

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

185,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Textile Reinforced Structural Composites for Advanced Applications

Nesrin Sahbaz Karaduman, Yekta Karaduman,
Huseyin Ozdemir and Gokce Ozdemir

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.68245>

Abstract

Textile-reinforced composites are increasingly used in various industries such as aerospace, construction, automotive, medicine, and sports due to their distinctive advantages over traditional materials such as metals and ceramics. Fiber-reinforced composite materials are lightweight, stiff, and strong. They have good fatigue and impact resistance. Their directional and overall properties can be tailored to fulfill specific needs of different end uses by changing constituent material types and fabrication parameters such as fiber volume fraction and fiber architecture. A variety of fiber architectures can be obtained by using two- (2D) and three-dimensional (3D) fabric production techniques such as weaving, knitting, braiding, stitching, and nonwoven methods. Each fiber architecture/textile form results in a specific configuration of mechanical and performance properties of the resulting composites and determines the end-use possibilities and product range. This chapter highlights the constituent materials, fabric formation techniques, production methods, as well as application areas of textile-reinforced composites. Fiber and matrix materials used for the production of composite materials are outlined. Various textile production methods used for the formation of textile preforms are explained. Composite fabrication methods are introduced. Engineering properties of textile composites are reviewed with regard to specific application areas. The latest developments and future challenges for textile-reinforced composites are presented.

Keywords: textile-reinforced composites, fiber architectures, textile production methods, advanced applications, engineering properties

1. Introduction

A composite material can be defined as a combination of a reinforcement material and a matrix. The properties of a composite are superior to the properties of the individual components. Reinforcement is the main load-bearing component and is responsible for the strength and stiffness of the composite material. Reinforcement forms include fibers, particles, and flakes. Matrix, on the other hand, keeps the reinforcement in a given orientation and protects it from chemical and physical damage. It is also responsible for the homogeneous distribution of an applied load between the reinforcement elements. Composite materials are generally employed when traditional materials such as metals, ceramics, and polymers do not satisfy the specific requirements of a certain application. One of the main advantages of composite materials is that they can be designed to obtain a wide range of properties by altering the type and ratios of constituent materials, their orientations, process parameters, and so on. Composites also have high mechanical properties with a low weight which makes them ideal materials for automotive and aerospace applications. Other advantages of composites include high fatigue resistance, toughness, thermal conductivity, and corrosion resistance. The main disadvantage of composites is the high processing costs which limit their wide-scale usage.

Fiber reinforcements basically cover short and continuous fibers and textile fabrics. Textile-reinforced composites consist of a textile form as the reinforcement phase and usually a polymer for the matrix phase. 2D or 3D woven fabrics, knitted fabrics, stitched fabrics, braids, nonwovens, and multiaxial fabrics can be used as textile materials. Each of these textile forms has its own fiber architecture and combination of properties such as strength, stiffness, flexibility, and toughness which are translated to composite performance to a certain extent. Different textile architectures offer an enormous potential for designing the composite properties. The first textile structure to be used in composite reinforcement was 2D biaxial fabric to produce carbon-carbon composites for aerospace applications. However, multilayered 2D fabric structures suffer from poor interlaminar properties and damage tolerance due to lack of through-the-thickness fibers (z-fibers). 3D textile fabrics with through-the-thickness fibers have improved interlaminar strength and damage tolerance. Therefore, 3D textile composites have attracted great interest in the aerospace industry since the 1960s in order to produce structural parts that can withstand multidirectional mechanical and thermal stresses [1]. Advantages of 3D textile-reinforced composites are their high toughness, damage tolerance, structural integrity and handleability of the reinforcing material, and suitability for net-shape manufacturing. Today, composites reinforced with 2D and 3D fabrics are in common use in various industries including aerospace, construction, automotive, sports, and medicine.

This chapter reviews the fabrication, properties, and application areas of textile-reinforced composites. Fiber and matrix types used for composite production are presented. Various textile forms and their production methods are outlined. Properties and performance of textile composites are reviewed with regard to specific application areas. The future possibilities and challenges for textile-reinforced composites are discussed.

2. Materials and structures used

2.1. Fibers

2.1.1. Carbon fibers

Carbon fibers are one of the oldest and most common classes of high-performance fibers used in composite production. The most important carbon fiber types with respect to carbon source are polyacrylonitrile (PAN)-based and pitch-based carbon fibers. Other types include vapor-grown fibers and carbon nanotubes. Graphite fiber refers to a specific member of carbon fibers whose atomic structure is similar to that of carbon; both consist of sheets of carbon atoms arranged in a regular hexagonal pattern (graphene sheets). The only difference is that in graphite, adjacent aromatic sheets overlap with one carbon atom at the center of each hexagon. **Table 1** lists the mechanical properties of selected carbon fibers [2].

PAN-based carbon fibers account for most of the carbon fibers ($\approx 90\%$) in commercial use. The first step in PAN-based carbon fiber production is the preparation of a suitable precursor which is critical for the quality of the resulting fibers. For this purpose, acrylonitrile monomers are mixed with plasticized acrylic comonomers and a catalyst, such as itaconic acid or methacrylic acid in a reactor. Free radicals are formed within the molecular structure of acrylonitrile by continuous stirring of the ingredients which leads to polymerization. The obtained acrylonitrile in powder form is then dissolved in either organic or aqueous solvents to prepare the spin “dope.” The next step is the spinning of PAN precursor fibers. Either wet spinning or dry spinning techniques can be employed. Wet spinning is the preferred method for the production of high-performance fibers. In the wet spinning process, the spin dope is forced through a spinneret into a coagulating bath, and then stretching is applied to form the fibers. In dry spinning technique, the spin dope enters a hot gas chamber after passing through the spinneret. The obtained PAN precursor fibers are then oiled, dried, and wound

Type	Manufacturer	Product name	Tensile strength (GPa)	Young's modulus (GPa)	Strain to failure (%)
PAN	Toray	<i>T300</i>	3.53	230	1.5
		<i>T1000</i>	7.06	294	2.0
		<i>M55J</i>	3.92	540	0.7
	Hercules	<i>IM7</i>	5.30	276	1.8
GP-Pitch	Kureha	<i>KCF200</i>	0.85	42	2.1
HP-Pitch	BP Amoco	<i>Thornel P25</i>	1.40	140	1.0
		<i>Thornel P75</i>	2.00	500	0.4
		<i>Thornel P120</i>	2.20	820	0.2

Table 1. Mechanical properties of selected carbon fibers [2].

onto bobbins. These fibers are fed through a series of ovens at a temperature of 200–300°C for the oxidation step which combines oxygen molecules from the air with the PAN fibers and causes the cross-linking of polymer chains. The oxidized PAN fibers contain approximately 50–65% carbon molecules together with hydrogen, nitrogen, and oxygen. After oxidation, PAN fibers are subjected to carbonization in an oxygen-free atmosphere by going through a series of specially designed furnaces with progressively increasing temperatures (from 700–800 to 1200–1500°C). Fibers must be kept under tension throughout the production process. The resulting carbon fibers contain more than 90% of carbon. The main difference between carbon and graphite is that the former is carbonized at about 1315°C and contains 93–95% of carbon, whereas the latter is graphitized at 1900–2480°C and contains more than 99% of carbon. PAN-based carbon fibers are the material of choice to obtain high-strength composites.

Pitch-based carbon fibers fall into two categories such as the low-strength general-purpose fibers and high-performance fibers. Low-strength fibers are produced from isotropic pitch which is obtained from high-boiling fractions of crude oil. Two different spinning techniques such as centrifugal spinning and melt blowing can be utilized to produce low-strength carbon fibers. In centrifugal spinning, molten pitch is forced through small holes in a rotating bowl. The pitch stream is converted into fibers by centrifugal forces. The fibers are obtained in the form of tows or mats [2]. In melt blowing, on the other hand, molten stream of pitch is extruded into a high-velocity gas stream which converts the pitch into fiber form [3]. High-performance fibers are produced from mesophase pitch by melt spinning process followed by stabilization and carbonization. Mesophase pitch, a liquid crystalline material, is synthesized from pure aromatic hydrocarbons such as naphthalene and methylnaphthalene. Mesophase pitch has high purity and aromaticity which leads to high orientation in the final material [4]. Liquid crystalline materials readily orient during fiber formation and create a high degree of molecular orientation which leads to fibers with high moduli and thermal conductivity [5].

2.1.2. *Aramid fibers*

The development of aramid fibers (aromatic polyamides) dates back to as early as the 1960s when DuPont released its meta-aramid fiber with product name Nomex® in 1967. Later, in 1971, the same company developed and commercialized a para-aramid fiber, Kevlar®, with high strength and modulus [6]. Then, in the late 1980s, another para-aramid fiber, Twaron® was developed (Twaron® is a registered product of Teijin). Aromatic copolyamide fiber Technora® which is a more flexible fiber having high tenacity appeared on the market in 1987 [7].

