Advanced fibrous architectures for composites in aerospace engineering

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2.1 Introduction

In 2013, the output of the composites industry is estimated to have been worth €95 billion (US$126 billion) at the finished parts stage, and a growth of 9–10% per annum is projected up to 2020 and beyond. Until recently, investments have been driven by the aerospace industry with a focus on reducing the weight of the aircraft. At the moment, the emphasis appears to be on reducing the weight of passenger cars and other vehicles (Anon, 2014).

Due to the higher stiffness-to-weight and strength-to-weight ratios of some fibres (Table 2.1), as compared to other materials, such as metals, they are favourite candidates in many applications in aerospace engineering.

A *fibre* is a unit of matter characterized by flexibility, fineness and a high ratio of length to thickness (Anon, 1963). Because fibres have a high surface-to-volume ratio, they can be extremely strong materials.

Table 2.1 Specific properties of some high-performance fibres in comparison with some metals

Specific properties	Carbon HM	Para-aramid HM	E-Glass	Aluminium	Steel
Specific modulus: E/ρ (N m/kg)[a]	256	80	28	26	27
Specific strength: σ/ρ (N m/kg)[b]	1.2	2	0.775	0.05–0.23	0.04–0.27

ρ = density.
σ = tensile strength.
E = Young's modulus.
HM = high modulus.
[a]Also known as the stiffness-to-weight ratio.
[b]Also known as the strength-to-weight ratio.

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The fibres used to form structures which are useful for the reinforcing of composite materials used in aerospace engineering are *high-performance fibres*. These are mostly organic and inorganic man-made fibres that are engineered for specific applications that require very high performance in terms of strength, stiffness, heat resistance or chemical resistance. These fibres have generally higher tenacity and higher modulus than standard fibres. The most important of these fibres are carbon, aramid and glass fibres.

Fibres are anisotropic materials, and they normally are very strong and stiff along the fibre length but may bend under their own weight. Fibres have low bending and torsional rigidities, and they buckle easily.

As the term implies, *textile structural composites* are rigid textile-containing materials designed for structural or load-bearing applications.

The specific assemblage of flexible fibrous materials (fibres, yarns and fabrics) is known as the textile composite *preform*. Textile preforms vary considerably in terms of fibre orientation, entanglement and geometry. Moreover, a textile preform architecture can vary from a simple planar sheet to a complex three-dimensional (3D) net shape.

For aircraft, rockets and other applications wherein the stiffness-to-weight ratio (modulus-to-weight ratio) is the major consideration, carbon fibres have become the dominant material. Where the tensile strength-to-weight ratio is the major consideration, aramid fibres are the chosen ones (Scardino, 1989).

The structure and properties of the various high-performance fibres: tenacity, modulus, toughness, thermal resistance, chemical resistance and so on must be transferred (translated) into yarn and fabric structures in order to produce preforms with the desired properties for an application. In the case of the mechanical properties, the translation efficiency will very much depend on the degree of orientation of the fibres in the yarn and fabric structures developed. It should be noted that the structure and geometry of fabrics also play a major role in achieving particular properties (ie, thermal resistance and porosity).

Fig. 2.1 illustrates how fibre properties are translated or transferred to a final application (ie, a composite material).

Textile fabrics designed for composite materials for load-bearing functions, such as in aerospace applications, are often required to exhibit functional elements in multiple directions. In this context, a biaxial woven fabric, being orthotropic, exhibits high strength and poor compliance in the axial and radial directions and the opposite in the bias directions. The same is true for a Raschel-knitted fabric incorporating warp and weft inlays. A braided fabric, on the other hand, exhibits low strength and high compliance in the axial and radial directions and the opposite in the bias directions. Many nonwoven fabrics made up of randomly oriented constituent elements enjoy a degree of isotropy. However, conventional products of all four fabric formation systems are invariably planar sheets, having no functional element in the thickness direction. Even if these planar sheets are joined one on top of the other, as in laminates, the functional elements in the third direction do not exist.

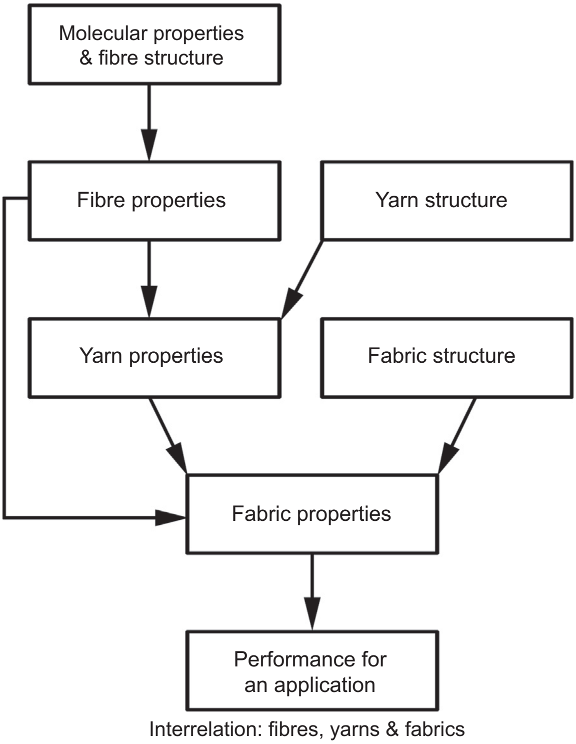


Figure 2.1 Transference of fibre properties to a final application.

In order to achieve an improved planar isotropy in woven, braided and knitted fabrics, yarns may be introduced in different directions. This approach results in triaxial woven and triaxial braided fabrics as well as multi-axial woven and knitted fabrics. The introduction of load-bearing elements in the third direction in woven, knitted and braided structures has led to the 3D fabric formation systems (Banerjee, 2014).

2.2 Types of fibrous architectures

A fibre is a 1D material which can be engineered to form various 1D, 2D and 3D fibrous architectures through textile processes. The formed fibrous architectures can be classified in different ways, either based on structural integrity and fibre linearity and continuity, or based on the fabric formation techniques.

Fibrous architectures can be classified into four categories by considering structural integrity and fibre linearity and continuity: 2D discrete, 2D continuous, 2D planar interlaced or intermeshed and 3D fully integrated structures (Ko, 1999). A 2D discrete fibrous architecture with randomly distributed staple fibres has no material continuity. Its structural integrity comes from the interfibre friction, thereby giving low strength translation efficiency. A 2D continuous fibrous architecture is a unidirectional or multidirectional fibre system which is realized by aligning continuous filaments. It has the highest level of fibre continuity and linearity, and therefore has the highest level of strength translation efficiency. However, this fibrous architecture without in-plane and out-of-plane yarn interlacing has intra- and interlaminar weaknesses. To overcome the intralaminar failure problem, 2D planar interlaced and intermeshed fibrous architectures using continuous filaments are developed, but their interlaminar strength is still limited owing to the lack of through-thickness fibre reinforcement. Unlike the 2D fibrous systems, the 3D fully integrated fibrous architectures have fibres oriented in various in-plane and out-of-plane directions. The additional reinforcement in the through-thickness direction makes the composite virtually delamination-free.

With the exception of the 2D continuous fibrous architectures for filament wound and angle ply tape lay-up structures, the other 2D and 3D fibrous architectures can be realized using industrialized textile processes and therefore can be classified into woven, nonwoven, knitted and braided structures. While 2D discrete fibrous architectures can be formed by nonwoven techniques, the other 2D and 3D fibrous architectures can be fabricated by weaving, knitting and braiding techniques. Since this chapter focuses on the fibrous architectures for composites in aerospace engineering, only the architectures that have been used or have potential to be used in aerospace-related composites will be covered.

2.3 2D fibrous architectures

2D discrete (nonwoven) and continuous fibrous architectures with intralaminar weakness are not included in the discussion because they are not suitable for aerospace applications. In this section, four types of 2D fibrous architectures are briefly introduced: woven structures, knitted structures, directionally oriented structures (DOS) and braided structures.

2.3.1 Woven structures

Conventional 2D woven structures are formed by interlacing warp and weft thread systems. There are three basic and most regular weaves: plain, twill and satin (Fig. 2.2). The plain weave is the simplest in which each weft yarn interlaces with each warp yarn. In a twill weave, each weft yarn floats across the warp yarns in a progression of interlacings to the right or left, forming a distinct diagonal line. Compared to plain weave of the same cloth parameters, twills have longer floats, fewer intersections and a more open construction. In a satin weave, each warp yarn interlaces with each weft yarn only once, each weft yarn interlaces with each warp yarn only once, and interlacing positions can never be adjacent which leads to a smooth fabric surface. Unlike conventional 2D weaves involving two orthogonal directions of yarn, triaxial weaves consist of three sets of yarn which form 60 degree angles to each other, as shown in Fig. 2.3. Triaxial fabrics possess exceptional mechanical properties in several

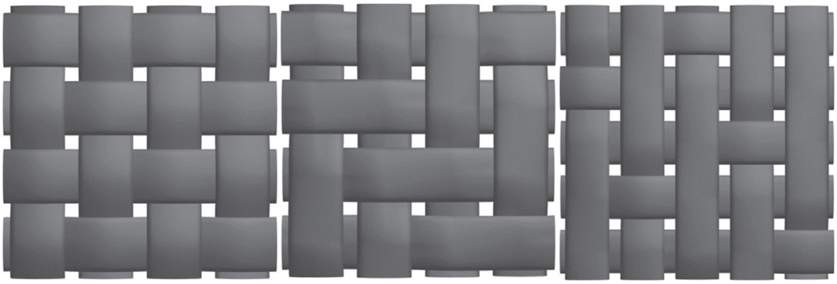


Figure 2.2 Basic 2D woven structures.

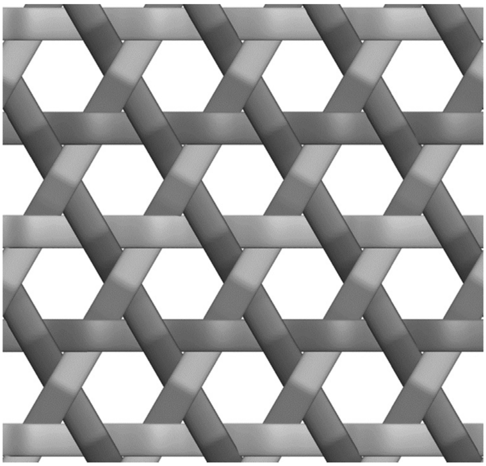


Figure 2.3 Triaxial weave.

directions. Since the interlacing points are fixed into the fabric structure, these fabrics exhibit high shear resistance.

2.3.2 Knitted structures

Knitted structures are formed from consecutive rows of intermeshed loops. The loop is the basic unit of a knitted structure. By intermeshing loops in different ways, various types of knitted stitches are formed. There are two types of knitting, namely, weft knitting and warp knitting. In weft knitting, the yarns fed into the machine form loops one by one across the fabric width (Spencer, 2001). A loop of a weft-knitted stitch consists of a head, two legs and two feet. Fig. 2.4 shows the four primary weft-knitted structures: plain, rib, interlock and purl. Each is composed of a different combination of face and reverse loop stitches. There are three basic weft-knitted stitches: loop, float and tuck, as illustrated in Fig. 2.5. Warp-knitted structures are quite different from weft-knitted structures, forming loops simultaneously at every needle in the needle

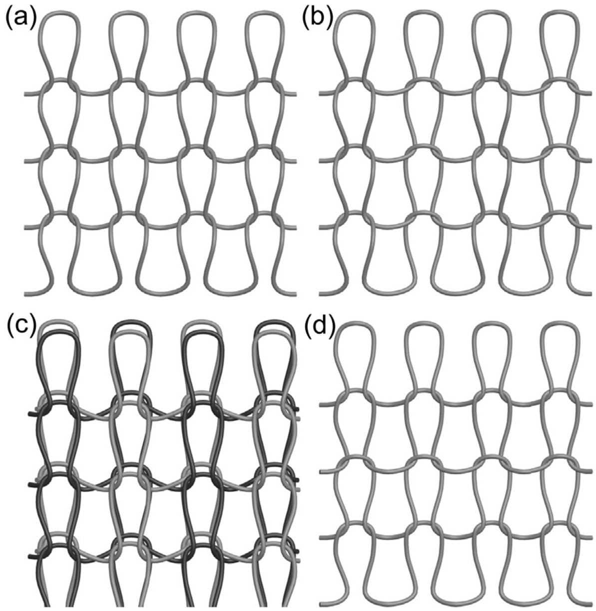


Figure 2.4 Primary base weft-knitted structures: (a) plain; (b) rib; (c) interlock; (d) purl.

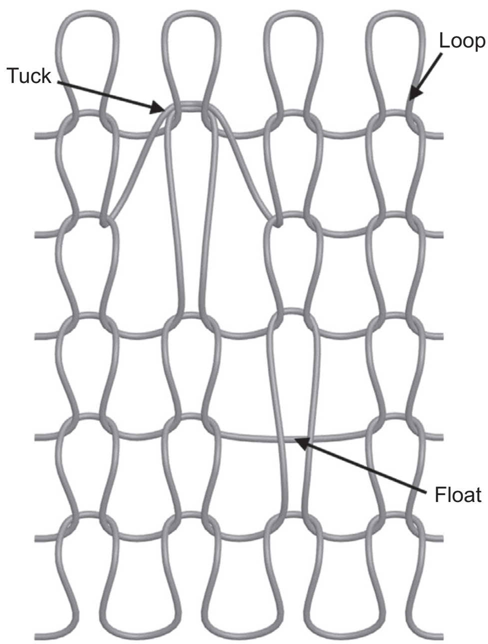


Figure 2.5 Basic knitted stitches.

