layers are stacked in different directions to create the desired fabric properties. The reinforcing fibre systems commonly consist of tows from glass or carbon, but other fibres are available as well. The binding yarn system is usually made from polyester fibres (Edgren, 2006).

There are several basic structures used for the binding yarn system. A knitted structure is characterized by the interlacing loops created by the knitting yarn or thread (Byun and Chou, 2000). In a warp-knitted structure each thread forming the loops runs in the warp direction (Chou, 1992). To create a fabric suited for reinforcement in composite laminates, warp and weft yarns can be inserted into the warp-knitted structure, creating a multiaxial fabric. A schematic of a warp-knitted tricot structure with inserted warp and weft yarns is presented in Fig. 3.12. Reinforcing yarns can be inserted also in other directions than the 0° and 90° directions, e.g. ±45° (Cox and Flanagan, 1997), and a triaxial fabric structure is shown in Fig. 3.13.



3.12 Structure of biaxial MWK fabric.

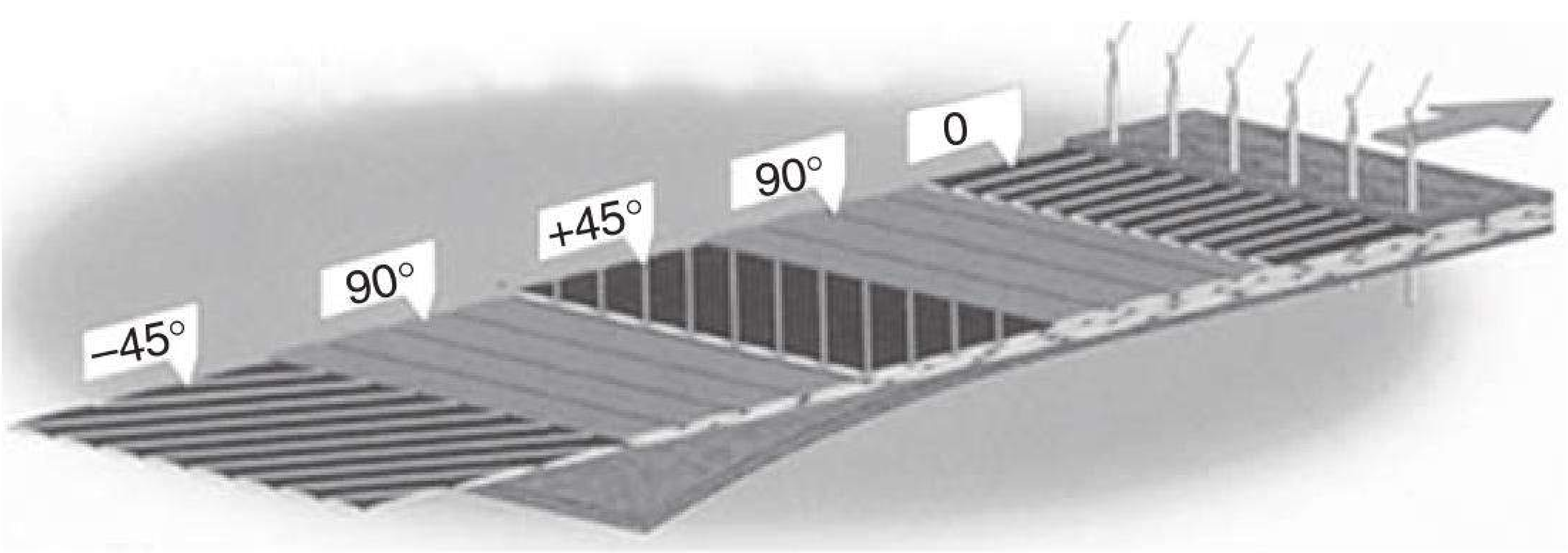


3.13 Structure of triaxial MWK fabric.

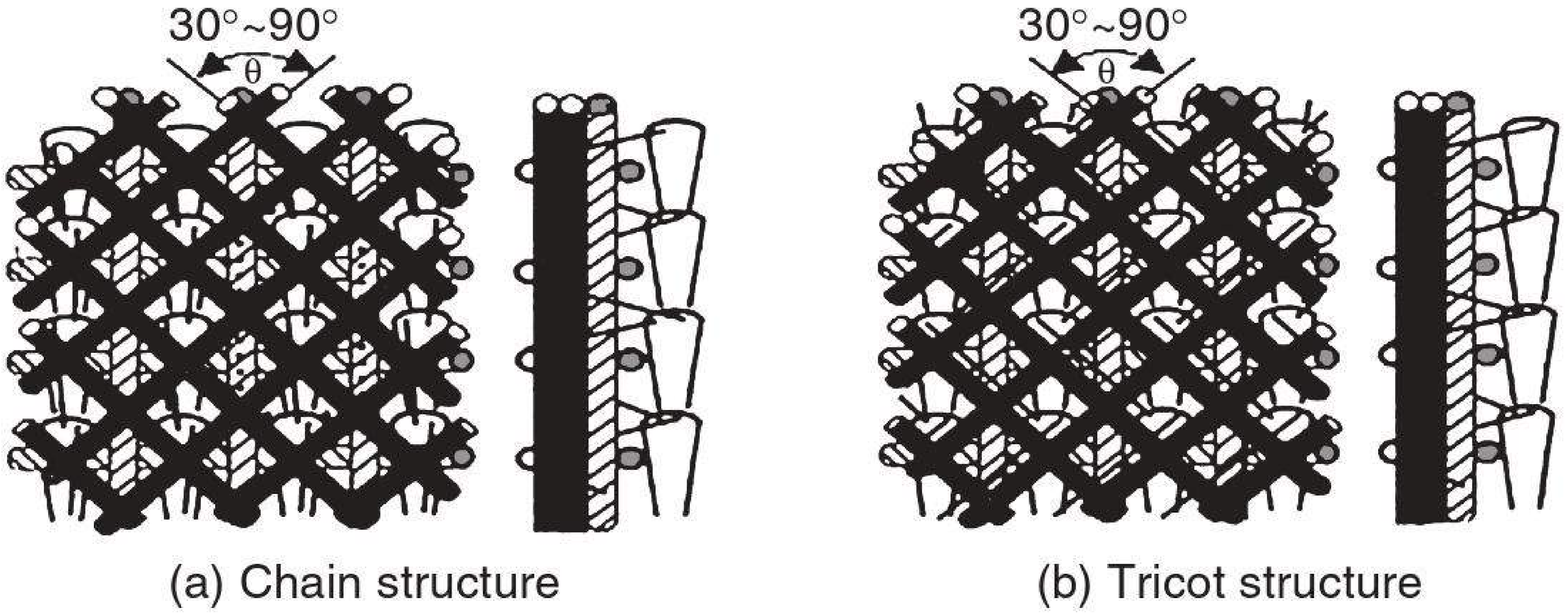
MWK fabrics are often characterized through the number of reinforcement yarn directions inserted into the binding structure. Biaxial, triaxial and quadraxial fabrics are the most common fabrics commercially available. It is also common to give information on the surface weight of reinforcing fibres in each direction. These weights can then, together with a known fibre density, be transformed into the fibre volume fraction if the ply thickness is known.

MWK fabrics can be produced on a multiaxial knitting machine, the principle of which is shown in Fig. 3.14. The typical structure of an MWK fabric is illustrated in Fig. 3.15. There are many kinds of MWK fabrics as variations of the typical structure, e.g. as shown in Fig. 3.16 in which the structure is less complicated than the typical one, e.g. structure (c) contains only two inserting yarn systems – warps and wefts – and according to the arrangement of inserted yarns, the MWK fabrics could be classified into five types, as shown in Fig. 3.16.

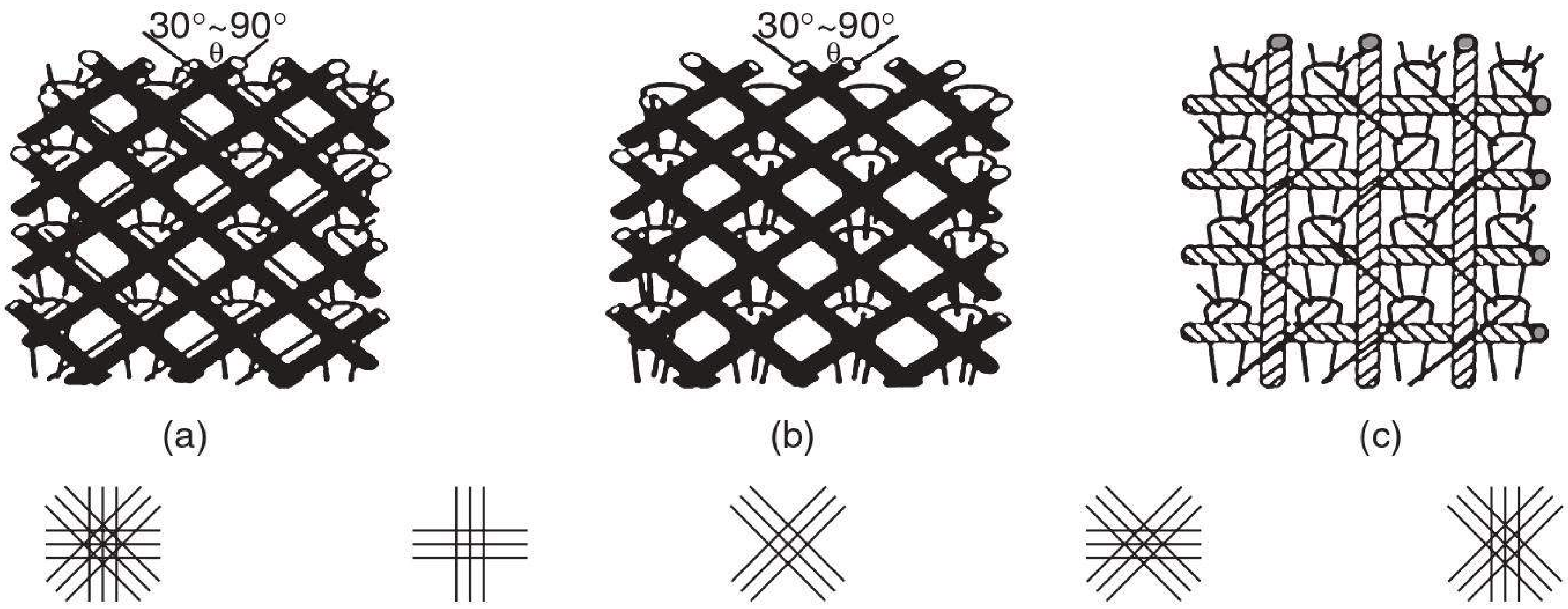
From Figs 3.15 and 3.16, it can be seen that there are four groups of yarns in the fabric structure. The vertical strength and formability depend on the inserted warp yarns while the horizontal strength and formability depend on the inserted weft yarns. The angled strength and formability are dependent on the oblique yarns with alterable angle arrangement of 30°–90°. The yarns in each plane group are unbent and parallel to each other. The four