Aromatic polyamides are synthesized using aromatic diamines and diacids or diacid chlorides [8]. There are two different well-established methods for the polymerization of aramid fibers such as low-temperature (<50°C) polycondensation [9] and direct polycondensation in solution using phosphites in the presence of metal salts [10]. Low-temperature polycondensation is generally preferred for the production of meta- and para-aramid fibers because of its high efficacy. Aramid fibers can be spun by using wet spinning or dry-jet wet spinning techniques. The wet spinning technique is used to produce meta-aramid fibers. It results in a semicrystalline fiber with partially oriented molecular chains. The dry-jet wet spinning technique is more effective in producing highly oriented high-strength/high-modulus fibers and usually

preferred to produce para-aramid fibers. In this technique, the anisotropic polymer dope is forced through spinnerets at approximately 100°C through a narrow air gap into cold water (0–4°C). The spinnerets and air gap ensure the alignment of liquid crystal domains and result in highly crystalline and oriented aramid fibers. The attenuated filaments are washed, neutralized, and dried to obtain high-strength and high-modulus aramid fibers. The as-spun fibers are subjected to heat treatment under tension to further improve their tenacity and modulus [11].

Meta-aramids such as Nomex® are highly resistant to temperature, chemical degradation, and abrasion. They are generally used for heat-resistant workwear and firefighter clothing. Para-aramids such as Kevlar®, on the other hand, have high tensile strength, modulus, and toughness. Applications of para-aramid fibers include composite reinforcement, ballistic protection, wire and cable, protective gloves, and so on.

2.1.3. Glass fibers

Modern glass fibers that we know today were discovered in the early 1930s when Dale Kleist of Owens-Illinois Glass Company accidentally produced glass fibers during his attempts to seal architectural glass blocks together by melting and spraying glass. This crucial breakthrough paved the way for the mass production of insulation-quality glass fibers. In 1938, Owens-Illinois joined with Corning Glass Company to form Owens-Corning Fiberglass Corporation which is still one of the leading glass fiber manufacturers today. During the same years, they patented the product “Fiberglas” which is the origin of generic reference to fiberglass. Later developments led to the mass production of continuous glass filaments for composite reinforcement and other advanced applications [12].

The main ingredient of all glass fibers is silica (SiO_2). Other ingredients such as Al_2O_3 (aluminum oxide), CaO (calcium oxide), and MgO (magnesium oxide) are incorporated for additional functionality and process viability. For example, B_2O_3 (boron oxide) is added to increase the margin between the melting and crystallization temperatures of E-glass in order to avoid nozzle clogging during the fiber formation step. Another example is S-glass which contains a higher percentage of SiO_2 for an enhanced tensile strength. The production of E-glass fiber takes place in five basic steps such as mixing, melting, fiber formation, coating, and drying/packaging. In the first step, the starting materials are thoroughly mixed with the aid of an automated blender. Extreme care must be taken when weighing and adding the ingredients since the slightest deviation could affect the properties of the resulting fibers. Then, the mixture is melted at a temperature of about 1400°C in a sectional refractory furnace. The next step is the fiber formation which involves extrusion and attenuation. In extrusion, the molten glass from furnace is delivered through a bushing with very fine orifices. Molten glass streams coming out of the bushing are cooled by water jets and attenuated by mechanically drawing with the aid of a high-speed winder in order to obtain the fine glass filaments with a diameter between 4 and 34 μm . Then, size is applied which typically contains lubricants for abrasion protection and adhesion promoters or coupling agents to increase the fiber/matrix adhesion in composite materials. Glass fibers can be produced in various forms such as rovings, chopped strand mats, and milled fibers [13]. There are various types of glass fibers such as E-glass, i.e., general-purpose glass for low electrical conductivity, S-glass for high strength,

R-glass for high strength and acid corrosion resistance, Te-glass for high strength at elevated temperatures, D-glass for low dielectric constant, ECR-glass for high corrosion resistance, and ultrapure silica fibers, hollow fibers, and trilobal fibers for more advanced applications [14]. **Table 2** lists the specific properties of glass and other fibers in comparison to conventional materials [15].

2.1.4. *Ultrahigh-molecular-weight polyethylene (UHMWPE) fibers*

Polyethylene (PE) is produced through polymerization of ethylene monomers via either free radical polymerization or ionic polymerization. Free radical polymerization results in low-density polyethylene (LDPE) which has a branched structure and low mechanical properties. Ionic polymerization of PE leads to the formation of linear chains with little or no branching with a high level of crystallinity [16]. This structure is referred to as high-density polyethylene (HDPE) and is used for the manufacture of high-performance PE fibers. Another important characteristic of PE fibers is the molecular weight. PE with low molecular weight is of no interest in fiber production since it has low mechanical properties and melting point. As the molecular weight increases, mechanical properties and thermal stability increase as a consequence of enhanced molecular entanglement and intermolecular interactions. PEs with molecular weight in the range of 10^4 – 10^5 Da are used to produce commercial products like injection-molded plastics, beverage container films, and melt-spun PE fibers used in high-tenacity ropes. When the molecular weight reaches approximately 2–6 million Da, PE is referred to as ultrahigh-molecular-weight polyethylene (UHMWPE). This structure is composed of very long chains of PE with a very high level of orientation and crystallinity. UHMWPE has

	Young's modulus (GPa)	Tensile strength (GPa)	Density (g/cm ³)	Specific modulus (Mm)	Specific strength (km)	Failure strain (%)	Fiber diameter (μm)
E-Glass	72	1.5–3.0	2.55	2.8–4.8	58–117	1.8–3.2	10–20
S-Glass	87	3.5	2.5	3.5	140	4.0	12
S2-Glass	86	4.0	2.49	3.5	161	5.4	10
Carbon	220–350	2.3–3.7	1.8–2.0	12–18	130–190	0.7–1.7	7
Aramid	60–180	2.65–3.45	1.44–1.47	4.0–12.2	180–235	4–1.9	12
PBT	250	2.4	1.5	17.0	160	1.0	20
PE	60–120	1–3	1.0	6–12	100–300	–	–
Steel	210	0.34–2.1	7.8	2.7	4.3–27	–	–
Aluminum	70	0.14–0.62	2.7	2.6	5–22	–	–
Bulk glass	60	0.05–0.07	2.6	2.3	1.9–2.7	0.08–0.12	–
Epoxy	2–3.5	0.05–0.09	1.2	0.16–0.29	4–7.5	1.5–6	–
HDPE	1.3	0.027	0.96	0.135	2.8	–	–

Table 2. Specific properties of glass and other fibers in comparison to conventional materials [15].

high strength-to-weight ratio as well as high resistance to abrasion, chemicals, and fatigue. Commercial UHMWPE fibers include DSM's Dyneema and Honeywell's Spectra fibers.

UHMWPE fibers are manufactured in a gel spinning process which enables draw ratios in excess of $50\times$ [16]. The PE gel precursor is formed by swelling UHMWPE in solvent at high temperatures [17]. The gel state reduces the level of polymer entanglement, thus enhancing the drawability of the polymer. It has been found that 5–8 wt% polymer in solution results in optimal drawability [18]. The gel is extruded through a quenching bath which is followed by heating and drawing. The optimum drawing temperatures are above 110°C at which the alpha relaxation occurs promoting the unraveling of folded chains and facilitating the orientation of the crystals [16]. UHMWPE fibers are used in a range of applications such as body armor and composite helmets, climbing ropes, cordages, sails, etc.

2.1.5. Ceramic fibers

Ceramic fibers in continuous form are commercially available in two different classes such as oxide fibers and nonoxide fibers. Oxide fibers are based on the alumina-silica ($\text{Al}_2\text{O}_3\text{-SiO}_2$) system and on α -alumina ($\alpha\text{-Al}_2\text{O}_3$), whereas the nonoxide fibers are based on β -phase silicon carbide (SiC) [19]. Two important ceramic fibers in commercial production are silicon carbide (SiC) and aluminum oxide or alumina (Al_2O_3); other types are available on a much smaller scale. Ceramic fibers are polycrystalline in structure and known for their outstanding temperature resistance and strength retention at high temperatures. For example, SiC retains its strength above 650°C , and Al_2O_3 up to about 1370°C . Ceramic fibers are mainly used as reinforcement in metal and ceramic matrix composites. Ceramic fibers can be manufactured by using either of the two techniques such as chemical vapor deposition (CVD) and spinning. In CVD, ceramic is vapor-deposited on a heated substrate usually made of tungsten or carbon filaments. For example, silane and hydrogen gases are reacted in a tubular glass reactor at about 1300°C to produce β -SiC vapors which is then deposited on a tungsten or carbon substrate filament. Spinning technique involves the preparation of a precursor polymer which is then converted into a precursor filament by using conventional spinning techniques such as melt, dry, or wet spinning or the sol-gel method. This precursor filament is finally converted cohesively to the desired ceramic structure via controlled pyrolysis [13].

2.2. Matrices

2.2.1. Thermosetting matrices

Thermosetting polymers have long been used as matrix materials for textile composites, and they are far more common compared with thermoplastics. Processing with thermosetting matrices takes place in two basic steps such as the application of the liquid resin to the textile material and curing the resin in the presence of heat and pressure. The resin hardens gradually upon the application of heat owing to cross-linking of its molecules. The processing temperature typically ranges from room temperature to about 200°C [20]. The curing process is irreversible unlike thermoplastics. The most important thermosetting matrices include epoxy, unsaturated polyester (PES), vinylester, and phenolics. Advantages of thermosets include low

processing temperatures, low viscosity/high wettability of the resins, high mechanical properties, high-temperature resistance, and good strength retention at high temperatures.

