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3D Fabrics for Technical Textile Applications

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Abstract

Two dimensional (2D) woven, braided, knitted and nonwoven fabrics have been used for the fabrication of soft and rigid structural composite parts in various industrial areas. However, composite structure from biaxial layered fabrics is subject to delamination between layers due to the lack of through-the-thickness fibers. It also suffers from crimp which reduces the mechanical properties. Triaxial fabrics have an open structure and low fiber volume fraction. However, in-plane properties of triaxial fabrics are more homogeneous due to bias yarns. A 3D woven fabric has multiple layers and is free of delamination due to the z-fibers. However, 3D woven fabric has low in-plane properties. Three dimensional braided fabrics have multiple layers and they are without delamination due to intertwine type out-of-plane interlacement. However, they have low transverse properties. A 3D knitted fabric has low fiber volume fraction due to its looped structure. A 3D nonwoven fabric is composed of short fibers and is reinforced by stitching. However, it shows low mechanical properties due to lack of fiber continuity. Various unit cell based models on 3D woven, braided, knitted and nonwoven structures were developed to define the geometrical and mechanical properties of these structures. Most of the unit cell based models include micromechanics and numerical techniques.

Keywords: Fabric architecture, woven fabric, braided fabric, knitted fabric, 3D nonwoven fabric

1. Introduction

The objective of this chapter is to provide up-to-date information on the development of 2D and 3D fabric formation and formation techniques particularly on 2D and 3D nonwoven fabrics, methods, and properties of nonwoven web, including possible emerging application areas. Three-dimensional (3D) fiber structures produced by textile processes are used in various industrial applications since they have distinct properties when compared to conven-

tional materials. The most important application area of 3D textiles, by far, is composite industry, where they are used as reinforcement materials in combination with several matrices to make textile structural composites. These composites are used extensively in various fields such as civil engineering and military industry [1, 2], thanks to their exceptional mechanical properties and lower density in comparison with common engineering materials like metals and ceramics [3, 4]. Textile structural composites are also superior to conventional unidirectional composites when the delamination resistance and damage tolerance are taken into account [5]. Textile preforms are readily available, low-cost, and not labor intensive [1]. They can be manufactured by weaving, braiding, knitting, stitching, and by using nonwoven techniques. Each manufacturing technique has its own advantages and disadvantages in terms of specific composite properties and the selection can be made based on the end-use. The simplest form of 3D woven preforms is made up of two dimensional (2D) woven fabrics that are stacked one on top of another and stitched together in the thickness direction to impart through-the-thickness reinforcement. Three-dimensional weaving is another preform production technique that can be employed to manufacture 3D woven preforms by using specially designed automated looms. Near-net shape parts can be produced with this technique which substantially reduces the amount of scrap [6, 7]. In-plane properties of 3D woven composites are generally low due to through-the-thickness fiber reinforcement, despite of its positive effect on out-of-plane properties [8]. Simple 3D braided preform consists of 2D biaxial fabrics that are stitched together in the thickness direction depending on a chosen stacking sequence. Three-dimensional braiding is a preform technique used in the multidirectional near-net shape manufacturing of high damage tolerant structural composites [9, 10]. Three-dimensional braiding is highly automated and readily available. Three-dimensional braided preforms are fabricated by various techniques such as traditional maypole braiding (slotted horn gear matrix), novel 4-step and 2-step braiding (track and column) or more recently 3D rotary braiding and multi-step braiding [11, 12]. The fabrication of small sectional 3D braided preforms is low-cost, and not labor intensive [1]. However, the fabrication of large 3D braided preforms may not be feasible due to position displacement of the yarn carriers. Three-dimensional knitted preforms are fabricated by the 3D spatial formation of 2D warp or weft knitted fabrics in order to make near-net shape structures like spheres, cones, ellipsoids and T-pipe junctions. Three-dimensional knitted composites generally have low mechanical properties as a result of their characteristic looped architecture and low fiber volume fraction. A 3D nonwoven preform is a web or felt structure consisting of randomly positioned short fibers. There is no particular textile-type interlacing or intertwining between the fibers other than random entanglements. Through-the-thickness stitching of layered nonwoven webs is also possible. The most common methods for nonwoven production are needle-punching, stitch-bonding, high-frequency welding, chemical bonding, ultrasound and laminating. Recently, electrospinning method is utilized to make nonwoven nano web structure [13]. The entanglement type defines the fabric properties such as strength and modulus, flexibility, porosity and density [14]. Nonwoven fabrics and their composites display low mechanical properties due to fiber discontinuity. Multiaxis knitted preform comprises four fiber sets such as +bias, -bias, warp (0°) and weft (90°) along with stitching fibers which enhance in-plane properties [15]. Multiaxis knitted preform suffer from limitation in fiber architecture, through-

thickness reinforcement due to the thermoplastic stitching thread and three dimensional shaping during molding [3]. Multiaxis 3D woven preforms and their composites exhibit improved in-plane properties due to off-axis fiber positioning [16, 17].

In this chapter, 3D fabrics including 3D nonwoven for technical textile applications are reviewed in the light of the existing literature. First, the classification of textile fabric structures was introduced based on various classification schemes suggested by experts in the field. Types of textile fabric structures were explained under two main groups such as 2D and 3D fabrics. Various formation techniques including 2D and 3D nonwoven techniques were reviewed with regard to manufacturing processes and resulting fabric and composite properties. Applications of technical textiles in various industrial areas were covered with an emphasis on the future trends and technologies.

2. Classification of fabrics

Three-dimensional woven preforms are classified based on various parameters such as fiber type and formation, fiber orientation and interlacements and micro- and macro-unit cells. One of the general classification schemes has been proposed by Ko and Chou [3]. Another classification scheme regarding yarn interlacement and process type was proposed (Table 1) [18]. In this scheme, 3D woven preforms are subdivided into orthogonal and multiaxis fabrics, and their processes have been categorized as traditional or new weaving, and specially designed looms. Chen [19] categorized 3D woven preforms made by traditional weaving techniques based on their macro-geometry. According to this classification, 3D woven preforms are grouped as solid, hollow, shell, and nodal structures with varying architectures and shapes (Table 2). Bilisik [20] suggested a more precise classification of 3D woven preforms according to their interlacement types (fully interlaced woven/non-interlaced orthogonal), macro geometry (cartesian/polar) and reinforcement direction (2-15) (Table 3).

Non-interlacing Orthogonally Orientating and Binding	Type Uniaxial	Direct Binding	Modified 2D Weaving Machine	Thick Panel [21]
			Specially Designed Machine	Profiled Bar/Beam [22]
		Indirect Binding	Modified 2D Weaving Machine	Profiled Bar/Beam [23]
			Specially Designed Machines	Profiled Bar/Beam [24-26]
				Thick Tubular [27]
	Type Multiaxial	Direct Binding	Specially Designed Machine	Thick-Walled Tubular [28]
		Indirect Binding	Modified Warp Knitting Machine	Thin Panel [29]
			Specially Designed Machines	Thick Panel [30, 31]
				Thin Panel [32]

Table 1. Three-dimensional woven fabric classification based on non-interlace structuring [18].

Structure	Architecture	Shape
Solid	Multilayer; Orthogonal; Angle interlock	Compound structure with regular or tapered geometry
Hollow	Multilayer	Uneven surfaces, even surfaces, and tunnels on different levels in multi-directions
Shell	Single layer; Multilayer	Spherical shells and open box shells
Nodal	Multilayer; Orthogonal; Angle interlock	Tubular nodes and solid nodes

Table 2. Three-dimensional woven fabric classification based on macro-structure [19].

Direction	Three dimensional weaving			
	Woven		Orthogonal nonwoven	
	Cartesian	Polar	Cartesian	Polar
2 or 3	Angle interlock; Layer-to-layer; Through the thickness — Core structure	Tubular	Weft-insertion	Weft-winding and sewing
3	Plain and Plain laid-in — Twill and Twill laid-in — Satin and Satin laid-in	Plain and Plain laid-in — Twill and Twill laid-in — Satin and Satin laid-in	Open-lattice Solid	Tubular
4	Plain and Plain laid-in — Twill and Twill laid-in — Satin and Satin laid-in	Plain and Plain laid-in — Twill and Twill laid-in — Satin and Satin laid-in	Corner across Face across	Tubular
5	Plain and Plain laid-in — Twill and Twill laid-in — Satin and Satin laid-in	Plain and Plain laid-in — Twill and Twill laid-in — Satin and Satin laid-in	Solid	Tubular
6 to 15	Rectangular array — Hexagonal array	Rectangular array — Hexagonal array	Rectangular array — Hexagonal array	Rectangular array — Hexagonal array

Table 3. The classification of three-dimensional weaving based on interlacement and fiber axis [20].

Three-dimensional braided preforms are classified based on various parameters, including manufacturing technique, fiber type and orientation, interlacement patterns, micro-meso unit

cells and macro-geometry [10, 33]. Kamiya et al. [2] considered manufacturing techniques i.e., solid, 2-step, 4-step and multistep to classify 3D braided preforms. Grishanovi et al. [34] used a topological approach based on knot theory to describe and group braided structures whereby the braided fabric is considered as a multiknot structure. Bilisik [35] classified 3D braided structures as 3D braid, 3D axial braid, and multiaxis 3D braid, as shown in Table 4. These three categories were further divided according to their fiber directions (2-6) and geometry (cartesian/polar).

Number of Yarn Sets	Three Dimensional Braiding					
	3D Braid		3D Axial Braid		Multiaxis 3D Braid	
	Cartesian	Polar	Cartesian	Polar	Cartesian	Polar
1 or 2	Square ——————— Rectangular (Out-of-plane at an angle) 1×1 pattern 3×1 pattern	Tubular (Out-of-plane at an angle) 1×1 pattern 3×1 pattern			Rectangular (Out-of-plane at an angle)	Tubular (Out-of-plane at an angle)
3			Triaxial fabric (In-plane) Rectangular (Out-of-plane at an angle) 1×1pattern 3×1 pattern	Triaxial fabric (In-plane) Tubular (Out-of-plane at an angle) 1×1 pattern 3×1 pattern	Rectangular (Out-of-plane at an angle)	Tubular (Out-of-plane at an angle)
4					Rectangular (Out-of-plane at an angle)	Tubular (Out-of-plane at an angle)
5 or 6					Rectangular (Out-of-plane at an angle)	Tubular (Out-of-plane at an angle)

Table 4. The classification of 3D braiding based on interlacement and fiber axis [35].

Hamada et al. [36] classified 3D knitted structures based on engineering applications, as shown in Table 5. Type I fabrics are simple 2-D flat knitted fabrics. These fabrics can be cut to the required dimensions and laminated just as woven fabric composites. Two dimensional knitted fabrics with 3D shapes are categorized as Type II fabrics. Type III fabrics are multiaxial warp knitted fabrics. Type IV fabrics are called sandwich fabrics or 3D hollow fabrics. Type IV fabrics are sometimes called "2.5 D fabrics" and are very effective for the production of high damage-tolerant composites [37].

Type	Fabric classification	Weft knitted fabric	Warp knitted fabric
I	2D fabric	Plain, Milano rib, inlaid fabrics	Dembigh, Atlas
II	2D fabric base 3D shape	Plain, rib	Dembigh, Atlas
III	3D solid fabric	Plain and rib fabrics with inlay fiber yarns	Multiaxial warp knitted fabrics
IV	3D hollow fabric/sandwiched fabric	Single jersey face structure	Single Dembigh face structure

Table 5. Classification of typical warp and weft knitted fabrics [36].

Two- and three-dimensional nonwoven preforms are classified depending upon web bonding techniques, web structure, and fiber orientation (Table 6). The nonwoven structure is composed of short fibers that are held together by employing various techniques. The extent of fiber-fiber bonding is dependent upon fiber geometry, fiber tenacity and flexural rigidity, fiber location within the web, the areal mass of the web, etc. Mechanical, chemical or thermal methods can be utilized to achieve fiber-fiber bonding and thus create a continuous nonwoven web. Mechanical methods aim to commingle the fibers by an applied force (i.e., needling or water-jet) so that fiber-fiber entanglements occur in the web holding the structure together. In the chemical method, fiber surfaces are bonded together by using suitable binding agents, or the bonding is achieved by dissolving the fiber surfaces with a solvent followed by merging and solidification. Thermal bonding is generally used for thermoplastic fibers and powders. Fibers are melted by heat exposure, merged together, and solidified again by cooling [38]. Two- and three-dimensional nonwoven nano-web fabricated via electrospinning is a new development to make nanofiber-based nonwoven fabrics [39].

Nonwoven fabric	Web formation	Formation techniques	Web structure	Fiber orientation in web
		Needling	Plugs	In plane and out-of-plane fiber orientation
	Mechanical	Looping	Loops	Short fiber in plane and continuous fiber in the out-of-plane orientation
2D fabric 3D fabric		Entangling	Balls	In plane fiber placement and entanglement
	Thermal	Hot air; Calendaring; Welding	-	-
	Chemical	Impregnation; Spraying; Printing; Foaming	-	-

Nonwoven fabric	Web formation	Formation techniques	Web structure	Fiber orientation in web
	Electric field	Nanofiber entanglement under electric energy	nanofiber	In plane continuous nano fiber placement and entanglement

Table 6. Classification of nonwoven fabrics [38].

3. Types of fabrics

3.1. Two-dimensional fabrics

3.1.1. Woven fabric

The 2D woven fabric is the most widely used material in the composite industry. It contains two yarn sets i.e., warp (0°) and weft (90°), that lie perpendicular to each other in the fabric plane. Warp and weft yarns make a series of interlacements with one another according to a weave type and pattern to make the woven fabric. Basic weave types produced by traditional weaving are plain, twill and satin. Different fabric structures can be constructed from a weave type by changing the weave pattern. There are also derivative weave types that are created to obtain desired combinations of fabric properties. Some of the weave types are shown in Figure 1 [40]. In plain weave, each warp yarn passes alternately under and over each weft yarn. Hence, it is symmetrical and has a good dimensional stability. However, plain woven fabric has high crimp and is difficult to form during molding due to high number of interlacements for a given area. In twill weave, a warp yarn passes over and under two or more weft yarns based on a diagonal pattern. The twill woven fabric has a smoother surface in comparison with plain weave, simply because of multiple jumps between interlacements. It has also lower crimp. In addition, it has a good wettability and drapability. However, it shows less dimensional stability compared to the plain weave. In satin weave, warp yarns alternately weave over and under two or more weft yarns to make fewer intersections. Therefore, it has a smooth surface, good wettability and a high degree of drapability. It has also low crimp. However, it has low stability and an asymmetrical structure. Another 2D woven architecture is leno weave in which adjacent warp yarn is twisted around consecutive weft yarn. One of the derivatives of the leno weave is mock leno in which occasional warp deviate from the alternate under-over interlacing and interlaces every two or more weft. This results in a thick and rough surface with high porosity [41-43].

Two dimensional woven fabric composites show poor impact resistance as a consequence of fabric crimp. They also have low in-plane shear properties due to absence of off-axis fiber orientation other than material principle directions [4]. Another major problem of these composites is that they experience delamination under load due to lack of through-the-thickness binder yarns (z-yarns). Through-the-thickness reinforcement eliminates the delamination problem, but it reduces the in-plane properties [1, 2]. Biaxial noncrimped fabric was
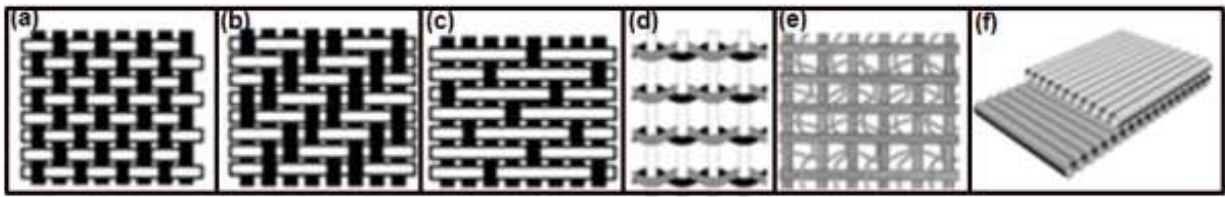
Figure 1. Two dimensional various woven fabrics (a) uniform plain (b) twill (2/2) (c) satin (4/1) (d) leno (1/1), and (e) non-interlace woven fabric with stitching (f) non-interlace woven fabric without stitching yarn [41-43].

developed to replace the unidirectional cross-ply laminate [42]. This fabric has warp ($0°$ direction) and filling yarns ($90°$ direction) as separate layers so that there is no interlacement between them, unlike traditional woven fabrics. Warp and weft layers are linked at intersection points by two sets of stitching yarns, one in $0°$ direction and another in $90°$ direction, as shown in Figure 1. Biaxial noncrimped fabrics largely eliminate the crimp and delamination problems of 2D woven composites.

3.1.2. Triaxial woven fabric

Triaxial weave structure consists of three yarn sets such as +bias (+warp), -bias (-warp), and filling [44]. These yarn sets make interlacements as in traditional biaxial fabric (Figure 2). The fabric generally has large hexagonal openings between interlacements. Open-reed process used in the fabrication of this type of fabric does not allow making fabrics as dense as a traditional woven fabric. Triaxial fabrics have two variants, namely, loose-weave and tight-weave. It was shown that loose-weave fabric has certain stability and higher shear stiffness in ±45° directions when compared to the biaxial fabrics as well as having a more isotropic structure. Quart-axial fabric has four sets of yarns such as +bias, -bias, warp and filling as shown in Figure 2. All yarns are interlaced to each other to form the fabric structure [45]. Warp yarns are inserted to the fabric at selected places to increase directional strength and stiffness properties. Therefore the fabric structure can be tailored to fulfill various end-use requirements.
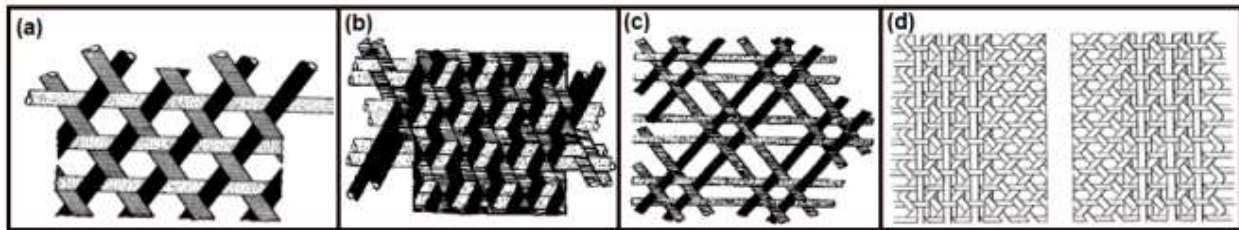

Figure 2. Triaxial woven fabrics (a) loose fabric (b) tight fabric (c) one variant of triaxial woven fabric, and (d) quart-axial woven fabric [44, 45].