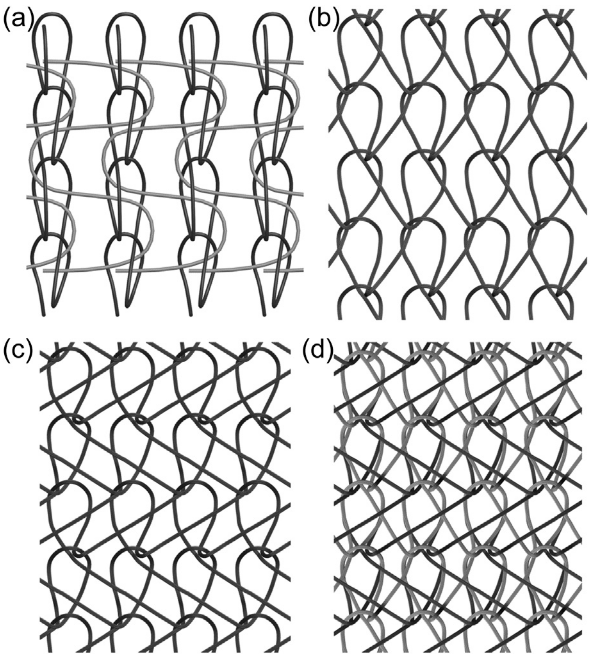


Figure 2.6 Typical warp-knitted structures: (a) pillar inlay; (b) tricot; (c) cord; (d) locknit.

bar in the fabric lengthwise direction (Spencer, 2001). The basic unit of a warp-knitted structure consists of one overlap and two underlaps, and the overlap may be open or closed. Fig. 2.6 shows four typical warp-knitted structures in which both open and closed overlaps are employed. The simplest warp-knitted structure is the pillar stitch where lappings are carried out over the same needle. Since there are no lateral connections with wales, no fabric is created. To form a complete fabric, inlay yarns are introduced by underlapping movements to connect the separate wales as shown in Fig. 2.6(a). If the laps are carried out in alternate overlap and underlap motions on two adjacent needles, then a tricot construction is produced as shown in Fig. 2.6(b). In the tricot stitch, one needle space is underlapped. By increasing one needle space for underlap motion, a cord stitch is formed as shown in Fig. 2.6(c). In this way, by employing different needle spaces for underlapping, a large family of tricot stitch derivatives is available. Tricot and cord stitches are both knitted using one guide bar. By combining tricot and cord stitches with two guide bars, a locknit structure is formed as shown in Fig. 2.6(d).

2.3.3 Directionally oriented structures

DOS are unique multiply fabrics (Au, 2011). In these structures, straight ends of absolutely parallel and noncrimped yarns are inserted into the structures at different angles (Raz, 1987). With these techniques, fabric properties can be engineered to enhance the

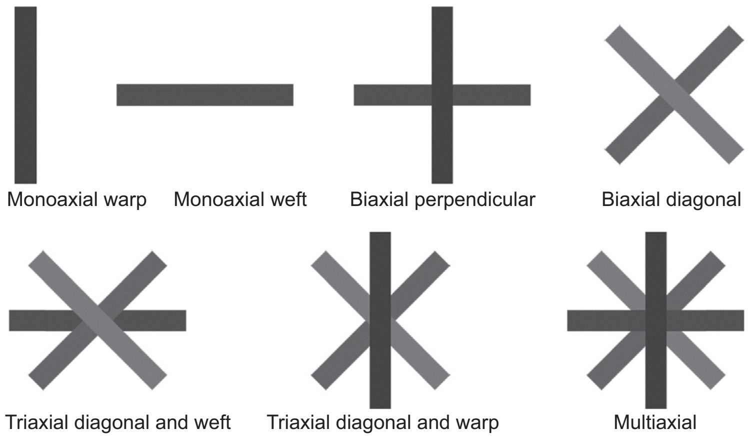


Figure 2.7 The range of DOS.

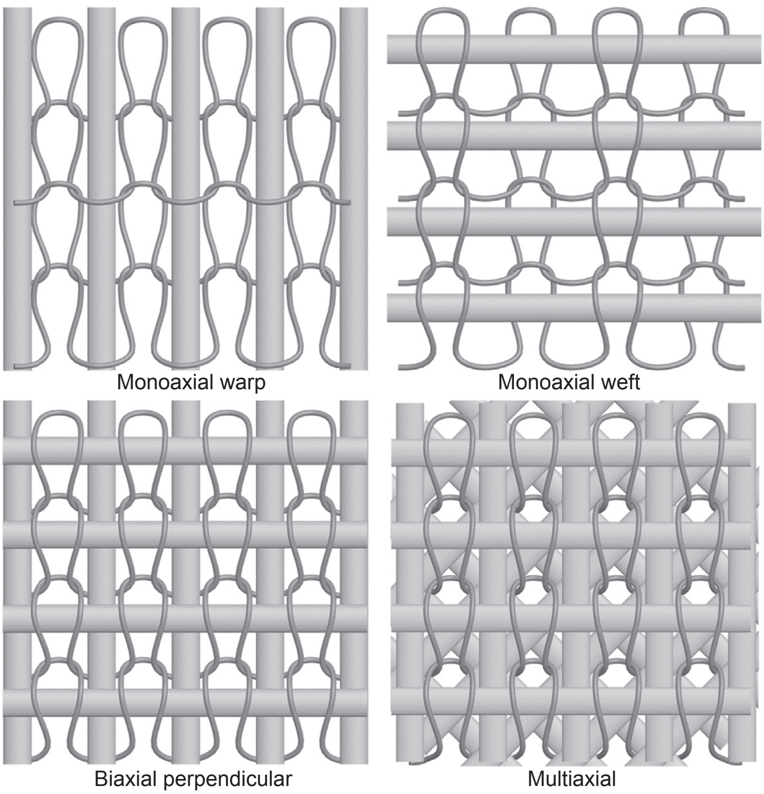


Figure 2.8 Typical weft-knitted DOS.

in-plane properties only in the required orientations, thereby producing the fabric with the ideal combination of excellent mechanical properties and cost-effective production. DOS include mono-, bi-, tri- and multiaxial structures as illustrated in Fig. 2.7, which can be produced with weft- and warp-knitting technologies.

There is a large family of weft-knitted structures suitable for manufacturing weft-knitted DOS. Some typical DOS formed by weft knitting are illustrated in Fig. 2.8. The monoaxial warp DOS uses purl as the basic structure, while the monoaxial weft DOS uses a 1×1 rib as the basic structure. Single jersey can be used to fix the biaxial perpendicular noncrimped yarns because the warp and weft yarns are interlocked within the basic structure. The multiaxial straight ends also can be bound by a single-jersey structure. It should be noted that Fig. 2.8 only gives the most simple and effective way of producing the respective DOS. There are plenty of other possibilities to fix the straight yarns for weft-knitted DOS. For instance, double-jersey structures are also able to bind the four types of DOS.

Warp knitting is the most used technology for manufacturing DOS. Warp-knitted DOS are commonly bound by pillar and tricot stitches in the warp-knitting process. Fig. 2.9 shows some typical warp-knitted mono-, bi-, tri- and multiaxial DOS bound by pillar and tricot stitches. Up to eight layers of straight ends are possible to be combined by warp-knitting technology.

2.3.4 Braided structures

In braiding, three or more threads interlace with one another in a diagonal formation, producing linear (1D), flat (2D), tubular or solid constructions (3D). Fig. 2.10 shows some typical 2D flat braids. The most common and simplest braided structure is the bias braid. Fig. 2.10(a) gives a bias with a braid angle of 45 degree. Longitudinal or axial yarns may be introduced into the braiding process to create triaxial braids. Three possible triaxial braids are illustrated in Fig. 2.10(b)–(d).

2.4 3D fibrous architectures

Laminates reinforced with 2D fibrous architectures have inferior mechanical properties, and their manufacture is expensive due to high labour requirements in the manual lay-up of plies. The application of 2D laminates in aerospace engineering has been restricted by their inferior impact damage resistance and low through-thickness mechanical properties. 3D architectures not only improve the 3D structural homogeneity but also reduce the waste of expensive materials and manufacturing costs due to the elimination of cutting and making-up operations. Composites reinforced by 3D fibrous architectures provide better through-thickness mechanical properties than those made with the traditional 2D fibrous architectures. This section briefly reviews 3D woven, knitted and braided fibrous architectures.

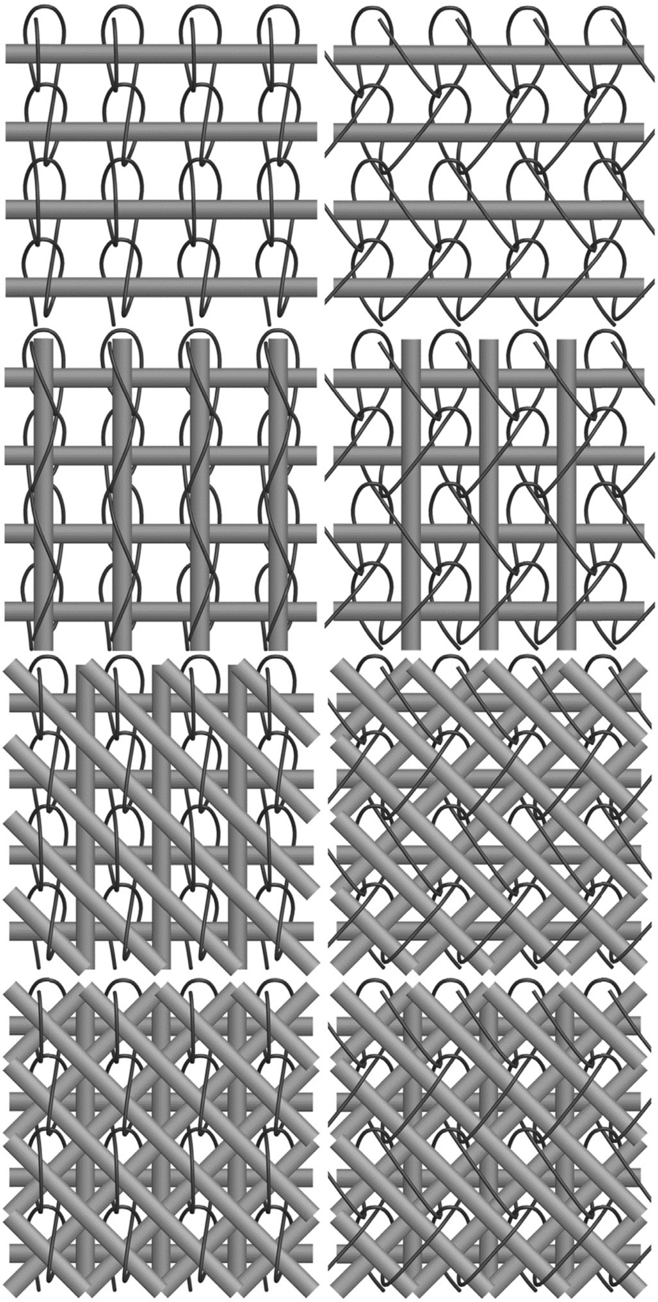


Figure 2.9 Typical warp-knitted DOS.

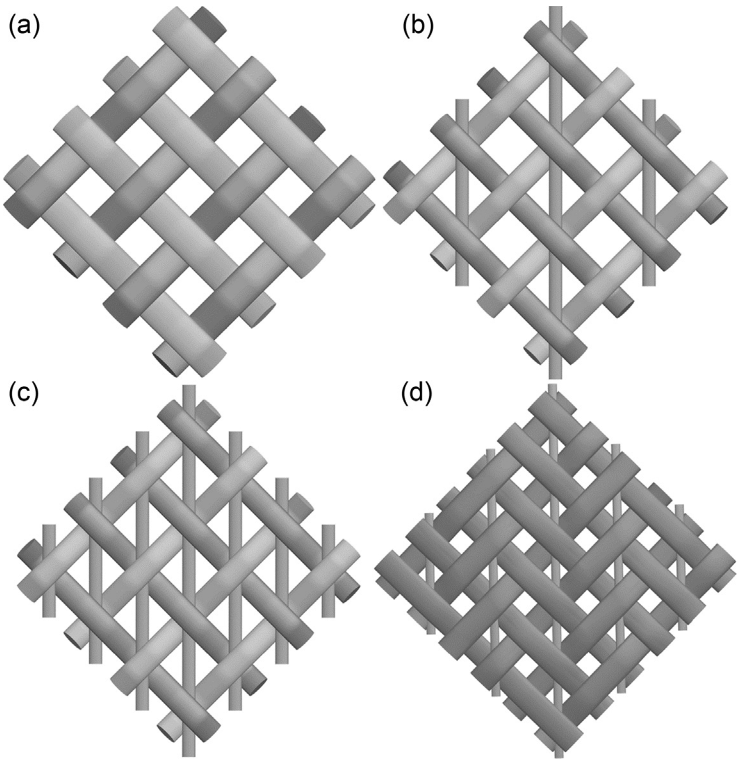


Figure 2.10 Typical 2D braided structures: (a) 1 × 1 bias; (b) 1 × 1 triaxial, axial yarns at alternate cross-overs; (c) 1 × 1 triaxial, axial yarns at each cross-over; (d) 2 × 2 triaxial.

2.4.1 3D woven structures

The weaving technology is capable of constructing 3D fibrous architectures with many different geometrical features. 3D woven structures can be classified into four categories: solid, hollow, shell and nodal as listed in Table 2.2.