3.14 Principle of MWK production.



3.15 Typical structure of MWK fabrics.



3.16 Variations in the MWK structure.

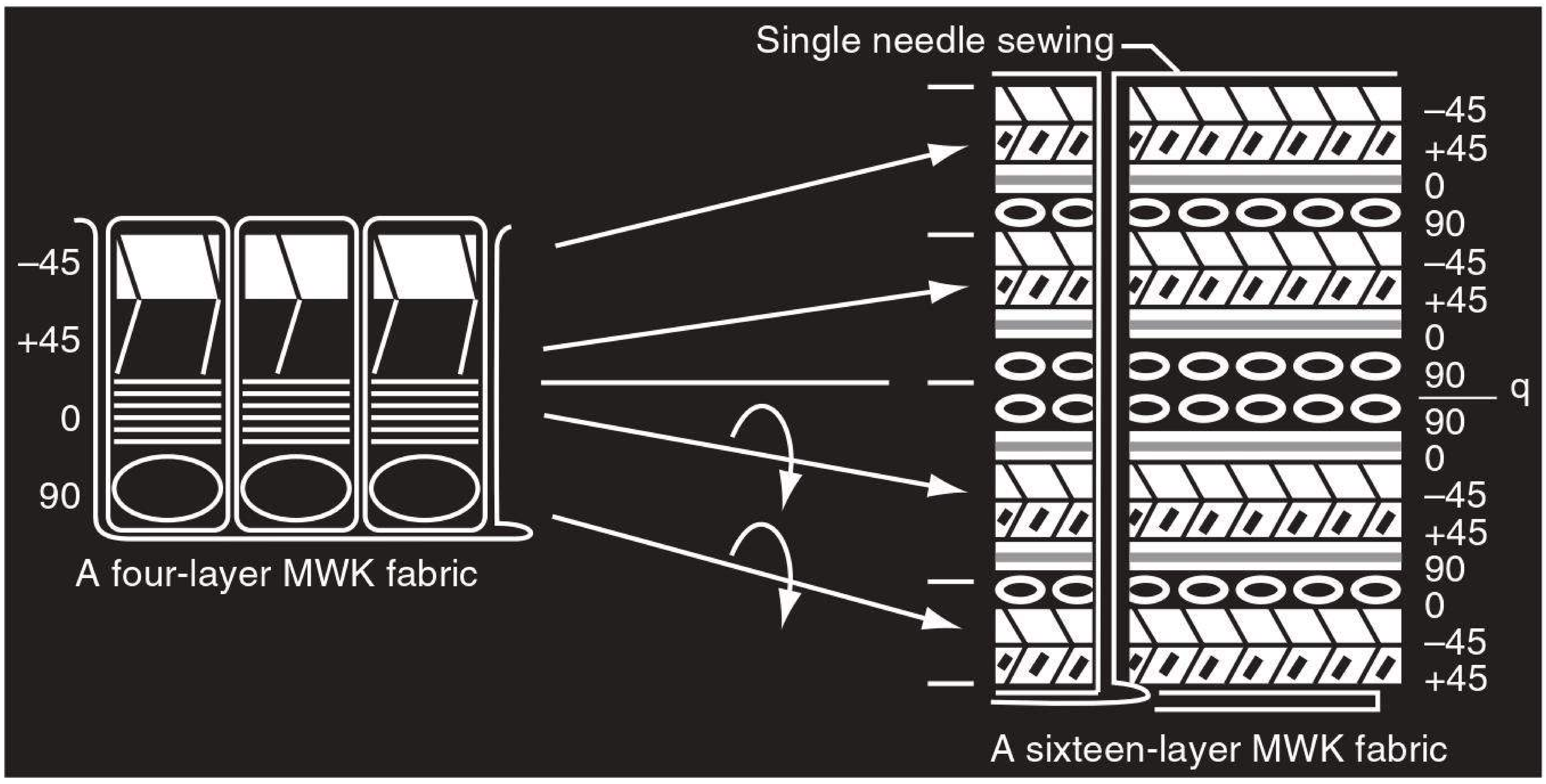
groups of yarns are bonded together by a group of yarns called warp-knitting ground yarns.

From a structural geometry viewpoint (Fig. 3.15), fabrics consist of warp (0°), weft (90°) and bias (± various degrees) yarns that are stitched together by a chain or tricot stitch during the warp-knitting process by a fifth yarn system through the thickness of the fabric structure. The warp and weft yarns stabilize the fabric in the machine and cross-machine directions while the diagonally arranged or biased yarns absorb tension from any required angle. The fifth yarn precisely binds together all of the load-bearing yarn systems. The bias or diagonal yarns in the fabric can be inlaid at any angle along the plane of the machine direction, the most common of which is ±45 degrees. It should be noted that all four load-bearing yarn systems do not have to be used in an MWK fabric construction. Also, different yarn types and counts can be used in each of the yarn systems (Kaufmann, 1991a).

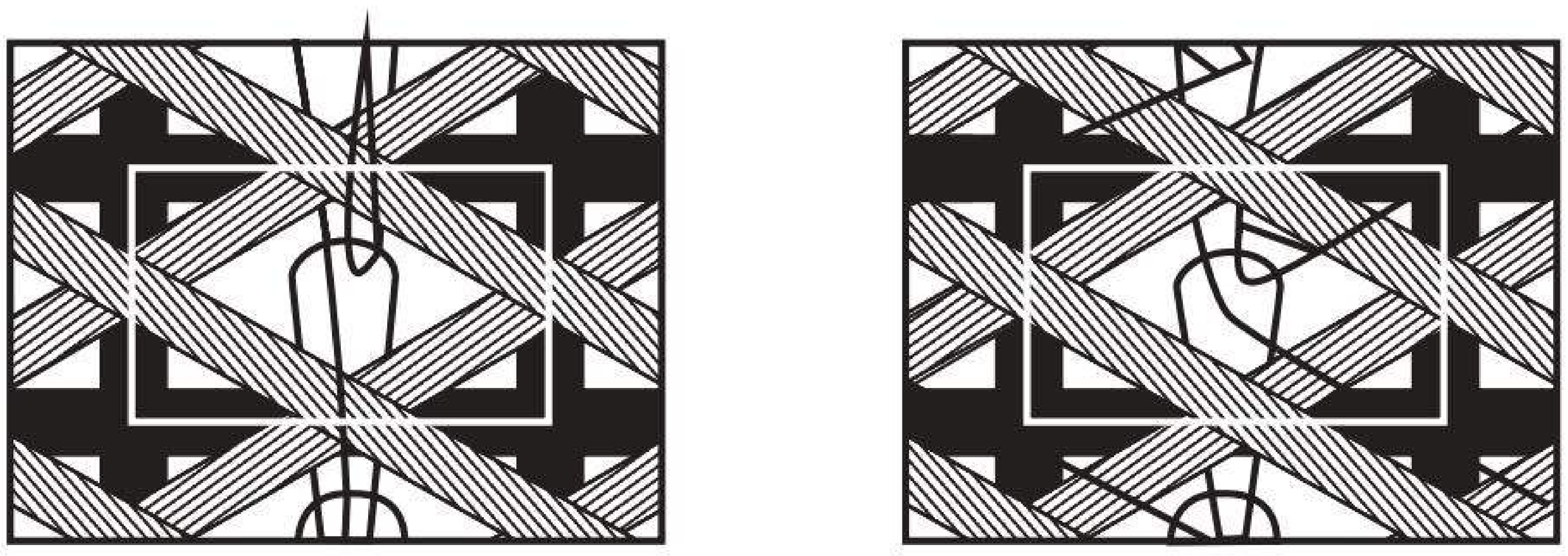
By using sewing methods, more complicated structures of MWK fabrics can be made. For example, in Fig. 3.17, the part on the left is the MWK fabric with four groups of inserted yarns. More layers of MWK fabrics can be combined together, and the part on the right shows four layers of fabric piled up together using the single needle sewing method to make a 16-layer MWK fabric.

Unit cell geometry

The key geometric parameters of the MWK fabric preforms, which affect the reinforcement capability and the composite processability, include the number of yarn axes, the orientation of bias yarns, total fibre volume fraction, pore size and pore distribution, and percentage of stitch fibres to total fibre volume fraction. The process variables adjustable to control the MWK microstructure include the type of knit stitch, the ratio of stitch-to-insertion yarn linear density, the orientation angle of bias yarns, and the thread count.



3.17 A 16-layer MWK fabric.



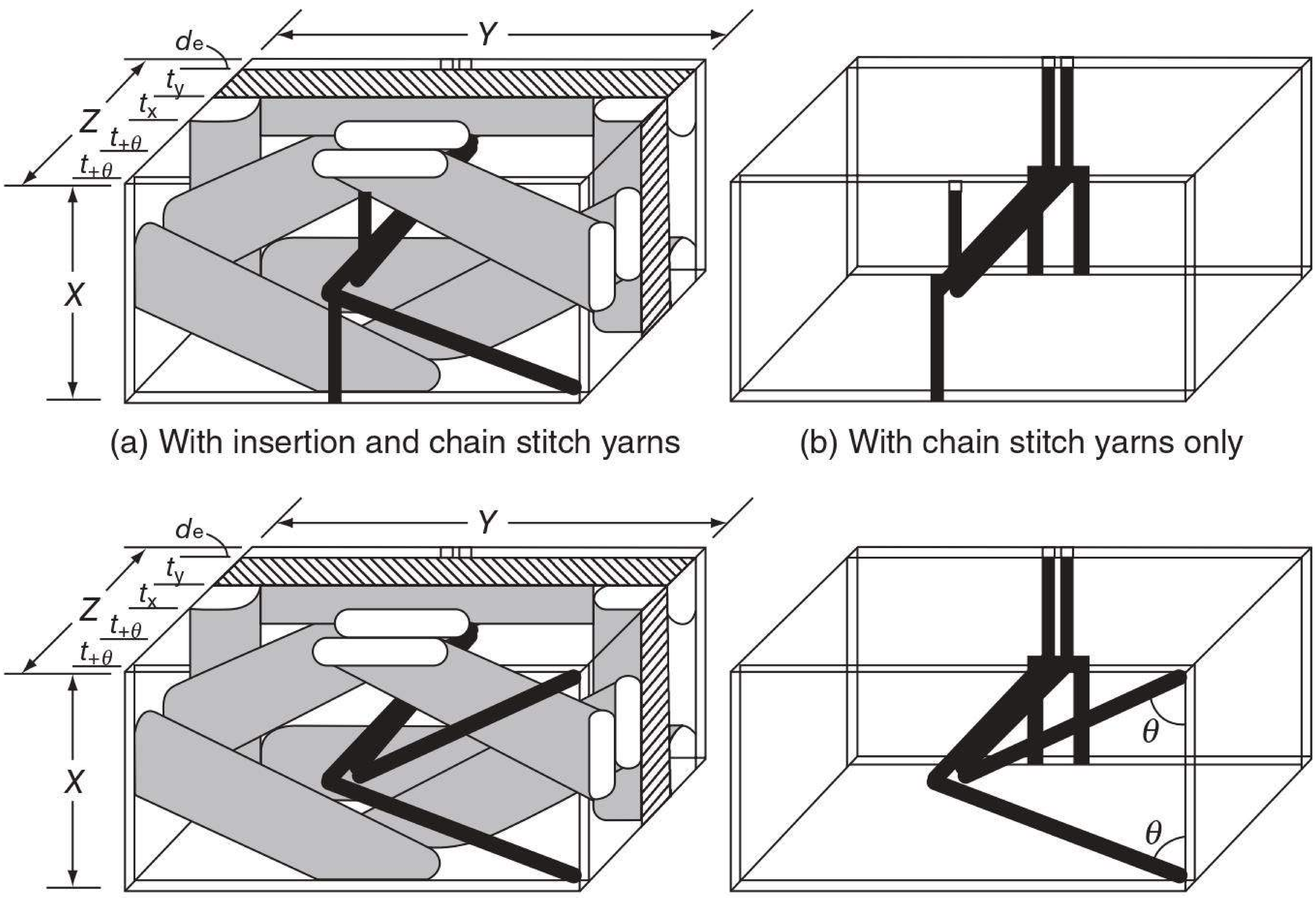
(a) Chain stitch (b) Tricot stitch

3.18 Unit cell of MWK fabric.

The concept of a unit cell is used to establish the relationship between the geometric parameters and process variables.

Normally, yarn bundles consisting of numerous continuous filaments are used for fabric preforms; thus, the fabric has three microstructure levels: geometry of interfibre packing in the yarn bundle (fibre level), cross-section of yarn bundles in the fabric (yarn level), and orientation and distribution of fibres in the 3-D network (fabric level). The first step in the unit cell-based modelling is to determine the unit cell dimensions, so that it is the smallest repeating unit of the structure. The second step is to assume some idealized cross-sectional shapes of the yarn bundles, based on experimental observations. The final and most important step is to identify the overall unit cell geometry, from which expressions for the key geometric parameters can be derived, and the geometric limits applied to the structure can be defined. This unit cell-based modelling technique has been demonstrated successfully for 3-D braided structures.