3.1.3. Braided fabric

Two-dimensional braided fabrics are extensively used in industrial textiles and composites. It has one yarn set, braiders oriented in +θ and −θ directions. In order to produce the fabric

surface shown in Figure 3, braiders are intertwined with each other. Basic braid patterns that can be produced by traditional methods are diamond, regular and hercules braid [46]. The 2D braided fabric reinforced composite fabrication is similar to that of 2D woven composites. Multiple braided fabrics can be stacked one on top of another to produce reinforced composites. These composites suffer from yarn crimp and lack through-the-thickness reinforcement (z-yarns) and thus experience delamination leading to a poor impact behavior [4]. In order to overcome the delamination and related problems, 2D fabric layers can be stitched together in the thickness direction to impart out of plane fiber reinforcement. Stitching was shown to substantially decrease delamination but it can lead to a reduction in in-plane properties due to the holes created by stitching needle which act as stress concentration points.
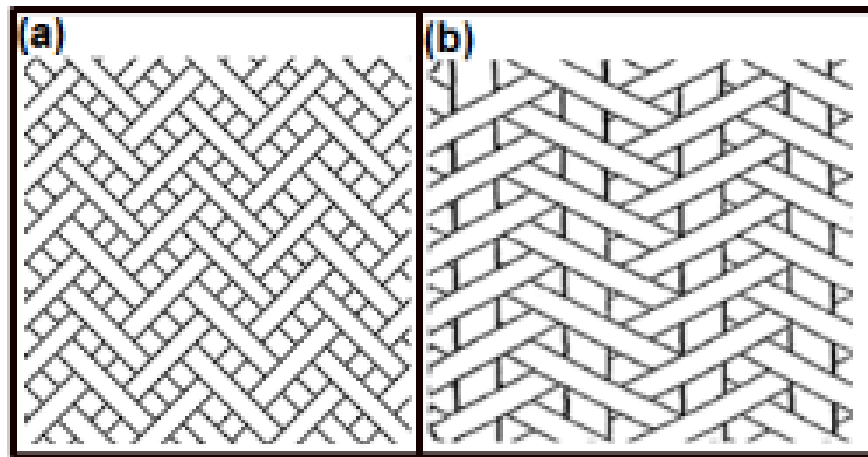
Figure 3. (a) Two-dimensional traditional biaxial braided fabric, and (b) triaxial braided fabric [47].

3.1.4. Triaxial braided fabric

Triaxial braided fabric has basically three sets of yarns: +braid (+bias), -braid (-bias), and warp (axial). Axial yarns lie across the fabric whereas braided yarns intertwine with each other around the axial yarns making about 45° angle (Figure 3). The intertwining is similar to that of a traditional braided fabric. –Braided yarns cross under and over the +braided yarns according to a pattern and this process is repeated throughout the fabric structure. Triaxial braided fabric generally has large openings between the axial yarns, intertwining regions. Although dense fabrics can be produced, the process is not suitable for the fabrication of fabrics as dense as a traditional biaxial braided fabric. It was shown that the mechanical properties of triaxial fabric are significantly higher than biaxial braided fabrics, especially in the direction of axial yarns [47]. This shows that the incorporation of axial yarns strongly enhances the directional properties of the fabric.

3.1.5. Knitted fabric

Knitted fabric is composed of yarn loops connected to each other and to the neighboring rows and columns by various techniques. This process is also called "interloping." The basic knitting

types are weft knitting and warp knitting. In weft knitting, a continuous yarn forms one horizontal row of loops called a "course" connecting it to the previously formed courses in the process (Figure 4). The vertical columns of loops are called "wale." In warp knitting, yarn loops are connected vertically to form the fabric structure. Knitted fabrics are characterized by their 'wale density' and 'course density.' The wale density is defined as the number of wales per unit length in the course direction. The course density is defined as the number of courses per unit length in the wale direction. Stitch density is the product of course density and wale density [36, 48].
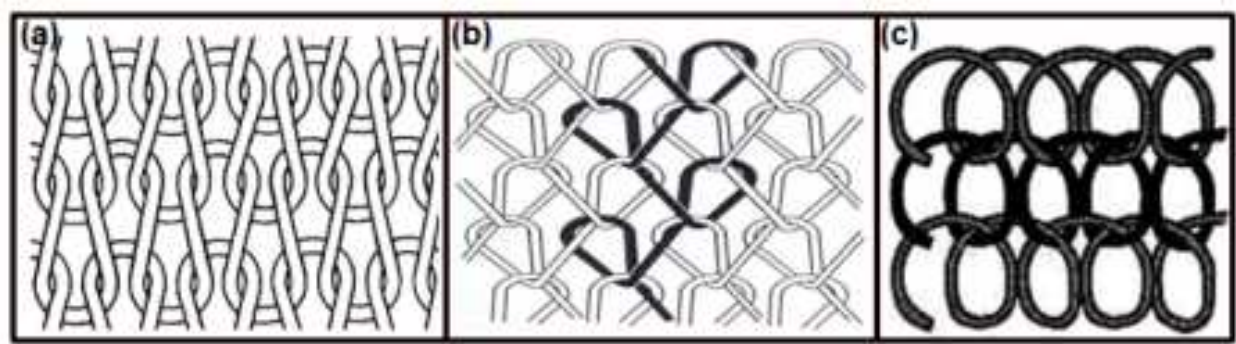
Figure 4. (a) Two-dimensional weft knitted fabric (b) warp knitted fabric, and (c) spiral knitted fabric [36].

3.1.6. Uniaxial knitted fabric

The special looped structure of knitted fabrics results in large gaps in the fabric structure. This reduces the overall fiber volume fraction of the composite leading to low mechanical proper‐ ties. Furthermore, the fabric is loosely formed unlike a woven fabric, which leads to high elongation and low stiffness. These problems have led to structural modifications of knitted fabrics by using inlay yarns either in fabric length or width direction to increase the mechanical properties of the resulting composites. Figure 5 presents the schematic views of these modifi‐ cations. The inlay yarns are trapped inside the knitted loops during the fabric formation. It was shown that the tensile strength of uniaxial knitted fabric composites can be improved significantly in the inlaid directions [49].
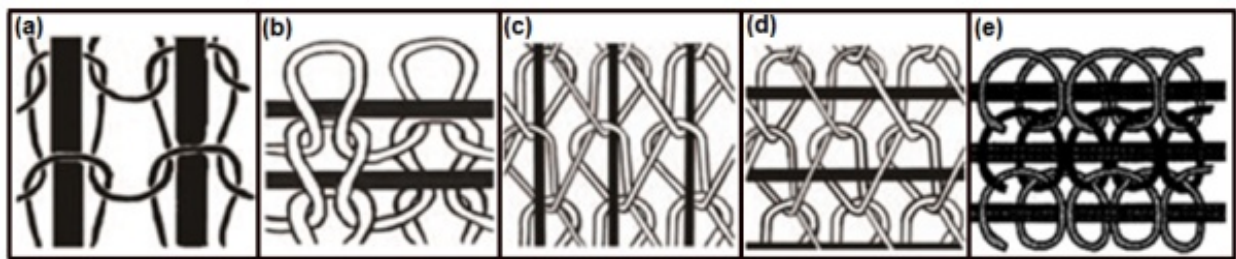

Figure 5. (a) Two-dimensional warp in-laid weft knitted fabric (b) 2D weft in-laid weft knitted fabric (c) 2D warp in-laid warp knitted fabric (d) 2D weft in-laid warp knitted fabric, and (e) 2D weft in-laid spiral knitted fabric [49].

3.1.7. Biaxial knitted fabric

Biaxial knitted structures were developed by the insertion of warp (0°), weft (90°) or diagonal (±45°) yarns to the weft or warp knitted fabrics, as shown in Figure 6. The in-laid yarns improve the directional mechanical properties of the resulting composites.
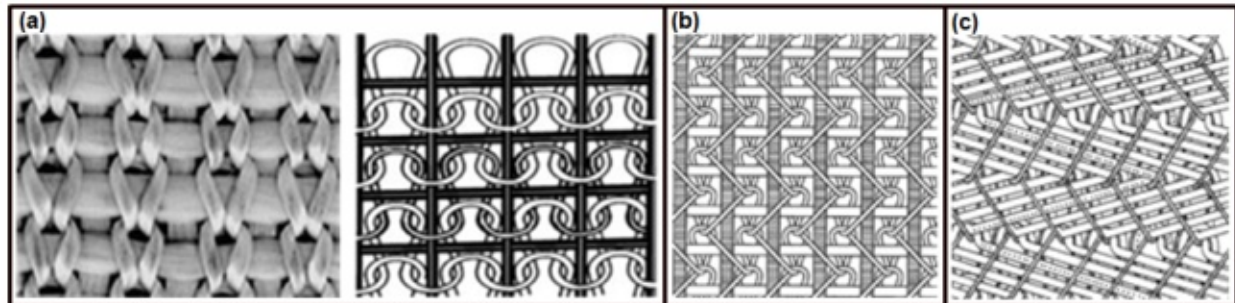

Figure 6. (a) Two-dimensional weft in-laid 0°/90° knitted fabric and schematic view (b) warp in-laid 0°/90° knitted fabric, and (c) warp in-laid ±45° knitted fabric [50-52].

3.1.8. Nonwoven fabric

Nonwoven fabric is a web structure made up of short fibers that are held together by various techniques. These techniques include needling, knitting, stitching, thermal bonding, chemical bonding, and electrospinning. Needling is a method where vertically positioned barbed needles or water jets strike into the fiber web so as to entangle the fibers and create a mechanical locking between them. Knitting aims to entrap the fibers and fix them in position with the aid of knitting loops. In stitching technique, the fiber web is stitched in through-the-thickness direction. Thermal bonding is generally applied to thermoplastic fibers and powders. Fiber web is subjected to heat treatment which softens and unifies the neighboring fiber surfaces. This process is followed by cooling that solidifies the fibers and gives the web its final form. In the chemical process, polymer dispersions are used as binders to consolidate the nonwoven fabric. In electrospinning method, polymer solution is drawn under high electric energy field by using needles. Various fibers can be used to make nonwoven nano fibers such as polyurethane, polyvinyl alcohol and carbon. The nonwoven produced from these fibers can provide interesting physical and electrical properties with their high surface area. Nanofibers with diameters in the range of 40-2000 nm (0.04-2 μm) can be made. Fiber diameters can be varied and controlled [53-55]. Figure 7 shows the schematic and real views of 2D nonwoven fabrics manufactured by various methods [56, 57].
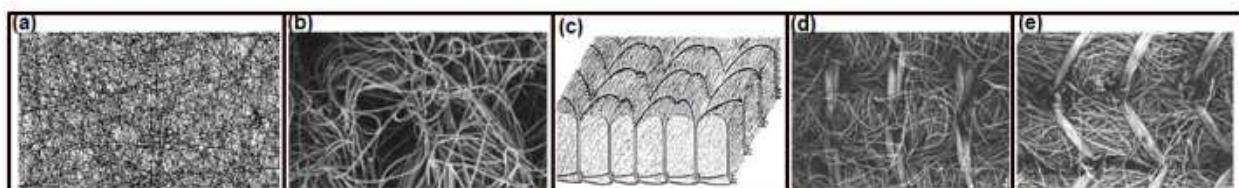

Figure 7. Schematic view of 2D nonwoven fabric by (a) mechanical needling (b) hydroentanglement (c) schematic view of stitched nonwoven structure (d) knitting loop surface, and (e) knitting loop reverse surface [58].

3.2. Three-dimensional fabrics

3.2.1. Non-interlaced fabric structures

Non-interlaced fabrics consist of multiple fiber layers that are stacked one on top of another. There is no interlacement between these layers so the fibers lie across the structure without crimping. This is an obvious advantage for in-plane properties since the fibers are well oriented in in-plane directions. Out-of-plane properties, however, are poor due to lack of through-the-thickness fibers (z-fibers). If the fabric has one set of yarn oriented in 0° direction it is referred to as uniaxial non-interlaced fabric preform. Biaxial non-interlaced fabric preform consists of two fiber sets oriented at 0/90°. A multiaxis non-interlaced fabric preform has four fiber sets oriented in 0/90/±45° directions (Figure 8) [43].

Figure 8. (a) Unidirectional non-interlaced fabric schematic and fabric (b) biaxial non-interlaced fabric schematic and fabric, and (c) multiaxis non-interlaced fabric schematic and fabric [43].

3.2.2. Multistitched fabric structures

A multistitched fabric preform is produced by stitching 2D fabric layers in thickness direction. Stitching can be applied (i) only in 0° direction, (ii) 0° and 90° directions, and (iii) 0°, 90° and ±bias directions as shown in Figure 9. Lockstitch is commonly used for pre-form production. Stitching can be done manually or with the aid of a stitching machine. Stitching can be applied to all fabric types such as woven fabrics, braided fabrics, knitted fabrics, or nonwoven fabrics [59].
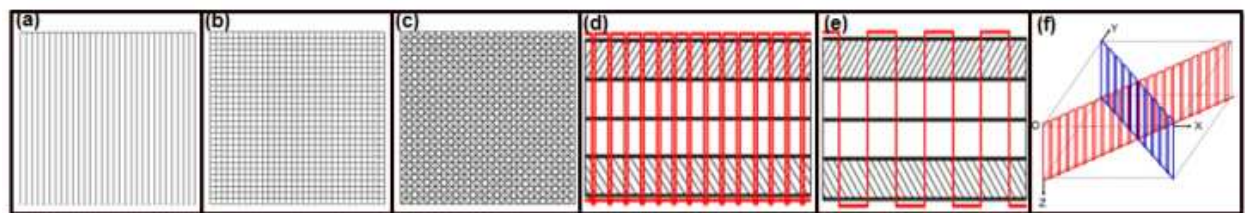

Figure 9. Schematic views of multistitched 2D woven fabric. Stitching directions (a) one direction (b) two direction (c) four direction; cross-sectional view of four directionally machine and hand stitched structures on (d) 0°, (e) 90°, (f) +45°, and -45° [59].

3.2.3. Fully interlaced woven fabric structure

The 3D flat fully interlaced woven fabric structure consists of three yarn sets such as warp, weft and z-yarn. The weaving process takes place in in-plane and out-of-plane directions according to respective weave patterns. Warp yarns are interlaced with weft yarns at each

layer according to the weave pattern in in-plane principal directions, whereas z-yarns are interlaced with warp yarns at each layer according to the weave pattern in out-of-plane principal directions. Three dimensional fully plain, 3D fully twill and 3D fully satin preform structures are shown in Figure 10. If the warp and weft yarn sets are interlaced based on any weave pattern but the z-yarns are not interlaced and only laid-in orthogonally between each warp layers, these 3D woven structures are called semi-interlaced woven structures.

The 3D circular fully interlaced woven fabric structure is composed of three yarn sets such as axial (warp), circumferential (weft) and radial (z-yarn) yarns. Here, radial yarns are similar to z-yarns in flat woven fabrics. Circumferential yarns are interlaced with axial yarns at each circular layer according to the weave pattern in circumferential direction, whereas radial yarns are interlaced with axial yarns at each layer according to the weave pattern in radial directions. Figure 11 shows the 3D fully plain, 3D fully twill and 3D fully satin circular woven preform structures [60, 61].
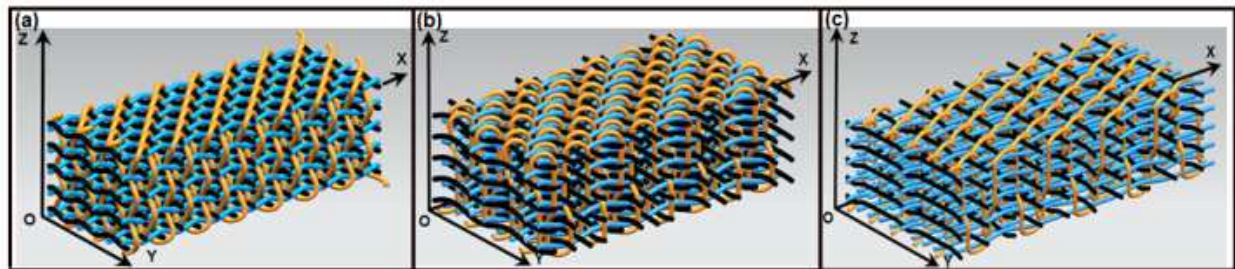

Figure 10. Three-dimensional fully-interlaced woven preform structures. General view of the five-layer computer-aided drawing of (a) 3D plain (b) 3D twill, and (c) 3D satin woven preform structures [60].
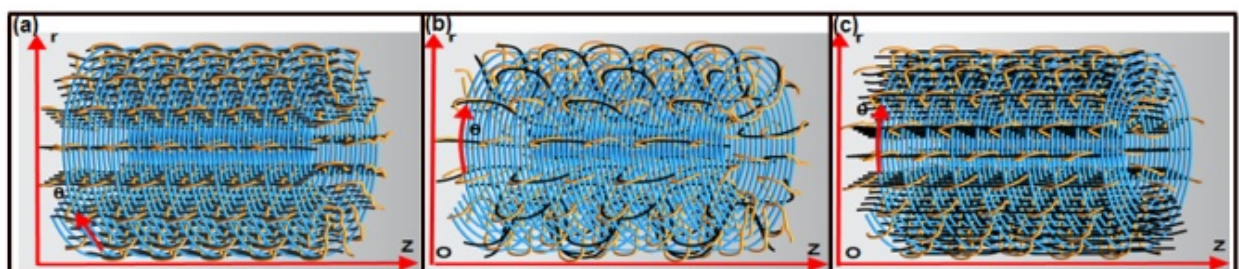

Figure 11. Three-dimensional fully-interlaced circular woven preform structures. General view of the five-layer computer-aided drawing of (a) 3D plain (b) 3D twill, and (c) 3D satin circular woven preform structures [61].

3.2.4. Orthogonal woven fabric

In orthogonal woven fabric, warp, filling, and z-yarn sets constitute the fabric. They are interlaced to one another and oriented in three orthogonal directions to form the fabric [60]. The schematic and real views of fabric unit cell are shown in Figure 12 [60, 62]. Warp yarns are placed in the fabric length direction whereas filling yarns are inserted between the warp

layers to form double picks. Z-yarns lock the other two yarn sets and provide structural integrity.
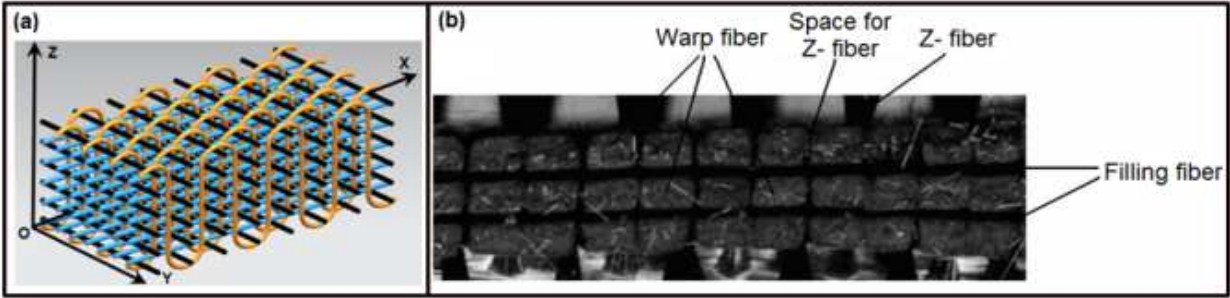

Figure 12. (a) Schematic view of 3D orthogonal woven unit cell (b) 3D woven carbon fabric preform [60, 62].