2.2.2. Thermoplastic matrices

Thermoplastic matrices melt when they are heated and harden upon cooling. Thermoplastic composites are produced in a heat-form-cool cycle, and thus they can potentially be recycled at the end of life. The process is reversible unlike thermosets. Thermoplastics such as polypropylene (PP), polyethylene (PE), polyamide (PA), polyester (PET), polystyrene (PS), and polyether ether ketone (PEEK) are increasingly used in reinforced composites. Among the numerous advantages of thermoplastics over thermosets are lower material and manufacturing costs, short processing times, unlimited shelf-life, reprocessability/recyclability, fewer safety risks, thermoformability, ductility, high toughness, and environmental tolerance [20].

2.3. Textile reinforcement forms

2.3.1. Two-dimensional (2D) fabrics

2.3.1.1. 2D woven fabrics

A woven fabric consists of two or more sets of yarns interlaced together to form a continuous 2D surface. The most common 2D woven fabric is the biaxial (orthogonal) fabric which is composed of longitudinal (warp) yarns and transverse (weft or filling) yarns interlaced at right angles [21]. **Figure 1** shows the schematic view of a loom used for the fabrication of woven fabrics [21]. Basically, four distinct motions are required to complete the fabric production cycle such as (1) shedding, (2) filling insertion, (3) beat-up, and (4) warp and fabric control. Shedding involves the movement of harnesses which contain warp yarns in order to open a path for weft insertion. The vertical movement of harnesses is achieved by using separate cams. In addition to the cam system, there are other mechanisms for shedding control. For example, the dobby head mechanism uses a maximum of 24 harnesses, thus enabling the control of interlacing 24 different groups of warp yarns. Jacquard looms, on the other hand, enable the control of every individual yarn across the fabric width and hence provide greatly enhanced design possibilities. The number of harness frames depends on the weave type. For example, two harness frames are used for plain-weave fabrics. Other weave types used in composites such as twill, basket, and satin require more harness frames. **Figure 2** shows the basic weave types used for composite reinforcement [22]. For the filling insertion, filling yarn is fed through the shed opening across the fabric width. There are different alternatives for carrying the filling yarn such as projectiles, rapiers, air jets, and water jets. The final operation is beat-up which incorporates the filling yarn into the fabric structure. A wire grate called a reed is used for this purpose. Biaxial woven fabric has a good dimensional stability and balanced properties in the fabric plane. Another advantage of this fabric type is the ease of handling and low fabrication cost. Disadvantages include poor in-plane shear resistance, lack of through-the-thickness reinforcement, and poor fiber-to-fabric tensile strength translation

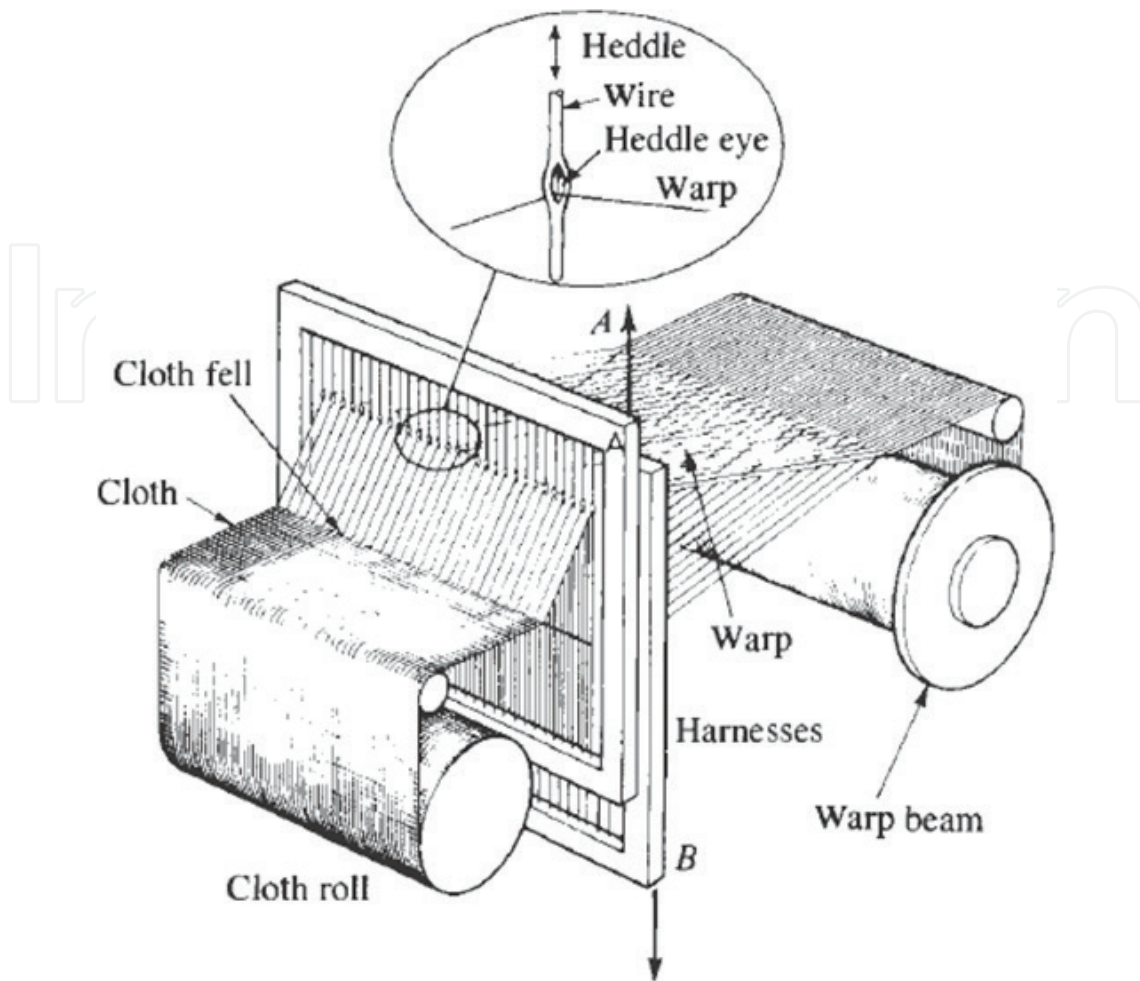


Figure 1. Schematic view of a weaving loom [21].

efficiency due to yarn crimp. Another type of 2D woven fabrics is triaxial fabric which consists of three yarn sets interlaced together at 60° angles. Triaxial fabrics are more isotropic and possess higher in-plane shear rigidity compared with the orthogonal woven fabrics [23].

2.3.1.2. 2D knitted fabrics

A knitted fabric is constituted from interlacing loops in transverse or longitudinal direction. There are two basic types of 2D knitted fabrics such as weft knitted and warp knitted fabrics. In weft knitting, the loops are formed in widthwise direction by a single yarn. In warp knitting, loops are formed in lengthwise (**Figure 3**) [24]. There are four primary base weft knitted structures such as plain, rib, interlock, and purl from which all the other weft knitted structures are derived. Horizontal rows of knitted loops are termed “courses,” whereas the vertical columns of intermeshed loops are termed “wales.” The length of the yarn in a loop is referred to as “stitch length.” The total number of loops in a given fabric area is termed “stitch density” which is a very important fabric parameter for composite applications. Stitch density is the product of the number of courses in one inch and the number of wales in one inch. The most

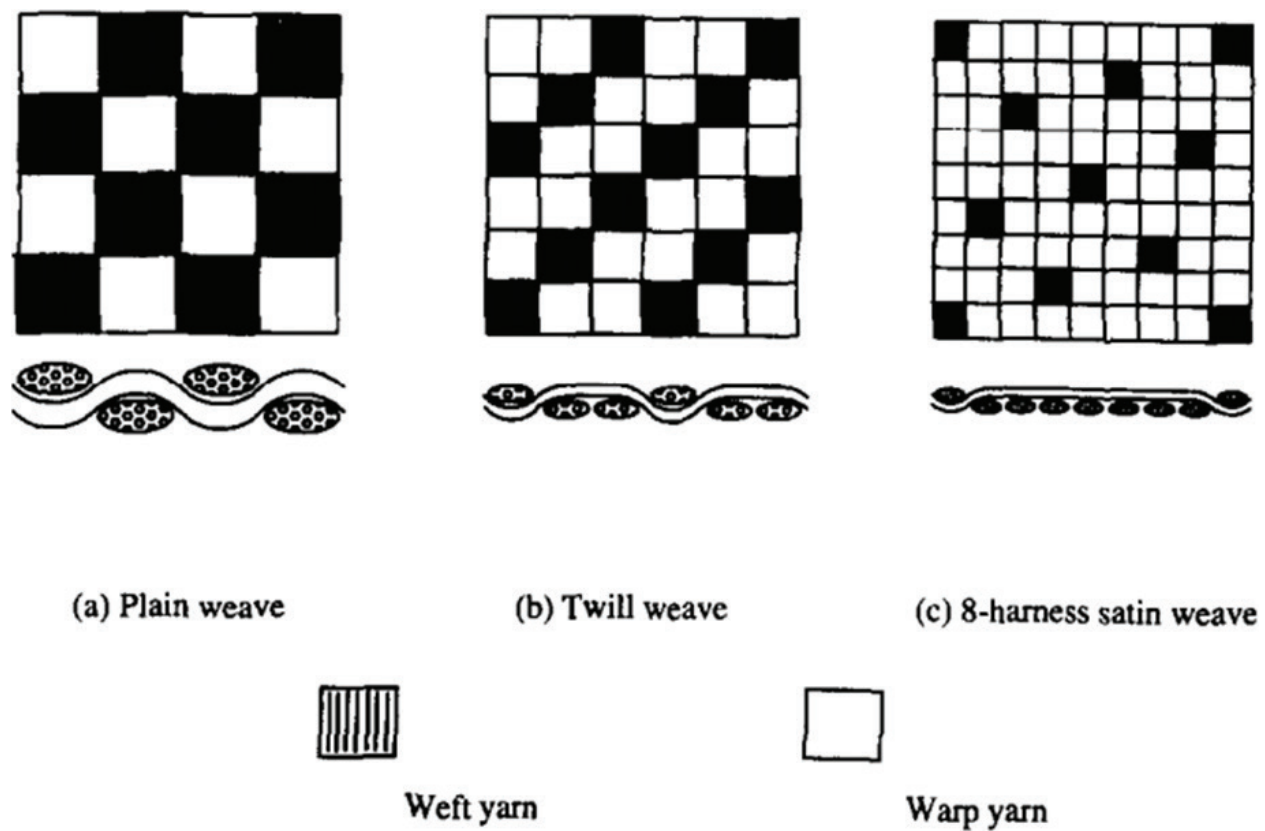


Figure 2. Basic weave types: (a) plain weave, (b) twill weave, and (c) eight-harness satin weave [22].