As can be seen in Fig. 3.18, the unit cell for the MWK fabric preform can be defined in many ways to meet the definition for a unit cell. However, it



(a) With insertion and chain stitch yarns (b) With chain stitch yarns only

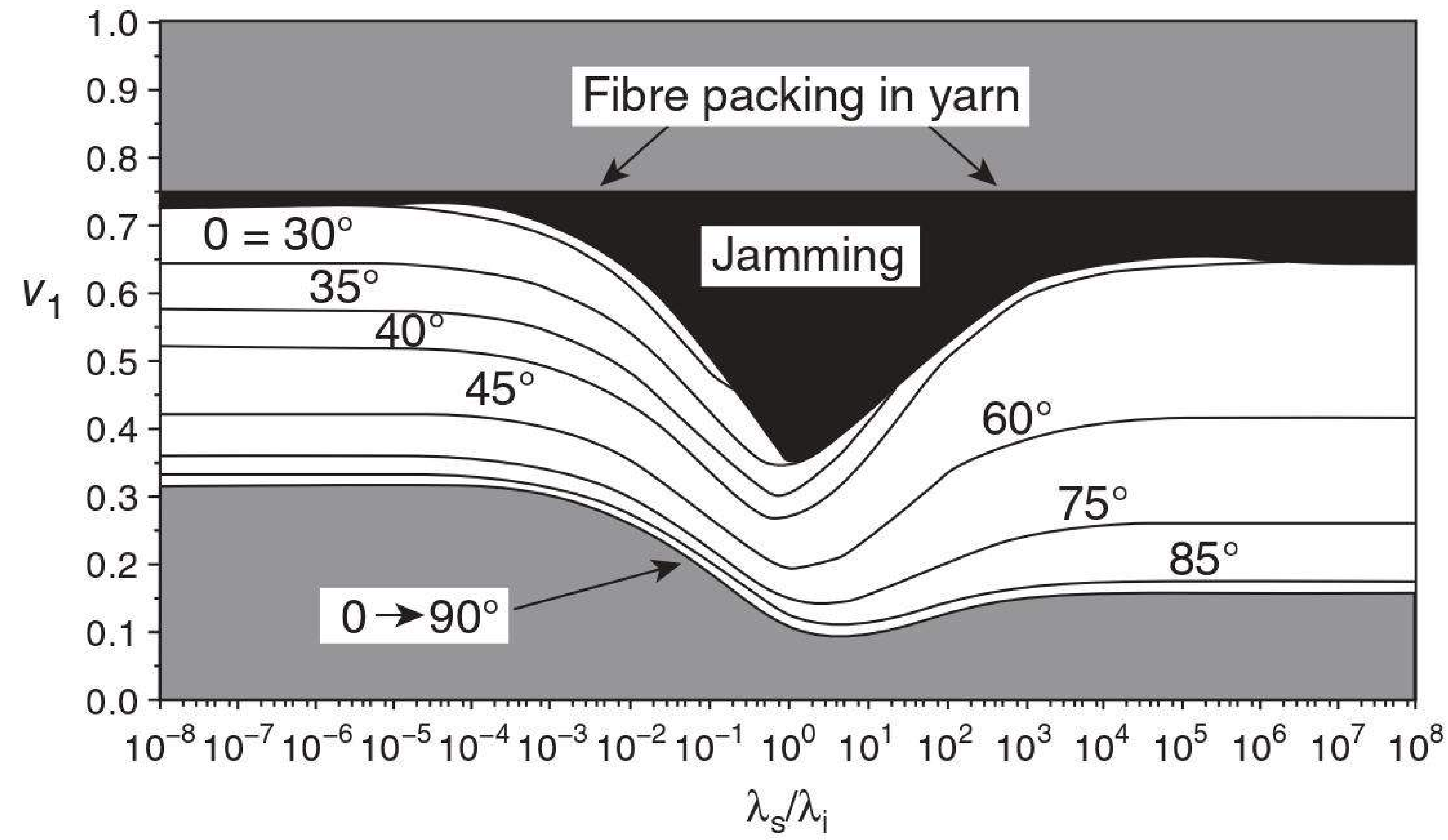
(c) With insertion and tricot stitch yarns (d) With tricot stitch yarns only

3.19 Unit cell geometry of MWK structure.

would be most reasonable to have a unit cell which consists of a complete knitting stitch, and the insertion yarns in the unit cell are all symmetrical. Figure 3.18(a) and (b) show the unit cells for the MWK structure with chain and tricot stitch, respectively. Within the outline in the figure, the unit cell consists of one each of 0° and 90° yarns, two each of $\pm\theta$ and $-\theta$ yarns as well as a knit stitch (Du and Ko, 1996).

Figure 3.19 shows the idealized unit cell geometry for the MWK structure, including the shape, dimension, orientation and position of all the insertion and stitch yarns within the fibre 3-D network. The knit stitch is assumed to have the tightest loop construction, and the curved loop is idealized to a rectangular shape, as illustrated in Fig. 3.19(b) and (d). The dimensions of the unit cell are X, Y and Z, corresponding, respectively, to the 0° axis, the 90° axis, and the thickness axis vertical to the 0°–90° plane, as shown in Fig. 3.19(a) and (c).

The unit cell geometric analysis of a four-layer system is used as an example to generate the $V_f - \theta$ functions for the MWK fabric, where V_f denotes the volume fraction. This analysis can be generalized to include other MWK systems with six or more layers of insertion yarns. The fibre volume fraction relation in Fig. 3.19 shows that for the fixed parameters selected, only a limited window exists for the MWK fabric construction. The window is bounded by two factors: yarn jamming and the point of 90° bias



3.20 Fibre volume fraction versus ratio of stitch-to-insertion yarn linear density (tricot stitch, $\kappa = 0.75$, $\rho = 2.5$ kg/m^3, $f_i = 5$, $\eta = 0.5$).

yarn angle. Fabric constructions corresponding to the curve marked 'jamming' are at their tightest allowable point, and constructions at the $\theta \to 90°$ curve have the most open structure. When $\theta < 30°$, jamming occurs in the whole range of yarn linear density ratio from zero to infinity.

The fibre volume fraction relation is shown in Fig. 3.20. When θ is in the range of 30° to 40°, the fibre volume fraction decreases with an increase in yarn linear density ratio until jamming occurs. When $\theta = 45°$, the fibre volume fraction decreases with an increase in yarn linear density ratio to a minimum at about $\lambda_s/\lambda_i = 1$ where λ_s = stitch yarn diameter and λ_i = insert yarn diameter, and starts to increase until jamming occurs. When $\theta \geq 60°$, the fibre volume fraction has the same trend as when $\theta = 45°$, but yarn jamming never occurs. The fibre packing in the yarns, taken as 0.75, limits the maximum fibre volume fraction in the fabric (Ko, 1999).

3.4.2 Mechanical behaviour

MWK fabrics have good dimensional stability that allows them to be handled easily in the composites manufacturing processes. The stitches allow relative fibre movement in the fabric while at the same time maintaining uniform fibre spacing. The fabrics' excellent conformability makes them suitable for making composite parts of complicated shapes (e.g. parts with double curvatures) without excessive cutting, joining and post-consolidation machining. Since multiple fibre layers are handled in a single step, the composites manufacturing process is significantly simplified. The mechanical properties of the MWK composites, especially in compression, may be superior to those of conventional woven fabric composites due to the elimination of fibre crimp. A thin, textured polyester yarn is often used as the stitching yarn. A fabric's dimensional stability and conformability can be altered by controlling the stitching yarn density or the stitching pattern. A high performance aramid or glass yarn may be used as the stitching yarn to improve the interlaminar properties and damage tolerance of the composites.

The literature on the mechanical properties of MWK fabrics and their composites is very limited. Due to their close fibre packing and dense structures, a reasonably high fibre volume fraction (about 60%) in the final composite part can be obtained even from the wet manual lay-up process. This can result in good mechanical properties as well as significant savings in resin consumption.

In an attempt to understand the mechanical behaviour of MWK fabrics and their composites, some researchers have studied the properties of fabrics such as tearing, shear, compression, impact strength, etc. The effect of reinforcement of MWK fabrics on the performance of composites has also been studied. This section summarizes the works of various researchers on the mechanical behaviour and properties of MWK fabrics and their composites.

The basic mechanical properties of MWK fabrics are somewhat superior to the equivalent volume fraction of woven roving-reinforced material. For example, Hogg *et al.* (1993) determined the Young's modulus and tensile strength of a biaxial fabric with glass-reinforced polyester, volume fraction 33%, to be 21 GPa and 264 MPa, respectively, which are 13% and 20% higher than the values found for an equivalent volume fraction of plain woven-reinforced composite. Quadraxial reinforcement of the same fibre volume fraction gave similar results (24 GPa and 286 MPa, respectively).

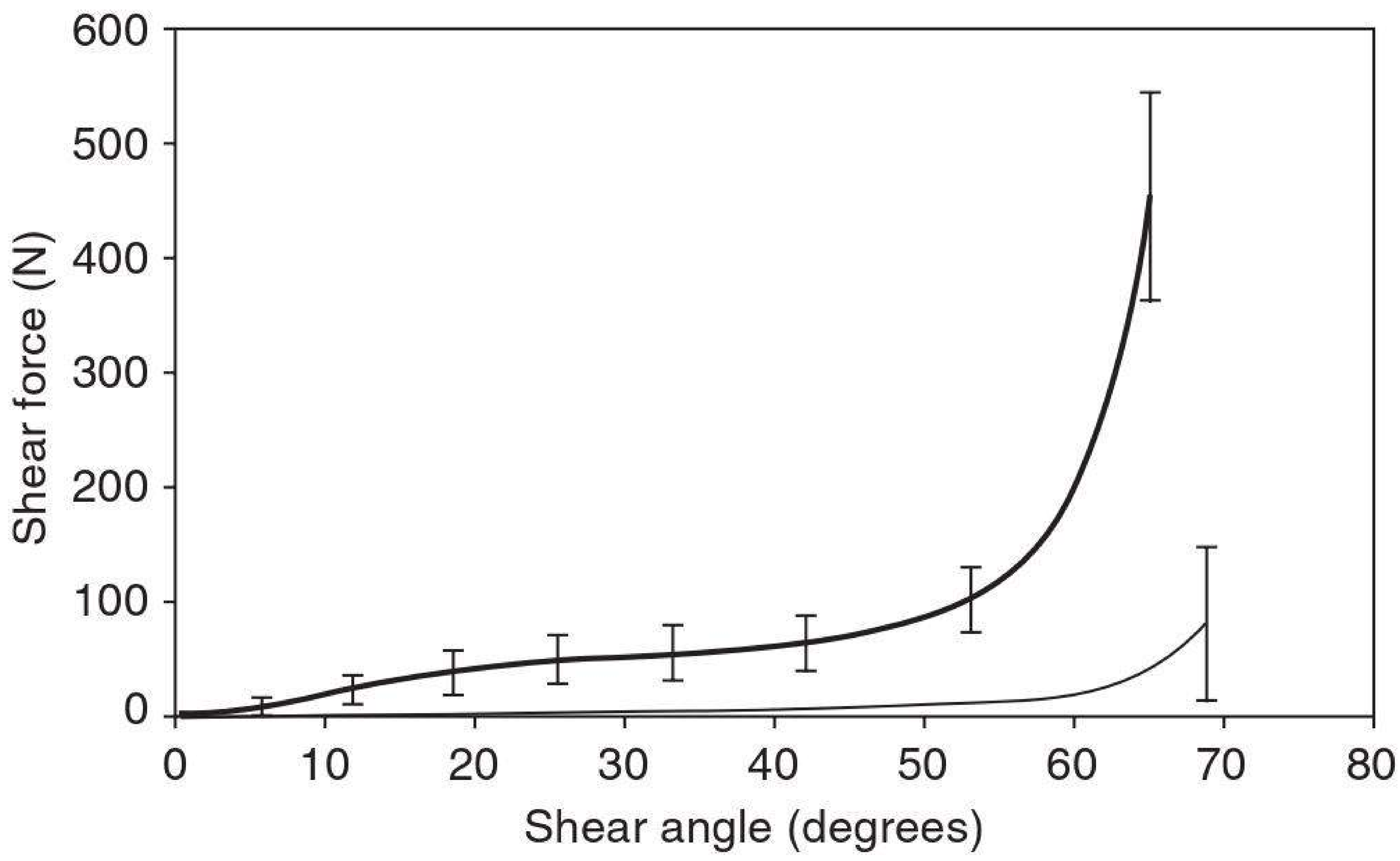
The improvement in properties compared to woven-reinforced composites is emphasized by the work of Godbehere *et al.* (1994) in tests on a carbon fibre reinforced MWK fabric epoxy resin and equivalent unidirectional (UD) laminates. All the composites had 0°/±45° orientations. Although the MWK laminates had poorer properties than the UD laminates, the reduction was small (e.g. less than 7%) in the 0° direction. For example, the UD equivalent laminate gave values of Young's modulus and tensile strength of 58 GPa and 756 MPa, respectively, compared to MWK fabric values of 56 GPa and 748 MPa (for fibre volume fractions of 56%).