The 3D angle interlock is another type of 3D woven fabric that is produced by 3D weaving loom [63]. The fabric has a total of four yarn sets namely filling yarns, +bias yarns, -bias yarn, and stuffer (warp) yarns. Bias yarns are oriented in the thickness direction. There are two types of this fabric structure such as layer-to-layer and through-the-thickness as shown in Figure 13. In layer-to-layer fabric, bias yarns travel between two successive fabric layers making interlacements with several filling yarns according to the weave pattern. In through-the-thickness fabric, on the other hand, bias yarns take a straight path along the fabric thickness until reaching to the top or bottom surface and then reverse its movement to make the same travel until reaching the other surface (Figure 13). This zig-zag movement continues across the fabric length. Bias yarns are locked by several filling yarns in the process depending upon the number of layers [60].
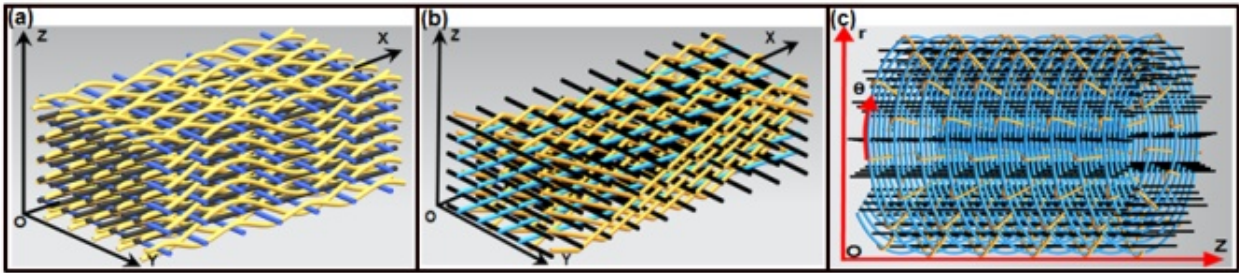

Figure 13. General view of the five-layer computer aided drawing of traditional (a) 3D angle interlock (b) 3D through-the-thickness, and (c) 3D circular orthogonal woven preform structures [60, 61].

Three-dimensional circular weaving (i.e., 3D polar weaving) and fabric was developed [64]. The preform has mainly three sets of yarns such as axial, radial and circumferential as shown in Figure 13. In addition, central yarns are inserted to form the rod. Circumferential yarns are laid between adjacent axial yarn layers, whereas radial yarns are inserted between adjacent axial yarn layers in radial direction.

3.2.5. Multiaxis woven fabric

Multiaxis 3D woven fabric, method and machine based on lappet weaving principals were developed by Ruzand and Guenot [65]. The fabric is composed of four yarn sets i.e., +bias, -bias, warp, and filling. Bias yarns are oriented across the fabric width. They are placed on the top and bottom surfaces of the fabric and are kept in place by selected weft yarns that are interlaced with warp yarns. Other warp and weft yarns are interlaced together forming the middle layers of the structure.

Uchida et al. [66] developed a five-axis 3D woven fabric. This fabric is composed of five yarn sets such as +bias, -bias, filling, warp, and z-yarn. The fabric is made up of four layers and sequences i.e., +bias, –bias, warp and filling from top to bottom. All the layers are fixed by z-yarns. Mohamed and Bilisik [30] developed a multiaxis 3D woven fabric, method and machine. The fabric is made up of five yarn sets such as +bias, -bias, warp, filling, and z-yarn. ±Bias yarns are placed on the front and back face of the structure. These yarns are locked to the other yarn sets by the z-yarns (Figure 14). Many of the warp yarns, on the other hand, lay at the center of the preform. This structure can enhance the in-plane properties of the resulting composites.
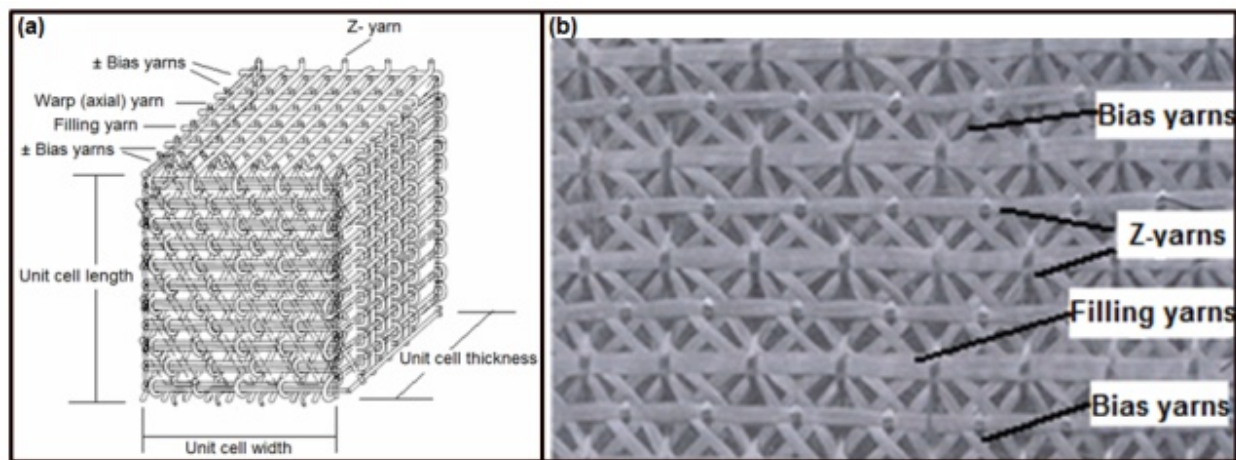

Figure 14. (a) The unit cell of multiaxis fabric (b) Top surface of multiaxis small tow size carbon fabric [30, 67].

Bilisik [28] developed a multiaxis 3D circular woven fabric, method and machine. The schematic view of the preform is shown in Figure 15 together with a real aramid preform structure. The 3D circular woven fabric consists of axial and radial yarns along with circumferential and ±bias layers. The axial yarns (warp) are arranged in radial rows and circumferential layers within the required cross-sectional shape. ±Bias yarns are placed at the outside and the inside ring of the cylinder surface. Filling (circumferential) yarns lay between each helical corridor of warp yarns. Radial yarns (z-fiber) were locked to the all yarn sets to form the cylindrical 3D preform. Cylindrical preform can be made with thin and thick wall sections depending upon end-use requirements.
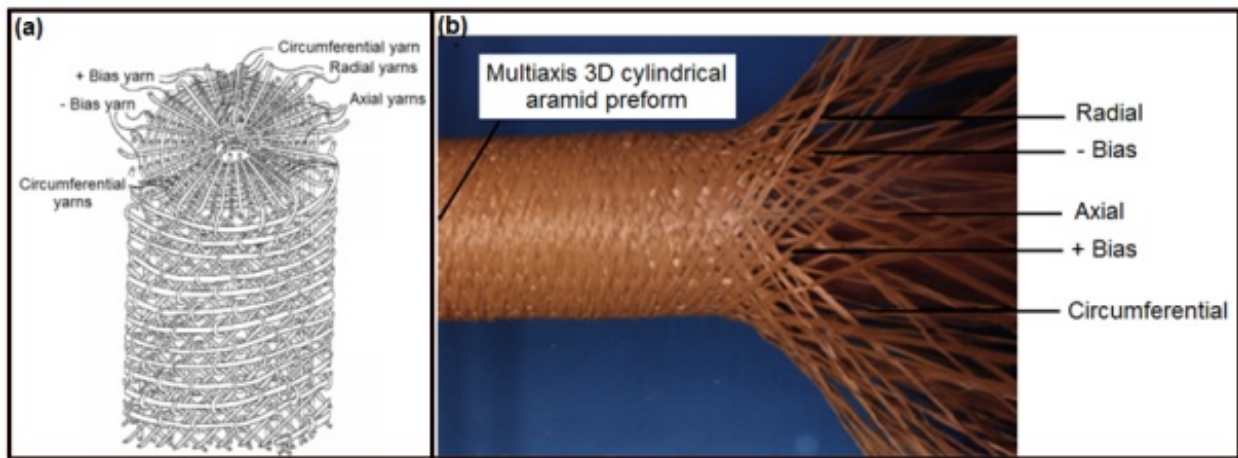
Figure 15. (a) The unit cell of multiaxis 3D circular woven fabric (b) Multiaxis 3D aramid circular woven fabric [28, 68].

3.2.6. Three-dimensional fully braided fabric

Florentine developed a 3D braided preform and a method [69]. The preform is layered and yarns are intertwined with each other according to a predetermined path. Yarn travels through the thickness of the fabric and is biased such that the width of the fabric is at an angle between 10° and 70°. The representative and the schematic views of the 3D braided preform with yarn paths are shown in Figure 16.
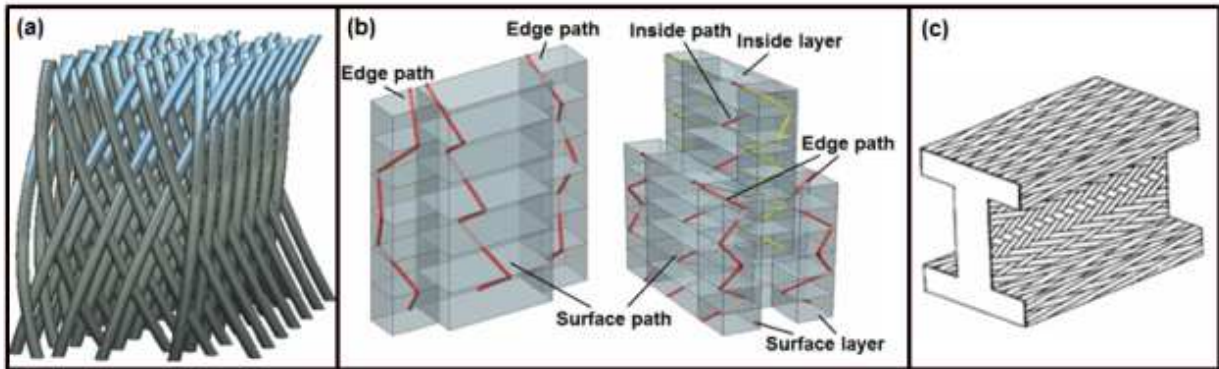

Figure 16. (a) Unit cell of 3D braided preform (b) braider yarn path on the edge and inside of the 3D representative braided preform with 4 layers (left) and 6 layers (right) [70], and (c) schematic views of 3D braided I-beam preform [71].

Tsuzuki [71] developed various 3D sectional braided preform in which four yarn carriers can surround a rotor and move in four diagonal directions. The addition and subtraction of braider yarns allow the making of various fabric geometries such as I-beam, H-beam, TT-beam etc.

3.2.7. Three-dimensional axial braided fabric

The 3D circular axial braided preform can be manufactured by maypole technique which requires two yarn sets such as warp (axial) and braider yarns. The axial yarns are fixed and

the braiders intertwine with axial yarns by making radial movements along circumferential paths. This allows more flexibility in the preform size, shape and microstructure. This type of braided structure is also called "solid braided fabric," as shown in Figure 17 [72].
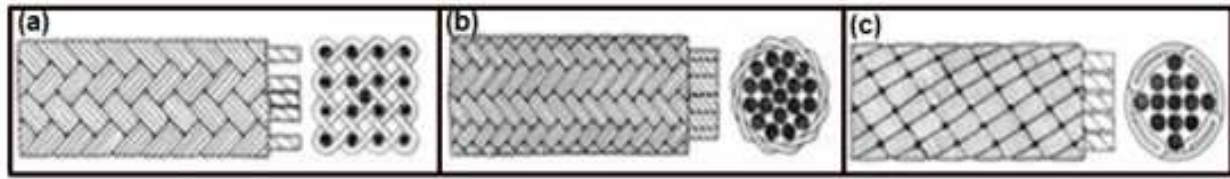

Figure 17. Solid braid fabrics (a) 4×4 axial braided fabric (b) axial round core braided fabric, and (c) axial spiral core braided fabric [72].

A tubular fabric with a helical structure was developed by Brookstein et al. [73]. This fabric is made up of warp (axial) yarns and braiders (±bias yarns) (Figure 18). Each axial yarn is held in place by braiders through an intertwine-type pattern. It is well suited to produce thick tubular structures and also has a potential for other geometries with a mandrel. Another 3D braided preform in a 1×1 braid pattern was developed. The braider carrier and the axial yarns are arranged in a matrix of rows and columns. The braider yarns are intertwined around each axial yarn row and column to the through-the-thickness direction as shown in Figure 18. McConnell and Popper developed a 3D axial braided fabric with a layered structure [74]. The fabric consists of axial and braider yarns. Axial yarns are positioned with regard to a pre-determined cross-section whereas braider yarns travel through the gaps between axial yarns in the row and column directions. In this way, the braided yarns are intertwined to make a bias orientation through the thickness and on the surface of the structure.
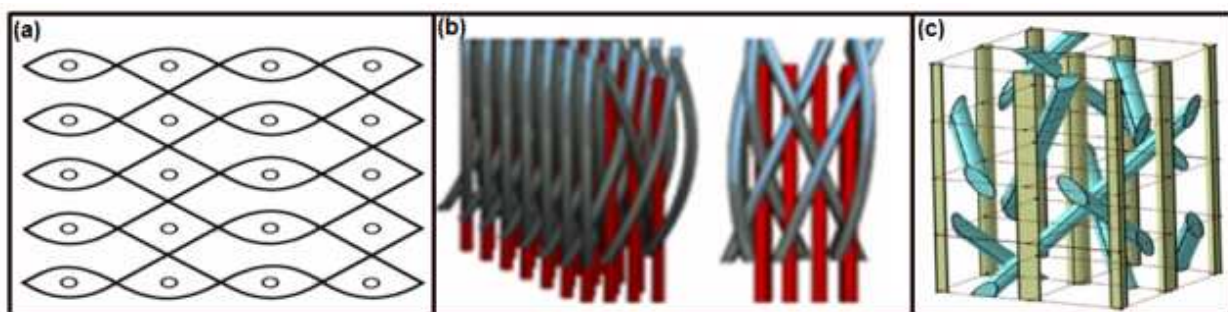

Figure 18. (a) Unit cell of the 3D braided preform [73], (b) 3D axial braided preform and unit cell [75], (c) schematic view of 3D axial braided preform [76].

3.2.8. Multiaxis 3D braided fabric

Multiaxial 3D braided structure is shown schematically in Figure 19. This fabric is constituted from ±braider yarns, warp (axial), filling, and z-yarns. The braider yarns are intertwined with the orthogonal yarn sets to form the multiaxis 3D braided preform. This preform structure has enhanced properties especially in transverse direction. Moreover, it has identical directional

Poisson's ratios throughout its structure [77]. Another multiaxial 3D braided structure has ±bias yarns placed in-plane, and warp (axial), radial (z-yarns), and ±braider yarns placed out-of-plane [78]. The braider yarns are intertwined with the axial yarns whereas ±bias yarns are oriented at the surface of the structure and locked by the radial yarns to the other yarn sets. Figure 19 shows the multiaxial cylindrical and conical para-aramid 3D braided structures. The properties of the multiaxial 3D braided structure in the transverse direction can be enhanced and the non-uniformity in the directional Poisson's ratios can be decreased [78].
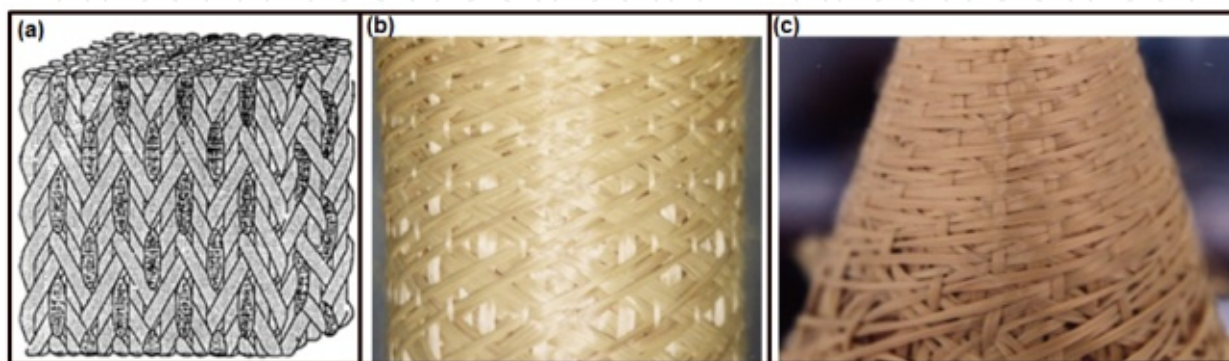

Figure 19. (a) The unit cell of multiaxis 3D braided preform [77]; multiaxis 3D braided para-aramid preforms (b) cylindrical Kevlar® preform and (c) conic Kevlar® preform [78].

3.2.9. Three-dimensional knitted fabric

Wunner [32] developed a multiaxis warp knit machine for Liba GmbH. The machine uses a total of four yarn sets such as ±bias, warp and filling. These yarn sets are placed as separate layers and these layers are locked by stitching yarn by using tricot pattern, as shown in Figure 20.
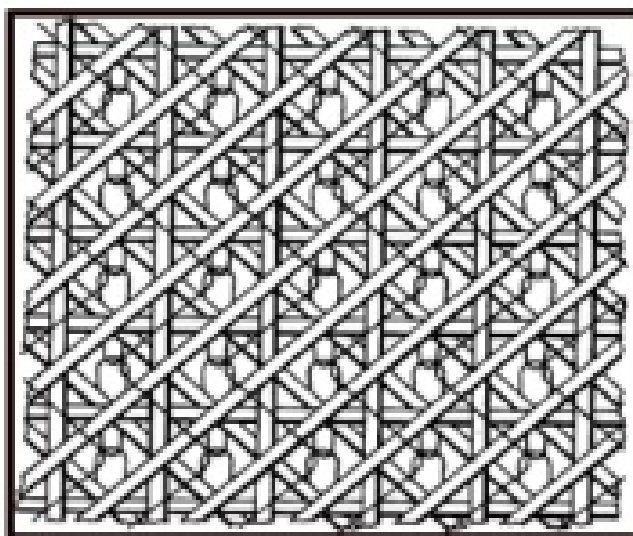

Figure 20. Multiaxis warp knit structure [32].

3.2.10. Three-dimensional knitted spacer or sandwiched structure

The 3D knitted spacer fabric consists of two separate fabric layers (top and bottom surfaces) that are connected by intermediary yarns or knitted layers [79]. The top and bottom fabrics can be weft or warp knitted fabrics with or without inlays. Three-dimensional spacer fabrics are renowned for their excellent resilience and air permeability properties. Figure 21 shows schematic and real views of various 3D knitted sandwich fabrics.
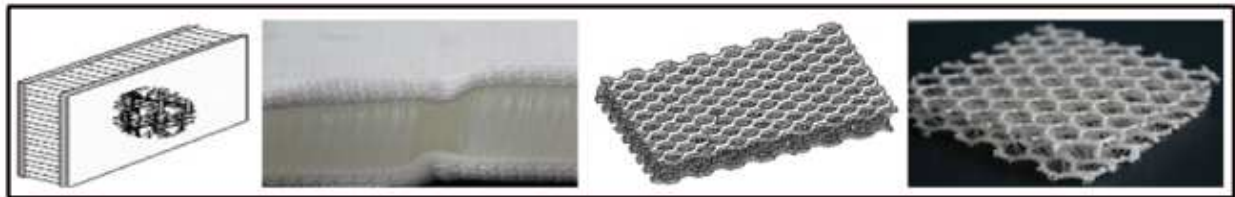

Figure 21. Various developed actual and schematic 3D knitted sandwich or spacer fabrics [79].