important elements of the knitting machine are the yarn supply unit which consists of the yarn package or beam accommodation, tensioning devices, yarn feed control, and yarn feed carriers; knitting elements; the fabric takeaway mechanism, and quality control systems such as stop motions and fault detectors [24].

Weft and warp knitted fabrics can readily extend in all directions and are thus suitable for the manufacture of complex-shaped composite parts and deep-draw molding applications. Knitted fabrics have a great extensibility under tension which gives them a strong energy

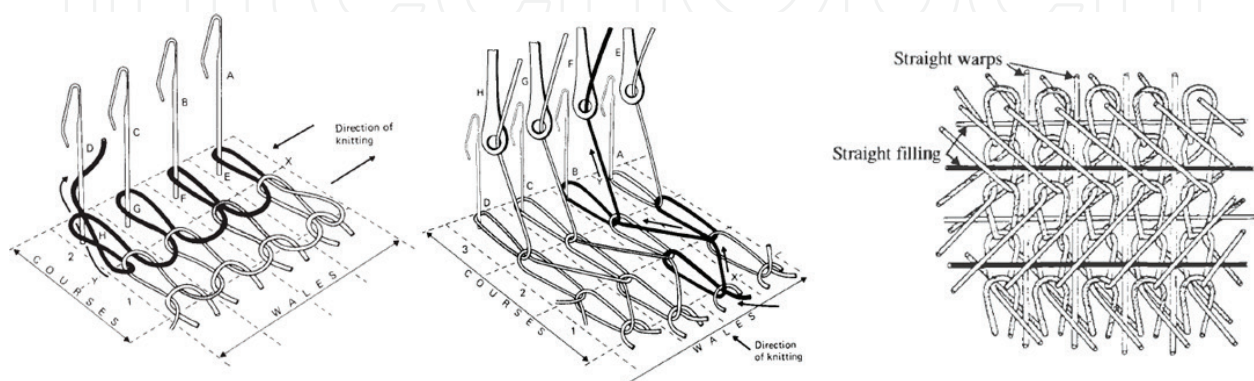


Figure 3. Weft knitting (left), warp knitting (middle) [24], and laid-in fabric [25].

absorption and dissipation capability when used in composite materials. Inlaid knitted fabrics offer dimensional stability and high mechanical properties of the resulting composites. These fabrics consist of a base weft or warp knitted structure together with non-knitted yarns which were incorporated (laid in) into the structure during the same knitting cycle (**Figure 3**) [25]. The base fabric structure holds in position the laid-in yarns. An inlay yarn may be 6–8 times coarser than the optimum yarn count for that particular machine type [24]. It is possible to introduce the laid-in yarns in weft knitting or warp knitting by using traditional knitting machines or by employing special equipment. Especially, weft-inserted warp knits with laid-in warp yarns offer high yarn-to-fabric translation efficiencies and greater in-plane shear resistance compared with their woven equivalents [23].

2.3.1.3. 2D braided fabrics

A braided fabric is produced by intertwining yarns about each other. 2D braiding technique can be used to produce complex-shaped tubular preforms. The process is best described by Maypole process in which the yarns are braided over a mandrel by yarn carriers moving in a rotational fashion around the mandrel. The braiding machine consists of three main components: (1) yarn carriers, (2) interlinking mechanism, and (3) take-up mechanism (**Figure 4**) [26]. The braiding fiber tows are placed onto spools that are then loaded onto the carriers. The carriers are connected to the braiding machine through “horndogs” and “horngears,” which propel the carriers into their rotational path. Different braid patterns can be obtained by modifying the horn gears. Axial yarns can be introduced in the braids for enhanced stiffness by using hollow horn gears [26].

There are three basic braided structures such as diamond, regular, and Hercules braid. The regular braid is the most common form in production. In diamond braid, any given yarn passes over and under one opposing yarn, and this pattern repeats itself. Following the same notation, regular braids can be designated as 2/2, whereas Hercules braids are 3/3. Triaxial braided fabrics can be formed by incorporating longitudinal (triaxial) yarns within the tubular biaxial fabric structure. The most important parameters of a braided fabric are braid angle, θ , (which can vary between 10 and 80°), cover factor, and the volume percent of longitudinal yarns in the structure. Braided fabrics are generally used for complex-shaped round composite parts due to their high extensibility in fabric state and also in tubular form [27]. 2D braiding is well established in composite industry in terms of knowledge and expertise unlike 3D braiding which is still in its infancy.

2.3.1.4. 2D nonwoven fabrics

A nonwoven fabric is basically a web structure made of fibers which is consolidated by employing various techniques. The production of nonwovens involves two basic steps such as the web formation and consolidation. For web formation various techniques can be employed:

- The drylaid system (carding or airlaying)
- The wetlaid system
- The polymer-based system (spunbonding, melt blowing, flashspun)

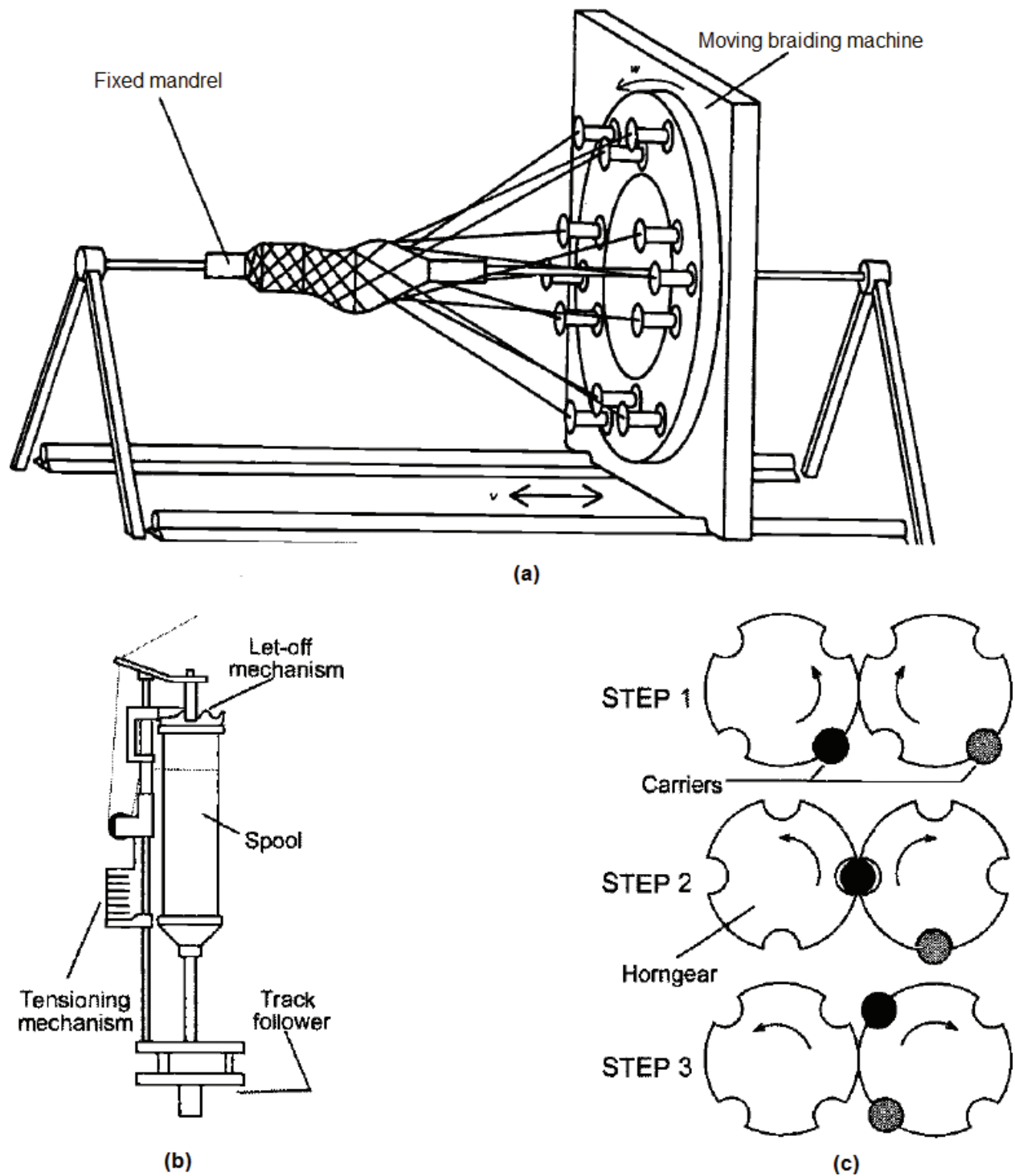


Figure 4. (a) Schematic diagram of a typical braiding machine, (b) yarn carrier, and (c) horngear movement [26].