The increases in through-thickness reinforcement achieved by MWK fabrics have been demonstrated by a number of authors. For example, Backhouse *et al.* (1995) compared the ease of delaminating polyester stitched 0°/±45° carbon fibre MWK fabric with equivalent carbon fibre/epoxy UD laminates. There were large increases, some of 140%, in the measured parameters used to quantify resistance to delamination (the mode I and mode II toughness values) for the MWK fabrics compared to the UD material.

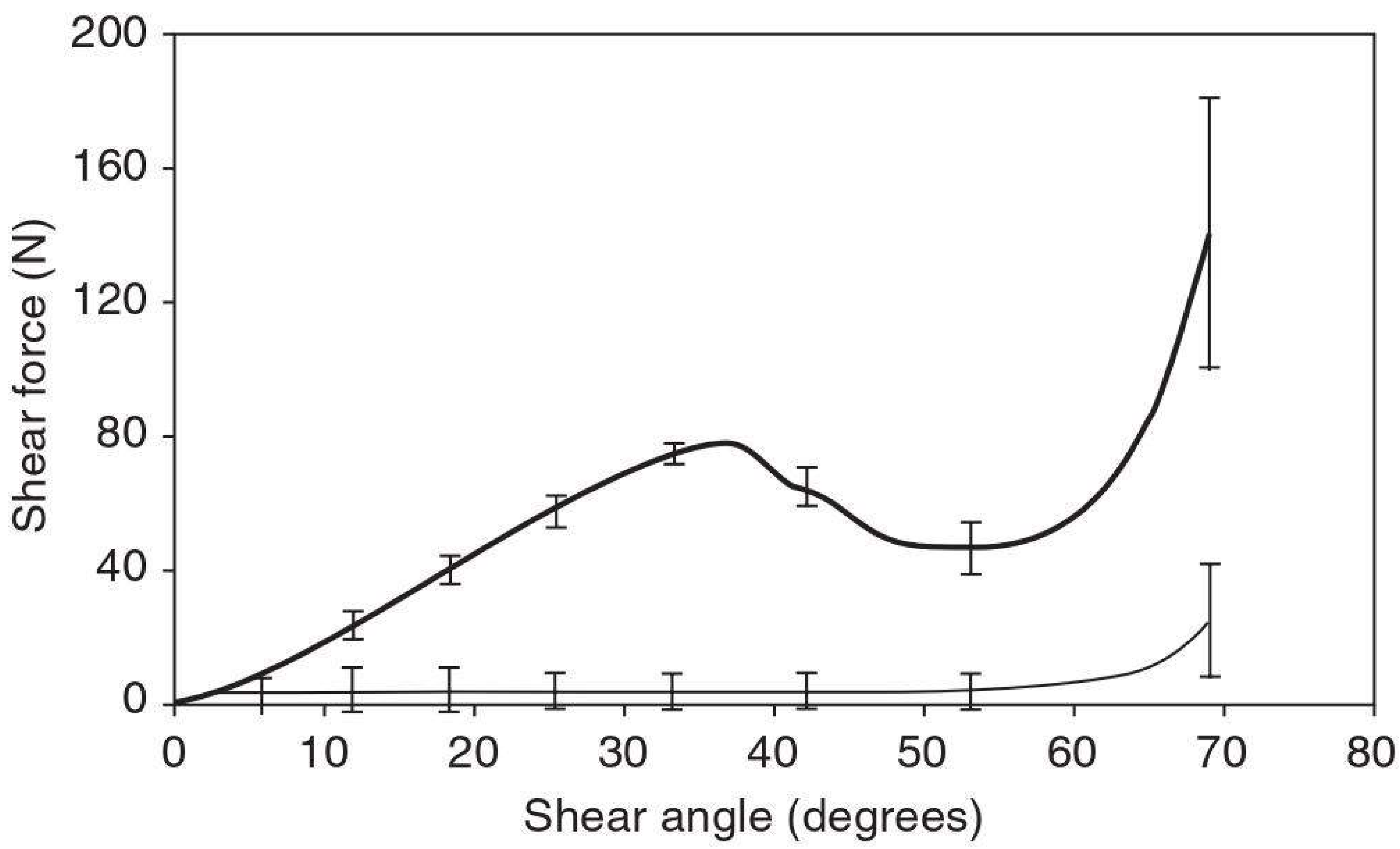
Shear behaviour

Traditional fabrics, such as woven, non-woven and knitted fabrics, tend to form a large deformation in the direction of the shearing stress which is parallel to the diagonal direction of the fabric. Consequently, they cannot perform well as reinforcement material in composites when there is a parallel shearing stress on the composites. Typical MWK fabrics have yarns inserted in the diagonal directions called binding yarns, which retard the shearing deformation. Compared with biaxial warp-knitted fabrics and other woven fabrics, MWK fabrics have better shearing properties (Zhou Rongxing and Chen Mingzhen, 1999).

Typical shear compliance curves obtained for MWK fabrics with both tricot and pillar warp-knitted stitching threads are presented in Fig. 3.21



(a) Tricot 1×1



(b) Pillar warp knit

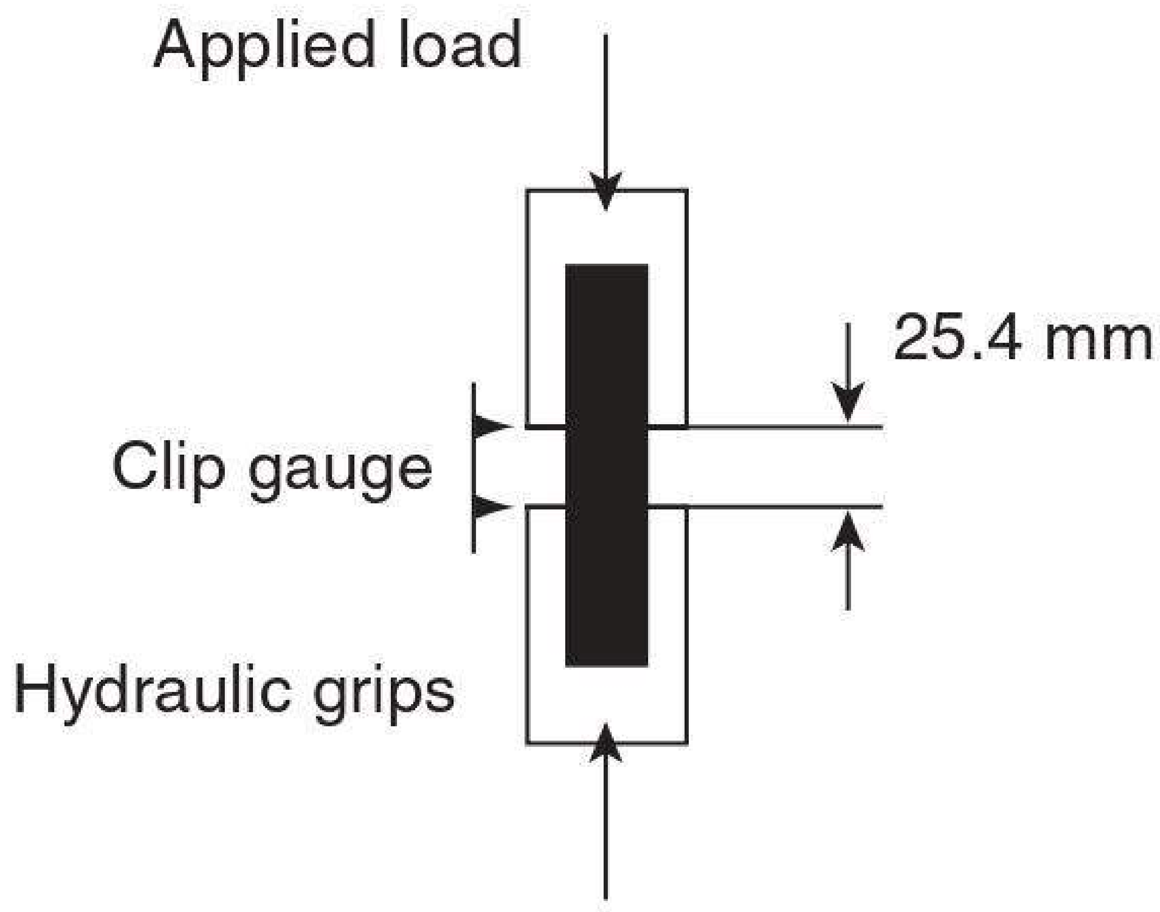
3.21 Shear compliance curves for MWK fabrics (adapted from Wang, 2002).

(Long *et al.*, 2002). A zigzag stitching pattern was observed for tricot warp knit, whereas the pillar warp knit was similar to a chain stitch. In both cases it was apparent that the compliance was lower when the fabric was sheared parallel to the stitching direction. The authors observed that testing in this direction resulted in a tensile strain within the stitch and caused an increase in shear force. In the case of pillar warp stitch, as the majority of the stitching thread was aligned with the applied force, the effect was more pronounced. Testing parallel to the stitch resulted in a linear increase in force until the stitching thread snapped. The force reduces after this point until interrow compaction occurs. The authors opined that the directionality exhibited by non-crimp fabrics during shear could result in non-symmetric fibre patterns during forming.

Compression

Compressive behaviour of MWK fabric composites has been reported by Wang (2002). In this study different varieties of biaxial, triaxial and quadraxial fabrics were manufactured and incorporated into composites as reinforcing fabrics. The mechanical testing of these fabrics included tensile, flexural and compressive tests. The compression test was carried out to determine the compressive strength and modulus using Surfalloy-faced hydraulic grips without tabs. The sample dimensions were 100 mm by 25.4 mm and the specimen gauge length (between grips) was about 25.4 mm. The test procedure for the compressive behaviour of fabrics is illustrated in Fig. 3.22.

The test results for the compression test are summarized in Table 3.1. The compressive moduli measured were lower by about 30% than their respective tensile values, as observed from the experiments. This could partially be due to experimental errors, as the small specimen gauge length in compression hinders mounting the transducer directly on the specimen. The compressive strengths are generally similar to or higher than their tensile values. Typical compressive test curves are shown in Fig. 3.23. Ductile failure is observed for laminates with all the fibres oriented at ±45° to the loading



3.22 Compression test for MWK fabrics.

Table 3.1 Compression and flexural test results of MWK fabrics

Fabric	Volume fraction (V_f) (%)	Direction	Compression*		Flexural*	
			E (GPa)	σ (MPa)	E (GPa)	σ (MPa)
Biaxial	47.8	0°	7.5	110	10.9	251
		90°	7.7	114	11.2	257
		45°	15.7	377	19.0	380
Biaxial	51.4	0°	6.5	84	7.2	187
		90°	7.3	90	8.1	201
		45°	16.1	254	17.0	531
Biaxial	38.3	0°	13.1	330	15.4	359
		90°	13.7	336	16.8	414
		45°	7.1	110	9.1	211
Triaxial	49.7	0°	11.6	270	16.4	423
		90°	12.2	256	14.9	440
		45°	14.3	353	17.2	503
Triaxial	52.1	0°	6.0	198	18.3	570
		90°	7.5	127	9.1	221
		45°	12.2	272	11.1	352
Quadraxial	41.5	0°	12.1	313	15.0	356
		90°	11.4	306	14.8	368
		45°	12.0	323	12.9	384