3.2.11. Three-dimensional nonwoven fabric

Multiple layers of 2D nonwoven webs are stacked and stitched together in thickness direction to obtain 3D nonwoven fabric. Stitching yarn provides through-the-thickness reinforcement in an effort to impart out-of-plane structural integrity and reduce delamination failures. Olry developed a method called "Noveltex" for 3D nonwoven preform fabrication [80]. This method uses needle punching as a means of fiber entanglement. A 3D nonwoven preform was developed using hydroentanglement method to create through-thickness fiber insertion. Biaxially reinforced nonwoven fabric is another type of 3D nonwoven preforms that is manufactured by employing warp knitting technology. The preform consists of warp and weft yarns along with a fiber web. Warp and weft yarns can be thought of as inlays such that they are laid in fabric structure as separate layers without any interlacements. Warp yarns, weft yarns and fiber web are all connected by stitching yarns to form an integrated structure as shown in Figure 22 [81]. Geogrid structures can be considered as a special type of nonwoven fabric. They can be classified based on their shape such as uniaxial, biaxial and triaxial geogrid structures used in wall, slope and road applications; and manufacturing methods such as punched and drawn geogrids, coated yarn geogrid and laser welded geogrids. The basic functions of geogrid structures are to interlock the aggregates, to redistribute the load over wider area to reduce the vertical stress, and to provide lateral restraint, improved bearing capacity, and tension membrane effect [82].
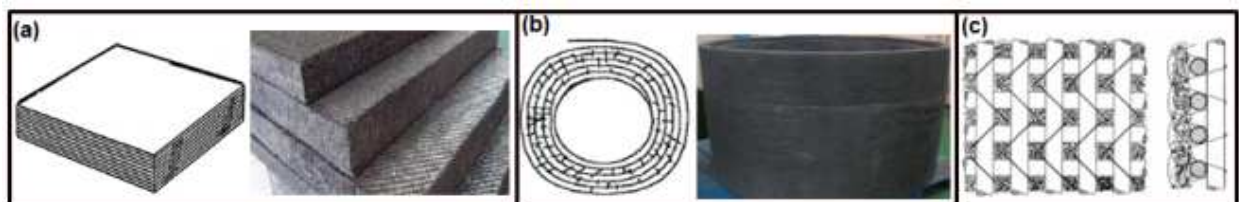

Figure 22. Three-dimensional nonwoven fabric; (a) schematic view of flat 3D nonwoven preform (left) and 3D PAN-based graphite felt composite (right); (b) schematic view of circular 3D nonwoven preform (left) and 3D PAN-based graphite felt composite (right); (c) top and side views of 3D biaxially reinforced nonwoven preform [80, 81, 83].

4. Fabrication of fabrics

4.1. Weaving

4.1.1. Two-dimensional weaving

The 2D woven fabric is the most widely used material in the composite industry with a share of about 70%. Traditional weaving machine (Figure 23) is used to manufacture the fabric [4, 84]. This machine is constituted of several units such as warp let-off, fabric take-up, shedding, weft insertion and beat-up. Recently, traditional weaving machine was modified to weave high modulus fibers such as carbon, E-glass, S-glass, and para-aramid. The machine is capable of weaving a range of fabric types and patterns including plain, twill, satin, and leno. It is also possible to fabricate hybrid fabrics by incorporating different fiber types in warp or weft yarns. Another approach is to use warp and weft yarns consisting of different types of fibers [4].
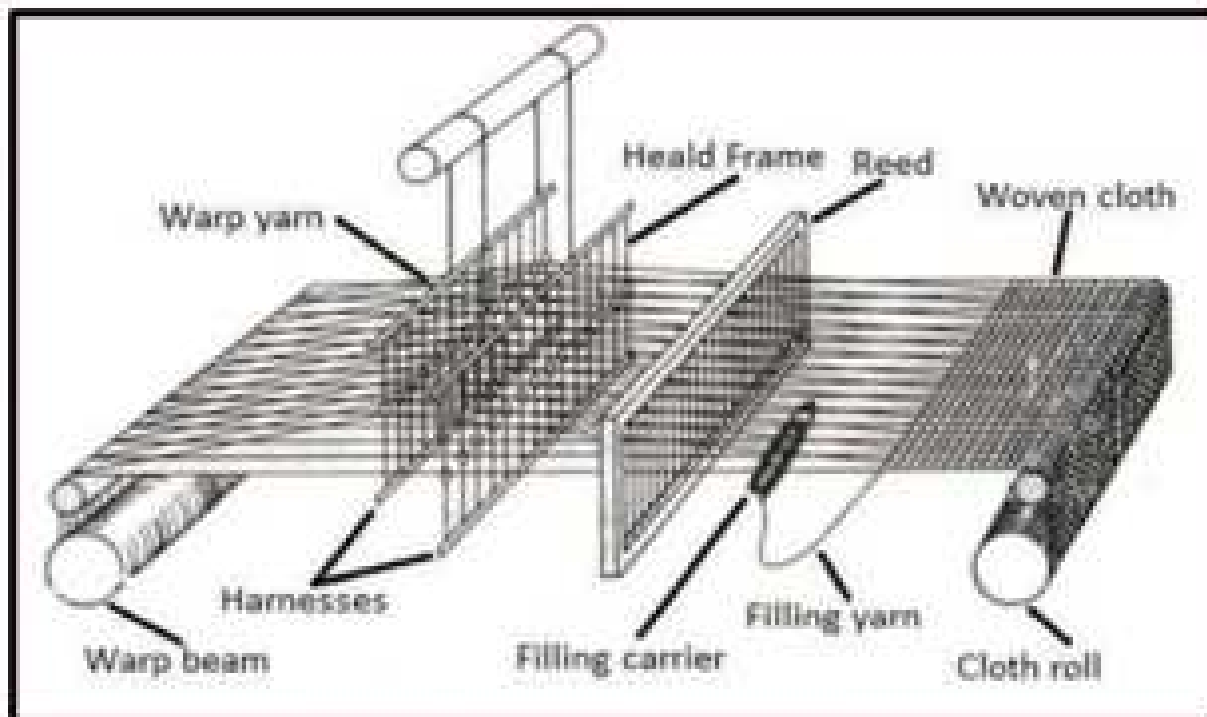
Figure 23. Schematic view of 2D weaving and shedding unit [4, 84].

4.1.2. Triaxial weaving

Triaxial weaving machine consists of multiple ±warp beams, filling insertion, open beat-up, rotating heddle and take-up unit, as shown in Figure 24. Warp beams are located above the machine. ±Warp yarns unwind from these beams and head to a separation unit where the warp yarns from each beam are separated into two layers. Then these layers are fed vertically into

the interlacing zone. The front layer is directed to the right, whereas the rear layer heads to the left. The directions are reversed after the outmost warp end reaches the edge of the fabric. As a result, the warp makes the bias intersecting in the fabric. Special hook heddles govern the shedding action by shifting after each pick. Two opposite reeds that are positioned in the front and back sides of the warp layers beat up the pick [45]. In order to make quart-axial fabric, warp yarns are inserted to the triaxial woven fabric at selected places depending upon the end-use. After that, ±bias yarns rotate just one bobbin distance and heddles are shifted one heddle distance. Then warp is fed to the weaving zone and the shedding action is carried out by the heddles. Filling yarn is inserted and is beaten against the fell to complete the fabric formation. Finally, the fabric is removed from the weaving zone with the aid of a take-up unit [45].
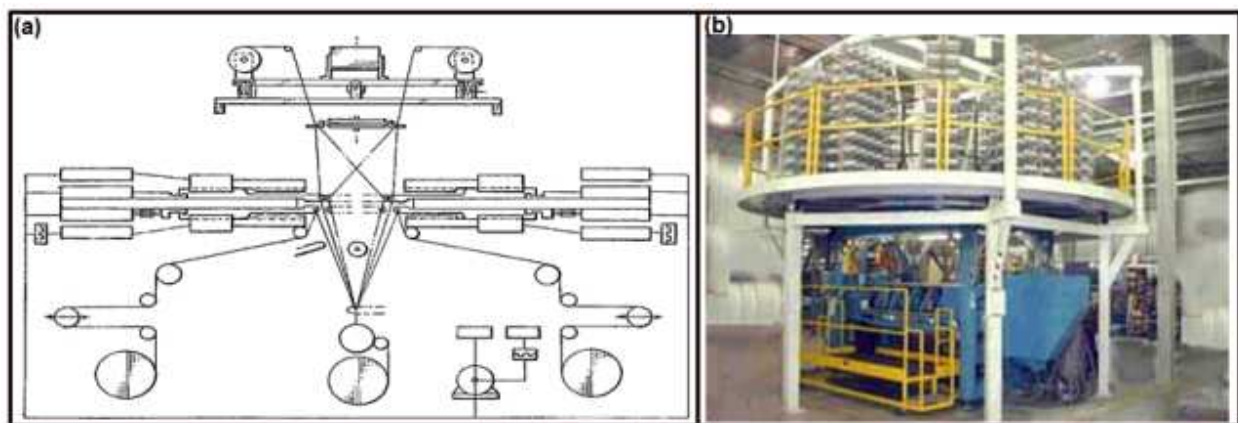

Figure 24. (a) Schematic view of (b) actual triaxial weaving loom [45, 85].

4.1.3. Three-dimensional weaving

In order to make the representative 3D plain woven preform, the warp must be arranged in a matrix of rows and columns, as shown in Figure 25. The first step is the one-step sequential movement of an even number of warp layers in the column direction (a2). This was accomplished with the aid of a 2D shedding unit (not shown). The second step is to insert filling yarn between each warp layer in the row direction (a3). The third step is the one-step sequential movement of an even number of warp layers in the row direction (a4). This was also accomplished via the 2D shedding unit. The fourth step is z-yarn insertion between each warp layer in the column direction (a5). After fulfilling the cycle of steps (a2-a5), 3D woven fabric is formed (a6). The length of the preform determines the number of cycles to be performed. Figure 25 shows the pattern of 3D plain-z yarn orthogonal preform. Steps (a1-a6) are followed to form the fabric structure. Z-yarn is inserted with no interlacement (a4-a6) Again, the preform dimensions determine how many warp layers to be used in the row and column directions [60].

Figure 26 shows the steps necessary to form a 3D circular plain woven fabric. In such an arrangement, axial yarns are positioned in a matrix of circular rows and radial columns according to desired cross section. The first step in the process is the one-step sequential movement of an even and odd number of axial layers in the radial column direction (a2). This
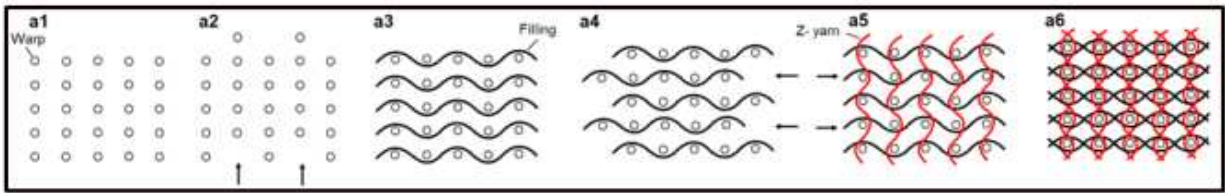
Figure 25. Three-dimensional weaving method to make representative fully-interlaced woven preforms; 3D plain woven preform (a1-a6) [60].

can be accomplished via a 2D circular shedding unit (not shown). The second step is to insert circumferential yarn between each axial layer in the circular row direction (a3). The third step is the one-step sequential movement of an even and odd number of axial layers in the circular row direction (a4) which is also accomplished with the aid of the 2D circular shedding unit. The fourth step is radial yarn insertion between each axial layer in the radial column direction (a4). The 3D circular plain woven preform is formed (a5) after repeating the steps (a2-a4). The length of the preform determines the number of repeats. The unit cell of 3D orthogonal circular woven preform consists of three yarn sets such as axial, circumferential and radial yarns. Axial yarns are arranged in a matrix of circular rows and radial columns. Circumferential yarns are single-end and are laid down between each adjacent axial yarn row. Radial ends are positioned between each axial row through the preform thickness and they locked all other yarn sets. Hence the structural integrity of the preform is achieved. An individual shuttle for circumferential yarn that is mounted on each individually rotated ring was used for the preform fabrication. In addition, the radial carriers reciprocated linearly to the radial corridor of the 2D shedding plane on the rig thus crossing the radial yarns in the preform structure (crossing shedding) [61].
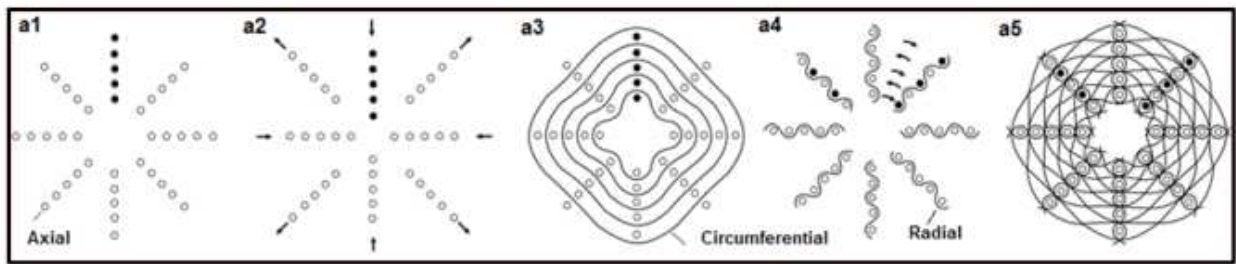
Figure 26. Three-dimensional weaving method to make representative fully-interlaced circular woven preform; 3D circular plain woven preform (a1-a5) [61].

The state-of-the-art weaving loom was modified to make 3D orthogonal woven fabric [86]. For instance, one of the looms which has three rigid rapier insertions with dobby type shed control systems was converted to make 3D woven preform. The new weaving loom was also designed to make various sectional 3D woven preform fabrics [23]. The 3D circular weaving method and fabric (or 3D polar weaving) were developed [63]. The device consists of a table that can rotate and a pair of carriers. The table holds the axial yarns. Each carrier contains radial yarn bobbins together with a guide frame to regulate the weaving position. The main task of the

carriers is to move vertically up and down in order to insert the radial yarns. A circumferential yarn bobbin is placed radial to axial yarns. After the circumferential yarn is wound over the vertically positioned radial yarn, the radial yarn is placed radially to outer ring of the preform.

Multiaxis 3D woven fabric, method and machine based on lappet weaving principals were introduced by Ruzand and Guenot [65]. The basis of the technique is an extension of lappet weaving in which pairs of lappet bars are reused on one or both sides of the fabric. Uchida et al. [66] developed a fabric called five-axis 3D woven which has five yarn sets such as ±bias, filling, warp and z-fiber. The process includes a bias rotating unit; filling and z-yarn insertion units; warp, ±bias and z-fiber feeding units; and a take-up unit. The yarns are oriented by the rotation of horizontal bias chain while the filling is inserted to the fixed shed. All yarns are locked together by z-yarns. This is followed by beat-up and fabric take up procedures. Mohamed and Bilisik [30] developed a multiaxis 3D woven fabric, method and machine. This fabric is constituted from five yarn sets, such as ±bias, warp, filling and z-yarns. ±Bias yarns are placed on the front and back face of the structure. These yarns are locked to the other yarn sets by the z-yarns. Warp yarns, on the other hand, generally lay at the center of the preform (Figure 27). This formation generally improves the composite in-plane properties.
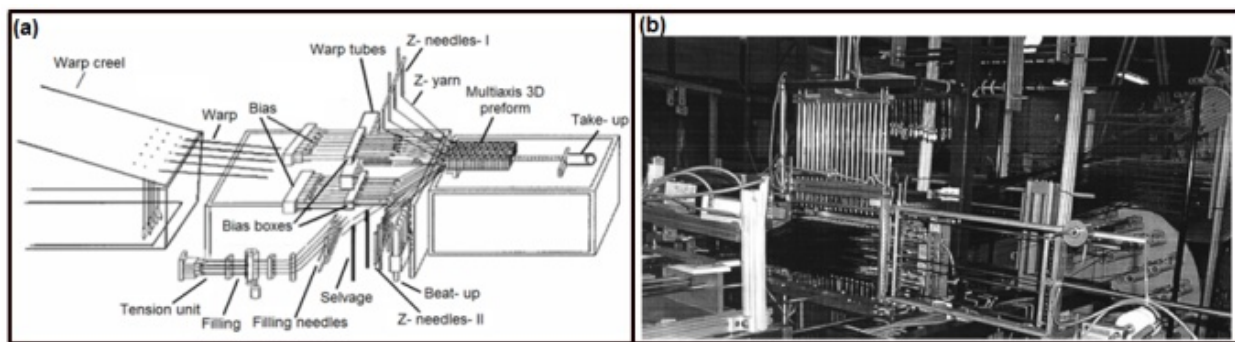

Figure 27. (a) Schematic view of multiaxis weaving machine (b) Side view of multiaxis weaving machine [30, 67].

The warp yarns are arranged in a matrix of rows and columns within the desired cross-section. First, a pair of tube rapiers positions the front and back bias yarns relative to each other. This is followed by the incorporation of filling yarns via needles between warp rows. Then selvedge and latch needles lock the filling yarns by using selvage yarns before returning to their starting position. Z-yarns are inserted across the filling yarns by z-yarn needles. Then filling needles insert the filling yarns and these yarns are locked by selvage needles located at the opposite side of the preform. After that, the filling needles return to their initial position. Then bias yarns and filling yarns are secured in place by z-yarns which return to their initial position by traveling between the warp yarns. This is followed by beat up and fabric take-up procedures. Bilisik [28] developed a multiaxis 3D circular woven fabric, method and machine. The preform consists of axial and radial yarns together with circumferential and ±bias layers (Figure 28). The axial yarns (warp) are arranged in radial rows and circumferential layers within the desired cross section. ±Bias yarns are placed outside and inside ring of the cylinder surface. Filling (circumferential) yarns lay between each warp yarn helical corridors. In order to achieve

the cylindrical form, radial yarns (z-yarns) are linked with other yarns. The thickness of the preform section can be adjusted regarding the end-use. The process requires a machine bed, ±bias and filling ring carriers, a radial braider, a warp creel and a take-up unit. First, shedding mechanism orients the bias yarns at an angle of ±45° to each other. Then the carriers wind the circumferential layers by rotating about the adjacent axial yarns. Special carrier units insert the radial yarns and link the circumferential yarn layers with ±bias and axial layers. Then the fabric is removed from the weaving zone by take-up unit. This process results in enhanced torsional properties for both preform and composite owing to bias yarns.
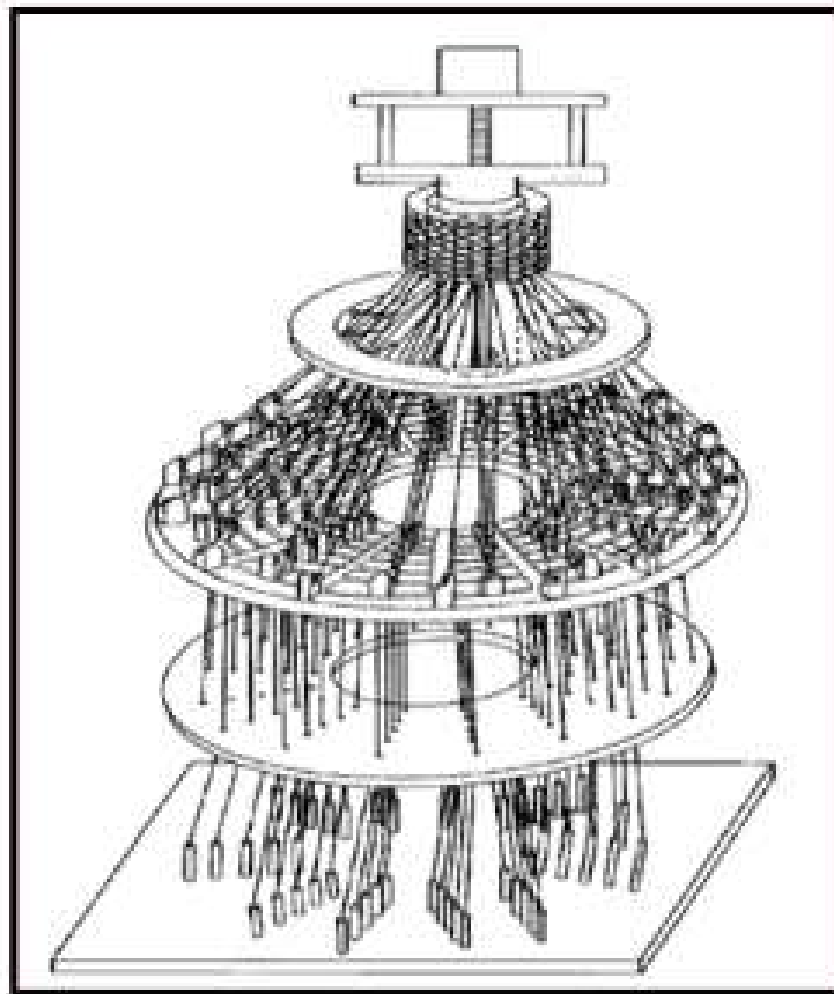

Figure 28. Schematic view of multiaxis 3D circular weaving loom [28, 68].