3D solid woven structures consist of warp and weft yarns in the in-plane directions and *z*-binder yarns in the through-thickness direction. There are three types of 3D solid woven structures according to the binding pattern: orthogonal, angle interlock and fully interlaced (Chen et al., 2011). Angle interlock structures are also of two types: through-thickness and layer-to-layer. Fig. 2.11 shows a typical example for each type of the 3D woven structures. The *x*- and *y*-yarns of the orthogonal and angle interlock structures are not interlaced, whereas the *x*-yarns are interlaced with both *y*- and *z*-yarns in the fully interlaced structure (Stig and Hallström, 2012). The angle of the *z*-binder yarns can be adjusted to form a variety of angle interlock structures. In addition, combinations of angle interlock and orthogonal structures can evolve into four basic binding possibilities: angle interlock/through-thickness binding (A/T), angle

Table 2.2 **3D woven fibrous architectures**

Structure	Architecture	Production techniques
Solid	Orthogonal	2D weaving, 3D weaving
	Angle interlock	2D weaving
	Fully interlaced	3D weaving
Hollow	Spacer structure of a fabric spacer layer	2D weaving
	Spacer structure of a yarn spacer layer	Face-to-face weaving
	Honeycomb	2D weaving
Shell	Double curvature	2D weaving
Nodal	Tubular network with or without flanges	2D weaving

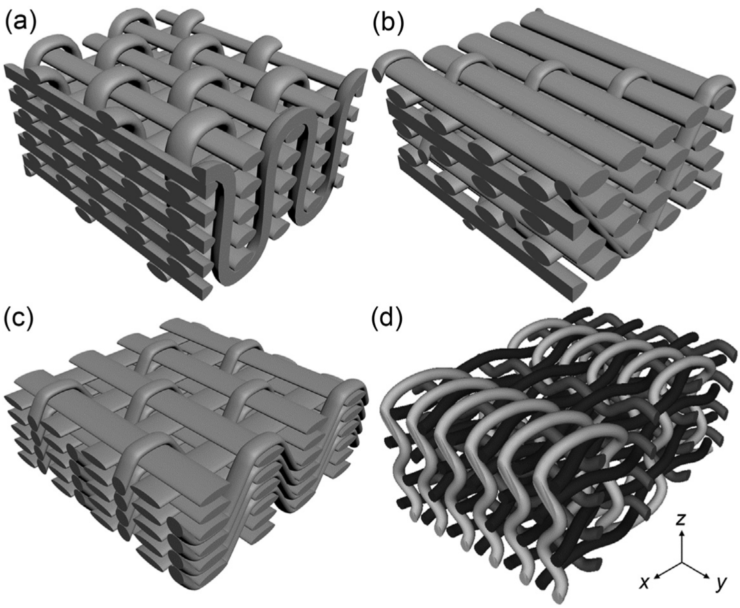


Figure 2.11 3D woven structures: (a) orthogonal; (b) through-thickness angle interlock; (c) layer-to-layer angle interlock; (d) fully interlaced.
Adapted from Stig, F., Hallström, S., 2012. Spatial modelling of 3D-woven textiles. Composite Structures 94, 1495−1502.

interlock/layer-to-layer binding (A/L), orthogonal interlock/through-thickness binding (O/T) and orthogonal interlock/layer-to-layer binding (O/L) as illustrated in Fig. 2.12 (Hu, 2008). Orthogonal and fully interlaced structures can be woven to form various profiled structures in solid, shell, tubular and a combination of these types directly.

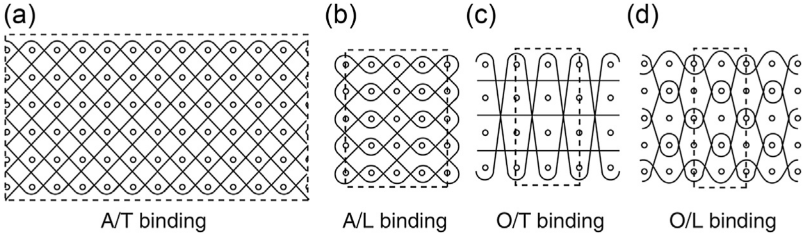


Figure 2.12 3D angle interlock woven structures: (a) angle interlock/through-thickness binding; (b) angle interlock/layer-to-layer binding; (c) orthogonal interlock/through-thickness binding; (d) orthogonal interlock/layer-to-layer binding.
Adapted from Hu, J.L., 2008. 3D Fibrous Assemblies Properties, Applications and Modelling of Three-dimensional Textile Structures. Woodhead, Cambridge, pp. 104−130.

3D hollow woven structures can be divided into two types: spacer structure and honeycomb structure. The spacer structure has normally three layers: two surface layers connected by a spacer layer. The spacer layer can be formed either by fabrics or by spacer yarns. In the case fabrics are used in the spacer layer, the cross-section of the woven spacer structure can be trapezoidal, triangular or rectangular as illustrated in Fig. 2.13, in which a fabric construction for the triangular woven spacer structure is also given. Fig. 2.14 shows a typical woven spacer structure whose two surface layers are joined together by spacer yarns. The 3D hollow honeycomb structure is a multi-layer cellular architecture where adjacent layers of fabrics are joined and separated

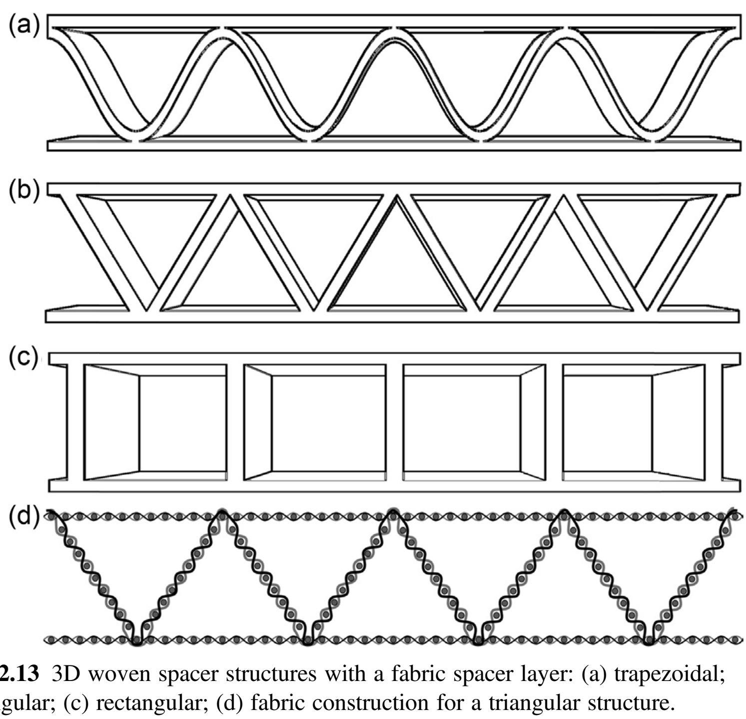


Figure 2.13 3D woven spacer structures with a fabric spacer layer: (a) trapezoidal; (b) triangular; (c) rectangular; (d) fabric construction for a triangular structure.

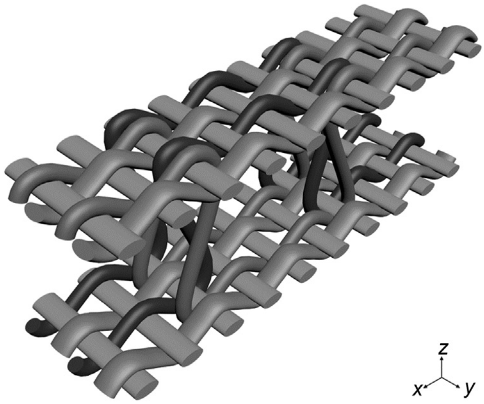


Figure 2.14 3D woven spacer structure with a yarn spacer layer.

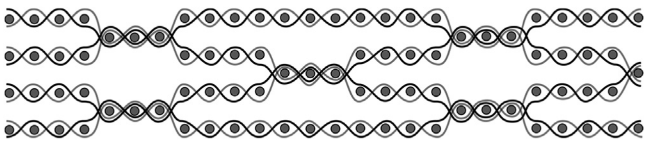


Figure 2.15 3D woven honeycomb structure.

at arranged intervals as shown in Fig. 2.15. The special connection between adjacent layers makes the fabric structure open up to form a cellular honeycomb structure after it is taken off the machine.

3D shell woven structures normally have doubly curved surfaces which can be formed by weaving with profiled take-up systems or a combination of different weaves. The profiled take-up of the fabric results in double curvatures in the fabric. Fig. 2.16 shows an example of using a combination of short-float weaves and long-float weaves to form a dome structure (Chen and Tayyar, 2003).

3D nodal woven structures are a network formed by deferent tubular or solid members (Chen et al., 2011). Fig. 2.17 shows some typical nodal woven structures with or without flanges. The basic weaves for constituting 3D nodal woven structures can be plain, twill and satin weaves.

2.4.2 3D knitted structures

3D knitted fibrous architectures, including net-shape structures and spacer structures, are produced by either the weft-knitting or warp-knitting processes. Weft knitting is very flexible to produce net-shape tubular structures and spatial shells. Fig. 2.18 gives some typical knitted tubular structures produced on a computerized flat knitting machine with two needle beds. The basic knit stitch for these tubular structures is plain knit. It is also possible to knit 3D tubular structures with flanges similar to the 3D

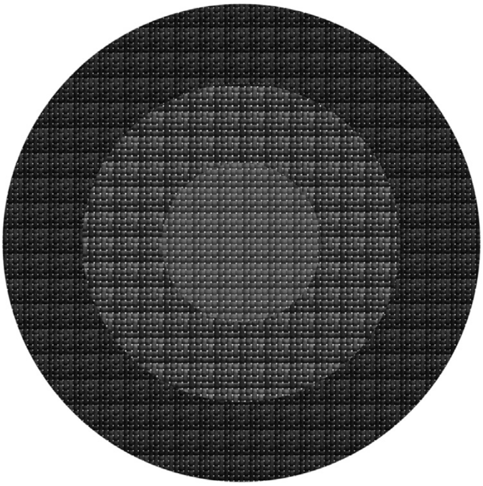


Figure 2.16 A design for a 3D dome structure by combining plain, twill and satin weaves.

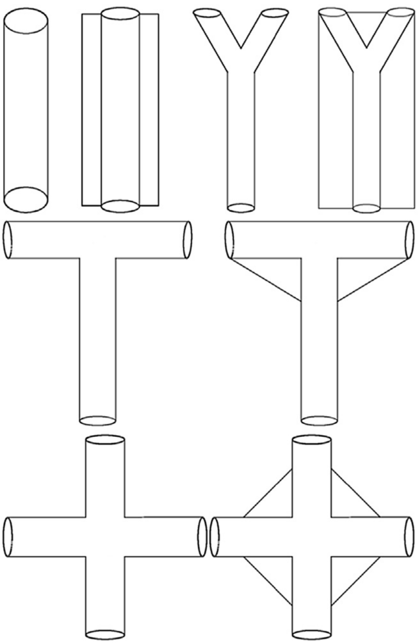


Figure 2.17 3D woven nodal structures.

woven nodal structures, as shown in Fig. 2.17. Flat weft-knitting technology is also able to produce 3D shell structures, such as a 3D dome structure and a box structure as shown in Fig. 2.19. The capability of individual needle controlling offers the greatest potential of computerized flat knitting machines to form a variety of 3D net-shape

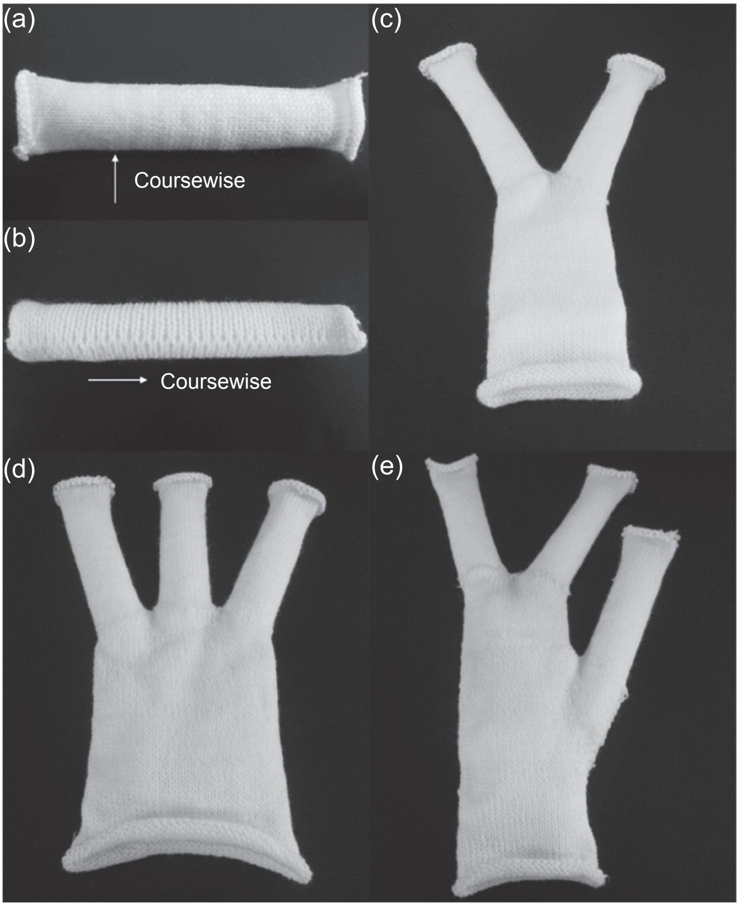


Figure 2.18 3D knitted tubular structures: (a) single tube knitted parallel to transverse direction; (b) single tube knitted parallel to axial direction; (c) bifurcated tube; (d) trifurcate tube branched at the same course; (e) trifurcate tube branched at different courses.
Adapted from Liu, Y.P., Hu, H., 2015. Three-dimensional Knitted Textiles in Advances in 3D Textiles. Woodhead, Cambridge, pp. 125−152.

forms. Warp-knitting machines equipped with double needle bars can also be used to form various 3D tubular structures of more compact, uniform and fine construction.

The spacer structure is another type of 3D knitted structure which consists of two separate surface layers joined together but kept apart by spacer yarns or a fabric spacer layer (Hu et al., 1996). Both weft- and warp-knitting technologies are able to produce spacer structures in which surface layers are connected by spacer yarns. Fig. 2.20 shows a typical warp-knitted spacer structure and a typical weft-knitted spacer structure. The surface layers of the warp-knitted spacer structure are based on the reverse locknit structure, whereas those of the weft-knitted spacer structure are based on a

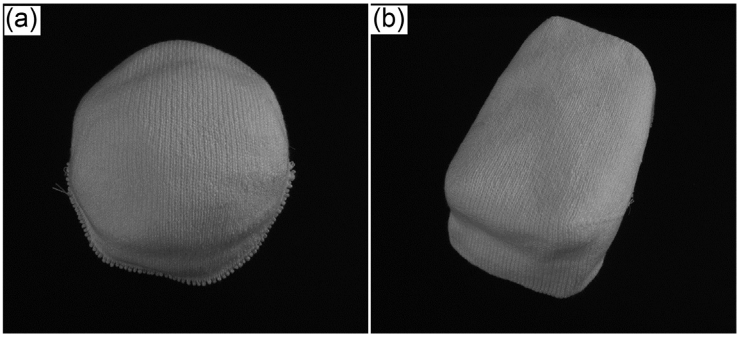


Figure 2.19 3D knitted shell structures: (a) A 3D knitted dome and (b) a 3D knitted box. Adapted from Liu, Y.P., Hu, H., 2015. Three-dimensional Knitted Textiles in Advances in 3D Textiles. Woodhead, Cambridge, pp. 125−152.

plain-knit structure. The two surface layers of warp-knitted spacer structures can either be the same or different; either both surfaces or only one can be of mesh structure, even with different mesh sizes on each side. The thickness of warp-knitted, flat weft-knitted and circular weft-knitted spacer structures can be 1−65 mm, 3−12 mm and 1.5−5.5 mm, respectively (Liu, 2012). Flat weft-knitting machines are also able to produce spacer structures whose spacer layers are fabrics similar to 3D woven spacer structures with fabric spacer layers as shown in Fig. 2.13.