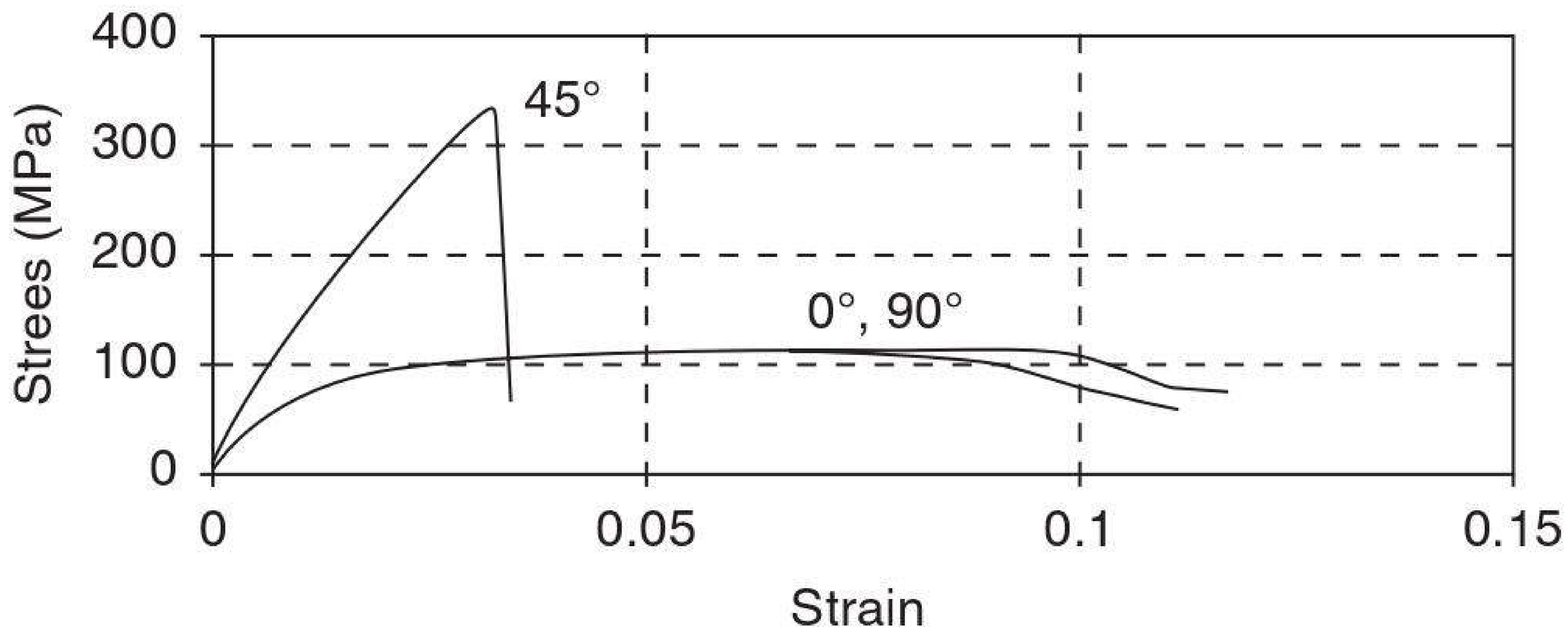
* E = Young's modulus, σ = strength.
Source: adapted from Wang (2002).

direction. Delamination associated with in-plane shear deformation is evident and the ×-shaped failure bands are along the ±45° fibre directions as seen in Fig. 3.23.

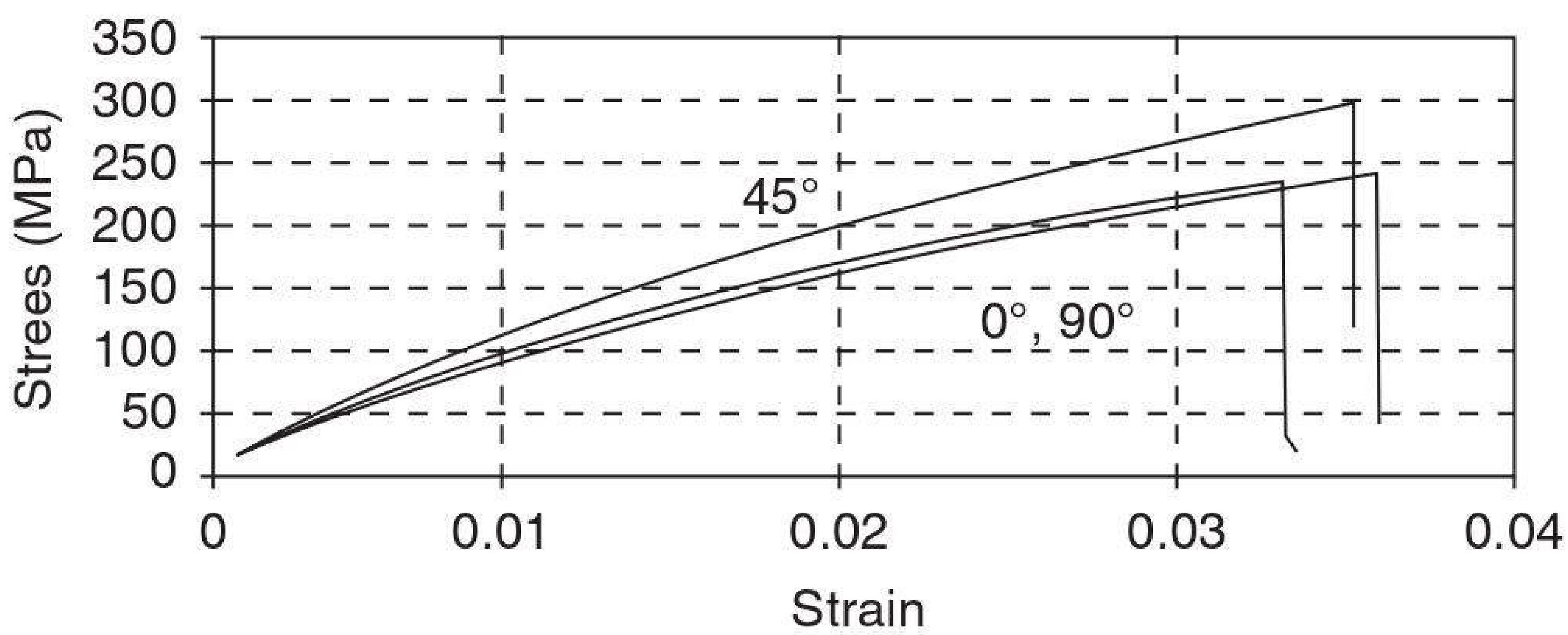
A higher compressive strength is generally observed when tested along a fibre direction. In such cases the laminates showed a brittle failure with a sudden load drop after reaching the maximum load. Examination of the failed specimens reveals that the dominant mode is delamination, and the single failure band is perpendicular to the loading direction. Figure 3.24 shows the compressive failure pattern typical of all the laminates tested along a fibre direction. In contrast, for a woven composite with yarn undulations, it is easier for a ply to buckle under compressive load. It has been observed that compressive failure in woven composites is initiated in the crimped yarn along the loading direction (Wang and Li, 1995).

Flexural behaviour

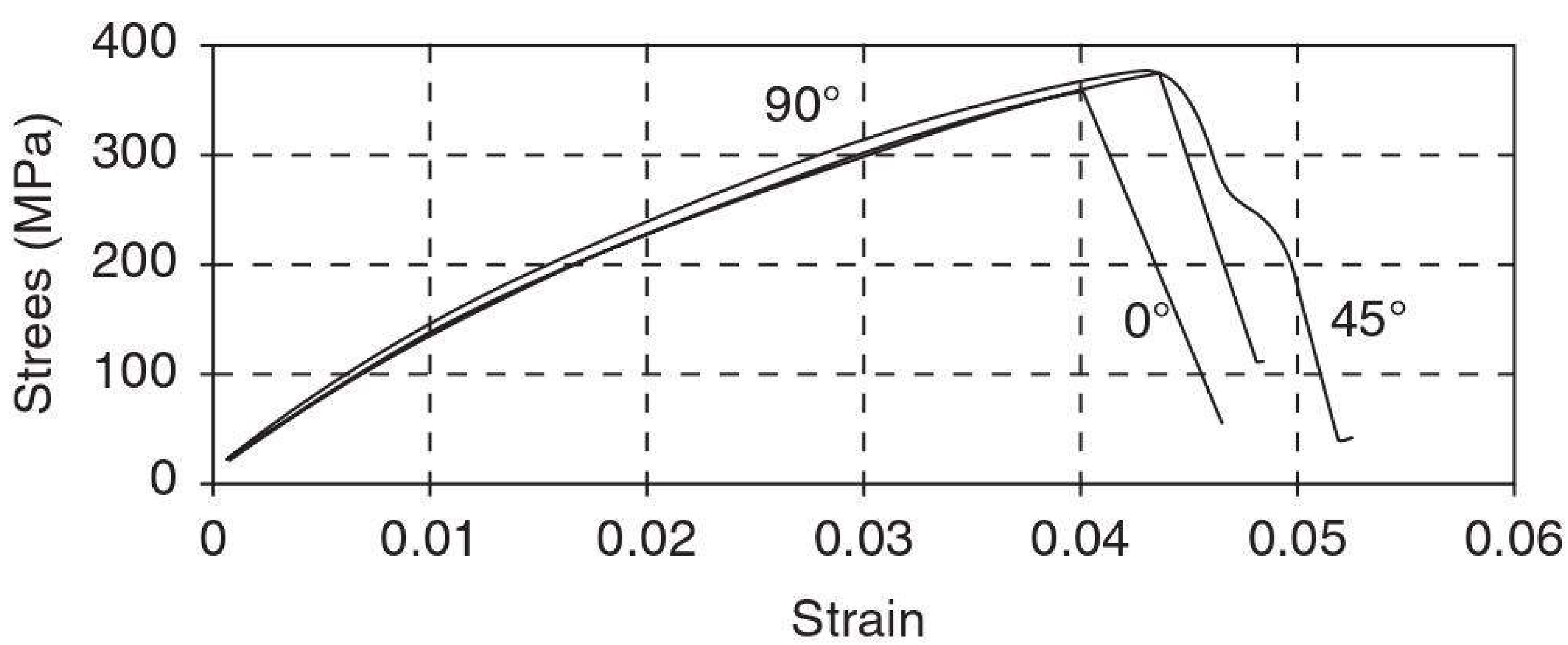
The flexural modulus is similar to the respective tensile modulus, as reported in Table 3.1. The flexural strengths of all the laminates tested are