4.2. Braiding

4.2.1. Three-dimensional braiding

Two-dimensional braiding is a simple traditional textile based process to make bias fabric. A typical braiding machine consists of a track plate, a spool carrier, a former, and a take-up. The

track plate supports the carriers, which travel along the path of the tracks. The movement of the carriers can be provided by horn gears, which propel the carriers around in a maypole arrangement. The carriers are devices that carry the yarn packages around the tracks and control the tension of the braiding yarns. At the point of braiding, a former is often used to control the dimension and shape of the braid. The braid is then delivered through the take-up roll at a predetermined rate. If the number of carriers and the take-up speed are properly selected, the orientation of the yarn (braiding angle) and the diameter of the braid can be controlled. Braiding can take place in horizontal or vertical direction [87].

4.2.2. Triaxial braiding

A large scale 2D circular triaxial machine was developed by the Boeing Company (Figure 29). The fabric consists of warp (axial) and ±bias fibers. It is possible to cast variously shaped structural elements by using a mandrel [88].
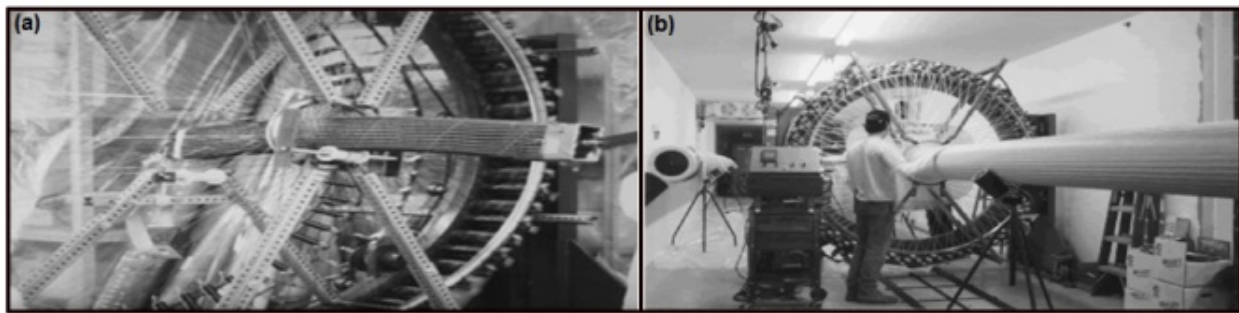

Figure 29. Two-dimensional triaxial braiding machine (a) by Boeing Inc. [88] and (b) by Fiber innovation Inc. [89].

Fiber Innovation Inc. developed a large circular 2D triaxial braider machine (Figure 29). The machine consists of a circular bed, an axial guiding tube, a large braider carrier together with formation, mandrel, and take-up units. The braider carrier moves around the axial fiber tubes according to a predetermined path to make ±bias orientation around the axial yarn. Thick structures can be produced by over-braiding on the mandrel. Complex structural parts can be made by cutting/stitching the fabrics [89].

4.2.3. Three-dimensional fully braided fabric

4.2.3.1. By 4-step braiding method

In the 4-step braiding method, each machine cycle involves four different motions in order to intertwine the longitudinal yarns that are positioned in row and column directions along the cross-section. Braider yarns, on the other hand, are intertwined by braider carriers that move in predetermined paths within the matrix so as to form the fabric. Florentine developed a 3D braided preform that has a layered structure [69]. Yarns are intertwined with each other according to a certain path and are biased such that the width of the fabric is at an angle between 10° and 70°. The process involves rectangular layout of individual row/column arrangements

in the machine bed. Each individual row has a braider carrier in order to carry out four different cartesian motions (Figure 30).
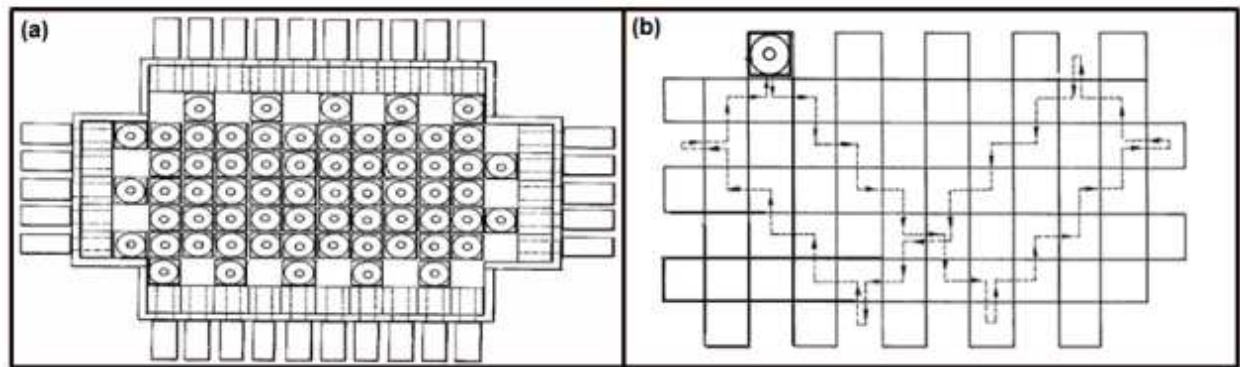
Figure 30. Schematic views of (a) 3D braiding machine and (b) yarn carrier path [69].

Brown developed a 3D circular braided fabric having one set of fiber sets [90]. In order to form the fabric structure, these fiber sets are intertwined with each other. The machine has concentric rings that are attached to a joint axis. Braid carriers are circumferentially mounted to the inside diameter of the ring. The ring is adjusted depending upon the thickness of the fabric. The rings rotate one braid carrier distance depending on a pre-determined path. Then, the braid carriers move in the axial direction. After that, the cycles are repeated in the above sequence. The fabric has ±bias yarn orientation through the thickness of the cylinder wall and cylinder surface at the helical path, as shown in Figure 31.

Figure 31. (a) Schematic views of 3D circular braiding machine [90] (b) yarn carrier path [69].

4.2.3.2. By rotary braiding

This method is essentially a derivative of the maypole braiding. In 3D rotary braiding braider carrier can move freely and arbitrarily over a base plate. Hence, each braider yarn can be interlaced into the fabric [9, 91]. Tsuzuki developed a 3D braider that contains star-shaped rotors arranged in a matrix of multiple rows and columns [92]. Each rotor is surrounded by four carriers that are able to move in four diagonal directions. The directions in which the carriers move are governed by the rotation of the rotors (Figure 32).
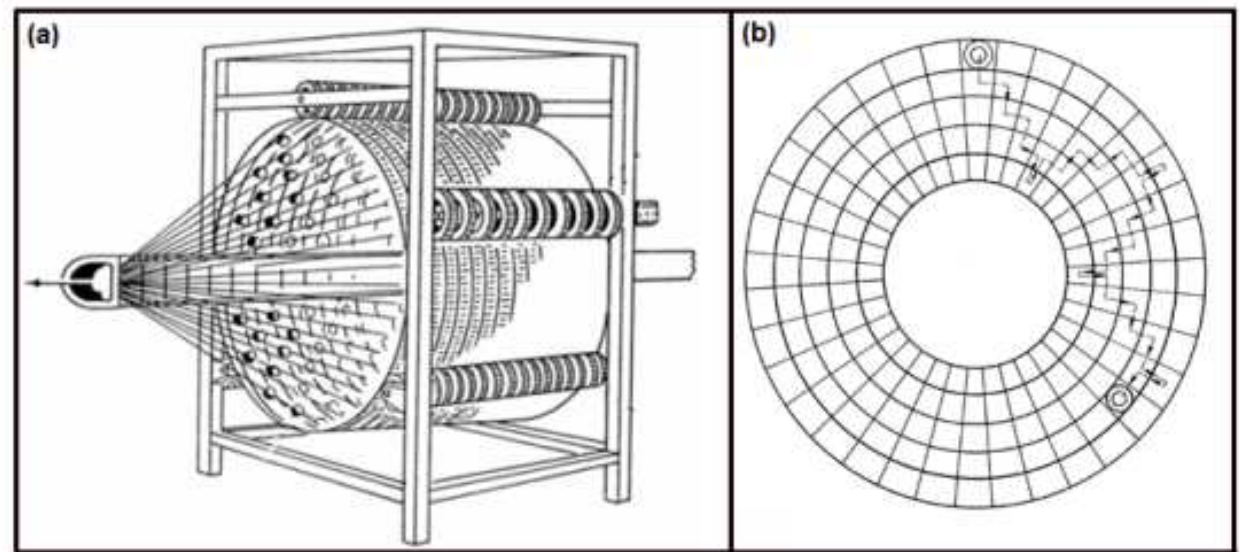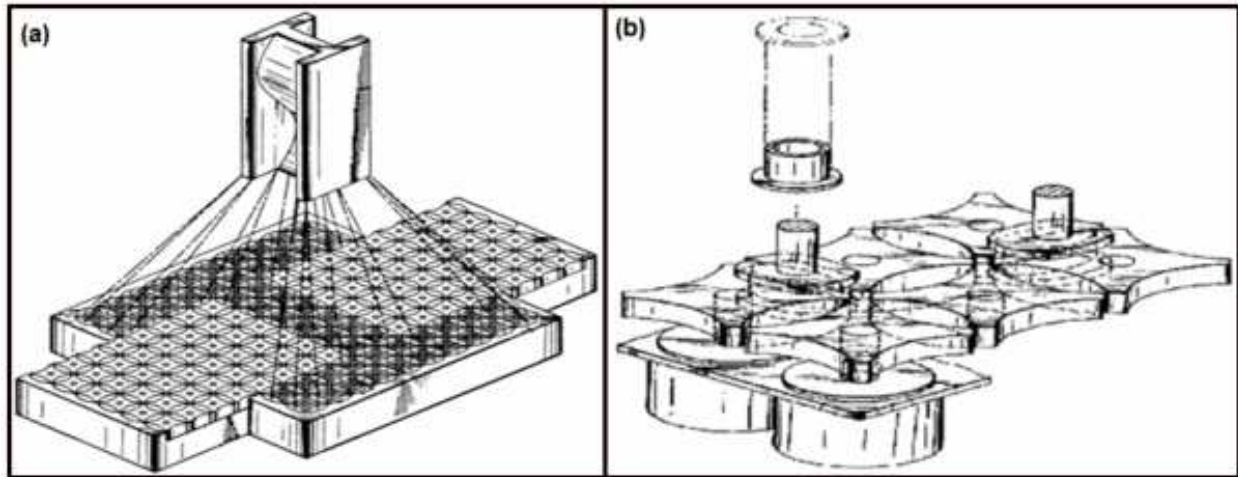

Figure 32. Schematic views of (a) 3D rotary braiding machine and (b) yarn carrier actuation unit [92].

4.2.4. Three-dimensional axial braided fabric

4.2.4.1. By maypole braiding method

Maypole braiding method requires two yarns sets such as warp (axial) and braider yarns. Axial yarns are fixed and the braiders intertwine with the axial yarns by moving back and forth radially about circumferential paths. Uozumi [93] produced a 3D circular braided fabric by using multi-reciprocal braiding process. This process relies on the 2D circular triaxial braiding essentials and requires two sets of yarns such as ±bias (braider) and warp (axial) yarns. Thick fabrics with different cross sections including structural joint, end-fitting and flange tube were made by over-braiding [9]. Multi-reciprocal braiding process is shown in Figure 33.

Brookstein et al. [94] developed a tubular fabric that consists of braiders (±bias yarns) and warp (axial) yarns. Braiders intertwined around each axial yarn so that they lock each individual axial yarn in its place. This intertwining forms a helix structure. In the process, a horn-gear type machine bed is arranged cylindrically so that the axial and braider carrier are positioned inside the diameter of the cylinder. In this way, adding layers and ensuring the structure compactness becomes easy. A horn gear mechanism governs the movement of the braider yarns. They travel in a pre-defined path about the axial yarns to form the fabric (Figure 34). A take-up unit removes the preform from the weaving zone. This process is well suited to
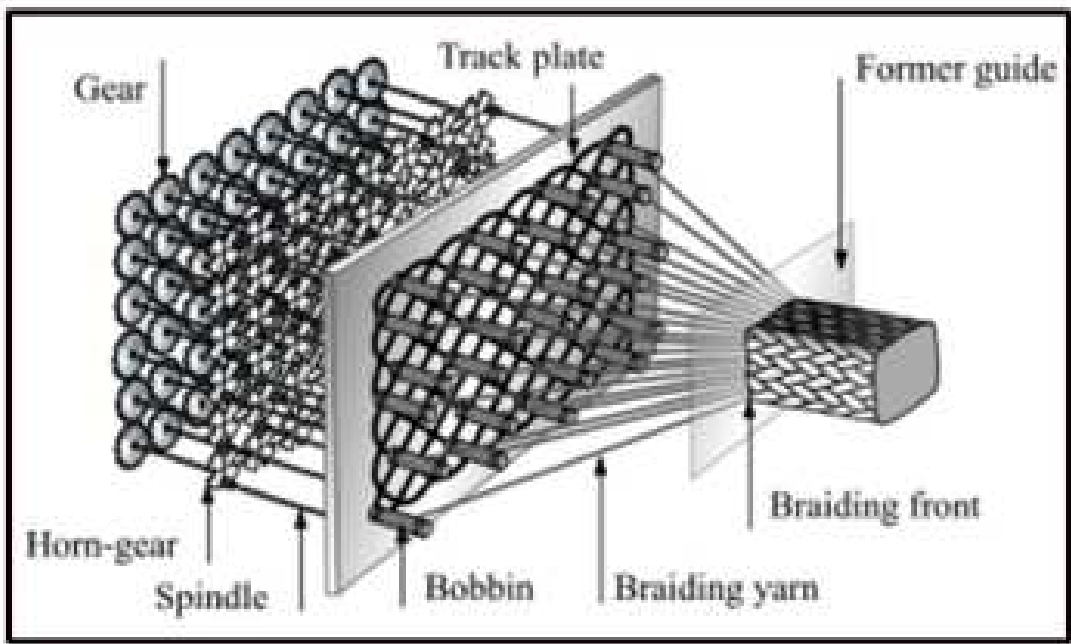
Figure 33. Schematic view of 3D circular axial braiding based on maypole method [9].

produce thick tubular structures and also has the potential for other geometries with a mandrel. Similar 3D axial braiding machine based on maypole method was also developed by Japan as shown in Figure 34 [95].
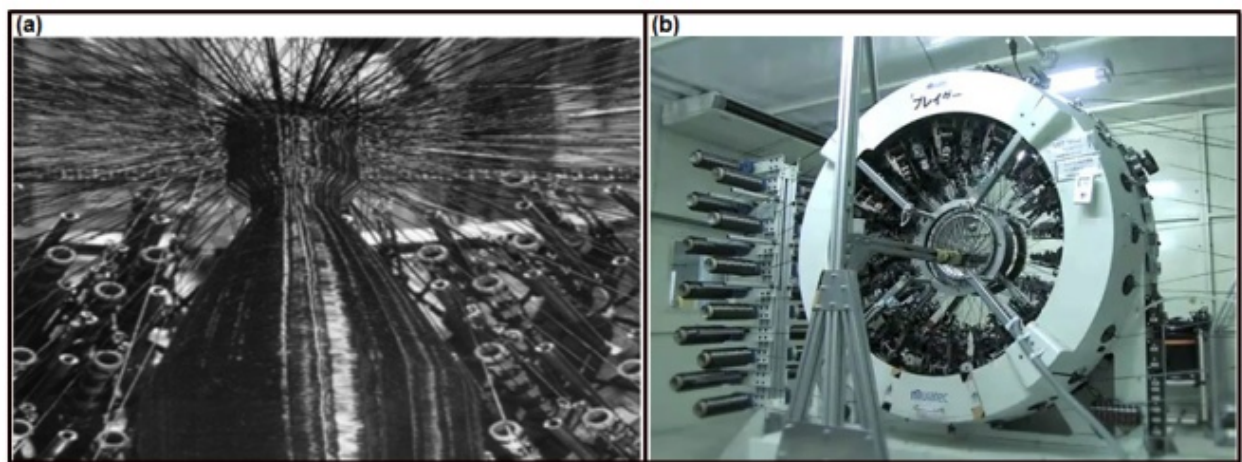
Figure 34. (a) 3D circular braiding by maypole method [94] (b) another type 3D axial braiding machine from Japan [95].

4.2.4.2. By 4-step braiding method

Figure 35 shows the required matrix setting for braider carriers and axial yarns so as to form a 3D fabric having 1×1 pattern. The steps involved are the following: The first step is sequential

and the reversal movement of the braider carriers in the column direction (b). The second step is sequential and the reversal movement of the braider carriers placed on the rapier in the row direction (c). The third step is again sequential and the reversal movement of the braider carriers in the column direction (d). The fourth step is again sequential and the reversal movement of the braider carriers placed the rapier in the row direction (e). The number of these steps can be adjusted regarding the desired fabric length. More braider carriers and axial yarn may be used if the preform dimensions are to be increased [75].

Figure 35. Three-dimensional axial braided preform fabrication principles (steps a-e) [75].