2.4.3 3D braided structures

3D braiding technology is an extension of the well-established 2D braiding technology wherein the fabric is constructed by the intertwining of two or more yarn systems to form an integral structure. 3D braiding is capable of manufacturing a wide variety of tubular and complex solid constructions. Some examples are given in Fig. 2.21.

2.5 Hybrid fibrous architectures

Hybrid structures are formed by combining different kinds of textile structures to balance some characteristics or weaknesses of the individual structure. From the synergy of the properties of each structure, a fibrous architecture with improved properties is obtained. Fig. 2.22 shows a typical hybrid structure by combining two nonwoven fabrics and a multiaxial DOS produced on a Liba warp-knitting machine (Kruse and Gries, 2011). Fig. 2.23 illustrates a stitched woven-knitted fibrous structure consisting of two outer layers of a plain-woven fabric and two inner layers of weft-knitted fabrics (Hu et al., 2010). Fig. 2.24 shows a co-woven-knitted structure in which both knitted and woven structures are combined in a single fabric construction (Xu et al., 2011).

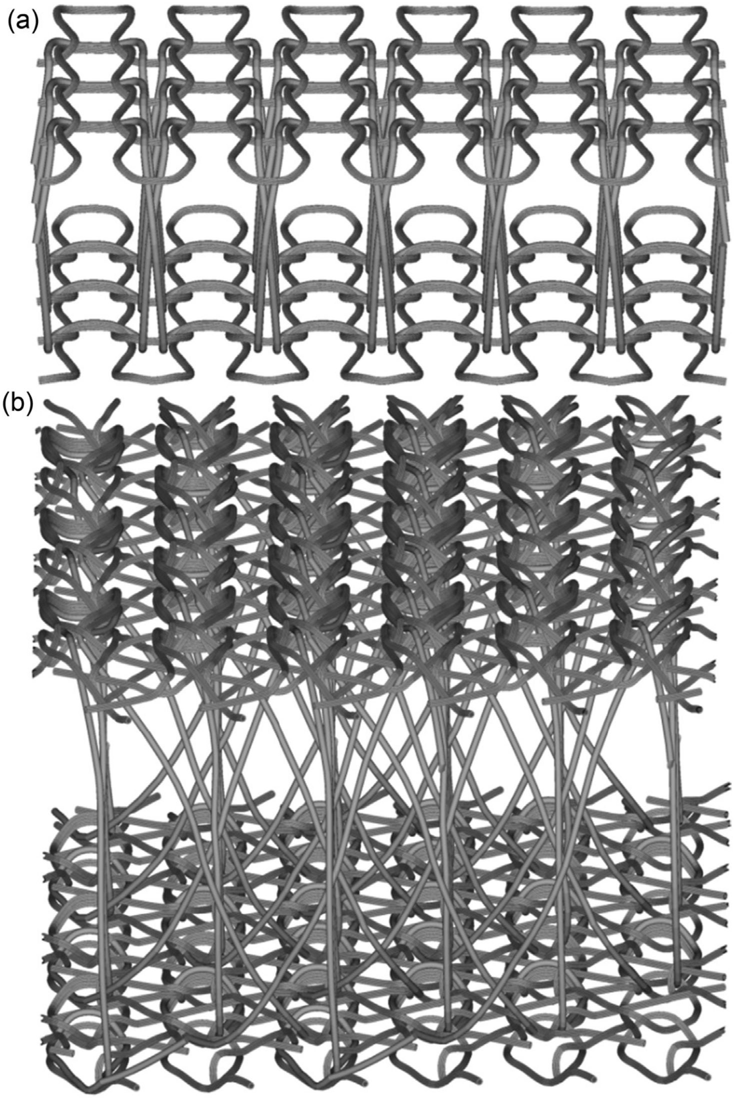


Figure 2.20 3D spacer structures: (a) weft-knitted; (b) warp-knitted.

2.6 Production techniques

This section describes the production techniques of the 2D and 3D textile structures discussed above.

2.6.1 Woven structures

Conventional 2D woven fabrics are produced by interlacing warp and weft yarns to form plain, twill and satin structures on either tappet or dobby looms. There are five

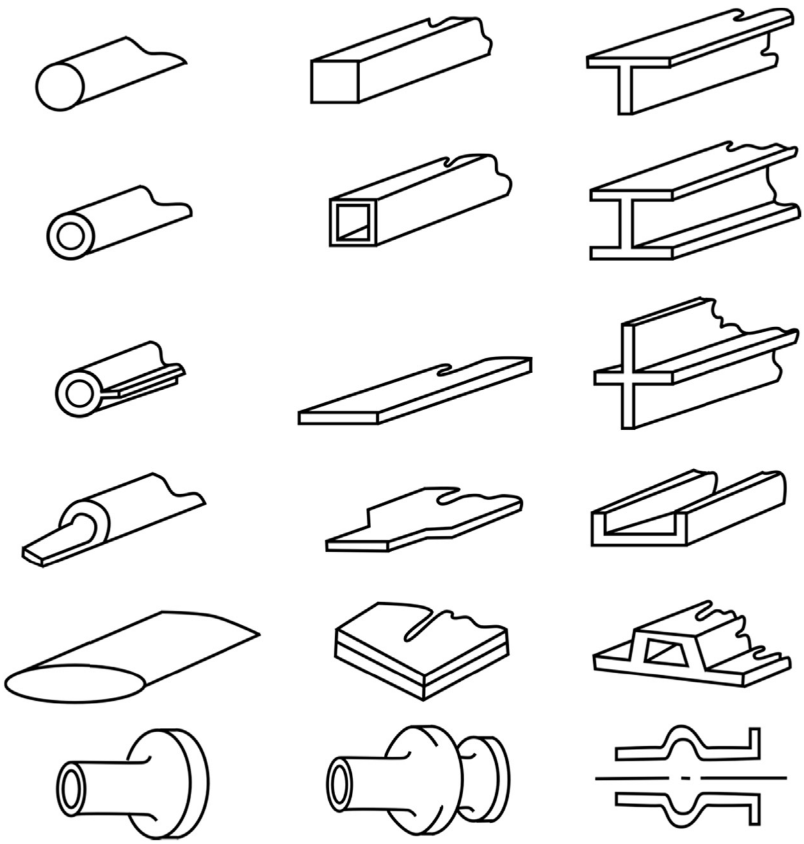


Figure 2.21 3D braided structures.
Adapted from Ko, F.K., 1989. Three-dimensional fabrics for structural composites. In: Chou, T.W., Ko, F.K. (Eds.) Textile Structural Composites, Elsevier, Amsterdam.

basic weaving motions constituting the weaving process: let-off, shedding, weft insertion, beat-up and take-up. A number of weft insertion technologies including shuttle, rapier, projectile and air-jet are available. The 2D-weaving process employing the mono-directional shedding is also suitable for weaving some 3D woven structures, as described in Section 2.4.1, including 3D solid orthogonal and angle interlock structures, 3D hollow spacer structures with fabric spacer layers and honeycomb structures, 3D shell structures and 3D nodal structures. Fig. 2.25 illustrates the 2D-weaving principle for manufacturing 2D conventional and 3D angle interlock woven structures.

3D hollow spacer structures with spacer yarns are produced by using a velvet face-to-face weaving technology. A velvet loom weaves warp and weft yarns into two separate ground fabrics simultaneously (face-to-face with a space between them), while pile warp yarns interlace alternately with the two separate ground fabrics (Fig. 2.26).

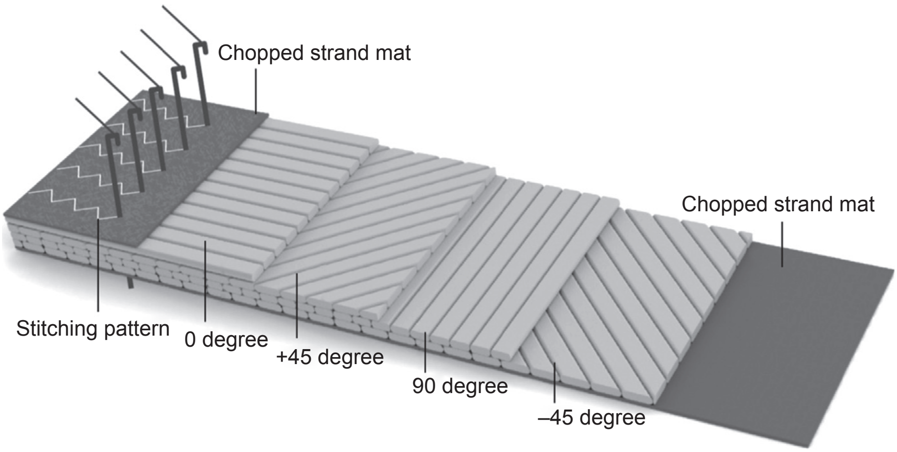


Figure 2.22 A hybrid fibrous architecture by combining nonwoven fabric and DOS using warp-knitting technology.
Adapted from Kruse, F., Gries, T., 2011. Standardisation of production technologies for non-crimp fabric composites. In: Lomov, S.V. (Ed.), Non-crimp Fabric Composites, Woodhead, Cambridge, pp. 42–66.

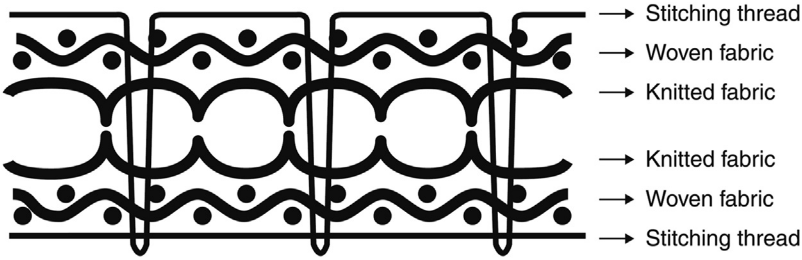


Figure 2.23 A hybrid fibrous architecture by combining woven and knitted fabrics using stitching technology.
Adapted from Hu, H., Zhang, M., Fangueiro, R., Araujo, M.D., 2010. Mechanical properties of composite materials made of 3D stitched woven-knitted preforms. Journal of Composite Materials 44, 1753–1767.

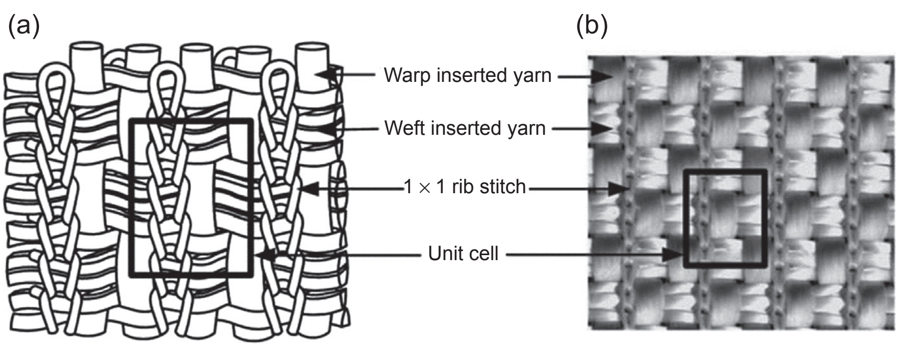


Figure 2.24 A hybrid co-woven-knitted structure: (a) structure diagram; (b) fabric.
Adapted from Xu, Y., Hu, H., Yuan, X., 2011. Geometrical analysis of co-woven-knitted preform for composite reinforcement. Journal of the Textile Institute 102, 405–418.

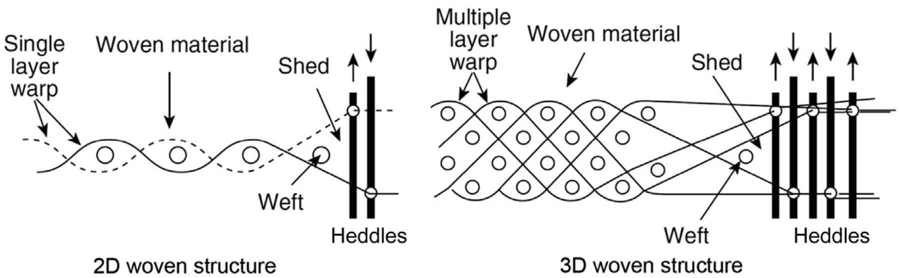


Figure 2.25 Illustration of the 2D-weaving principle for 2D and 3D woven structures. Adapted from Hu, J.L., 2008. 3D Fibrous Assemblies Properties, Applications and Modelling of Three-dimensional Textile Structures. Woodhead, Cambridge, pp. 104−130.

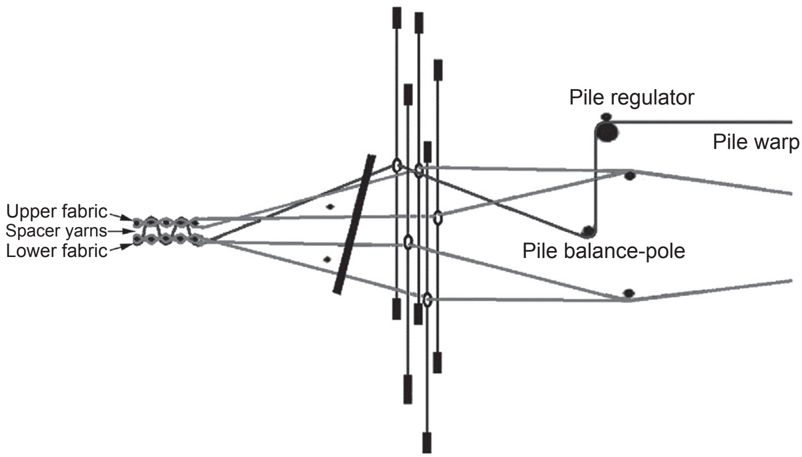


Figure 2.26 3D woven spacer fabric production on face-to-face principle.