(a) Biaxial



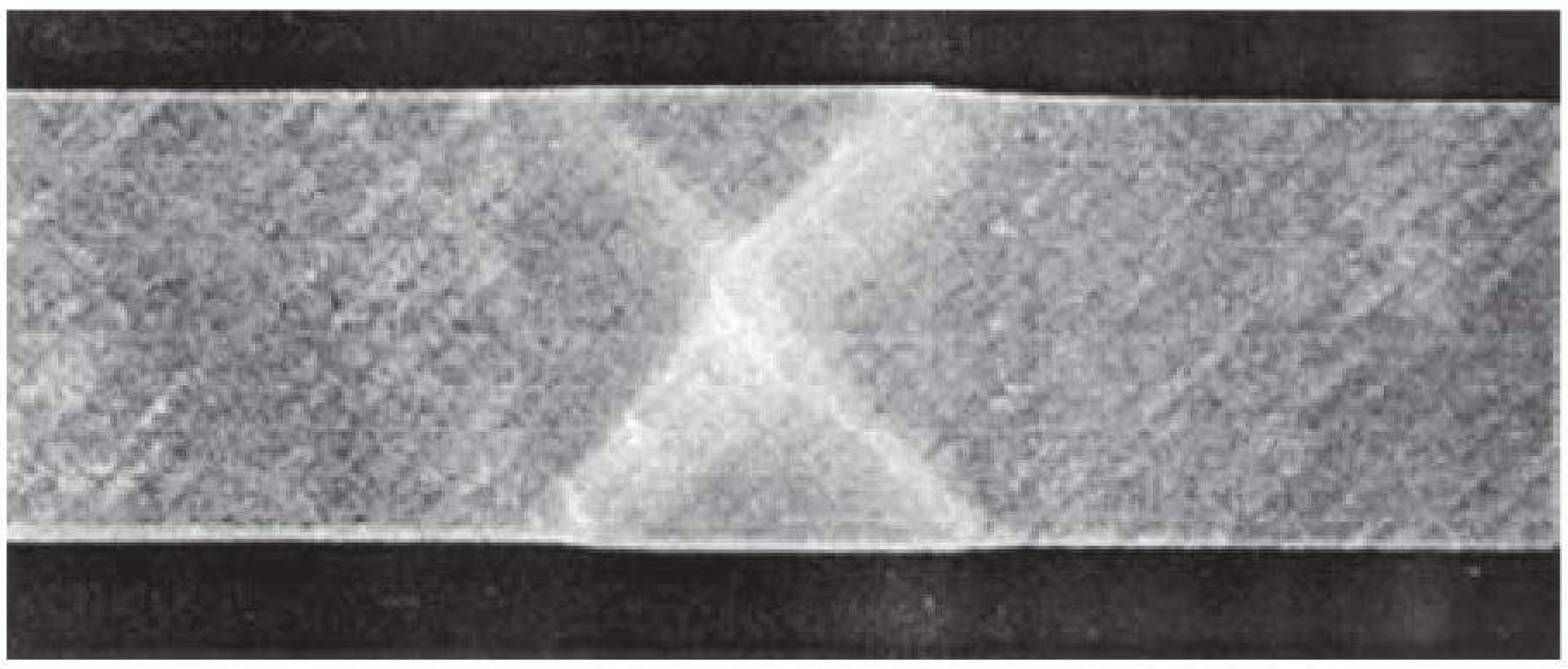
(b) Triaxial



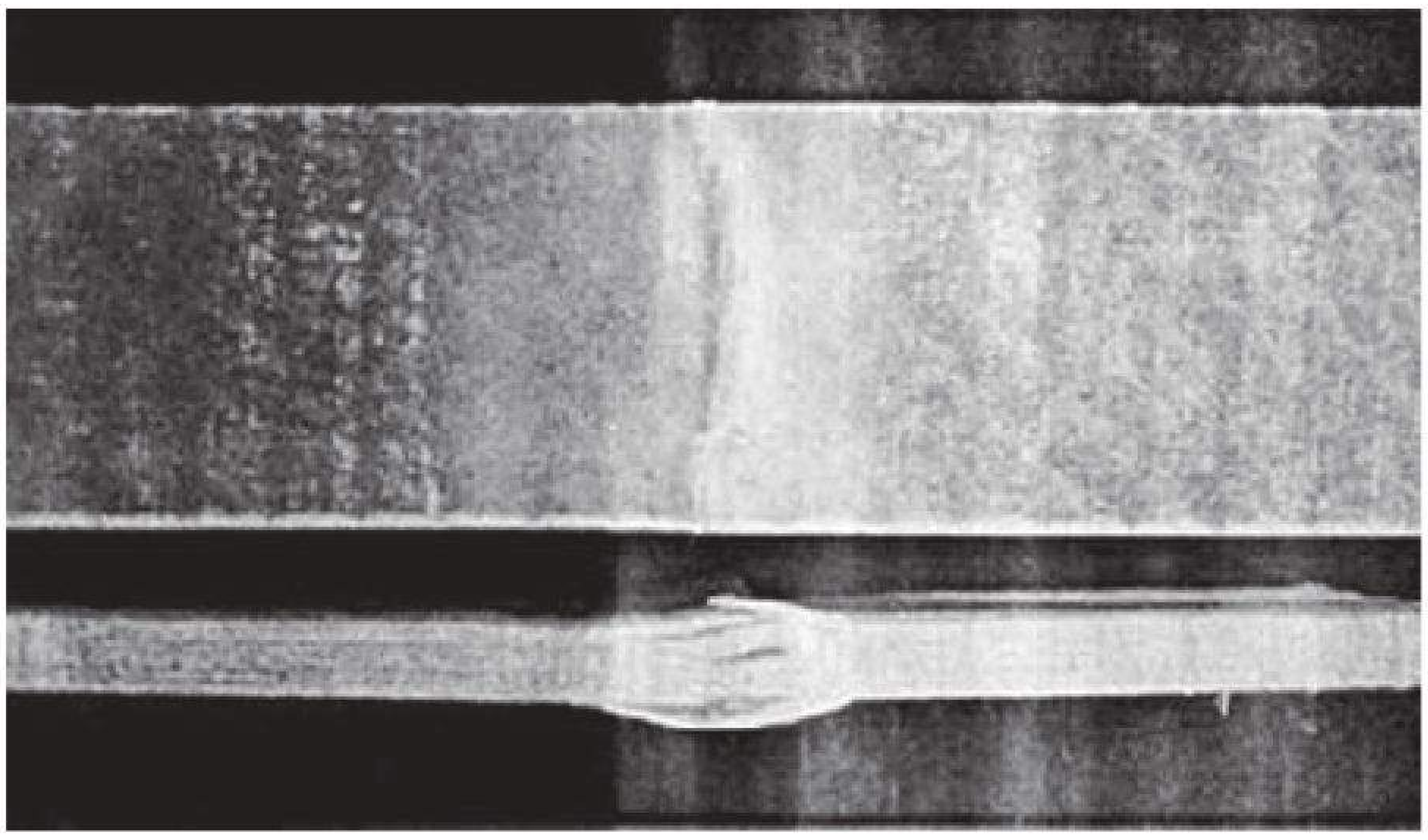
(c) Quadraxial

3.23 Typical compressive test curves for MWK fabric laminates (adapted from Wang, 2002).

significantly higher than their tensile strengths, and are also higher than or similar to their compressive strengths. The flexural load–deflection responses, shown in Fig. 3.25, exhibit less non-linearity than the tensile and compressive responses. All the laminates tested along a fibre direction show brittle failure, generally by outer ply delamination on a tensile surface. The delamination zone starts at the middle of the specimen where the bending moment is maximum, then propagates outwards until significant fibre rupture occurs at the middle section on the tensile surface. This typical failure mode can be observed in Fig. 3.26 for a biaxial specimen tested along a fibre direction. In contrast, laminates with all fibres oriented at ±45° to the specimen length direction show ductile failure, as in compression. Delamination along the fibre strands can be observed on both the tensile surface (Fig. 3.26(b)) and



(a) Biaxial, along 0° direction (fibres are at ±45° to the loading direction)



(b) Quadraxial, along 0° direction

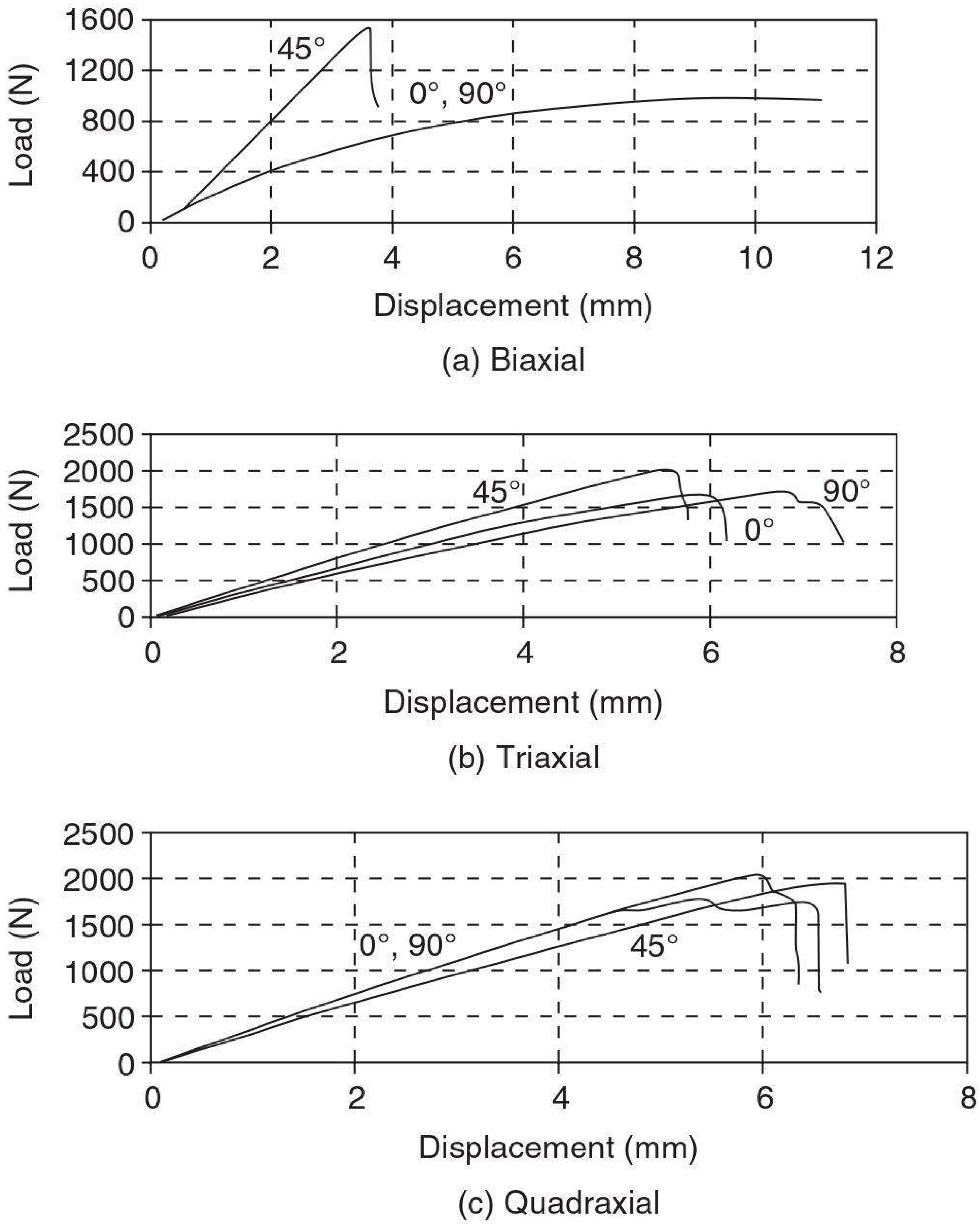
3.24 Typical failure pattern of compressive specimens (adapted from Wang, 2002).

the compressive surface (Fig. 3.26(c)). Large deflection is reached before the final failure when fibre rupture occurs.

Tearing behaviour

Fabrics are often subjected to the effects of external forces. When the external force works sharply on the fabrics, the fabrics could become torn or even pulled apart into pieces by the force. The tearing property is a very important mechanical criterion for fabric testing. There are many tearing test methods to evaluate the tearing properties of fabrics, such as tearing strength by the falling pendulum apparatus, by the tongue method, by the trapezoid method, etc.

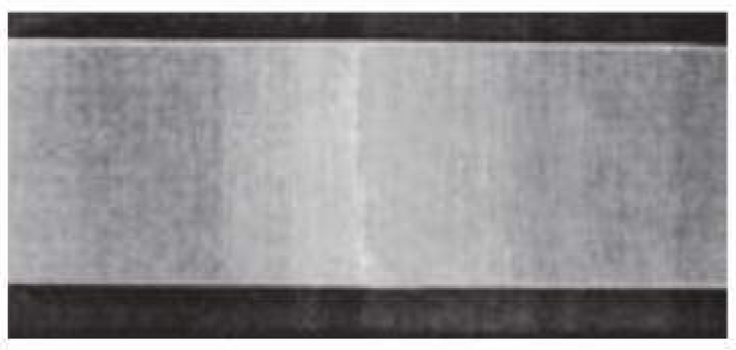
Many researchers have focused their work on the tearing properties of traditional fabrics in the past. Because of the complicated structure and multilayer knitting combination of MWK fabrics, it would be expected that the tearing properties of MWK fabrics are superior to those of traditional woven and knitted fabrics. Actually, many researchers have compared the tearing resistance of woven fabrics and MWK fabrics and their results show that the MWK fabrics have a higher initial Young's modulus, lower rupture



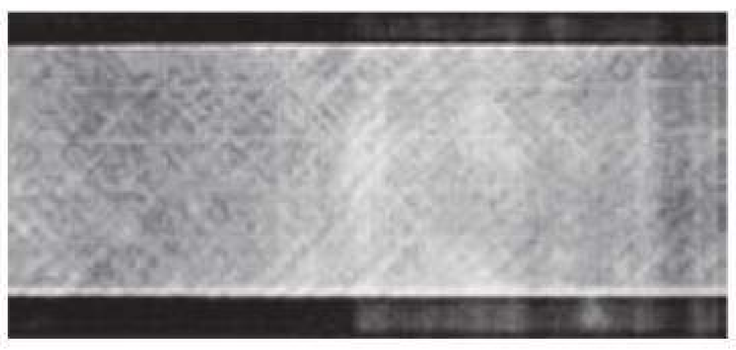
3.25 Typical flexural test curves for MWK laminates (adapted from Wang, 2002).

elongation, higher tear resistance and a higher percentage of usable potential. Further applications of MWK fabrics put the requirements on how exactly the best tearing resistance property can be achieved and what parameters of the MWK fabrics affect the entire tearing properties. The tearing property of MWK fabrics has been one of the primary research areas within the published literature. As with many of the 3-D fibrous assemblies described here, the tearing properties and mechanisms of MWK fabrics are very complex and not well understood. However, the available research results allow some general behaviour to be understood. Figure 3.27 compares the appearance of tearing in woven fabric and biaxial knitted fabric.