4.2.4.3. By 2-step braiding method

In this method, the cross sectional geometry of the fabric determines the matrix setting of axial yarns. Braider yarns travel diagonally along the matrix arrangement and lock the axial yarns so as to form the required shape. Each braider carrier makes two distinct motions [12, 96]. The process demands relatively fewer braider yarns to impart directional r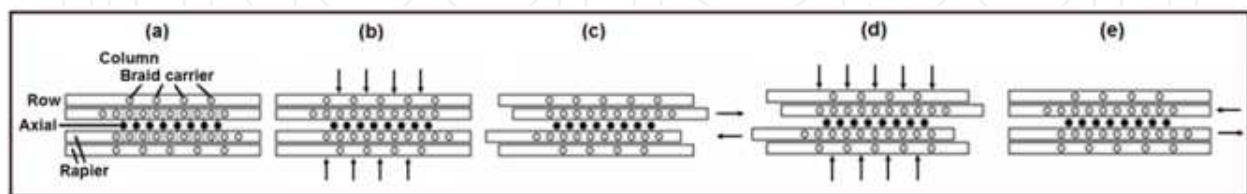einforcement. Since the number of braider carriers is reduced, the process can easily be automated. It is possible to produce various shapes such as T, H, TT and bifurcated fabrics [12]. Mc Connell and Popper developed a 3D axial braided fabric [74]. The machine comprises a machine bed, an axial unit, a braider carrier, and a compaction unit. The preform consists of layered and axial yarns. The shape of the cross section determines the positioning of axial yarns. Braider yarns are intertwined and oriented in bias directions along the thickness and the surface of the preform. They travel between the axial layers across the row and column direction. The braid carrier travels about the axial unit depending on a pre-defined path to make two distinct cartesian motions for creating braider type interlacements. The axial unit feeds the axial ($0°$) yarns in the machine direction. The final preform is formed by the compaction unit (Figure 36).

4.2.4.4. By rotary braiding method

Schneider et al. [91] developed a method and machine to make a 3D braided fabric which has multiple axial yarn networks and braider yarns. The method is called 3D rotary braiding which is similar to Tsuzuki's rotor braiding. Figure 37 shows the flat and circular 3D axial braiding machine. The machine is equipped with horn gears that can be activated individually by a servo motor. A clutch-brake mechanism controls the step and rotation of individual horn gears, axial yarn guide and braider carrier. If desired, a computer-aided design (CAD) tool can be added to produce different shapes and cross sections. In addition, this method employs
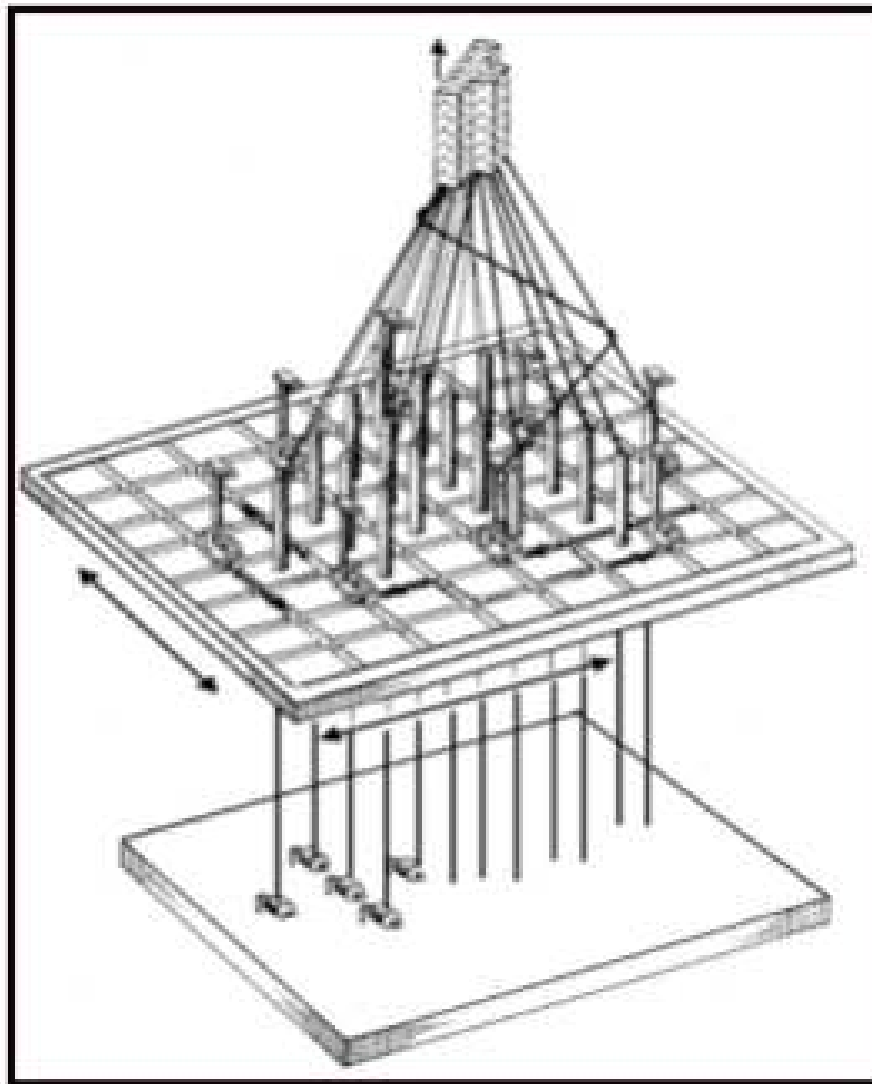
Figure 36. Schematic view of the 3D axial braiding by 2-step braiding [74].

individually controlled gripping forks, which can quickly move yarn carriers between the horn gears according to a pre-determined pattern [97].

4.2.5. Multiaxis 3D braided fabric

4.2.5.1. By 6-step braiding method

This method employs ±braider yarns, warp (axial), filling, and z-yarns. In order to form the fabric, the braider yarns are intertwined with the orthogonal yarn sets. The properties of the multiaxial 3D braided structure in the transverse direction are enhanced and the directional Poisson's ratios of the structure are identical. In this process, there are six distinct steps in each cycle. Steps 1 and 2 are identical to the 4-step method. Step 3 inserts yarn in the transverse direction. Steps 4 and 5 are identical to the steps 1 and 2, and step 6 inserts yarn in the thickness
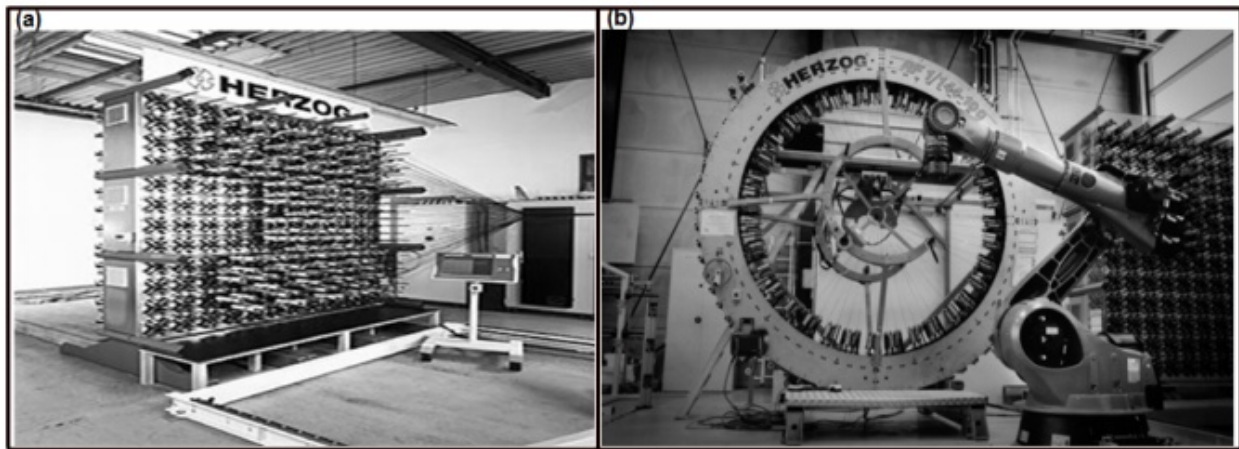
Figure 37. (a) 3D flat and (b) 3D circular axial braiding machines [91].

direction [77]. Another multiaxial 3D braided fabric produced by the 6-step method consists of ±bias, warp (axial), radial (z-yarns) and ±braider yarns. ±Bias yarns are oriented in-plane whereas the others are positioned out-of-plane [78]. The axial and braider yarns are intertwined with each other while ±bias yarns are positioned at the surface of the preform and secured by the radial yarns to the other yarn sets. The process takes place over six steps in each cycle. In steps 1 and 2, ±braider yarns are intertwined around the axial yarns as in the 4-step method. In step 3, ±bias yarns are laid down on the surface of the structure. In step 4, the radial yarns move in the thickness direction of the structure and lock the ±bias yarns to the ±braider and axial yarns. In steps 5 and 6, the ±braider yarns are intertwined around the axial yarns as in the 4-step method.

4.3. Nonwoven

4.3.1. Two-dimensional nonwoven fabric

The first step in the fabrication of a 2D nonwoven fabric is to prepare a short fiber web using various methods such as dry-laying, wet-laying and spun-laying. This web structure is loosely formed without any strong binding or connection between individual fibers other than weak cohesive forces. In order to obtain a continuous fabric structure with adequate strength, this fiber web must be consolidated by entangling or binding the individual fibers together. In order to achieve this, various techniques are used including mechanical ones such as needling, stitching and water-jet entangling; chemical methods such as impregnating, coating and spraying; or cohesion-based techniques like calendering, air blowing and ultrasonic impact [57].

4.3.1.1. By needling method

Needling method uses barbed needles located vertical to the fabric plane in order to achieve entanglement between the short fibers. These needles are fixed on a reciprocating needle board located above the fiber web. The needles strike in the web catching the fibers with their barbs

and orienting them in random in-plane and out-of-plane directions (Figure 38) [57, 98]. The most important goal of needling process is to reorient the fibers in fabric out-of-plane (i.e., thickness) direction as much as possible so that these fibers can act like a lock restraining any fiber movement and keeping the web together. It is essential to apply a certain pressure during the process in order to increase the so called "friction-lock" among fibers and to improve the degree of bonding in the felt. Important processing parameters during needling are needle design, needle density per fabric width, the stroke frequency, the delivery speeds and the working width [99-101].
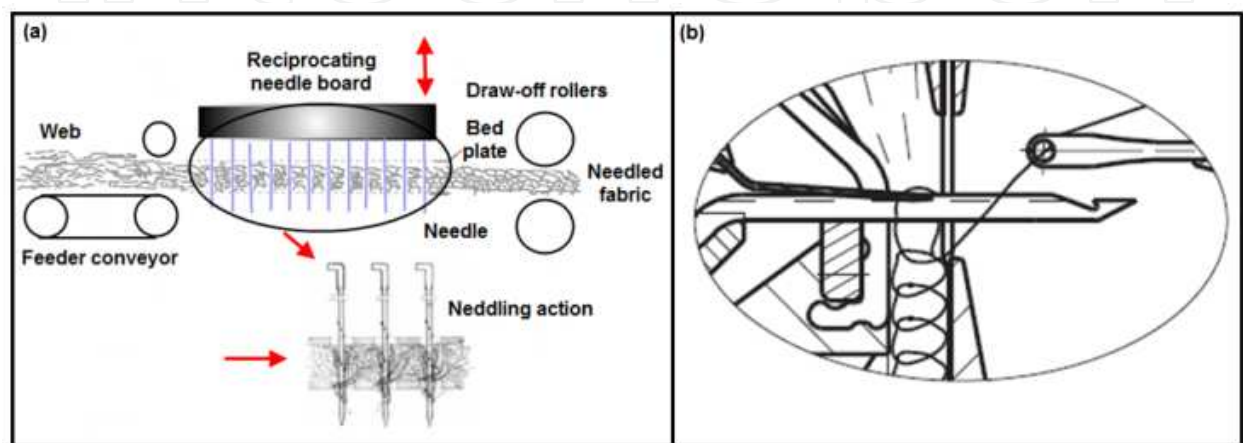
Figure 38. (a) Principle of needling a fiber web [57, 98] (b) Schematic views of stitching method in which loop formation cycle of a stitch bonding machine is shown [57].

The fiber movement caused by needling process leads to changes in fabric dimensions and local areal mass of the fabric. Needling can also result in fiber breakages due to fiber-fiber and needle-fiber frictions. The later can be minimized by treating the fibers with a suitable finishing agent prior to needling [57]. Web feeding and take-up speeds are important process parameters. The stitch density which is the number of penetrations per square area of the felt is calculated by using Eq. (1).

$$Ed = \frac{n_h \cdot N_D}{V_v \cdot 10^4} \tag{1}$$

where, E_d is the stitches per area (stroke per cm²), n_h is the number of lifts (per min.), N_D is the number of needles by nonwoven fabric width (per m), and V_v is the web take-up speed (m/ min).

4.3.1.2. By stitching method

Stitching method involves through-the-thickness stitching of the fiber web in order to consolidate the nonwoven fabric. Nonwoven production process consists of a carding machine, a

cross lapper and a stitch bonding machine. The stitching loop formation technique is shown in Figure 38 [56, 57]. The main elements for stitching process are the compound needle, closing wire, compound needle hook and guide. Compound needle and closing wire bar are connected to the driving cams and the knocking over sinker. Stitch bonding machines are equipped with one or two guide bars. Lapping is accomplished by the swinging and shogging movements. The swinging action is carried out by means of a rotary cam and a crank drive. Shogging allows the use of a cam disc. Working with two guide bars allows to use one guide for pillar stitch and the other for tricot-stitch. The degree of bonding is determined by the number of stitching loops per unit area which is a function of wale density (number of wales per unit length) and course density (number of courses per unit length). The density of stitching loops is determined by machine gauge and the stitch length. Twisted yarns, textured filaments and film yarns can be used for stitching.

4.3.1.3. By hydroentanglement method

In hydroentanglement method, water jets are used to entangle the fibers and obtain a continuous nonwoven surface. The main principle is the same as that of the needling method. Water jets strike onto the nonwoven web and reorient a portion of fibers in out-of-plane directions. These reoriented fibers wrap and lock the others in their vicinity ensuring a continuous surface. The web is soaked from the bottom side only after they have passed the jets which neutralize the part of the web densification [57, 102]. The effect of striking jets on fibers varies depending upon the position of the fiber in the web. Fibers located on the surface facing the water jets are influenced more in comparison with fibers at the bottom. The main process parameter that determines the bonding efficiency is the jet speed. The following relation can be used to find the jet speed.

$$v_w = a \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \qquad (2)$$

where, v_w is the speed of the jet at the exit point, Δ_p is the pressure differential between the nozzle element and the surroundings, ρ is the density of the medium, and a accounts for the friction.

4.3.1.4. By thermal and chemical methods

Thermal bonding process starts with a hot-air treatment to soften the thermoplastic fibers. Then calendering and welding processes are carried out to consolidate nonwovens. Chemical bonding involves the application of binder dispersions then curing and drying of the impregnated webs [57].

4.3.1.5. By electrospinning method

Electrospinning method uses an electric energy field to spin a polymer solution from the tip of single or multiple needles to a flat or cylindrical collector. A voltage is applied to the polymer

which causes a jet of the solution to be drawn towards a grounded collector. The fine jet stretches and elongates as it travels under energy field and is collected as a nonwoven nano-web structure [103]. Various publications indicate that the voltage required to produce fibers range from 5 kV to 30 kV [104]. This range of voltage is good enough to overcome the surface tension of the polymeric solution and to produce very fine charged jets of liquid towards a grounded target. This charged jet before hitting the target undergoes splitting and drawing and forming fibers with different sizes and shapes before evaporating to form a nonwoven nano-web structure. The electrospinning system consists of two separate entities, a sprayer and a collecting device. The sprayer essentially consists of a glass spinneret, which holds the polymer solution. One of the metal electrodes from the high voltage supply is given to the solution, which serves as the positive terminal. A collector, which collects the fibers is given the other end of the electrode, which serves as the negative terminal [105].

4.3.2. Three-dimensional nonwoven fabric

4.3.2.1. By needling method

Olry [80] developed a 3D nonwoven process based on the needling method. The method is essentially the same as 2D nonwoven process except for the usage of multiple nonwoven webs for fabric production. These webs are stacked one on top of another and needled in thickness direction to form a thick 3D structure. Figure 39 shows 3D flat and circular nonwoven machines schematically. Fukuta developed a hydroentanglement process where fluid jets are used to produce 3D nonwoven fabric [81].
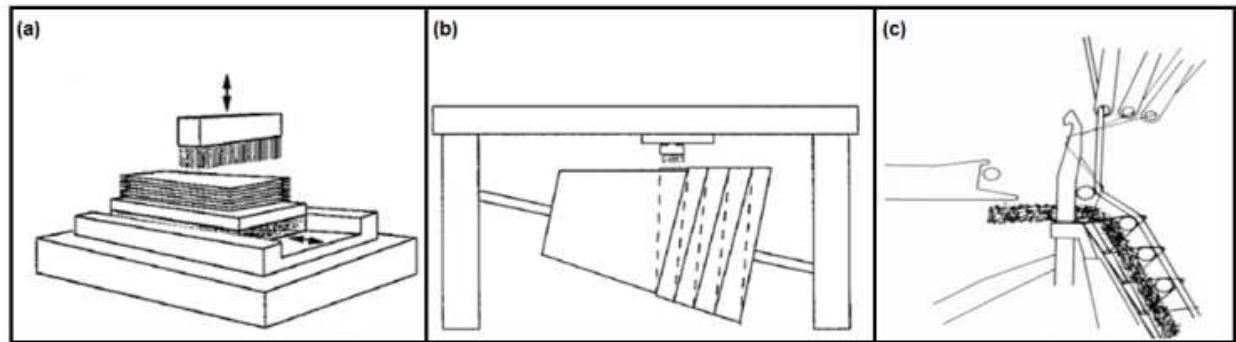
Figure 39. (a) 3D flat non-woven machine (b) 3D circular non-woven machine [80, 81] (c) Schematic view of 3D biaxially reinforced nonwoven structure made by warp knitting machine [57].

4.3.2.2. By stitching method

The 3D nonwoven structure is formed by using a warp knitting machine. Warp yarns are fed by one or more guide bars. Weft yarns are inserted between the warp yarns and the nonwoven web, whereas bias yarns are laid over the warp layers. Multiple compound needles insert the stitching yarns to lock the nonwoven web with warp, weft and bias yarns (Figure 39) [56, 57].

4.4. Knitting

4.4.1. Two-dimensional knitted fabric

The 2D knitted fabric is produced by mainly two methods, namely, weft knitting and warp knitting. In weft knitting, latch needles are arranged circumferentially in the axial and radial direction of the machine bed. Yarn guiding bars feed the yarns to the axial latch needles mounted on the cylinder. Both axial and radial latch needles interloop the yarns to make 2D circular weft knitted fabric for various composite applications. Figure 40 shows the interlooping action, 2D glass weft knitted fabric and cylinder section of a 2D circular weft knitting machine [49].
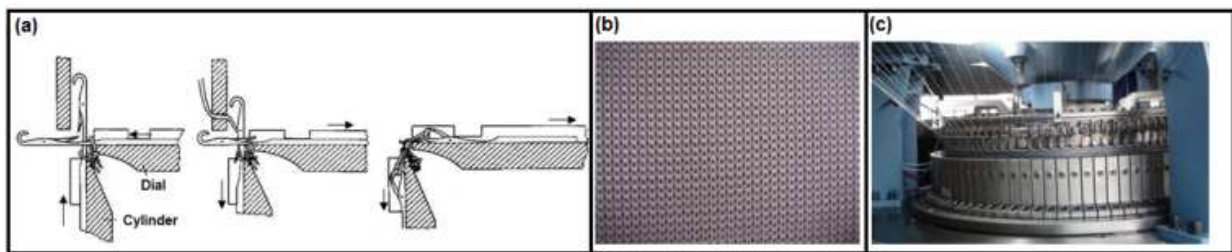
Figure 40. (a) Schematic views of 2D weft knitted fabric during formation (b) 2D weft knitted glass fabric (c) 2D weft knitting machine [49, 79].