Even though the conventional 2D-weaving process can be used to produce various 3D woven solid structures, the thickness dimension is limited. For this reason, different types of specially designed 3D-weaving machines have been developed for manufacturing 3D woven fabrics. King (1976) has developed a special weaving machine to produce orthogonal structures containing *X*, *Y* and *Z* yarns without interlacings as shown in Fig. 2.27. During weaving, the *Z* yarns are static, the *X* yarns are inserted first and then beaten up into place, and then the *Y* yarns are inserted and beaten up too. This is repeated to produce a compact structure until the desired height is achieved, producing a 3D rectangular cross-sectional configuration. There is no shedding involved in this production process. Khokar (1996) has developed a 3D-weaving machine employing a dual-directional shedding operation. Such a shedding system enables the warp yarns to interlace with both horizontal and vertical sets of weft yarns. This special 3D-weaving process also allows direct production of woven profiled materials. The 3D fully interlaced woven structures offer ultimate structural integrity even when the fabrics are cut and damaged.

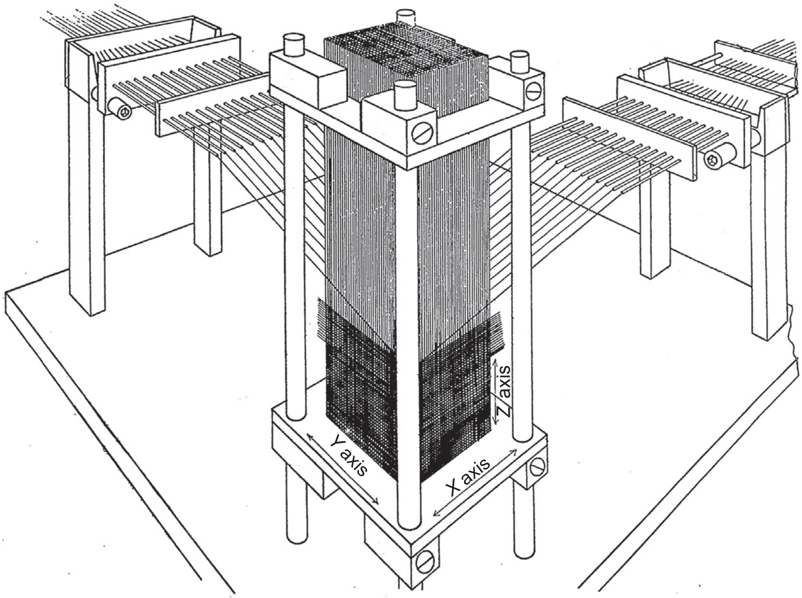


Figure 2.27 King's specially designed 3D-weaving machine for manufacturing 3D solid orthogonal structures.
Adapted from King, R.W., 1976. Apparatus for Fabricating Three-dimensional Fabric Material, US Patent No. 3955602.

The manufacture of triaxial woven structures is achieved by using techniques derived from traditional 2D-weaving and automatic braiding techniques. One typical triaxial weaving machine was designed by Dow (1975) and manufactured by Barber-Colman as illustrated in Fig. 2.28. The machine lays down warp yarns using a rotating wheel with mounted spindles. Heddles are then used to create a shed for weft insertion.

2.6.2 Knitted structures

The principles of weft knitting and warp knitting are illustrated in Fig. 2.29 (Spencer, 2001). In weft knitting, yarn feeding and loop formation occur at each needle in succession across the needle bed during the same knitting cycle. More specifically, the needles (A, B, C and D) are fed in turn with the same weft yarn so as to form a course of the fabric with loops (E, F, G and H). In warp knitting, yarn feeding and loop forming occur at every needle in the needle bar during the same knitting cycle. All needles (A, B, C and D) in the needle bar are simultaneously lapped by separate warp guides (E, F, G and H).

The key feature of circular weft knitting is to produce fabric structures in a tubular form. However, flat weft knitting is more flexible in constructing different types of tubular structures, including single, bifurcated and multibranched tubes due to the

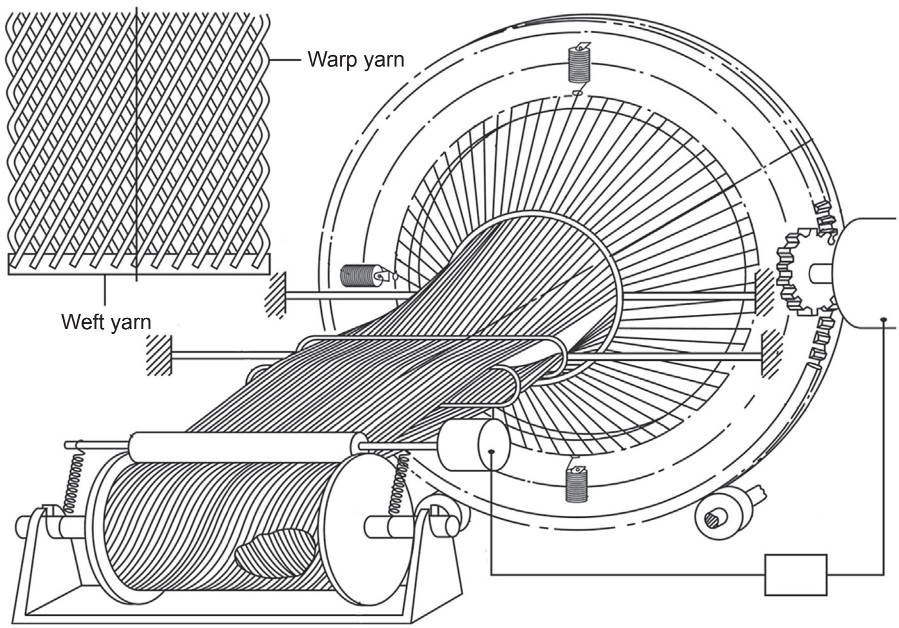


Figure 2.28 Rotating wheel with mounted spindles for manufacturing triaxial woven structures. Adapted from Dow, N.F., 1975. Warp Beam for Triaxial Weaving, US Patent No. 3884429.

capabilities of individual needle selection, loop transfer, multiple system knitting and the use of stitch pressers and holding down sinkers. Fig. 2.30 shows a single tube knitting on a computerized flat knitting machine using selected needles. Tubular knitting forms a tube by knitting one yarn on the two needle beds alternately, only passing the yarn from one needle bed to the other at the two selvages. By using tubular knitting in conjunction with intarsia technology, a number of variations from a single tube can be achieved (Fig. 2.18). Intarsia knitting technology enables knitting machines to use a number of different yarn carriers to knit different parts of the fabric. The yarn carriers can be used separately or at the same time. With this technology, a bifurcated tube can be formed by knitting a single tube of a certain length first with one yarn and then introducing an additional yarn carrier to form two tubes simultaneously with two yarns. In a similar way, by using more yarn carriers, multibranched tubular structures can be formed.

The versatility of computerized flat knitting machines offers the possibility of knitting 3D textiles with more complex shapes, such as domes, spheres and box-like shapes as shown in Fig. 2.31. A knitted dome structure can be formed by 2D repeated shaping segments (Fig. 2.31(b)). Such 2D segments were realized by repeatedly increasing and decreasing the number of needles in action. Each shaping segment represents an operation of gradually widening followed by gradually narrowing the fabric. Whereas the shaping segment type affects the angle of the dome and the height−base ratio, the number of shaping segments affects the dome shape. By changing the elliptical shaping segment for domes to a triangular segment, box-like structures can be

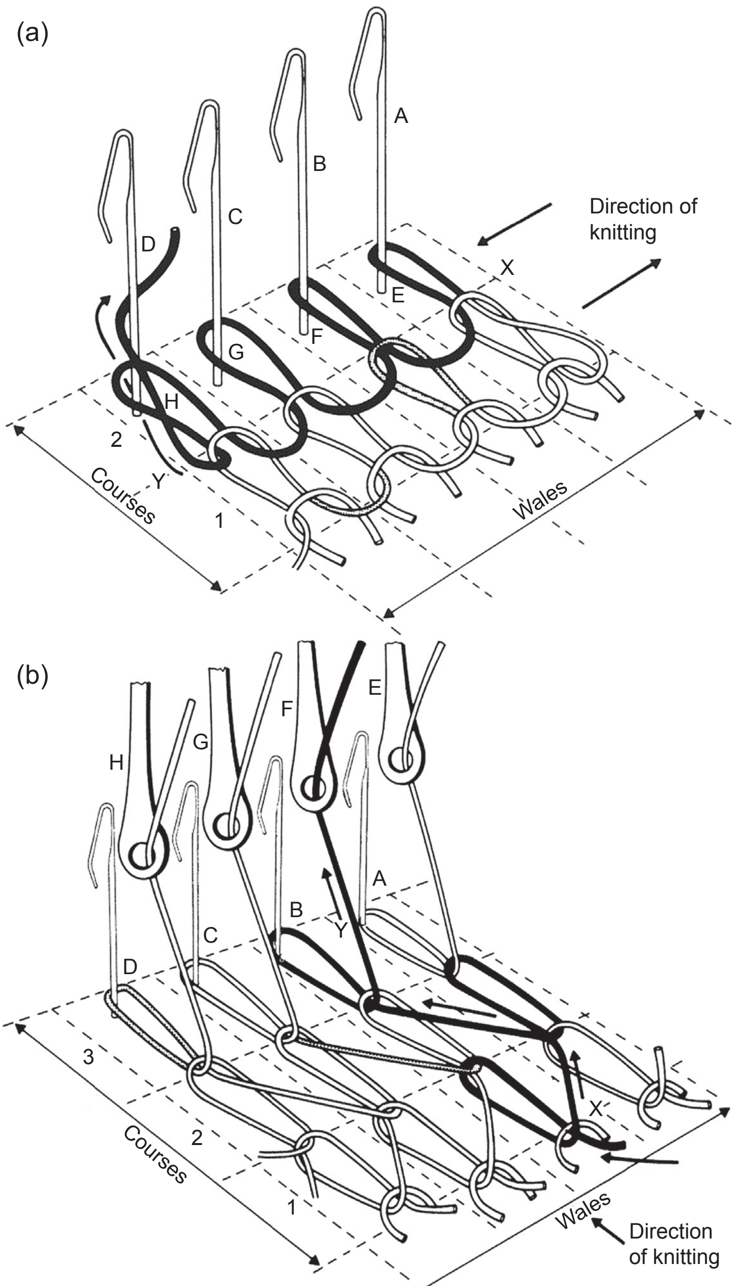


Figure 2.29 Knitting principles: (a) weft knitting; (b) warp knitting.
Adapted from Spencer, D.J., 2001. Knitting Technology, third ed. Woodhead, Cambridge.

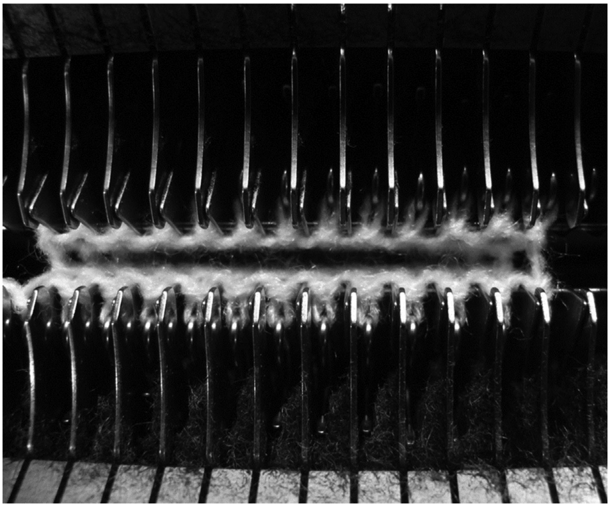


Figure 2.30 Knitting a single tube using selected needles on a computerized flat knitting machine.
Adapted from Liu, Y.P., Hu, H., 2015. Three-dimensional Knitted Textiles in Advances in 3D Textiles. Woodhead, Cambridge, pp. 125−152.

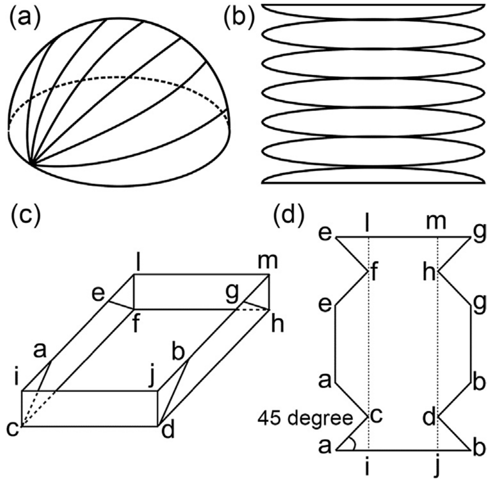


Figure 2.31 The knitting principle of 3D shells: (a) 3D theoretical form; (b) 2D pattern of a dome; (c) 3D theoretical form; (d) 2D pattern of a box.
Adapted from Liu, Y.P., Hu, H., 2015. Three-dimensional Knitted Textiles in Advances in 3D Textiles. Woodhead, Cambridge, pp. 125−152.

formed. As shown in Fig. 2.31(d), the straight lines representing the decrease or increase of the number of operating needles are linear rather than curved for the dome structure. The shaping segment type affects the angle of the box being formed. The ratio between the number of stitches being shaped and not being shaped determines the length−width ratio of the resultant box. The capability of varying the number of knitting needles offers the greatest potential of computerized flat knitting machines to form a variety of 3D net-shape forms.