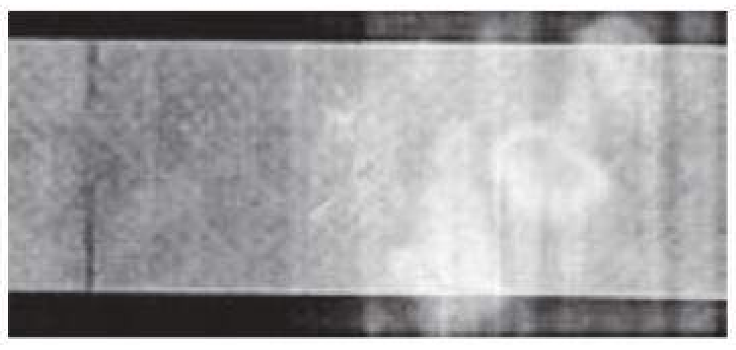
The tearing performance of biaxial warp-knitted fabric has been studied by Li Lvye and Shen Wei (2005). They attempted to find the relationship between the inserted warp and weft yarn density on the direction of suffering load and the tear resistance. The tearing characteristics of the biaxial warp-knitted fabric were also analyzed in their paper. They pointed out that the tearing strength has a general linear relationship with the density of the inserted warp yarn and weft yarn. With increase in the density, the tearing strength improves to a much higher extent. The knitting insertion method of the warp yarn also influences the tearing strength. From their test results, two samples with the same background weave (Denbigh plain tricot) and different warp insertion methods show that the tearing strength of the fabric knitted by using the single needle distance inserting method is poorer than the fabric knitted by using the zero needle distance inserting method. They also concluded that the background knitted weave plays an insignificant role in tearing propagation.



(a) Tested along 45° direction, tensile surface (fibres are at 0° and 90° to the loading direction)

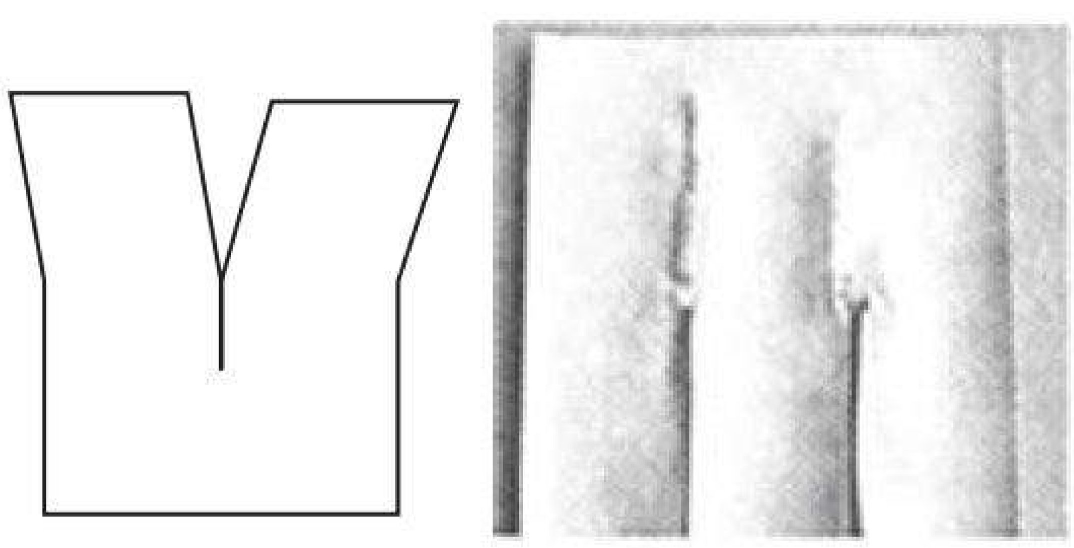


(b) Tested along 0°, tensile surface (fibres are at ±45° to the loading direction)