Warp knitting consists of a yarn feeding unit, multiple yarn guiding bars, multiple axial latch needles, a sinker and a fabric take-up unit. The guide bars are located at the front of the machine. The sinker bar holds the fabric by moving forward while the needle bar starts to rise from knocks-over (holding down action). As the needle bar rises to its full height, the old overlaps open the latches and slip down onto the stems. Then, the sinker bar withdraws in order to enable the overlapping of guide bars (clearing action). The guide bars move to the back of the machine and then make a shogging for the overlap (overlap action). Then the guide bars swing to the front and the yarns wrap into the needle hooks (return swing action). The needle bar moves down in order that the old overlaps contact and close the latches, trapping the new overlaps inside. The sinker bar now starts to move forward (latch closing action). As the needle bar continues to descend, its head passes below the surface of the trick-plate, drawing the new overlap through the old overlap, and as the sinkers advance over the trick-plate, the underlap shogging of the guide bar is commenced (knocking-over and underlap action). These knitting actions and the machine are shown in Figure 41 [49, 106].

4.4.2. Three-dimensional knitted fabric

4.4.2.1. By weft knitting method

The 3D weft knitting method was developed by Offermann et al. [108]. The weft knitting machine consists of warp and weft feeding, warp yarn guide track, weft yarn carrier, stitch yarn carrier, yarn feeding unit and fabric take-up unit as shown in Figure 42. Two layers of
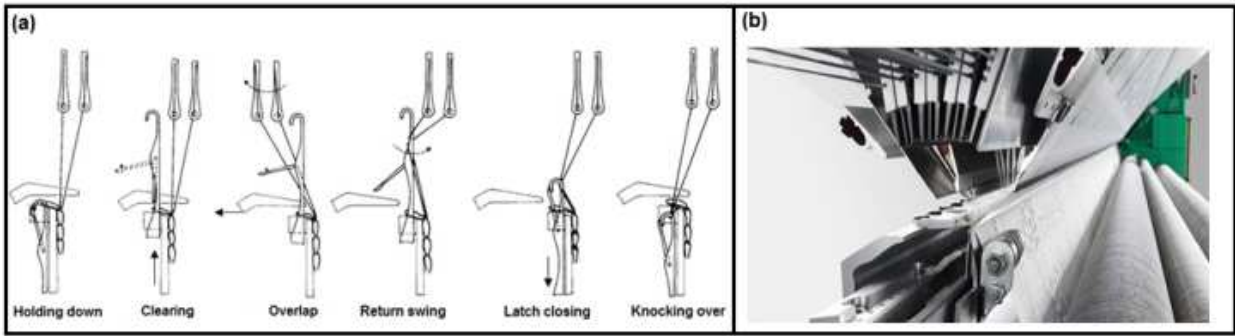
Figure 41. (a) Schematic views of the warp knitting action to form the 2D warp knitted fabric structure using the latch (b) Actual 2D warp knitting machine [36, 49, 107].

warp yarns are laid by warp yarn guide track. Two layers of weft yarns are laid over the warp layers by weft yarn carriers. The stitching yarn locks the warp and weft yarn sets using multiple latch needles in which stitched yarns were structured as weft loops. Simple as well as complex sectional knitted preforms were fabricated by the special take-up device. The critical process parameters are warp and weft densities, stitching density, yarn feeding, and fabric take-up ratios [51, 109].
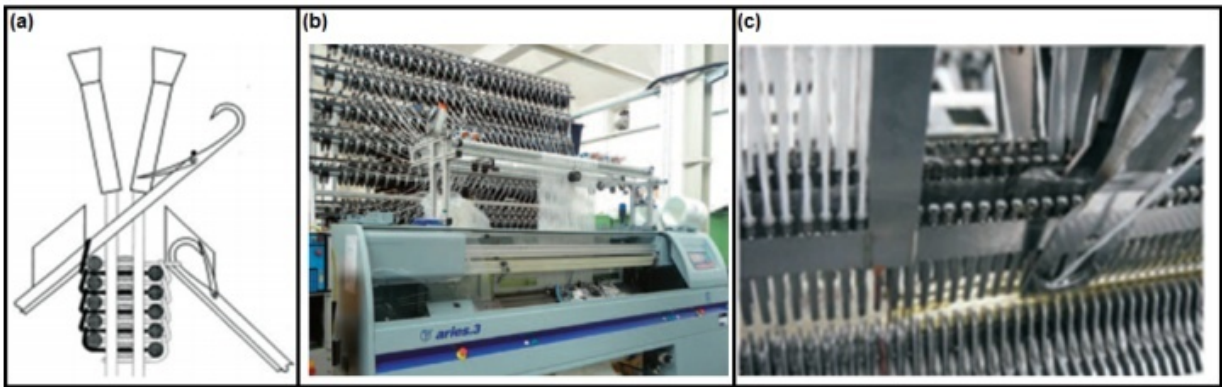
Figure 42. (a) Schematic views of 3D weft knitting methods (b) 3D knitting machine; and (c) weft yarn carrier during knitting [108, 109].

4.4.3. Multiaxis 3D knitted fabric

4.4.3.1. By warp knitting method

Wunner [32] designed a multiaxis warp knit machine for Liba GmbH. The machine is equipped with a pinned conveyor bed, a fiber carrier for each yarn set, a stitching unit, yarn creels and a take-up unit. It employs ±bias, warp and filling (90° yarn) yarn sets together with stitching yarn. Stitching yarn unites all the layers and provides structural integrity (Figure 43). Tricot pattern is generally used for this process.
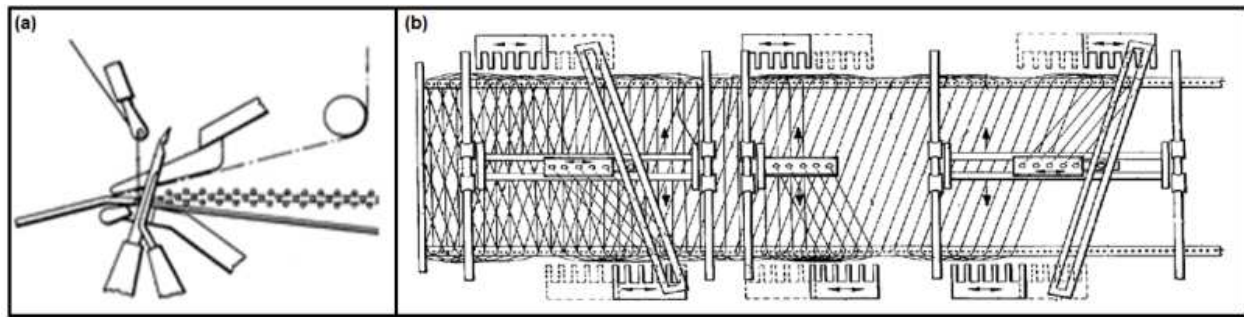
Figure 43. (a) Stitching unit and (b) warp knitting machine [32].

5. Properties of fabrics and composites

5.1. Two-dimensional fabric

5.1.1. Woven fabric structure

The 2D biaxial woven fabric is produced with a simple and highly automated process. It is by far the most economical structure in the composite industry in terms of fabric and composite production costs. The fabric is very stable and easy to handle during processing as well as has good drapability, which facilitates the fabrication of various countered parts. The fabric, however, contains numerous warp/weft interlacement points throughout its structure which impair fiber alignment and thus the load distribution capability of the reinforcing fibers. For this reason, the in-plane properties of 2D woven composite are somewhat lower than those of an equivalent UD composite. However, 2D woven composite still provides acceptably high in-plane properties especially in 0° and 90° direction due to fiber orientation in these directions. On the other hand, the in-plane properties of 3D woven composites are significantly lower than 2D woven composites for a number of reasons. Firstly, the 3D woven structure has z-yarns inserted in through-the-thickness direction in order to improve weak out-of-plane properties of 2D layered woven composites such as delamination resistance and impact strength. However, the incorporation of z-yarns reduces the in-plane directional volume fraction of the composite and leads to lower in-plane properties. One of the problematic issues with the biaxial fabric composites is their low mechanical properties in bias directions such as ±45° and ±60°. Triaxial fabrics bring a solution with their multidirectional fiber architecture. Scardino and Ko [110] reported that triaxial fabric has better properties in the bias directions when compared to biaxial fabric. The study revealed a 4-fold tearing strength and 5-fold abrasion resistance compared with a biaxial fabric with the same setting. Elongation and strength properties were found to be roughly the same. Schwartz [111] compared triaxial fabrics with leno and biaxial fabrics. He defined the triaxial unit cell and proposed the fabric moduli at crimp removal stage. He concluded that it is crucial to strictly define the fabric equivalency before comparing various kinds of fabrics. It was shown that triaxial fabric shows better isotropy compared to leno and plain fabric. This brings a clear advantage since isotropy

plays an important role in fabric bursting and tearing strength as well as shearing and bending properties. Skelton [112] proposed a relation between the bending rigidity and the angle of orientation. It was found that the bending behavior of highly isotropic structures like triaxial fabrics is not dependent upon the orientation angle. Triaxial fabric is more stable in comparison with an orthogonal fabric with the same percentage of open area. Triaxial fabric also shows a greater isotropy in flexure and has greater shear resistance when compared to an equivalent orthogonal fabric.

5.1.2. Braided fabric structure

Nishimoto et al. [113] investigated 2D circular biaxial braided fabrics. They used a step response model to examine the temporal change in braiding angle under unsteady-state conditions. An examination of the flow pattern during the consolidation revealed that the permeability of the fabric is determined by spaces between the fibers especially in the case of low braid angle. Permeability and porosity may result in a non-uniform flow pattern during liquid molding [114]. The effect of braiding angle on the mechanical properties of 2D biaxial braided composite was analyzed. It was shown that when the braiding angle is increased, the bending modulus and strength decreased [115]. Smallest braiding angle (approximately 15°) resulted in the highest bending properties [116]. The mechanical properties of 2D biaxial 2×2 pattern braided fabric composites were studied by a 3D finite element micromechanics model and compared with equivalent 2×2 twill fabrics to analyze their fracture modes under various loading requirements [117]. The biaxial compressive strength properties of 2D triaxial braided cylinders were investigated. It was reported that the fiber waviness affects the axial compression strength. The composites exhibited considerably higher compression and tension strength in the axial direction when compared to those in the braid direction [118]. Smith and Swanson [119] studied the response of 2D triaxial braided composites under compressive loading. It was shown that the laminated plate theory provided good stiffness predictions for low braid angle, whereas a fiber inclination model yielded close estimations for various braid angles. Tsai et al. [120] investigated the burst strengths of 2D biaxial and triaxial braided cylindrical composites. It was reported that the crack formation in biaxial braided composite starts in tow direction. In a triaxial fabric composite, on the other hand, the cracks first appear in the longitudinal direction.

Byun [121] developed an analytical approach to predict the geometric characteristics and mechanical properties of 2D triaxial braided textile composites. The model is based on the unit cell geometry of the braided structure. It was reported that the geometrical model can accurately predict some important properties such as the braid angle and fiber volume fraction. An averaging technique based on the engineering constants was used to calculate the stiffness properties of the composites. It was shown that the averaging technique yields more precise results when worked with small braid angles. It was also reported that the model gives more accurate results when the bundle size of the axial yarns is much larger in comparison with that of the braider yarns. Yan and Hoa [122] used an energy approach for predicting the mechanical behavior of 2D triaxially braided composites.

5.1.3. Nonwoven fabric structure

Properties of 2D nonwoven fabric structure depend on fiber type and size, packing density (fiber volume fraction), pore size and distribution in the web volume, and fiber orientation in the web [56]. The packing density (α) of a web is defined as the ratio of the volume occupied by the fibers to the whole volume of the web as defined by Eqs. (3) and (4):

$$\alpha = \text{ total fiber volume / total web volume} = \frac{V_f}{V_{web}} = \frac{W_f / \rho_f}{t\,A} = \frac{Basis\ weight}{t\,\rho_f} \tag{3}$$

where, V_f is the volume of fibers; V_{web} is the volume of the web; W_f is the weight of fibers = weight of the web; ρ_f is the fiber or polymer density; t is the thickness of the web and A is the area of the web.

Porosity (ε) can be obtained by following relation:

$$\varepsilon = 1 - \alpha \tag{4}$$

Nonwovens are composed of short fibers that are entangled or bonded together to form a continuous fabric structure. Therefore the mechanical properties of the fabric and its composite strictly depend upon fiber strength/stiffness and the bonding strength between the fibers. Unlike many other forms of reinforcement, nonwoven fabrics with randomly oriented fibers can be regarded as isotropic structures bearing similar properties in all possible in-plane directions. The main parameters that determine the mechanical properties of a nonwoven composite are fiber modulus/tenacity, packing density/fiber volume fraction, fiber orientation distribution and fiber length distribution [123].

It is demonstrated that various polymer solutions can be used in electrospinning process to make various sectional nanofibers including cylinder, rod, ellipse, flat ribbons and branched fibers. The arrangement of fibers in the nano-web is generally random, with a slight bias to the machine direction due to movement of the collector and the air drag/suction [124-126]. The process parameters in electrospinning are electric voltage, the distance between the spinneret and the collector, the polymer concentration, the diameter of the spinneret, and the web structural design parameters [127]. It is noted that the critical part of the electrospinning is the fluid instability. At high electric fields, the jet becomes unstable and has an appearance of inverted cone, which is a single, rapidly whipping jet [128, 129]. The dominant instability strongly depends on the fluid parameters of the jet, namely, the viscosity, the dielectric constant, the conductivity and the static charge density on the jet [130].

5.1.4. Knitted fabric structure

The 2D knitted fabric is thicker than an equivalent woven structure due to its special loop elements which are buckled toward an additional (third) fabric dimension. The fabric is highly extensible with a low flexural rigidity [131]. It was reported that the knit preform properties

are greatly influenced by the fiber strength and modulus, knitted structure, stitch density, pre-stretch parameters and incorporation of inlays [36]. The deformation behavior of knitted preforms can be predicted by initial load-elongation properties of knitted fabrics. The knitting process parameters influence the knitted preform during fabrication. Loop formation during the knitting process imposes dramatic bends and twists on fibers that cause fiber/machine element failures when working with high modulus/brittle fibers. It was shown that the knittability of these fibers depends on frictional properties, bending strength, stiffness, and fiber/yarn strength [49]. The knittability of a given yarn can be improved by certain machine parameter adjustments including low tension application during yarn input, fabric take down tension setting, and loop length control which is adjusted by stitch cam settings [109]. Also, the knittability of high performance yarns mainly depends on yarn-to-metal friction characteristics. Positive yarn feeding control and tension compensator improve the dimensional stability of the knitted preform. It was demonstrated that yarn bending rigidity and inter-yarn coefficient of friction are very important determinants for loop shape while the loop length of high performance yarns, glass yarns in particular, was found to vary with needle diameter, stitching cam setting and machine setting [49, 79, 109].

5.2. Three-dimensional fabric

5.2.1. Non-interlaced fabric structures

Bilisik and Yolacan [132] investigated the mechanical properties of non-interlaced/non-z single layer and multilayered uniaxial, biaxial and multiaxis E-glass/polyester composites. They reported that the number of layers as well as yarn orientation greatly affects the mechanical properties. An increment in packing density led to higher tensile and flexural strength which was attributed to increase in fiber volume fraction. All samples experienced mode-I delamination and subsequent failure under tensile loading due to layer/layer separation. This was attributed to the lack of z-yarns and the resulting weakness in out-of-plane direction. Bilisik [133] carried out the experimental determination of ballistic performance of novel composite structures with soft backing aramid fabric. It was reported that specific energy absorption of non-interlaced/non-z E-glass/polyester composite plate with para-aramid soft layered dense woven fabric structure is higher than that of the 3D woven carbon/epoxy and non-interlaced/non-z E-glass/polyester composite plates with para-aramid soft layered loose woven fabric structure. Damage propagation in the 3D woven structure is smaller than that of the non-interlaced/non-z multiaxis structure, and impact damage was restricted by the z-fiber. Carbon fiber shows brittle behavior during energy absorption, but E-glass fiber shows high extension and distributes the energy around the impacted zone.

5.2.2. Multistitched fabric structures

Warp and weft directional specific tensile strength and modulus of unstitched structure were higher than those of the four- and two-directional light and dense multistitched structures. Stitching causes minor filament breakages as well as creating stitching holes throughout the structure which reduces the in-plane properties of the stitched composite. Accordingly, when

the number of stitching directions, and stitching density increased, their warp and weft directional tensile strength and modulus decreased. These results indicated that stitching yarn type, stitching directions and stitching density generally influenced the warp and weft directional tensile properties of multistitched E-glass/polyester woven composites. On the other hand, the damage tolerance performance of the multistitched structures was enhanced due to stitching (in particular, four-directional stitching) [134]. In addition, stitching yarn type, stitching directions, stitching density, and amount of nano materials generally influenced the bending properties of multistitched E-glass/polyester woven composites [135].

5.2.3. Fully interlaced woven fabric structure

Geometrical properties of the representative 3D fully interlaced woven preforms were analyzed and the results are shown in Figure 53. Crimps in the 3D fully-interlaced and semi-interlaced representative woven preform structure were calculated based on the structure dimensions and the uncrimped representative yarn lengths [60]. The following relations can be used:

$$cw\left(\%\right)=\left(lw-Sl\right)\times100\ /\ Sl \tag{5}$$

$$cf\left(\%\right)=\left(lf-Sw\right)\times100\ /\ Sw \tag{6}$$

$$cz\left(\%\right)=\left(lzt-St\times100\right)/\ St \tag{7}$$

where, cw is the warp crimp (%), lw is the uncrimped warp length (cm), Sl is the structure length (cm), cf is the filling crimp (%), lf is the uncrimped filling length (cm), Sw is the structure width (cm), cz is the z-yarn crimp (%), lzt is the uncrimped total z-yarn length (cm) and St is the structure thickness. In addition, crimps in the 3D fully-interlaced representative circular woven preform structure were calculated based on the structure dimensions and the un-crimped representative yarn lengths [61]. The following relations can be used:

$$Ca\left(\%\right)=\left(la-Sl\right)\times100\ /\ Sl \tag{8}$$

$$Cc\left(\%\right)=\left(lc-Ssl\right)\times100\ /\ Ssl \tag{9}$$

$$Cr\left(\%\right)=\left(lrt-St\times100\right)\ /\ St \tag{10}$$

where, Ca is the axial crimp (%), la is the uncrimped axial length (cm), Sl is the structures length (cm), Cc is the circumferential crimp (%), lc is the uncrimped circumferential length (cm), Ssl

is the structures outside surface length (cm), *Cr* is the radial crimp (%), *lrt* is the uncrimped total radial length (cm) and *St* is the structures wall thickness.