Drylaid system has its origins in the textile processing. In this method, the fibers are carded or aerodynamically formed as loose webs with no practical strength. Then, these webs are bonded by various techniques such as needle punching, thermobonding, chemical bonding, hydroentanglement, etc. In the wetlaid system, first the fibers are dispersed in water, and the fiber/water suspension is transferred on a moving screen which can filtrate the water for web formation. Then, the web is dried and bonded. In spunbonding process, synthetic filaments

are extruded from polymer onto a conveyor in the form of a randomly oriented web. In melt blowing, on the other hand, molten thermoplastic resin coming out of an extruder die tip is blown onto a conveyor by using air to produce self-bonded webs.

After the formation, the webs are bonded by using mechanical, chemical, or thermal means. The extent of bonding determines the strength, flexibility, porosity, and density of the resulting nonwovens. Mechanical bonding covers the needle punching, stitchbonding, and hydroentanglement techniques. In the needle punching process, the fiber web is entangled by the action of reciprocating barbed needles. In stitchbonding, fiber webs are bonded using stitching yarns. Hydroentanglement employs high-velocity water jets and turbulent water flow to entangle the fiber web. In chemical bonding, adhesive binders are applied to webs by spraying, impregnating, foaming, or printing techniques, or the fiber surfaces are partially solvated by using suitable chemicals, and the fibers are bonded through these surfaces (a process called “solvent bonding”). Thermal bonding applies heat and pressure to soften and then fuse fibers together to form the final fabric [28]. Thermal energy can be transferred by calendering, welding, or using hot air.

2.3.2. *Three-dimensional (3D) fabrics*

3D fabrics offer through-the-thickness reinforcement and thus improve the interlaminar properties and damage tolerance of the resulting composites [29]. They can be also formed to near-net shape with complex architectures, thus eliminating the labor-intensive layering processes to create a composite part [30].

2.3.2.1. *3D woven fabrics*

3D woven fabrics are produced using multiple warp layers. The movement of each group of warp yarns is governed by separate harnesses so that some are formed into layers, while others weave these layers together. The most common classes of 3D weaves are angle-interlock, orthogonal, and fully interlaced weaves. Angle-interlock fabrics fall into two main categories depending on the number of layers that the warp weavers travel such as through-the-thickness angle interlock and layer-to-layer angle interlock. In through-the-thickness fabric, warp weavers pass through the entire thickness of the preform, while in layer-to-layer structure, they bind only two filling layers. Orthogonal interlock weaves, on the other hand, are characterized by warp weavers oriented from orthogonal to other in-plane directions and run through the thickness of the preform. The x- and y-yarns of the angle-interlock and orthogonal structures are not interlaced, whereas the x-yarns are interlaced with both y- and z-yarns in the fully interlaced structure [31]. **Figure 5** shows the schematic views of orthogonal, angle-interlock, and fully interlaced 3D woven structures [32]. 3D weaving is capable of producing a wide range of architectures [33]. The main limitations of 3D woven fabrics include the lack of in-plane bias reinforcement and long preparation and processing times.

2.3.2.2. *3D braided fabrics*

3D braiding technology is an extension of the well-established 2D braiding technology. 3D braids can be produced in either horgear or Cartesian machines. The main difference between

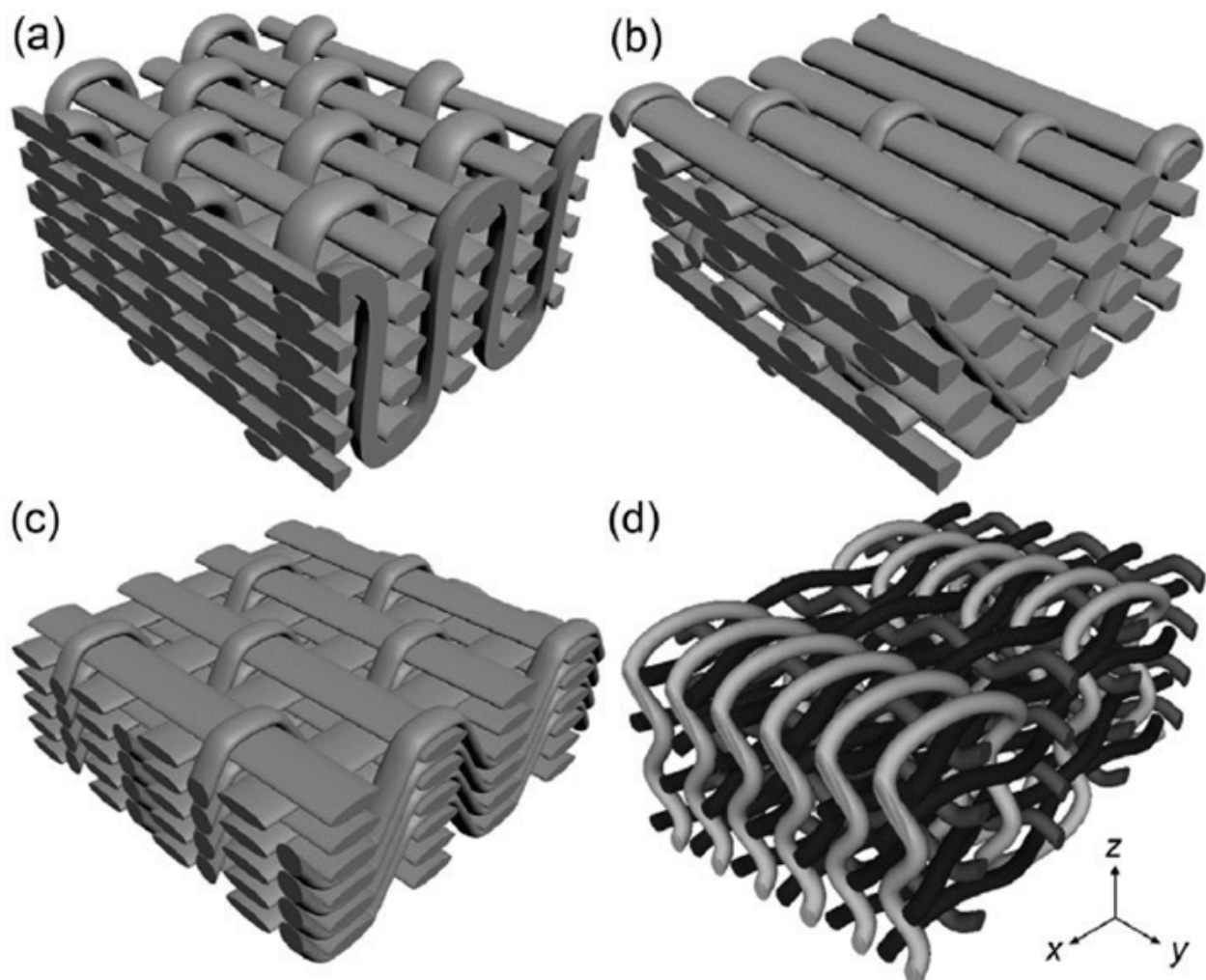


Figure 5. 3D woven structures: (a) orthogonal, (b) through-the-thickness angle interlock, (c) layer-to-layer angle interlock, and (d) fully interlaced [32].

these two types of machines originates from their yarn carrier displacement methods. Horn-gear-type machines have shorter braiding times, whereas the Cartesian machines are more compact and offer more design possibility for braid architecture. The first successful production of 3D braids dates back to the 1960s by using a technique referred to as four-step braiding (i.e., row and column). There are three major techniques of 3D braiding such as solid braiding, four-step braiding, and two-step braiding [34].

Solid braiding uses multiple interlocked braided layers. Complex 3D preforms can be produced by selective interlocking of braided layers which can be achieved through controlled movement of carrier yarns during braiding [35]. Some common braided structures that can be produced by solid braiding include two diagonal, three diagonal, four diagonal, spiral, and round braided structures.

Four-step braiding (also known as row and column) uses a flat bed which contains rows and columns of yarn carriers for forming the desired preform shape [36]. The number of steps

refers to the number of movements required for the yarn carriers to return to their original positions [37]. Additional carriers can be added outside of the array depending on the shape of the preform. As the name suggests, there are four different sequences of row and column motion which collaboratively intertwine the yarns and produce the braided preform. Various braid patterns can be obtained by changing the motion of rows/columns and take-up [38]. In the first step, alternate columns move a predetermined relative distance. In the next step, alternate rows shift. The third and fourth steps rearrange the rows and columns to return the device to its original configuration [37]. **Figure 6** shows the steps carried out in four-step braiding [38].