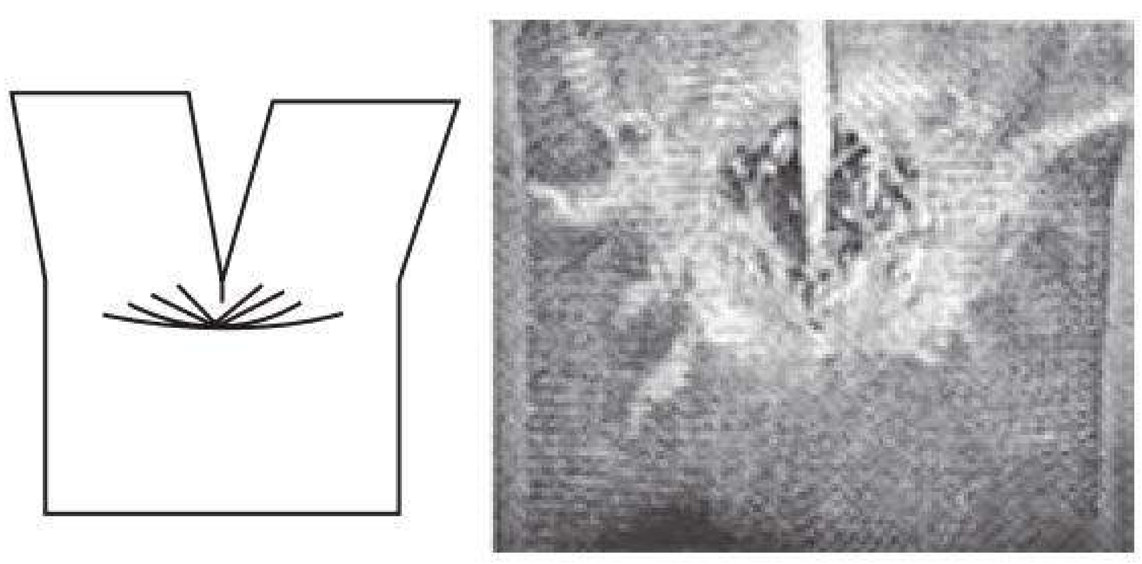


(c) Tested along 0°, compressive surface

3.26 Typical failure pattern of flexural specimens (adapted from Wang, 2002).

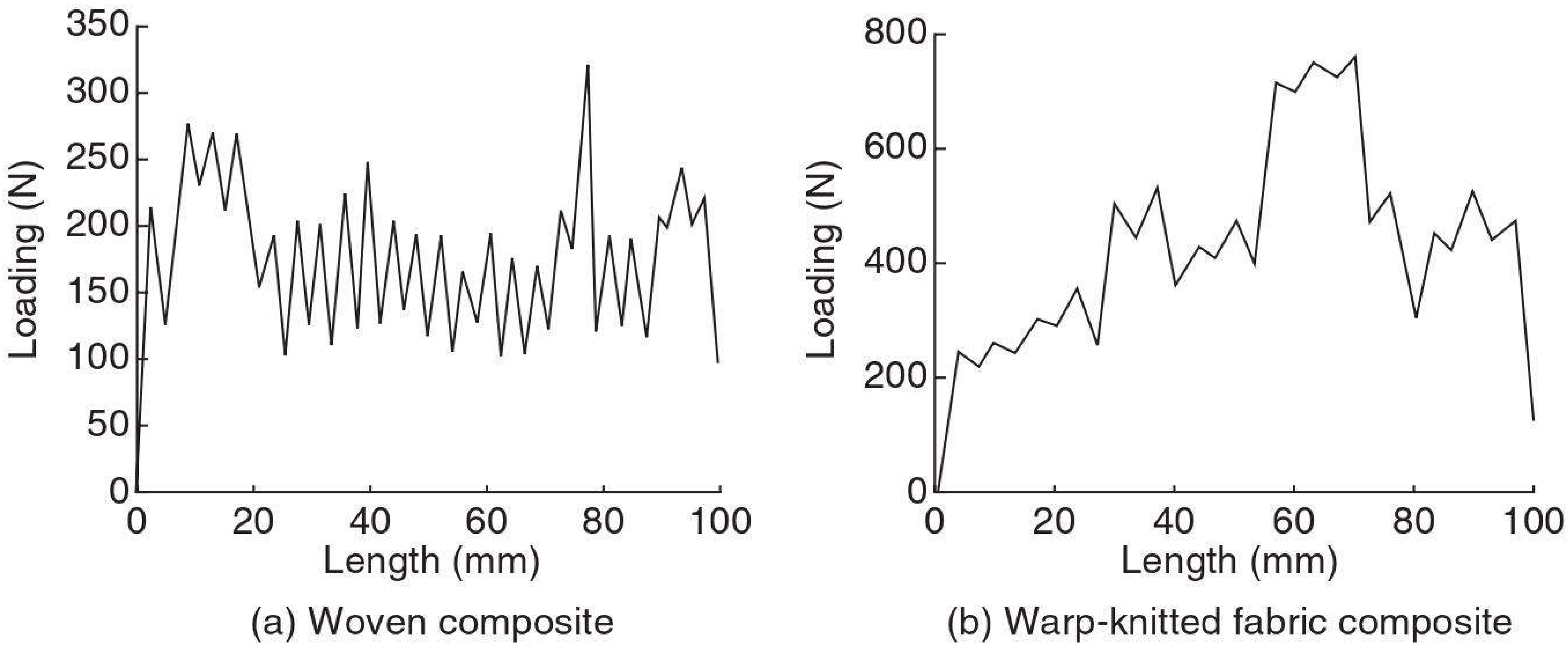


(a) Tearing of woven fabric



(b) Tearing of biaxial warp-knitted fabric

3.27 Comparison of tearing behaviour of woven and knitted fabrics.

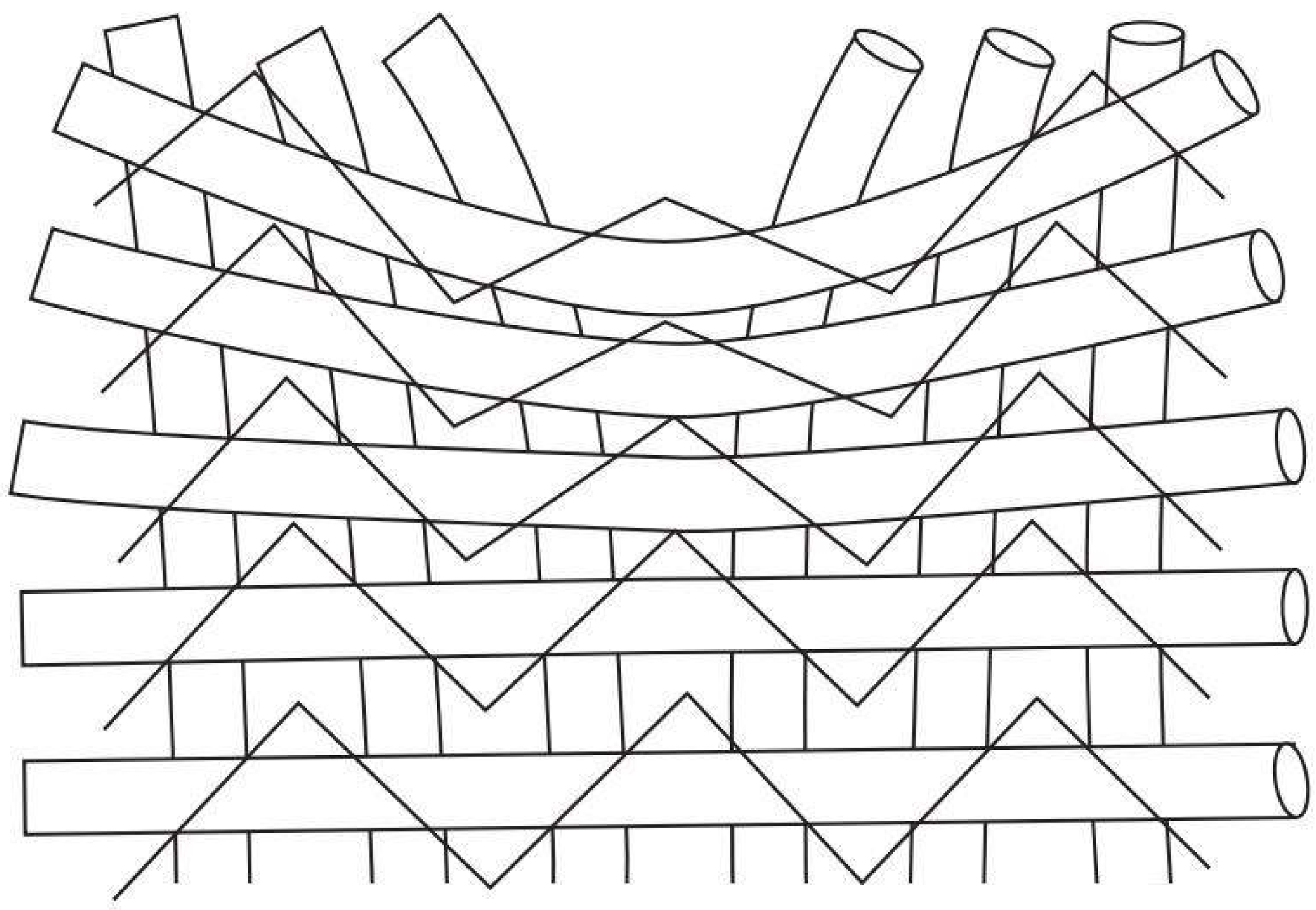


3.28 Tearing behaviour of woven and warp-knitted fabric composites.

Research on the tearing behaviour of reinforced plastic film with biaxial warp-knitted fabric skeleton by Shen Wei *et al.* (1998) further shows that the specification of laid-in and warp yarn has the greatest influence on the tearing strength of the reinforced plastic film and there is an exponential relation between the tearing strength of the reinforced plastic film and the number of yarns in the direction of the force.

Chen Nanliang and co-workers (Chen Nanliang, 1999; Jiao Wei-hong and Chen Nanliang, 2004; Xi Shiping *et al.*, 2005) studied warp-knitted reinforced composites and reported that the tearing resistance is much better than its counterpart in the woven plain weave, as shown in Fig. 3.28. The testing was conducted according to the UK industry standard (BS3424 Method 7A). In Fig. 3.28, the length means the tearing length, and the loading was recorded with the tearing length. It is clear that the tearing resistance of the biaxial knitted fabric reinforced composite is better than that of the woven plain fabric reinforced composite. The biaxial warp-knitted fabric shows high tearing strength because of the yarn clustering effect. The authors pointed out that the tearing resistance was largely dependent on the binding yarn's tearing strength and the higher density of the fabric.

From the literature above, it may be summarized that the tearing strength of MWK fabrics mainly depends on the following factors: the density of inserted yarns, the strength of the material, the insertion method of the warp and weft yarns, the knit structures of the MWK fabrics, the friction between the yarns and layers, the number of layers, etc. In addition, the tearing properties of MWK fabrics show different resistance under the same value of tearing force but with different values of tearing speed. If the speed is higher, the tearing resistance of the MWK fabrics will be poorer. All the previous results show that the MWK fabrics exhibit better tearing resistance than woven fabrics on the whole, because of the higher number of interlacing yarns in their structures.



3.29 Binding effect in MWK fabrics.

As far as the tearing mechanism of MWK fabrics is concerned, when MWK fabrics are subjected to the tearing force, slippage and deformation will occur in the structure. With increase of the tearing stress, the deformation becomes larger, and once it increases to the rupture point, the yarns break first and then the entire fabric. As long as the breakage heading direction comes across the yarns that are perpendicular to the breakage direction, the stress will be shared by the perpendicular yarns, preventing the breakage from advancing. If the tearing force acts continuously upon the MWK fabric, the yarns will break one by one. Hence it is recommended to consider two indices, i.e. the yarn's breakage strength and the maximum tearing resistance, when evaluating the tearing properties of MWK fabrics. The mechanisms of tearing resistance for MWK fabrics and traditional woven fabrics show an obvious difference. In the case of a biaxial warp-knitted fabric, for example, the inserted warp yarns and inserted weft yarns are not in the same plane and the MWK fabric will not easily be destroyed by the tearing force as in the traditional woven fabric because of the additional binding effect, as shown in Fig. 3.29. When the MWK fabric is subjected to the tearing stress, nearby yarns are inclined to slip towards the breakage. There will be more yarns to share the tearing stress, and that is another characteristic of the MWK fabric to prevent the tearing breakage from advancing.

3.5 Applications of multiaxial warp-knitted fabrics

The advantages of using MWK fabrics in composite structures are clearly the flexibility and freedom of choice in the desired properties in all directions which can be matched to individual needs. As a result, MWK fabric composites are uniquely suited to a wide range of industrial applications. The majority of current end-uses for industrial composites made from MWK fabrics can be separated into two different industries, marine and

Table 3.2 Current end-uses of MWK fabrics in composites

Industry	Marine	Aerospace	Other
Estimated % of MWK fabric composite market	65%	20%	15%
Applications	• Hulls • Decks, superstructure, substructure • Support beams • Motor bays • Sails • Racing shells	• Aircraft skin • Tail units • Fuselage panelling • Leading edges on wings and rudders • Engine panelling • Rotor blades • Ballistic protection	• Flooring • Geotextiles • Wall panels • Automotives • Protective helmets • Industrial belting • Inflatables

aerospace. Probably 65% of all MWK fabrics currently made are used in marine composite applications, while another 20% are used in the aerospace industry. The remaining 15% encompass all of the varied end-use applications being evaluated with MWK fabric composites. Table 3.2 shows many of the current end-uses of MWK fabrics.

MWK fabrics are becoming the fabric preform of choice in the marine industry, especially in yachts, sailboats and high-speed racing boats. The MWK fabric composite is generally used in these vessels for the hulls, deck superstructures and substructures, and motor bays. Because of the isotropic properties of the MWK fabric structure, boat designers are finding that they can use less MWK fabric in the composite structure and still maintain, or often improve upon, the structural integrity and torsional stiffness of the boat. This also means that boat hulls made of MWK fabric composites can withstand greater stresses and strains with less overall weight. Less overall weight obviously requires less energy to power the boat, which translates into fuel savings and/or faster boats. The improved structural integrity makes the boat safer at higher speeds.

MWK fabric composites are being used in most of the fastest ocean-going racing boats and yachts because of their increased stability and weight savings. The hulls and masts of several of the sailboats used in the America's Cup competition were made of MWK fabric composites because of the performance edge experienced by using these composite structures. Partially as a result of using MWK fabric composite structures, speedboats and racing boats are achieving speeds previously thought to be unreachable with any degree of safety.

Another example of improved performance as a result of using MWK composite structures in marine applications was seen in a new generation of racing shells used by some of the top rowing teams in the country. The shells (long narrow row boats, usually powered by eight rowers) were found to give a greater translation of power into speed because of the improved torsional stiffness. This allowed energy to be translated more directly into speed rather than being absorbed by the shell when flexing.

MWK fabrics are also being looked at for applications in sails. In this case, however, the composite structure is the MWK fabric combined with a plastic film, usually through laminating. Because of the lack of crimp in the yarn in the MWK composite structure, the force of the wind is immediately translated into power and not absorbed at all by the crimp deformation associated with woven fabric structures.

Fabric composites of all types are being used in the marine industry because of their inherent resistance to corrosion. This saves on the manufacturing cost because expensive metal treatments and repeated paintings are not needed to protect the craft from the corrosive nature of salt water.

MWK fabric composites are being used more and more in the aerospace industry, which includes the military, aerospace and commercial aircraft industries. Relatively speaking, they are being used in this industry for many of the same reasons as in the marine industry, namely reduced weight and increased strength and integrity. Because of the flexibility and tailorability of mechanical and physical properties, MWK fabric composites can be customized for the application and specific properties can be emphasized to suit the particular need.

Currently, there are very few aircraft that use MWK fabric composites in critical structures such as the fuselage or wings. Most current applications centre around the skin of the aircraft. Other areas of use are in the top and side tail units, fuselage panelling, leading edges on side rudders, and engine panelling. MWK fabric composites are also being evaluated for rotor blades, outer skin and ballistic protection for helicopters. It is thought that the use of MWK composites is also being evaluated in the new military plane/helicopter, the V-22 Osprey, and the all-composite Beech Starship business plane (Kaufmann, 1991b). The lower weight achieved through the use of MWK composite structures means that less fuel is consumed by the aircraft, which translates into significant energy savings for the user. Also, because of the improved structural integrity offered by the MWK fabric composite, it is believed that safety is enhanced.

Other various applications for MWK fabric composites can be found in the industrial composites arena. In Europe, MWK fabric composites are being used for flooring in sports halls where the combination of multidirectional force distribution and excellent tear resistance are beneficial. The MWK fabric composite also helps to improve the sound damping characteristics of the flooring. MWK fabrics coated with rubber are also being used in the industrial roofing industry. They can be used not only to replace traditional materials, but also to improve the performance of many new industrial composites which seem to have reached their performance limit. MWK fabric composites can be used to replace traditional structural materials such as concrete, wood and steel, thus creating new possibilities in various industries and end-uses.

MWK fabric composites incorporating a non-woven structure are ideally suited for many high-strength geotextile applications, where isotropic strength, resistance to tear and tear propagation, good water permeability, low creep and good fabric/soil interaction are required.

With the flexibility of fibre placement and potentially high productivity, MWK fabric composites are ideally suited for many structural load-bearing applications in the automotive and aerospace industries. MWK fabrics, because of their structural make-up, have good flexibility, which allows them to be formed during moulding into virtually any desired shape. The through-thickness reinforcement provided by the stitching process helps to reduce the possibility of delamination of layers in the composite structure.

Other applications for MWK fabrics include protective helmets and armoured protection of vehicles, buildings and people. Various drive belts, V-belts, fan belts and conveyor belts will benefit from the availability of diagonal load-bearing yarns in the composite structure. Inflatable rafts, cushions, balloons and fuel cells are ideal applications for MWK fabric composites because of their good isotropic strength and tear resistance.

3.6 Summary

This chapter presented a comprehensive study of the manufacture, structure and properties of multiaxial warp-knitted (MWK) fabrics. These newly developed fabrics offer an excellent means of reinforcement in high-quality composite structures. They hold a great deal of potential for the manufacture of specific types of composite components. Three-dimensional knitted fabric products have a number of important advantages over conventional 2-D fabrics, particularly very high drape properties and superior impact damage resistance. Their excellent impact performance makes them ideal for service conditions where energy absorption or damage tolerance are critical. Therefore, MWK fabrics are widely used as reinforcement in automotive, marine, transportation and construction applications, wind turbines, sports equipment, electronics and so on.

MWK fabric structures consist typically of two to four layers of straight fibre strands held together by a chain or tricot stitch through the thickness. The process involves arrangement of fibre layers followed by stitching. The fibres in each layer can be oriented in the warp (0°), filling (90°) or a bias direction (typically between 30° and 60°). Unlike a woven fabric in which yarns are crimped due to interlacing, MWK fabrics preserve the unidirectional characteristics of each fibre layer. They are densely packed structures, and a reasonably high fibre volume fraction (about 50%) in the final composite part can be obtained from the wet manual lay-up process. This can result in good mechanical properties as well as significant savings in resin consumption.

MWK fabrics exhibit excellent conformability and therefore are well suited for composite parts ranging from flat panels to complicated shapes. A single layer of MWK fabric may contain several plies of straight fibres oriented in different directions, and therefore the behaviour of an MWK composite can be easily tailored to meet specific needs.

Recently, MWK fabric composites have been developed to overcome the damage tolerance problem and weak strength in the through-thickness direction by improving the properties in that direction. The stitched MWK fabric composites are constructed with multiple stacks of multidirectional warp-knitted fabrics stitched together in the through-thickness direction. The reinforcement in the through-thickness direction by stitching can provide significant improvements in resistance to delamination, resistance to impact and strength in the through-thickness direction. The stitched MWK fabrics also have some excellent advantages in the fabrication aspect such as their ability to conform to complicated contours, low fabrication cost and mass productivity conjunction with resin transfer moulding to produce high-quality composite materials.

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