Spacer structures are produced on circular, flat weft-knitting or warp-knitting machines with two sets of needles. Circular weft-knitting machines equipped with a cylinder and a dial are able to produce the spacer fabrics whose separate outer layers are connected by yarns. Spacer fabrics on circular weft-knitting machines are produced using dial needles and cylinder needles to knit two distinctive layers of fabric separately and then connect the two fabric layers with tucks on both the dial and cylinder needles (Fig. 2.32). The distance between the two individual fabric layers can be adjusted by varying the dial height relative to the machine cylinder. Spacer fabric thicknesses pre-set in this way can vary between 1.5 and 5.5 mm (Kunde, 2004). Similar to the production of spacer fabrics on circular machines, the production of spacer fabrics with a spacer layer of yarns on flat machines is carried out by creating two independent fabric layers on the front- and back-needle beds separately and then connecting them by tucks on both the needle beds (Fig. 2.33). The distance between the two needle beds determines the spacer fabric thickness. Unlike circular weft-knitting machines, the distance between the two needle beds of a flat weft-knitting machine is normally fixed around 4 mm. The critical characteristic distinguishing warp-knitted spacer fabrics from the other kinds of spacer fabrics is that their three basic structural elements (ie, top layer, bottom layer and spacer layer) are knitted together in the same knitting cycle. Warp-knitted spacer fabrics are produced on double-needle-bar Raschel machines; the principle is schematically shown in Fig. 2.34(a). While guide bars 1 and 2 lap the front-needle bar and guide bars 5 and 6 lap the back-needle bar (to knit the top layer and the bottom layer, respectively), guide bars 3 and 4 lap the spacer yarns around both the needle bars in succession. The production of a spacer fabric on a double-bar Raschel machine, RD 6, by Karl Mayer is shown in Fig. 2.34(b).

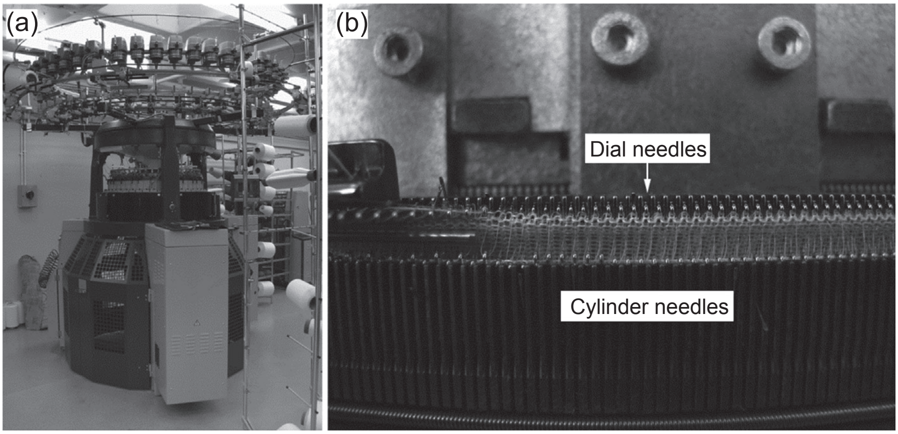


Figure 2.32 Producing a spacer fabric on a circular weft-knitting machine: (a) a Terrot double-jersey circular machine; (b) knitting a spacer fabric on the circular machine.
Adapted from Liu, Y.P., Hu, H., 2015. Three-dimensional Knitted Textiles in Advances in 3D Textiles. Woodhead, Cambridge, pp. 125−152.

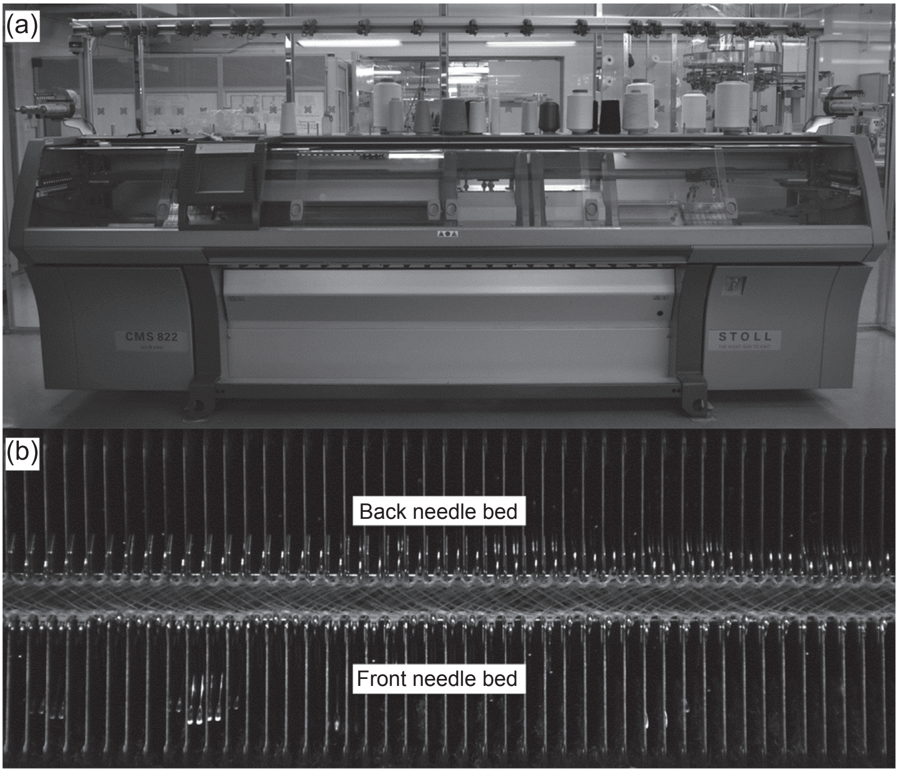


Figure 2.33 Producing a spacer fabric on a computerized flat knitting machine: (a) a Stoll computerized flat knitting machine; (b) knitting a spacer fabric on the flat machine.
Adapted from Liu, Y.P., Hu, H., 2015. Three-dimensional Knitted Textiles in Advances in 3D Textiles. Woodhead, Cambridge, pp. 125−152.

2.6.3 Directionally oriented structures

Weft-knitted DOS are produced on both circular and flat weft-knitting machines. Fig. 2.35 shows the knitting principle of a biaxial weft-knitted DOS on a circular knitting machine, in which straight yarns are introduced in both the wale-wise and the course-wise directions. Either single-jersey or double-jersey circular knitting machines may be selected according to the binding knitted structures desired. For the monoaxial DOS described in Fig. 2.8, a double-jersey machine may be used. While straight yarns should be introduced in the wale-wise direction for knitting the monoaxial warp DOS, straight yarns should be inserted in the course-wise direction for knitting the monoaxial weft DOS. Apart from inserting straight yarns in wale-wise and course-wise directions, it is also possible to introduce straight yarns at different angles to form multiaxial weft-knitted DOS. The knitting principle of weft-knitted DOS on flat knitting machines is similar for circular machines.

The warp-knitting technology is very productive for the manufacture of warp-knitted DOS. While a biaxial warp-knitted DOS consists of warp (0 degree) and weft (90 degree) yarns, a multiaxial DOS has additional bias ($\pm\theta$) yarns held

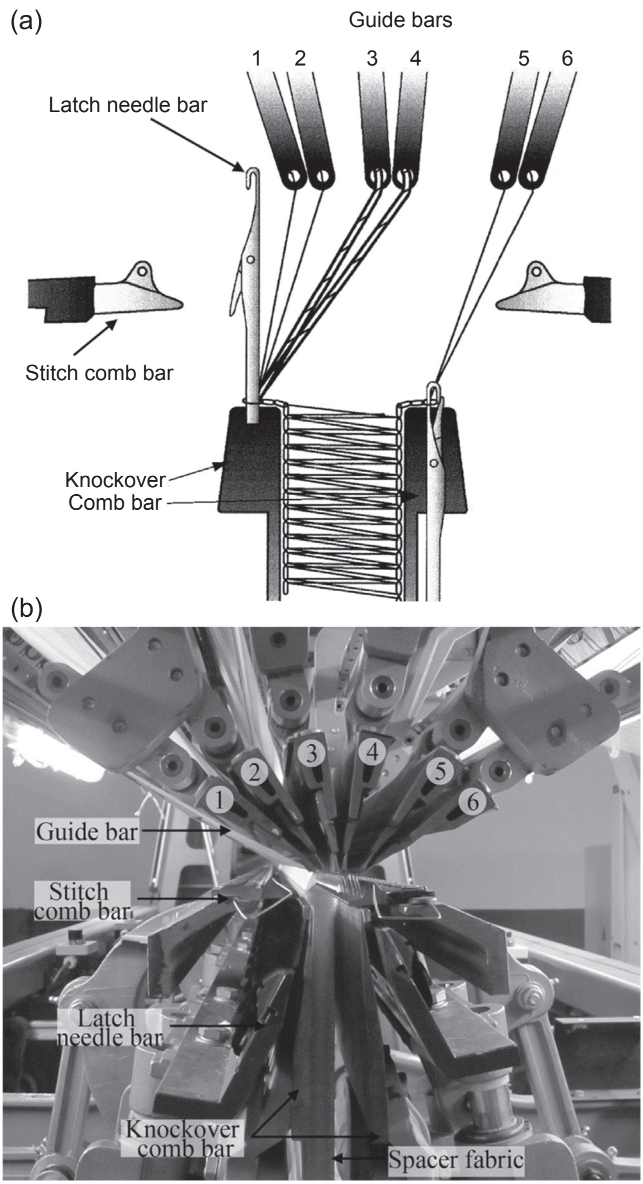


Figure 2.34 Principle of producing spacer fabrics on a double-needle-bar Raschel machine: (a) a schematic illustration; (b) RD 6 by Karl Mayer.
Adapted from Liu, Y.P., Hu, H., 2015. Three-dimensional Knitted Textiles in Advances in 3D Textiles. Woodhead, Cambridge, pp. 125−152.

together by a chain or tricot stitch through the thickness of the fabric. The warp-knitting machine used for the production of biaxial DOS can be divided into three machine modules: feeding, knitting and take-up, as illustrated in Fig. 2.36 (Schnabel and Gries, 2011). The feeding module consists of a weft insertion system,

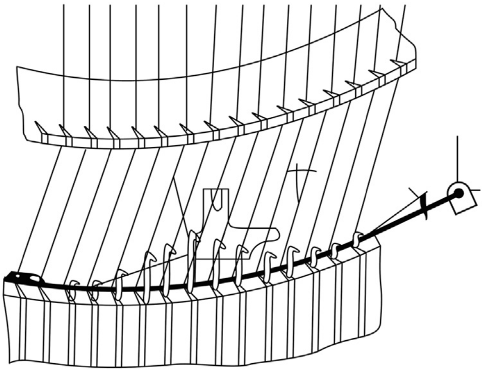


Figure 2.35 Knitting of a biaxial structure on a circular machine.
Adapted from de Araujo, M., Fangueiro, R., Hu, H., 2011. Weft-knitted structures for industrial applications in Advances in Knitting Technology, pp. 136−170.

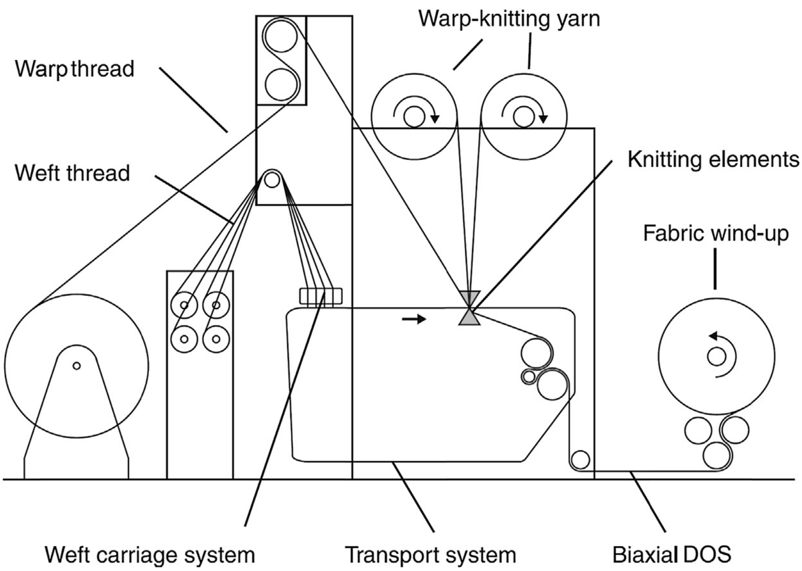


Figure 2.36 Warp-knitting principle for biaxial DOS.
Adapted from Schnabel, A., Gries, T., 2011. Production of non-crimp fabrics for composites. In: Lomov, S.V. (Ed.), Non-crimp Fabric Composites, Woodhead, Cambridge, pp. 3−41.

which is continuously feeding weft threads into the hooks or needles of two transport systems. There is one transport system on each side of the machine. The transport system continuously supplies the layers of weft straight yarns to the warp-knitting machine. The warp threads are directly fed to the needles by a yarn guide bar without both underlapping and overlapping movements. The weft and warp threads are fixed during the warp-knitting process by knitting yarns to form a biaxial DOS fabric which is subsequently wound onto the take-up module.

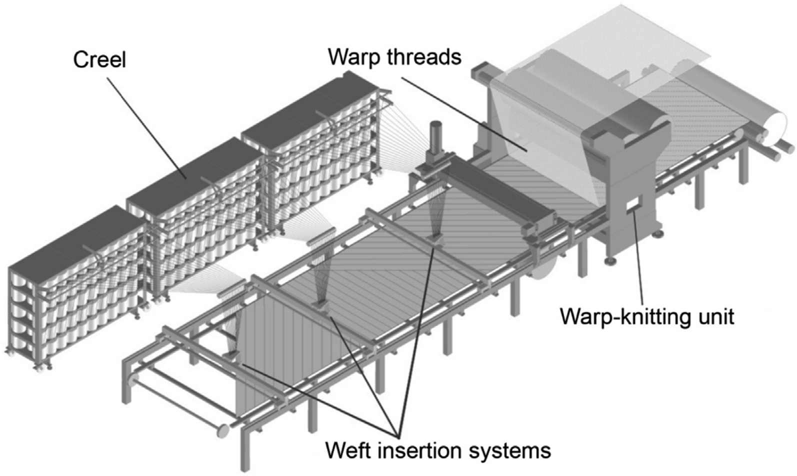


Figure 2.37 Warp-knitting principle for multiaxial DOS.
Adapted from Schnabel, A., Gries, T., 2011. Production of non-crimp fabrics for composites. In: Lomov, S.V. (Ed.), Non-crimp Fabric Composites, Woodhead, Cambridge, pp. 3−41.