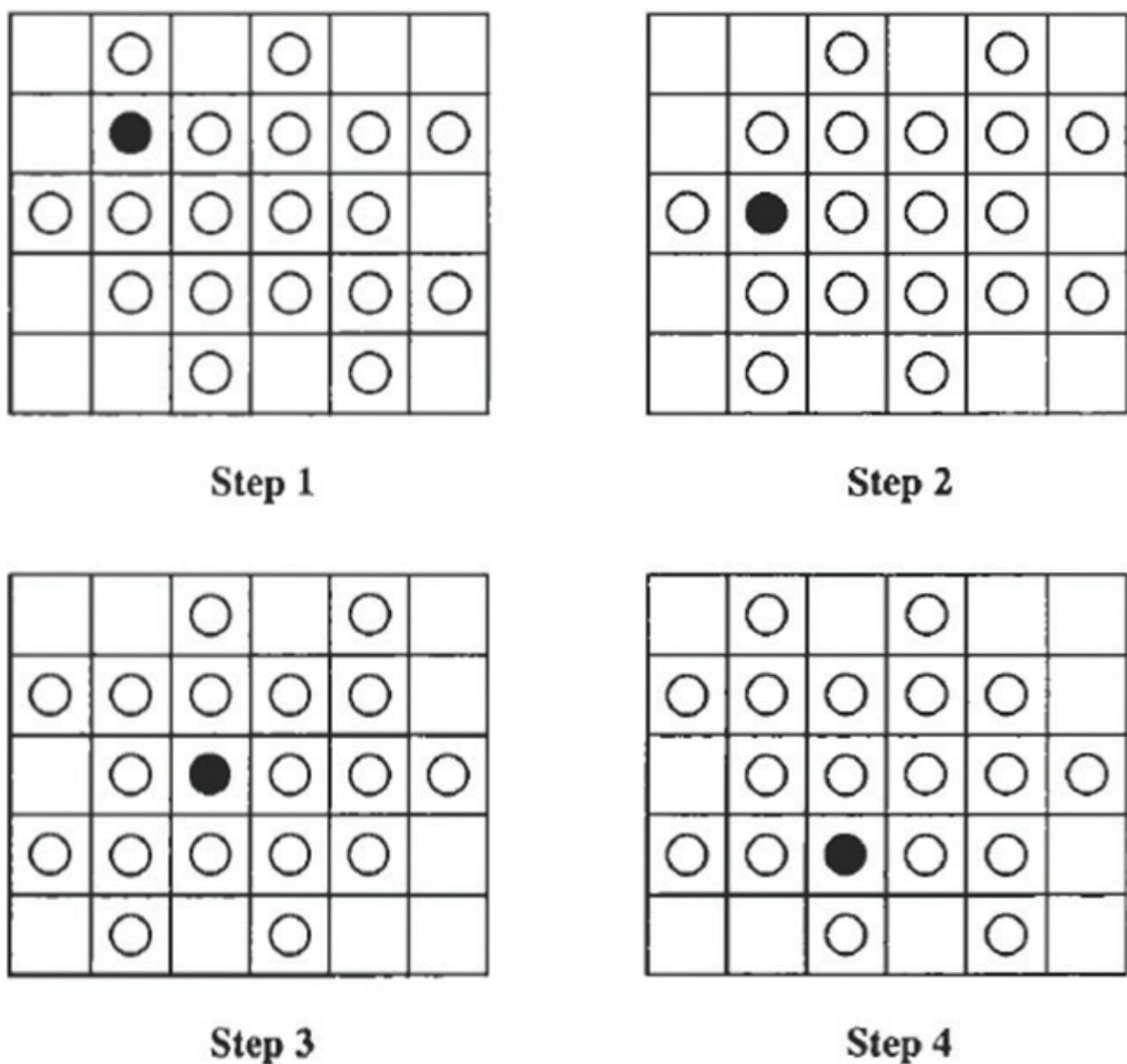


Figure 6. Schematic of the four-step braiding process [38].

Two-step braiding also uses a flat bed configuration, but unlike the four-step braiding, the two-step process utilizes a large number of yarns fixed in the axial direction and a smaller number of braiding yarns. Braiding carriers are positioned around the perimeter of the axial carriers. The final architecture of the braided preform is determined by the arrangement of axial carriers. The process is conducted in two steps in which the braiding carriers move completely through the structure between the axial carriers. This method is capable of producing a large number of shapes including circular and hollow fabrics. Complex-shaped parts can be produced by both four-step and two-step braiding processes [39]. It is also possible to braid holes into the preform structure which eliminates the drilling process. Sectional parts can be produced by adjusting the braiding process parameters which greatly reduce the problems related to section joints.

2.3.2.3. 3D knitted fabrics

3D knitted fabrics can be divided into three main categories: (1) integrally knitted fabric preforms produced by computer-controlled weft knitting machines, (2) multiaxial warp knit (MWK) fabrics, and (3) spacer fabrics which consist of two knitted fabric layers connected by through-the-thickness yarns between them.

Integrally knitted fabrics enable complex 3D shapes to be produced, eliminating labor-intensive sewing processes. Near-net-shape structures can be produced by using this fabric preforms. The first application of this type of fabric composites was a composite antenna made by Courtaulds Advanced Materials in the 1980s. Another example of near-net-shape structure was knitted by what is called the Pressure Foot® process [40]. This structure was used for carbon-carbon aircraft brakes in a collapsed form. The main advantage of integrally knitted preforms is their conformability which enables the production of very complex shapes. However, they have limited mechanical performance which restricts their wide-scale usage in composite applications.

Spacer fabrics are sandwich structures that consist of two knitted fabric layers connected by pile yarns that pass between them (**Figure 7**) [41]. A spacer fabric can be produced on a double needle bar Raschel machine. The center of the fabric may be filled with solid, liquid, or gaseous materials. The main advantage of this fabric is its low weight, flexibility, high bending stiffness,

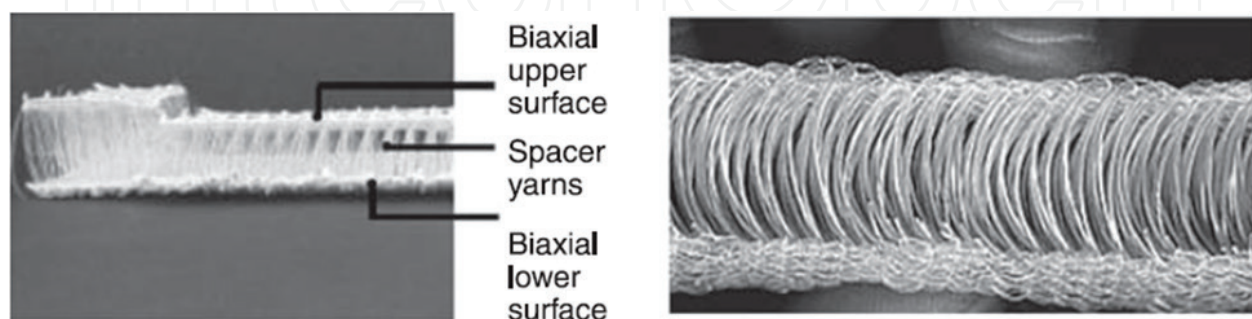


Figure 7. 3D spacer warp knitted fabrics [41].

and good acoustic and thermal insulating properties. The spacing can be up to 60 mm and widths up to 4400 mm [24]. Spacer fabrics are used in civil engineering as thin sheet-cement components, such as wall panels, claddings, and exterior siding [42, 43].

In MWK fabrics, several yarn layers each oriented in warp (0°), weft (90°), and bias ($\pm\theta$) directions are stacked one on top of the other and bonded by a through-the-thickness loop system to provide structural integrity (**Figure 8**) [44]. A chain or tricot stitch can be used for this purpose. MWK fabrics are designed to bear various loads in all in-plane directions as well as in through-the-thickness direction. These fabrics are also referred to as non-crimp fabrics since the constituent yarns lie straight in the fabric, making no interlacements or intertwine-type interactions. This non-crimp nature ensures the effective translation of yarn-to-fabric strength properties [45].

2.3.2.4. 3D stitched fabrics

Multi-stitched 3D fabric preforms can be obtained by simply stitching 2D fabrics of any kind in the thickness direction [46]. The main reason for using stitching in this way is to impart through-the-thickness reinforcement to 2D multilayered fabric constructions [47]. Stitching operation can be conducted manually or by using suitable stitching machines. The stitching can be applied in longitudinal (0°), transverse (90°), and bias ($\pm\theta$) in-plane directions. The most important processing parameters are the stitch density (stitch/unit length), the type and size of the stitching yarn, and the stitch type used. Lockstitch, modified lockstitch, and chain stitch are generally used [26]. Modified lockstitch is generally preferred because in this stitch type, the crossover knot between the bobbin and needle threads is positioned at either laminate surface, thus minimizing in-plane fiber distortion [26]. Aramid yarns are generally used for stitching although other yarns such as glass, carbon, and nylon have also been used. Stitching substantially increases the interlaminar delamination resistance of composite laminates under mode I and mode II loadings. They also exhibit higher postimpact