5.2.4. Orthogonal woven fabric structure

Gowayed and Pastore [136] reviewed computational methods for 3D woven fabric. The developed analytical methods were stiffness averaging, fabric geometry and inclination models. They were based on classical lamination theory, and a micromechanical approach was considered. Gu [137] reported that the directional/total fiber volume fraction in 3D woven preforms is influenced by the take-up rate during weaving process. It is possible to obtain higher packing densities by applying double beat-up. Cox et al. [5] stated that 3D woven preform with a low volume fraction may perform well under the impact load compared to 3D woven preform with a high volume fraction. Dickinson [138] studied 3D carbon/epoxy composites. It is realized that the amount and placement of z-yarn in 3D woven preform influence the in-plane properties of the 3D woven structure. When the volume ratio of z-yarns was increased, in-plane properties of the 3D woven fabric decreased. On the other hand, local delamination was monitored when the ratio of z-yarns was decreased. Bobcock and Rose [139] found that when 3D woven or 2D woven/stitched composites were subjected to an impact loading, the impact energy was confined to a limited area owing to the z-yarns.

5.2.5. Multiaxis woven fabric structure

Uchida et al. [17] examined five-axis 3D woven fabric composites. They reported that multiaxis woven fabric and stitched 2D laminate composites showed similar results in terms of tensile and compression properties whereas multiaxis fabric composite yielded better open hole tensile and compression values. Impact tests revealed that the damaged area is smaller in 3D woven composites when compared to that of the stitched laminate. Furthermore, 5-axis 3D woven composite gave better results in Compression After Impact (CAI) tests in comparison with stitched fabric composite. Bilisik [67] stated that the most important process parameters for multiaxis 3D flat woven preform production are bias angle, width ratio, packing, tension and fiber waviness. The bias angle can be manipulated by tube-block movement.

Bilisik and Mohamed [140] investigated the mechanical properties of 3D carbon/epoxy composites by applying the stiffness averaging method. The directional tensile and shear constants obtained are shown in Table 7. The shear properties were influenced by the orientation of yarns within the preform.

The process parameters for multiaxis 3D circular weaving are the following: bias orientation, radial and circumferential yarn insertion, beat-up and take-up. Bias yarns on the outer and inner surfaces of the structure create helical paths and there is a slight angle difference between them particularly in the case of thick-walled fabrics. It was shown that there is a correlation between preform density (fiber volume fraction), bias yarn orientation and take-up rate. The excessive yarn length during circumferential yarn insertion is because diameter ratio (preform outer diameter/outermost ring diameter) is not equal to 1. The diameter ratio depends on the number of the rings. When the excessive circumferential yarn is not retracted, it causes

waviness in the structure. However, there must be an adequate tension on the circumferential yarns to get proper packing during beat-up [68].

			Carbon Fiber	Epoxy Matrix
			Thornel™ T-300 PAN	(Tactix™ 123)
Material Properties	Tensile Strength (MPa)		3450	76.50
	Tensile Modulus (GPa)		230	3.45
	Modulus of Rigidity (GPa)		88.50	1.30
	Elongation (%)		1.62	5.70
	Poisson's ratio (v)		0.27	0.31
	Density (g/cm³)		1.76	1.16
			Preform 1	Preform 2
Bias angle (°) (measured)			30°	40°
Fractional volume (%) **(measured at preform)**	+ Bias		9.43	11.7
	- Bias		9.43	11.7
	Warp		10.5	13.7
	Filling		5.42	4.77
	z-yarn		3.67	5.61
	Total Volume (%)		38.4	47.5
Elastic constants **(calculated)**	Modulus of elasticity (GPa)	E_{11}	48.33	48.00
		E_{22}	19.87	23.85
		E_{33}	9.86	14.24
	Modulus of rigidity (GPa)	G_{12}	10.42	15.65
		G_{23}	2.78	3.47
		G_{31}	2.80	3.47
	Poisson's ratio	v_{12}	0.446	0.530

Table 7. Multiaxis 3D woven preform elastic constants from multiaxis 3D weaving [140].

5.2.6. Three-dimensional fully braided fabric structure

Geometric relations on the representative 3D fully braided and 3D axial braided structures were investigated in terms of unit cell angle, unit cell yarn length and unit cell yarn path. The results show that the unit cell from 4-step method is influenced by braid patterns for both preform types. Fully interconnected unit cell structures are obtained when patterns on odd numbered rows were used. Patterns on even numbered rows, on the other hand, mostly led to layer-to-layer connection on the unit cell edge forming an empty pocket between each

braided layer. The unit cell structure has a fine intertwine in the 1×1 pattern, whereas it has a coarse intertwine for other braid patterns. When the influence of number of layers is considered, it was found that, for all braid patterns, the unit cell thickness increases when the number of layers is increased in 3D braided and 3D axial braided structures. Furthermore, for the same number of layers, the unit cell thickness in the 1×1 pattern is less when compared to other patterns. This showed that all braid patterns except 1×1 resulted in a coarse form of unit cell structure [70].

Byun and Chou [141] examined the process-microstructure relationships of 2-step and 4-step braided composites by geometrical modeling of unit cells. The effect of process parameters such as braid pattern and take-up rate on the microstructural properties like braid yarn angle and fiber volume fraction was investigated. They also studied the fabric jamming phenomenon. Three-dimensional braided composites were characterized by using the fabric geometry model (FGM). This model uses the processing parameters as well as the properties of the fibers and the matrix. It basically relies on two parameters such as the fabric geometry and the fiber volume fraction. Fabric geometry is a function of the take-up rate, whereas row and column motions determine the yarn displacement values, which are expressed as number of yarns. The yarn orientation in a 3D preform is dependent upon fabric shape and construction as well as the dimensions of the braiding loom [142].

5.2.7. Three-dimensional axial braided fabric structure

Kuo [143] investigated topology of 3D braided fabrics by using pultruded rods as axial reinforcements. The effect of yarns size and spacing as well as the pitch length on the final preform geometry was examined. Structural analysis of 3D axial braided preforms revealed that braider yarn orientation and yarn volume fraction can be predicted from the measured values of yarn sizes, preform contour sizes, pitch length and number of axial and braider yarns [144]. Li [145] studied the structural mechanics of 3D braided preforms. It was observed that the load in the axial direction was mostly carried by axial yarns whereas the braider yarns carry the transverse loads. Therefore, it was desirable for the orientation angle of the braiders to be large.

5.2.8. Three-dimensional nonwoven fabric structure

The 3D nonwovens are anisotropic materials in which the fiber strength and modulus, fiber length and thickness, fiber volume fraction and fiber angle in the in-plane and out-of-plane directions are important preform properties [56]. The general stress–strain relationship is given by:

$$\sigma = C : \varepsilon \tag{11}$$

where σ is the stress, a second order tensor, ε is the strain, also a second-order tensor, and C is the stiffness constant, a fourth-order tensor [56]. For two-dimensional nonwovens, the in-plane directional stiffness of the nonwoven is given in Eqs. (12) and (13) based on fiber web theory [56].

$$C_{11} = E_f \int_0^\pi \cos^4 f(\theta) \, d\theta \qquad (12)$$

$$C_{12} = E_f \int_0^\pi \cos^2\theta \, \sin^2\theta \, f(\theta) \, d\theta \qquad (13)$$

where C_{11} is the stiffness constant in the x-direction on the plane perpendicular to the x-axis, C_{12} is the stiffness constant in the y-direction on the plane perpendicular to the x-axis, E_f is the fiber modulus and $f(\theta)$ is the distribution of fiber orientation.

Directional stiffness constants of a web can be obtained, given the fiber modulus and the fiber orientation distribution in the web. The fiber web theory can be applied to the 3D nonwoven preform in which some amount of z-fiber is oriented in the thickness direction of the web [102, 146]. It was claimed that there is a good agreement between the fiber web theory and the experimental measurement of needle punched web where the fibers between two bonded points are straight and that fibers are rigidly bonded. It is tedious and time consuming to determine the fiber orientation distribution in a web. However, several practical methods have been developed to measure the fiber orientation as X-ray diffraction, laser light diffraction, light reflection and refraction intensity [147].

5.2.9. Three-dimensional knitted fabric structure

The properties of 3D knitted structures including multilayered weft or warp knitted fabrics and 3D multiaxis warp knitted preforms were studied by various researchers. The fiber volume fraction of the 3D multilayered weft knitted structure was proposed by Eq. (14):

$$V_f = \frac{n_k \, D_y \, L_s \, C \, W}{9 \, \rho_f \, A \, t} \times 10^{-5} \qquad (14)$$

where n_k is the number of plies of the fabric in the composite, D_y is the yarn linear density, L_s is the length of yarn in one loop of the unit cell, C is the course density, W is the wale density, ρ_f is the density of fiber and A is the planar area over which W and C are measured, and t is the structure thickness.

It was concluded that the fiber content of weft knitted fabric composites can be increased by increasing D_y using the coarser yarns [36]. In general, the coarser yarns are difficult to knit and the coarsest yarn knittable is dependent on the yarn type and knitting needle size. In addition, the maximum V_f is limited by the knitting needles used in the knitting machine based on the relation $N = C/W$, where N is the stitching density. Hence, V_f is proportional to the structure parameters of L_s and N. The maximum V_f can be achieved by increasing the stitch density or the tightness of the knitted fabric. It was claimed that the attainable volume fraction of knitted fabric composite can be 40% [36, 79]. It was stated that the failure

mechanisms for weft knitted structures were dependent on both the wale and the course directional crack propagations, and demonstrated better interlaminar fracture toughness properties due to the 3D loop structure [49]. It was found that the failure process of weft knitted structures under tensile load includes crack branching, loop to loop friction, yarn bridging and fiber breakages. It was also shown that an increase in loop length or stitch density has opposite effects on the tensile strength and impact performance of the weft-knitted composites. The plain weft knitted structure exhibited good energy absorption capacity. Matrix cracking, matrix/fiber debonding, and fiber breakage were the major damage mechanisms [36, 49, 109]. The 3D loop structure was studied, and it was proposed that the loop structure was constituted by sets of arcs. Adoption of the arc shape loop geometry into micromechanical technique considers the influence of knitting parameters and the estimation of elastic properties of knitted composites [148].

6. Application of fabrics in technical textiles

6.1. Structural components

Two- and three-dimensional woven, braided, knitted and nonwoven composites as structural components for various industrial applications fulfilled the general requirements such as low cost, manufacturability, good mechanical performance and energy absorption, corrosion resistance, repairability and recyclability, fuel economy and low noise level [149]. Typical structural components in various industrial applications are knot elements for space frame-like structures, beams, shells, exhaust, seats and chassis. For instance, the use of woven and braided composites in structural applications allows a significant reduction in component number and provides a substantial weight reduction compared with metal [87]. In addition, 2D and 3D woven, braided and knitted composites as T-joints and T-shape connectors, cones, pipes, and I-beams are attractive applications in general engineering fields. Two- and three-dimensional nonwoven composites can be used in construction industry as a roofing and tile underlay, thermal and noise insulation, and house wrap. Some geotextile applications of 2D or multilayerd 3D nonvoven composites are asphalt overlay, soil stabilization, drainage, sedimentation and erosion control. Industrial applications of the 2D or 3D nonwoven structures are cable insulation, battery separators, satellite dishes and coating [149]. The 2D nonwoven nano web structures are increasingly finding applications in filtration industry, electromagnetic interference (EMI) shielding, electrical conductors, thermal and lightning protection, energy field in batteries, photovoltaic cells, polymer electrolytes and membrane fuel cells and advanced structural composites.

6.2. Ballistic applications

Two- and three-dimensional woven fabric and rigid ballistic plate are used extensively to protect the human and goods from various threats such as projectile, blast, fragment and high energy explosives. In addition, 2D and 3D braided, knitted and nonwoven fabrics and rigid composites can be utilized as protective products for vehicular crash guards, composite

helmet, interlinings, insulation and protective industrial workwear and firefighter suits [49, 149]. Two- and three-dimensional woven, braided, knitted and nonwoven structures for soft and rigid ballistic applications are made by using high modulus and high strength fibers like para-aramid and polyethylene. Ballistic structures are manufactured as multilayer to obtain required structural thickness by using the above mentioned 2D fabrics. In some cases, to enhance the out-of-plane properties, those 2D fabrics are formed by stitching or quilting. In particular, 2D woven fabric for soft ballistic applications is very effective due to the in-plane crimp between yarn sets since the crimps act as a secondary energy absorbing mechanism due to local intra-yarn frictional forces generated during impact loads. In addition, 2D nanofiber-based nonwovens are being applied as sound absorption materials and in protective clothing to combat chemical and biological warfare agents.

6.3. Space and aerospace applications

Two- and three-dimensional woven and braided fabrics are used in aerospace applications as soft space suits for astronauts, space shuttle components and aircraft seat cushions. Two- and three-dimensional woven, braided and multiaxis warp knitted composites are currently employed in critical structures of both civil and military aircrafts such as the fuselage, wings, and skin of the aircraft. Other areas of use are top and side tail units, fuselage panelling, leading edges on side rudders, and engine panelling. It was reported that multiaxis 3D warp knitted composites are also being evaluated for rotor blades, outer skin and ballistic protection for helicopters. Three-dimensional weft or warp knitted ceramic composite was also developed for use as a structural parts for jet engine vanes, radomes and rudder tip fairing [49].

6.4. Automotive applications

Fiber based dry and soft textile fabrics or structures are the main interior materials for automobiles as well as trains, aircrafts and ships. This provides the users well-being and comfort. They also withstand daylight and ultraviolet radiation. The maintenance cost is low and easy to care. Two- and three-dimensional woven and knitted fabrics are used as airbag, and car seat parts which has better air permeability and moisture removal properties and car seat cover for the aesthetic and durability requirements. Two- and three-dimensional textile preform composite structures are widely used as parts of the suspension, gears, drive belts, tires, heater hoses, battery separators, brake and clutch linings, air filters, gaskets and crash helmets. Two- and three-dimensional warp knitted fabrics and nonwovens are widely used as preassembled interior components such as boot liners, seatbacks, door panels, oil and cabin air filters, molded bonnet liners, heat shields, wheelhouse covers, parcel shelves and shelf trim. Two- and three-dimensional braided preform and composites have been used in racing car bodies, structural members such as beams which are made up of foam cores over braided with a carbon preform structure, aprons and spoilers, connecting rods, drive shafting and flexible couplings. Also, car noses, monocoques and bumpers are made from braided carbon struc-tures. They reduce weight and improve the crash behavior [49, 149].

6.5. Medical applications

Two- and three-dimensional fiber based structures are used in protective medical apparel such as baby diapers, feminine hygiene products, adult incontinence items, dry and wet pads, nursing pads or nasal strips, operation drapes, gowns and packs, face masks, surgical dressings. Two- and three-dimensional woven, braid, warp knitted and nonwoven structures find also more functional applications as in vascular prosthesis due to good mechanical properties and better ingrowth of tissue to seal the prosthesis walls, grafts for inborn vessel anomaly or arteriosclerotic damage, soft tissue such as skin and cartilage, artificial tendons and ligaments, wound dressing, absorbable and non-absorbable sutures, stents, tissue engineering scaffolds as to repair or regenerate tissues through combinations of implanted cells-biomaterial scaffolds-biologically active molecules, blood filters, plasters, compression bandages, surgical hosiery, and hospital bedding. It was also demonstrated that 2D and 3D fabrics are dimensionally stable, have similar mechanical properties with human organs and are biocompatible [57, 87, 149]. Recently, 2D nanofiber-based nonwoven fabrics are considered to be used in wound healing, artificial organ components and tissue engineering and implant materials.

6.6. Sports applications

Two- and three-dimensional woven and braided composite structures are employed in various sports especially golf, baseball and tennis. The specific applications are roller blades, bike frames, golf stick, tennis rackets, baseball stick, ski and surf equipment and footwear. Three-dimensional warp knitted spacer fabrics are also extensively used in both sports shoes and garments due to its lightweight, springiness, washability and air permeability properties [149].

7. Future trend and technology nonwoven fabrics

Two- and three-dimensional textile fabrics are increasingly utilized technical textile areas from garments to structural load-bearing materials for various industries such as aerospace, defense, civil engineering, and transportation industries [150]. Novel fabric formation techniques are also being developed from the fundamental methods like weaving, braiding, knitting and nonwoven technology.

The 2D nonwoven fabric is the basic planar sheet material that can be produced by various methods including needling, stitching, hydroentanglement, spunbonding, meltblown and electrospinning techniques. In addition, 3D nonwoven fabric serves as a thick fabric structure with various uses and is fabricated by needling, stitching and electrospinning techniques. More development on nonwoven technology is expected with the evolution of electrospinning process to make nano-fiber-based nonwoven planar sheet or 3D entangled fabrics. This will open up new opportunities especially in medical and hygiene applications. Furthermore, the use of bioactive and alloy fibers in nonwoven materials produced by needlepunching or hydroentanglement improves the performance of hygiene nonwoven materials from many aspects such as absorbency, thermo-physical and comfort properties, prevention of cross-infection of diseases and suppression of the generation of unpleasant odors. The reliability and

durability of surgical implants such as hip and knee replacements could be improved by electrospun nanofiber coatings [151]. The filtration materials could be reusable, and durable, as well as biodegradable, and recyclable [152]. The natural fiber based nonwoven fabric will be extensively used for the future transportation industries due to the fuel efficiency, environment protection, recycling and economic performance [153]. Nonwoven nanomaterials are expected to be the subject of future research and will find extensive usage in medical, energy, electronics, automotive and other industrial applications.

8. Conclusions

Two and three-dimensional fabric architectures and fabrication techniques have been reviewed. Two dimensional woven, braided, knitted and nonwoven fabrics have been widely used as various structural composite parts in civilian and defense related areas. However, composite structure from biaxial layered fabrics is prone to delamination between layers due to the lack of z-fibers and has crimp that lowers the properties. Biaxial fabric method and techniques are well developed. Triaxial fabrics have an open structure and low fabric volume fractions. However, in-plane properties of triaxial fabric are more homogeneous in comparison with biaxial fabric due to bias yarns. On the other hand, biaxial and triaxial braided fabrics have size and thickness limitations. Triaxial fabric method and techniques are also well developed.

The woven fabric consists of multiple layers and is not subject to delamination due to the z-fibers. However, 3D woven fabric has low in-plane properties because of low fiber volume fraction. Three-dimensional braided fabrics are constituted from multiple layers. The characteristic intertwine type interlacement of these fabrics provides out-of-plane reinforcement preventing any delamination. Nevertheless, 3D braided fabrics suffer from low transverse properties due to lack of filling yarns like those in a 3D woven fabric. They also have limitations in terms of size and thickness. Various 3D woven and braided fabrication method and techniques are commercially available.

Various unit cell-base models on 3D woven, braided and knitted structures were developed to define the geometrical and mechanical properties of these structures. Most of the unit cell based models include micromechanics and numerical techniques.

Multiaxis 3D knitted fabric has four layers integrated with stitching. The production process has been perfected. The fabric is not subject to delamination owing to the out-of-plane reinforcement provided by the stitching yarn. It has also superior in-plane properties due to ±bias yarns. However, it has some limitations related to layering. Multiaxis 3D woven fabric consists of multiple layers. Out-of-plane reinforcement is provided by z-fibers which prevent delamination. In-plane properties are improved by ±bias yarn layers. Multiaxis 3D braided fabrics have also multiple layers and no delamination, and their in-plane properties are enhanced due to the ±bias yarn layers. However, multiaxis 3D technique has its early development stages. This will be the future technological challenge in multiaxis 3D preform formation subject.

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