The working principle of warp-knitting machines for the production of multiaxial DOS is comparable to that of biaxial DOS. The standard machine configuration consists of three weft carriage systems, which are adjustable in small ranges between −45 degree and +45 degree (Fig. 2.37). The single yarn layers are fed in consecutive steps into the weft lay-in units of the transport system. The warp threads made of rovings are supplied directly to the needles.

2.6.4 Braided structures

Braiding is a process of interlacing three or more threads diagonally to the product axis to obtain a thicker, wider or stronger product or in order to cover some profile. There are several types of braiding machines developed for manufacturing 2D and 3D braided structures. The classical and most commonly used braiding machines equipped with horn gears are known as maypole machines, which can be used to produce 1D linear, 2D flat and 3D tubular and solid braids. Fig. 2.38 demonstrates the principle of using a maypole machine to braid a linear product (Kyosev, 2015). The key parts of the machine include tracks, carriers and horn gears. The track determines the path of the motion, but the carriers are moved forwards by the horn gears. The process can be extended to more yarns to produce 2D flat and 3D tubular structures by placing a string of horn gears in an open-ended circular and complete circular form, respectively. 2D flat and 3D tubular triaxial braids can be produced by introducing inlay yarns in the braiding process. Fig. 2.39 shows a tubular braiding process with a third set of longitudinal inlay yarns. For structural composite applications, mandrel overbraiding is always employed to produce 3D tubular braids for profiled sections, as shown in Fig. 2.40 (Potluri and Nawaz, 2011). Unlike flat and tubular braids with only one

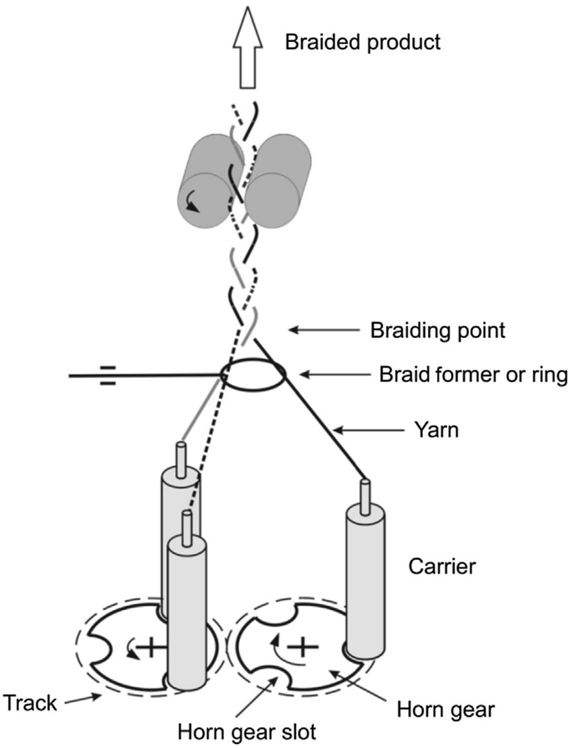


Figure 2.38 Principal construction of a maypole braiding machine.
Adapted from Kyosev, Y., 2015. Braiding Technology for Textiles, Woodhead, Cambridge.

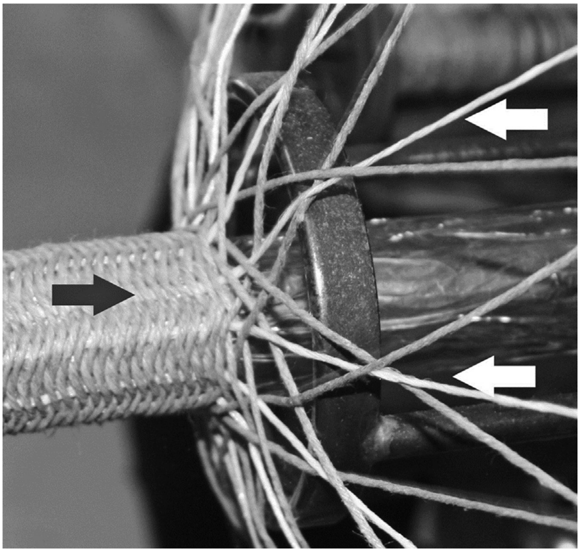


Figure 2.39 Triaxial tubular braid with inlay yarns. The arrows point to the inlay yarns.
Adapted from Kyosev, Y., 2015. Braiding Technology for Textiles, Woodhead, Cambridge.

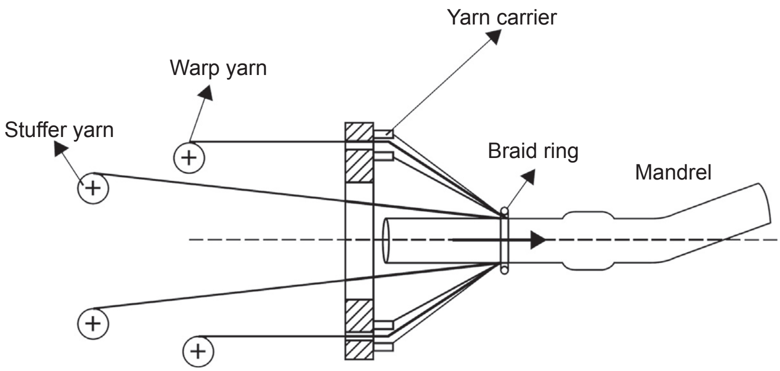


Figure 2.40 Mandrel overbraiding.
Adapted from Potluri, P., Nawaz, S., 2011. Developments in braided fabrics. In: Gong, R.H. (Ed.), Specialist Yarn and Fabric Structures, Woodhead, Cambridge, pp. 333−353.

interlaced layer, 3D solid braids have several interconnected layers. There are two basic types of machines to form a 3D solid braid: horn gear and Cartesian machines which differ only in their method of yarn carrier displacement. Similar to 2D braiding, horn-gear-based machines with square or circular arrangement can also produce 3D solid braids. To allow for more flexibility in preform size, shape and microstructure, 3D Cartesian braiding machines have been developed (Fig. 2.41). Moving carriers around a rectangular mesh, the so-called two-step and four-step braiding processes, involve the placement of the carriers over a special table into rows and columns. Motion is performed by moving an entire row or column in a given sequence, usually alternately. This process is used mainly for composite profiles with 3D cross-sections as illustrated in Fig. 2.21.

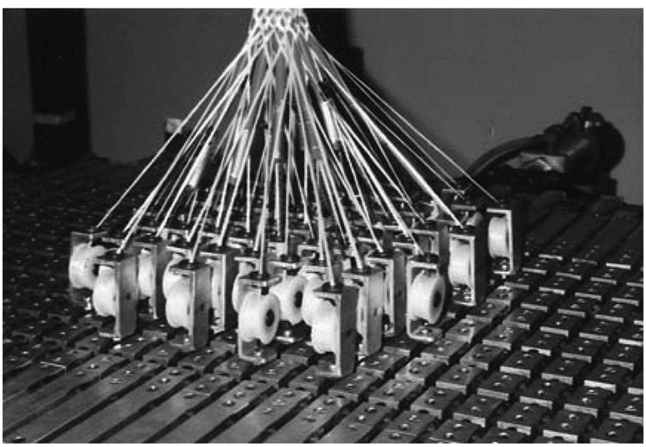


Figure 2.41 3D Cartesian braiding machine.
Adapted from Kostar, T.D., Chou, T.W, 1999. Braided structures. In: Miravete, A. (Ed.), 3D Textile Reinforcements in Composite Materials, Woodhead, Cambridge, pp. 217−240.

2.7 Properties of advanced fibrous architectures: advantages and disadvantages

The published literature regarding the mechanical properties of textile reinforcement is scarce. However, some basic principles and requirements may be discussed and taken into account.

As illustrated in Fig. 2.1, the translation efficiency of the fibre properties to the final application (i.e. a composite material) should be maximized. Therefore, it is of utmost importance to choose the appropriate structure for the application.

The use of straight, noncrimp continuous filament yarns with very low twist for the reinforcement is an important requirement. These have to be placed in 2D and 3D assemblies to form preforms.

Concerning woven structures, at least one set of yarns must have crimp and therefore is not straight. The effect of crimp on the tensile properties is well illustrated in Figs 2.42 and 2.43.

The strength of a woven fabric depends essentially on the strength of the composing yarns. There are, however, some additional effects due to the structure of the fabric. In order to achieve the maximum tensile strength at rupture, the load must be uniformly distributed by all the yarns in a particular direction (warp or weft). This is the case for the structures illustrated in Fig. 2.42: for structures (a) and (b) in both directions, and for the structure in (c) in the weft direction. However, this will not be the case for structure (c) in the warp direction as the crimp is not the same for all the yarns in the warp direction. Any load applied to (c) in the warp direction will be essentially taken up by the warp yarns without crimp. The yarns with crimp will merely contribute with a small force, just enough to straighten them out. By the time the yarns with crimp are straight and ready to support larger loads, the yarns initially without crimp will probably be at the stage of rupture. For this reason, the tensile strength at rupture of structure (c) in the warp direction will be a little more than half the tensile strength of structure (a).

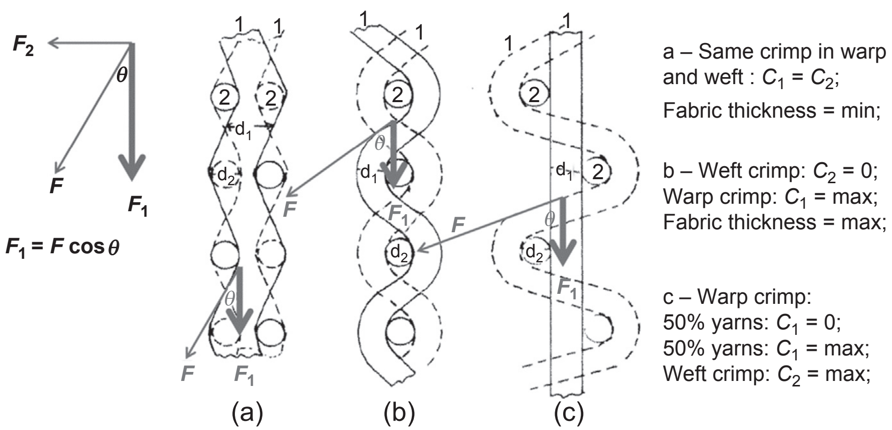


Figure 2.42 Section of a variety of plain-weave structures: effect of crimp on tensile properties (1, warp; 2, weft).

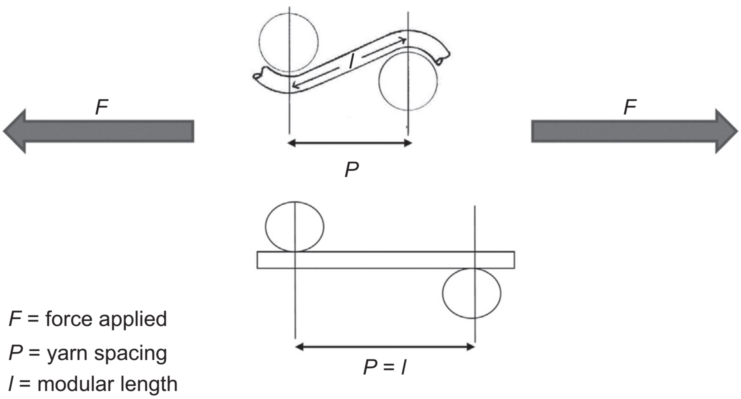


Figure 2.43 Illustration of crimp interchange in a woven fabric.

The effect of crimp interchange at the initial stage of loading is illustrated in Figs 2.43 and 2.44. Fig. 2.43 shows that when a woven fabric is extended in one direction (warp or weft), only when the modular length (l) is equal to the yarn spacing (p) does the yarn start supporting in full the load applied. Before that, the effect of the applied load is to deform the structure just enough to remove the crimp in the yarn.

The tensile behaviour of a woven fabric under a gradually increasing applied force is usually shown by the load-extension curve (Fig. 2.44) in which the slope of the primary linear region of the curve, the low-resistance region, is called the primary modulus and corresponds to the deformation of the structure. The slope of the secondary linear region of the curve, the high-resistance region, is called the secondary modulus and corresponds to the extension of the yarns. There is a nonlinear region between these two linear regions that could be affected by the fabric structure. In this

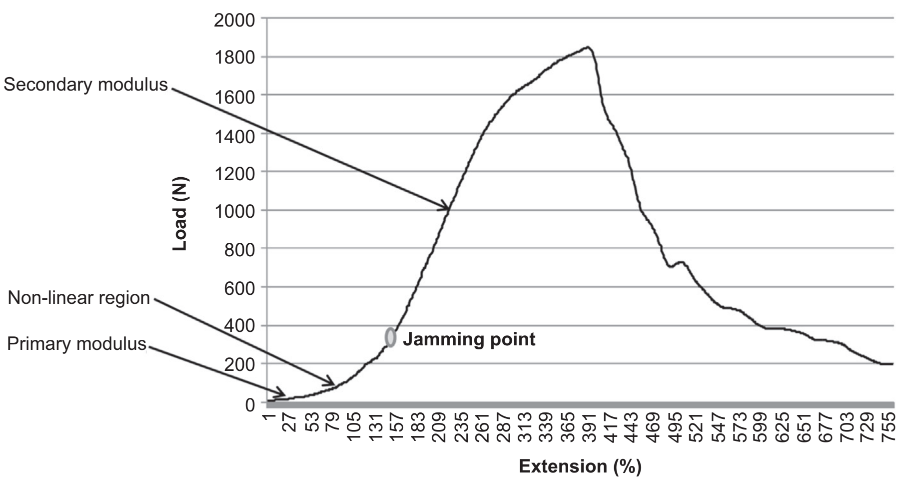


Figure 2.44 Typical load-extension curve of a woven fabric (weft direction).

latter region, a stick-slip effect due to interyarn friction may occur as yarns are displaced further. Extension of the yarn starts occurring when the structure is jammed and the yarns are straight.