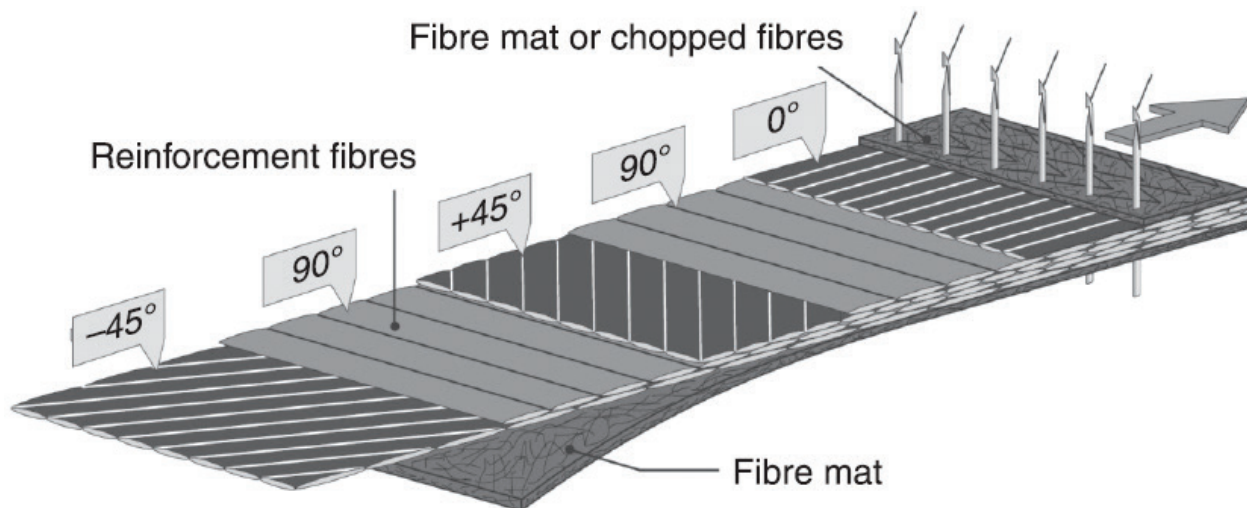


Figure 8. Multi-axial warp knit system [44].

residual mechanical properties compared with their unstitched counterparts [48]. Stitching also improves shear lap joint strength under both static and cyclic loadings due to reduced peel stresses. Therefore, stiffeners stitched onto a panel are more resistant to disbanding with reported improvements in load-carrying capability of up to 15% [26]. The main limitation with stitching, however, is the low in-plane properties and fatigue performance of the resulting structure because of the stitching holes which induce resin cracking, fiber breakages, and fiber misalignment [49].

2.3.2.5. 3D auxetic fabrics

An auxetic material has negative Poisson's ratio which means that they laterally expand upon stretching and laterally contract when compressed in longitudinal direction. Auxetic textile structures include fibers, yarns, and fabrics [50, 51]. 2D auxetic fabrics can be produced with auxetic yarns and fibers by using traditional textile technologies like weaving and knitting [52, 53]. Auxetic materials have several advantages over conventional materials such as high shear modulus and fracture toughness. They have synclastic property which means that they take dome shape when fixed on a curved surface rather than saddle shape in the case of conventional materials. Auxetic materials also have better impact and ballistic resistance due to the fact that in the event of an impact, the material flows toward the impact point unlike conventional materials which flow away from it [54]. These properties make auxetic composites quite attractive for automotive, aerospace, and civil engineering applications. Nonwoven and stitching technologies can be combined to produce 3D auxetic fabric structure [55]. The fabric consists of three yarn systems such as warp, weft, and stitch yarns. There is no interlacement between warp and weft yarns; they are held in position by out-of-plane stitch yarns. There is half-yarn spacing between the warp yarn sequences on alternating weft layers. When the fabric is compressed in the through-the-thickness direction, the warp yarns remain straight, whereas the weft yarns get crimped so that the structure remains unchanged in warp direction while shrinking in weft direction, thus exhibiting auxetic property (**Figure 9**) [55]. It was stated that the auxetic effect is mainly produced by spaces between the warp yarns. In order to ensure more strong auxetic effect, the weft yarns used should be flexible, whereas the warp yarns should be more rigid.

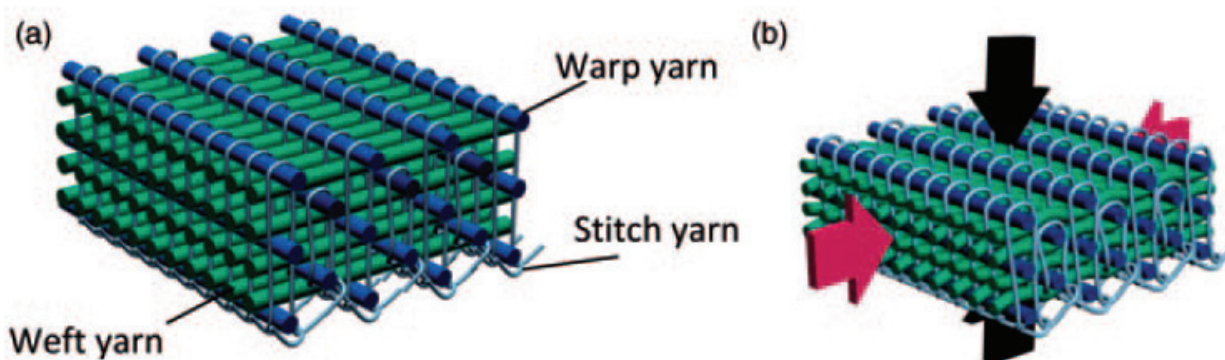


Figure 9. 3D auxetic textile structure: (a) initially and (b) under compression [55].

3. Composite manufacturing techniques

The type of matrix material, i.e., thermosetting or thermoplastic, is the main factor that determines the manufacturing technique used for the production of composites. Other parameters include the matrix material used, reinforcement form, fiber volume fraction, dimensions of the part to be produced, and complexity of the part shape. In the thermosetting resin-based methods, the matrix material is generally used in liquid resin form, whereas thermoplastic-based composite processing requires the melting of the polymer material. Thermosetting composites can be manufactured using a range of methods such as hand lay-up, resin transfer molding (RTM), autoclave molding, compression molding, filament winding, resin infusion, and pultrusion. For thermoplastic matrix-based composites, injection molding and thermoforming are the most commonly used techniques.

3.1. Hand lay-up

Hand lay-up is the simplest and most common manual technique for composite manufacture. The technique does not require much experience to apply, and the equipment cost is lower than that of other more advanced methods. Wooden, plastic, or metal molds in the shape of the composite part to be made are used. The first step in composite production is the application of surface-release agents on the surface of the mold to ensure an easy removal of the produced part. After the application of the release agent, a gel coat can be applied to the mold surface for high-quality part surface. Then, the reinforcement fabric or mat is placed inside the mold, and the resin-hardener mixture is applied on the surface of this reinforcement with the aid of a brush. Then, the entrapped air is removed, and the fabric surface is evened using a roller. This procedure is repeated after placing each layer of the reinforcement. The number of layers used depends on the desired part thickness. After laying-up is finished, the part is left for curing process. Finally, the cured part is removed from the mold. Hand lay-up is a labor-intensive and time-consuming technique with relatively poor quality results.

3.2. Resin transfer molding (RTM)

Resin transfer molding (RTM) produces composite parts with a good finish on both surfaces. The mold consists of male and female parts. The reinforcement fabrics are stacked one on top of the other and placed inside the female mold part. Then, the male part of the mold is closed on the fabric. The resin-hardener mixture is then pumped into the mold cavity. The mixture is pumped until the mold is completely filled after which the resin is allowed to cure. After curing, the mold is opened and the product is removed. RTM is less labor intensive and faster compared with hand lay-up. An advanced form of RTM is referred to as vacuum-assisted resin transfer molding (VARTM) which can apply vacuum to remove the entrapped air bubbles and improve the wetting of the fabric.

3.3. Autoclave molding

Autoclave is a high-temperature pressure vessel in which the produced composite parts are cured to obtain a high-quality product. In this technique, a composite part produced with hand

lay-up can be used. The part is covered with a vacuum bag, and vacuum is applied to remove the air bubbles. With high temperature and pressure, the curing of the composite parts takes place in a slow manner. This technique yields to high-quality products with good surface finish.

3.4. Compression molding

Compression molding can be used for the manufacture of thermoplastic composites as well as thermosets. In this technique, a compression molding press capable of applying high pressures and temperatures is used. Pre-impregnated fibers, fabrics, and/or mats as well as sheet molding compounds (SMCs) and bulk molding compounds (BMCs) can be used as the starting material. The curing process typically starts upon the application of heat and pressure. Metallic dies are used due to high-pressure and high-temperature conditions. The curing reaction generally takes a few minutes. After curing, the die is opened and the part is removed. The product has a good surface finish on both sides.

3.5. Filament winding

Filament winding is generally used to produce cylindrical parts such as long composite pipes for liquid transportation. Fiber volume fraction ratios of up to about 70% can be attained in this method. Fiber rovings are first impregnated with resin and then wound on a rotating mandrel. The winding angle which depends upon the speeds of the mandrel and fiber feeder determines the directional and overall properties of the composite part. Various combinations of properties can be attained by changing the fiber volume ratio and winding angle depending on the end-use requirements.

3.6. Vacuum infusion (VI)

In this process, a large mold made of wood or plastic is generally used. The fabric is placed inside the mold cavity and covered with a polyethylene bag. The bag is sealed to the mold to prevent the entrance of air from the sides. A vacuum pump evacuates the air inside the bag creating atmospheric pressure on the fabric and at the same time sucks the resin from a container and right into the mold cavity. The surface of the part experiences a pressure of 1 atm. After the fabric is sufficiently wetted out by the resin, the vacuum is stopped, and the part is allowed for curing in room temperature. The process is suitable for the manufacture of very large but not complex composite parts such as boat hulls and automobile hoods.