To diminish the effect of crimp interchange when loading woven fabrics, flat yarns may be used instead of round ones.

DOS knitted fabrics seem to be the most successful technology for developing preforms for textile structural composites, as this technology enables the placement of straight noncrimp yarns in a variety of directions. Fig. 2.45 illustrates loading of a DOS structure with straight yarns as compared with loading a woven structure with crimped yarns. It should be noted that the greater the crimp, and consequently the greater the obliquity of the yarn, the smaller will be the contribution of the yarn to bear a load. When the same yarn is placed without crimp, as is the case of a DOS structure, it will be able to withstand greater loads.

Fig. 2.46 illustrates a typical load-extension curve of a DOS fabric in which the load is immediately borne by the yarn as soon as it is applied.

At the present time, the DOS warp-knitting-based technology is the most widely used by far, and the rate of production of these machines is very high. However, the DOS weft-knitting-based technology is much more flexible and may be of great interest in the future.

With regard to braided structures, the main limitation is fabric width, as the number of carriers needed to manufacture a wide fabric is very large and often impractical. It should be noted that problems of crimp interchange may be encountered, especially when loading in the bias directions.

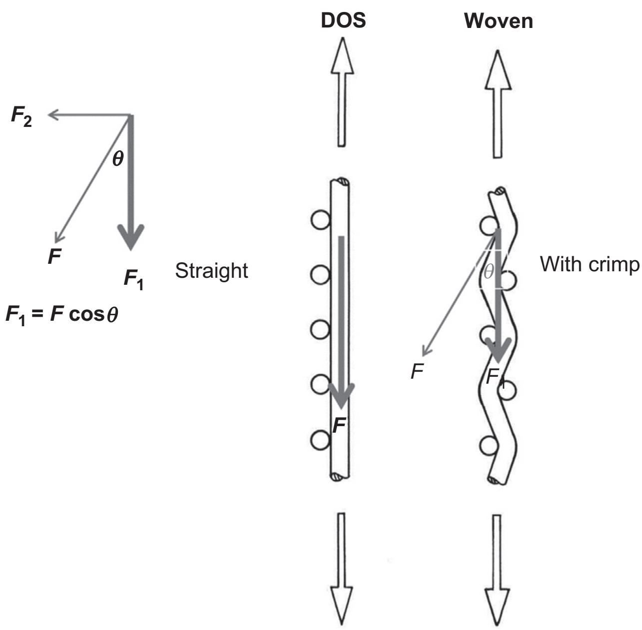
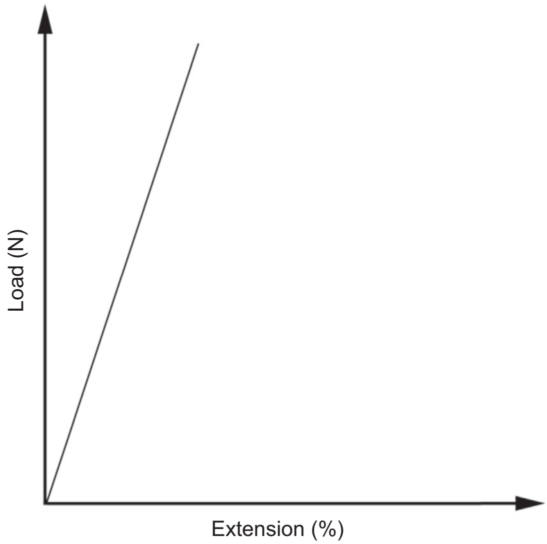


Figure 2.45 Effect of crimp on the load applied.

Figure 2.46 Typical load-extension curve of a DOS fabric (reinforcement yarn direction).



Braided fabrics are highly deformable via the mechanism of fabric shear in the axial and radial directions, and the opposite is true in the bias directions. It may be said that they exhibit high compliance in the axial and radial directions and low compliance in the bias direction. In the case of woven fabrics, the opposite of what happens in braided fabrics is true, and so they exhibit low compliance in the axial and radial directions and high compliance in the bias directions. In order to increase the rigidity of braided fabrics in the axial direction, an axial yarn may be introduced in that direction by using the technique of triaxial braiding. In the case of woven fabrics, the rigidity in a third direction may be achieved by using the triaxial weaving technique.

Concerning the use of 3D fabrics in the composites sector, in which properties such as high energy absorption, good impact resistance, good formability, good through-thickness stiffness, strength, and fatigue resistance to flexural and torsional strains along with a certain degree of isotropy and low density are required, the developed 3D products do not fully satisfy all the desired criteria. Furthermore, commercial applications normally call for well-established design strategies that relate the functional properties of a product with its structural parameters and material properties as well as production systems that are efficient and reliable. In this respect, a considerable amount of development is yet to be undertaken in the area of 3D fabric technology (Banerjee, 2014).

2.8 Applications

The drive within the aerospace composites field over the last decade has been to reduce cost, increase component performance and reduce component weight (Lowe, 2005).

Due to their superior weight-to-specific stiffness and weight-to-specific strength ratios, and their potential for integral design, the use of textile structural composites in aerospace applications is increasing. The share of composite structures in the Airbus A340, A380 and the upcoming A350 XWB was around 17%, 25% and 50%, respectively, showing a rapidly increasing trend (Middendorf and Metzner, 2011). The in-plane mechanical performance of textile composites made by the liquid moulding method (vacuum assisted resin transfer moulding (VARTM), resin transfer moulding (RTM) or resin film infusion (RFI)) is almost equal to those made by the prepreg method. However, the out-of-plane impact resistance of textile structural composites manufactured by the liquid moulding method is lower than that developed by the prepreg method. It should be noted that glass and aramid fibres have gained relatively limited use in the aerospace sector, due to the higher density and lower stiffness of glass fibre and the high moisture absorption of aramid fibre. Hence, the majority of composite parts used in the aerospace industry are produced using the preimpregnated carbon fibre fabric with thermoset matrices. Woven, knitted, DOS, braided and other textile structures have been used in the development of composite parts for aerospace applications, whereas the most used textile structure is DOS.

2.8.1 Woven structures

One example of using woven structures in the aerospace field was realized in Japan by Kawasaki Heavy Industries, where a 380 g/m^2 2 × 2 twill carbon fibre fabric using Tenax HTS 5631 12K yarn was fabricated with a special weaving technique. The prepreg developed using this fabric has found several applications, including the Embraer ERJ 170 inboard flaps, the Embraer ERJ190 outboard flaps and wing stubs and the Boeing 737−300 winglets (Fig. 2.47).

2.8.2 Knitted structures

An example of using knitted structures in developing aerospace composite parts was conducted at Daimler-Benz. Fig. 2.48 shows a stiffened panel which was manufactured with warp-knitted skin and 3D braided stiffeners stitched together to a complex preform. The fibre structure was subsequently impregnated in an RTM process by DLR in Braunschweig (Drechsler, 1999).

Figure 2.47 Boeing 737−300 winglet programme for Aviation Partners Boeing.
Adapted from Lowe, J., 2005. Aerospace applications. In: Long, A.C. (Ed.), Design and Manufacture of Textile Composites, Woodhead, Cambridge, pp. 405−423.

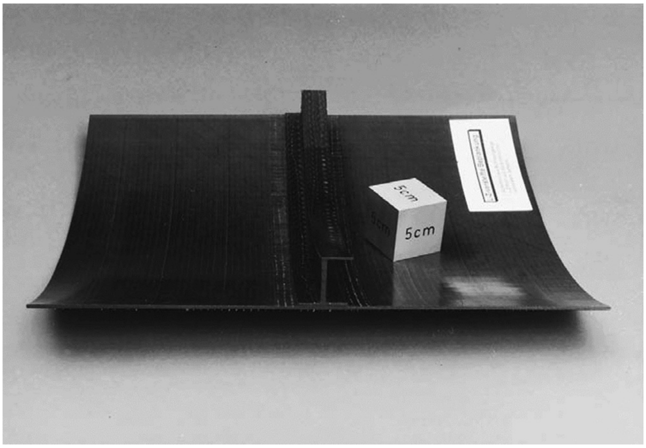


Figure 2.48 Stiffened panel consisting of braided profiles and warp-knitted skins.
Adapted from Drechsler, K., 1999. 3D textile reinforced composites for the transportation industry. In: Miravete, A. (Ed.), 3D Textile Reinforcements in Composite Materials, Woodhead, Cambridge, pp. 43−66.

2.8.3 Directionally oriented structures

DOS using 12K carbon fibre are the most commonly used structures in aerospace applications. There are two typical application examples: the Airbus A380 rear pressure bulkhead (RPB) and Airbus A400M cargo door (Middendorf and Metzner, 2011). The A380 RPB is produced at the Airbus plant in Stade, near Hamburg, using the preform made of multiaxial carbon fibre DOS supplied by Saertex. This preform is draped over a positive mould and then laminated using the RFI process (Fig. 2.49). After an initial curing of the 3 mm thick basic laminate and the attachment of stringers, the part is finally cured in an autoclave. The finished bulkhead weighs about 240 kg of size 6.2 m by 5.5 m (Middendorf and Metzner, 2011). The Airbus A400M cargo door consists largely of multiaxial carbon fibre DOS with additional monoaxial DOS fabric for local reinforcements and skin lay-up. The A400M cargo door is processed using the EADS/Premium Aerotec patented vacuum-assisted process (VAP) infusion technology (Fig. 2.50). The A400M cargo door is manufactured at the Premium Aerotec site, Augsburg. Besides the large-scale structures described above, there are some additional aerospace applications on the substructure level, such as the Airbus A380 flap track diaphragms, side shells and straps.

2.8.4 Braided structures

Large braiding machines have opened up interesting applications of braided structures in the aerospace industry. A&P developed a Vectron sock of 2 m in diameter and 3 m in length using an 800 carrier braiding machine (Potluri and Nawaz, 2011). Fig. 2.50 shows a prototype airlock developed for NASA using the braided sock developed by A&P (Fig. 2.51).

Figure 2.49 Draping of the DOS fabric in the Airbus A380 rear pressure bulkhead production.
Adapted from Middendorf, P., Metzner, C., 2011. Aerospace applications of non-crimp fabric composites. In: Lomov, S.V. (Ed.), Non-crimp Fabric Composites, Woodhead, Cambridge, pp. 441−448.

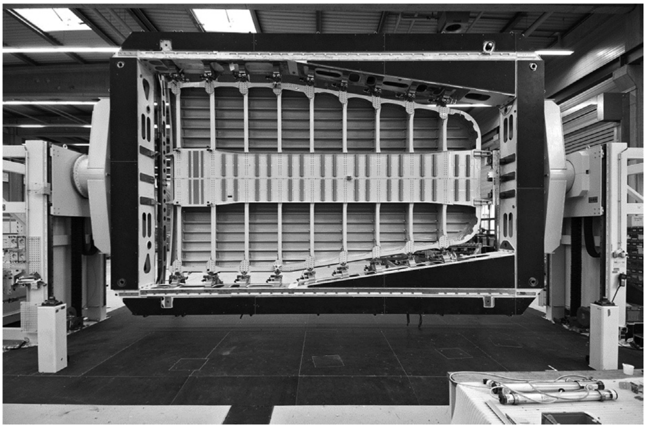


Figure 2.50 Airbus A400M cargo door manufactured at Premium Aerotec.
Adapted from Middendorf, P., Metzner, C., 2011. Aerospace applications of non-crimp fabric composites. In: Lomov, S.V. (Ed.), Non-crimp Fabric Composites, Woodhead, Cambridge, pp. 441−448.

2.8.5 Future applications

The current applications of textile structures in the aerospace industry are mainly based on 2D structures using prepreg technology because 2D textile reinforcements are stronger in-plane than 3D solid textile reinforcements. The out-of-plane impact

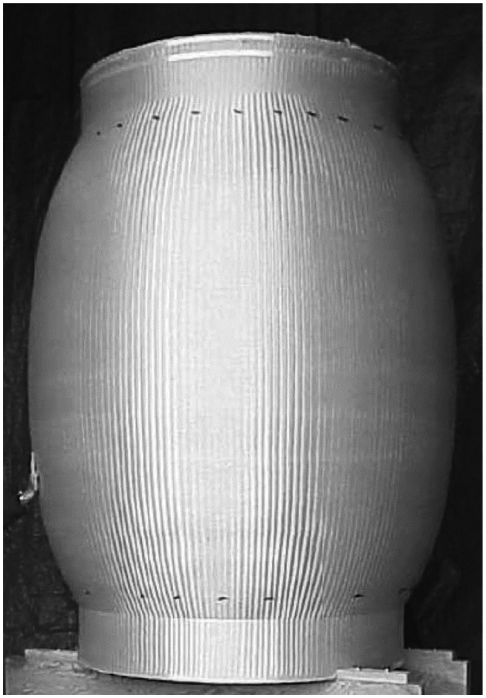


Figure 2.51 Braided airlock developed for NASA.
Adapted from Potluri, P., Nawaz, S., 2011. Developments in braided fabrics. In: Gong, R.H. (Ed.), Specialist Yarn and Fabric Structures, Woodhead, Cambridge, pp. 333–353.

resistance is another important load case consideration in the development of aerospace composite parts. 3D solid textile structures with yarns orientated in the thickness direction give the composite very strong out-of-plane properties. Hence, the use of 3D solid textile structures is beneficial for aerospace composite parts to avoid delamination and fractures. However, especially in parts such as stiffeners and stringers, not all loads are in-plane, making the prepreg laminates less suitable. It can be expected that in the near future, 3D solid woven, knitted and braided fibrous architectures will attract great attention in the aerospace industry.

2.9 Summary and concluding remarks

The various types of advanced fibrous architectures (woven, knitted, braided and others) that are used for producing composites for various applications in aerospace engineering were discussed. The various production techniques used for advanced fibrous architectures were described, and the properties, advantages and disadvantages and applications of the various products were analysed. It was concluded that warp-knitted DOS structures using 12K carbon fibre are the most commonly used structures in aerospace applications. It is expected that in the near future, 3D solid woven, knitted and braided fibrous architectures will attract great attention in the aerospace industry.

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