3.7. Pultrusion

This method is used to manufacture long composite profiles of constant cross section such as beams used in roof structures, bridges, ladders, frameworks, and so on. In pultrusion process, the fibers are pulled from a creel through a resin bath where they are impregnated with a thermosetting resin. Then, they are pulled through a heated die for curing. The finished profiles are cut to length with the aid of a saw at the end of the process line [56]. Fabrics may also be introduced into the die to provide directional reinforcement. Pultrusion is a very fast and economic composite production method. High fiber volume fractions can be attained.

3.8. Injection molding

Injection molding is one of the most common techniques for the production of thermoplastic-based composites. Short fibers or particulates are used as the reinforcing phase. Complex-shaped parts can be produced at high production rates. There are several factors which limit the mechanical properties of the resulting composites such as short fiber lengths, low fiber volume fraction ratio, and random fiber positioning. The molding compound in pellet form which is composed of short fibers and thermoplastic matrix is heated in the injection chamber of the extruder. The material is melted by the heat and shearing action of the screw. The melted material is then injected into a die under high pressure. After a short cooling cycle, usually 20–120 s, the part is removed from the mold.

3.9. Reinforced reaction injection molding (RRIM) and structural reaction injection molding (SRIM)

Reaction injection molding (RIM) is a process for producing unreinforced thermoset parts. Polyurethanes are the most commonly used resin type, whereas nylons, acrylics, polyesters, and epoxies can also be used. For the production of polyurethanes-based composites, a two-component resin made up of isocyanate and polyol is used. These two components are mixed in a dynamic mix head under high pressures and injected into the mold cavity. Reinforced reaction injection molding (RRIM) is similar to RIM except that short fibers are incorporated to one of the resin components. The fibers must be extremely short (e.g., 0.03 inches) to allow for easy flowing of the resin. In structural reaction injection molding (SRIM), a preform is placed in the die before injection [57].

3.10. Thermoforming

In the thermoforming process, fiber-reinforced thermoplastic sheet is preheated using contact heating panels or rods, ovens, or IR heaters above the glass transition temperature of the thermoplastic matrix. The preheated sheet is then compressed within a preheated mold to form the final composite part. The final part is trimmed from the sheet.

4. Fiber-matrix interface in composite materials

Fiber-matrix interface has a profound effect on the mechanical properties and performance of composite materials. The main tasks of fiber-matrix interface are to transfer the loads from matrix to stronger fibers and distribute the loads across the main body of the material. Fiber-matrix bonding can take place through chemical bonding such as ionic, covalent, and metallic bonds; through intermolecular interactions such as ion-dipole forces, van der Waals forces, and hydrogen bonds; through coulombic interactions if the surfaces of the fibers and resin have a net charge of opposite signs; and through mechanical locking. There are various methods for improving fiber-matrix interface such as surface coating, plasma treatment, and chemical modification which are described briefly in this section.

4.1. Surface coating

This method involves coating of the fiber surface for a better fiber-matrix bonding. The most common coating techniques include electrodeposition, chemical vapor deposition (CVD), metallorganic deposition, and vacuum deposition. Electrodeposition is used to deposit metals onto carbon fibers. In CVD, the ingredients in a gaseous mixture react with one another and with the fiber surface to produce a solid film having the desired properties. Metallorganic deposition uses a liquid precursor that contains metallorganic species dissolved in an organic solvent. This precursor is applied onto the fiber surface for the desired coating. Vacuum deposition includes sputtering, physical vapor deposition, e-beam evaporation, plasma-assisted CVD, and ion-plating techniques [58].

4.2. Plasma treatment

In plasma treatment, plasma of different gases is used to alter the surface of the fibers. In this technique, an ionized region including excited species such as ions and radicals is formed around the fiber surface, thereby increasing its reactivity with polymer matrices and leading to an improved fiber-matrix bonding.

4.3. Chemical modification

Chemical modification techniques aim to change the chemical structure of the fibers and/or matrix in order to improve the fiber-matrix compatibility and adhesion.

4.3.1. Silane treatment

Organosilanes are generally used as coupling agents to improve the strength and durability of glass fiber-reinforced composite materials, and they are still the largest group of coupling agents used in composite industry today. A silane that contains at least one carbon-silicon bond (Si-C) structure is referred to as an organosilane. The organosilane molecule can be represented by the formula $R-(CH_2)_n-Si(OR')_3$ where $n = 0-3$; R is a non-hydrolyzable functional organic group that is reactive toward various groups such as amino, epoxy, vinyl, methacrylate, sulfur; and OR' is a hydrolyzable group like an alkoxy group that can react with hydroxyl groups present in inorganic or organic substrates. Organosilanes can act as bridges between fibers and polymer matrices and can substantially improve adhesion between them.

4.3.2. Alkali treatment

In this method, natural fibers are treated with a dilute solution of sodium hydroxide (NaOH) with varying concentration, temperature, and duration. Alkali treatment has been shown to remove the impurities from the fiber surface, thus creating a rougher surface morphology. Consequently, the number of available sites for matrix penetration is increased which results in an improved mechanical interlocking between fibers and matrix.

4.3.3. Esterification-based treatments

In esterification technique, hydroxyl groups, $-\text{OH}$, in natural fibers are reacted with the carboxyl groups, $-\text{COOH}$, which is the functional group found in carboxylic acids. As a result, the $-\text{OH}$ groups, which give the fibers their hydrophilic character, are eliminated, and the fibers gain a more hydrophobic character and hence become more compatible with most polymer resins. Esterification techniques include acetylation, benzylation, propionylation, and treatment with stearates.

4.3.4. Graft copolymerization

In this method, the cellulose material is treated with an aqueous solution of selected ions and then exposed to high-energy radiation. This process results in the cleavage of cellulose macromolecules and formation of radical groups. Then, the cellulose material is treated with a suitable polymer that is compatible with polymer matrix. The most important grafting method is the treatment of natural fibers with maleic anhydride-grafted polypropylene (MAPP) copolymers which results in the formation of covalent bonds across fiber-matrix interface.

4.3.5. Treatment with isocyanates

Polymethylene polyphenyl isocyanates (PMPPIC) can make strong covalent bonds with $-\text{OH}$ groups of cellulose through their $-\text{N}=\text{C}=\text{O}$ functional groups. The isocyanate treatment is very effective and can be used to modify both fibers and the polymer matrix.

5. Testing and modeling methods for textile-reinforced composites

It is important to have a good understanding of the stiffness and strength properties of textile-reinforced composites for successful design and application of these materials. Basically, there are two different approaches for determining the physical and mechanical properties of composite materials: (1) experimental measurement using suitable testing standards and (2) theoretical prediction from the properties of the constituent materials (fiber and matrix).

5.1. Testing methods

In this section, the most common testing methods for the evaluation of the physical and mechanical properties of textile composites are listed. A detailed discussion of the test procedures is beyond the scope of this chapter, and the interested reader is referred to the related standards and very detailed texts on the experimental characterization of composite materials [59, 60].

5.1.1. Testing for physical properties

Physical characterization of composites includes the determination of density (ASTM specification D792); fiber volume ratio (ASTM D2584 for burn-out method and ASTM D3171 for

the acid digestion method and also optical methods based on image analysis); void content (ASTM D2734 and image analysis method); coefficients of thermal expansion (interferometric, dilatometric, optical noninterferometric, or strain gage methods); coefficients of moisture expansion; and heat conduction coefficients (for detailed information on the last two tests; see Ref. [60]).

5.1.2. Testing for mechanical properties

Mechanical characterization includes the determination of in-plane tensile (ASTM D3039), flexural (ASTM D790), compressive (ASTM D3410M), and shear (Iosipescu-type beam test with V-notches described in ASTM D5379M or the standard two-rail or three-rail shear tests described in D4255M) properties; determination of interlaminar properties (i.e., tensile, compressive, shear, toughness); material behavior under special conditions of loading (e.g., multiaxial, fatigue, creep, impact, and high-rate loading); stress and failure analysis of composite structures with structural details and nondestructive testing [60].

5.2. Modeling methods

Modeling studies basically cover three aspects such as the determination of physical properties, stiffness properties, and strength properties of the material. Approaches range from simple procedures based on micromechanics and classical laminate theory (CLT) to more sophisticated ones developed specifically for textile-reinforced composites. There are various methods to predict the behavior of the composites from the properties of its constituent materials. The most commonly used methods are the basic rule of mixtures (ROM), Halpin-Tsai method which is a refinement of the rule of mixtures, and a more sophisticated method referred to as Hashin's composite cylinder assemblage model.

5.2.1. Modeling for physical properties

ROM approach can be used to determine various physical properties of the composites using the properties of the constituent materials. Fiber (V_f) and matrix volume fraction (V_m) can be calculated using the following relations [61]:

$$V_f = \frac{v_f}{v_c} \quad (1)$$

$$V_m = \frac{v_m}{v_c} \quad (2)$$

where $v_{f,m,c}$ = volume of fibers, matrix, and composite, respectively.

The weight fraction of fibers (W_f) and matrix (W_m) is given by

$$W_f = \frac{w_f}{w_c} \quad (3)$$

$$W_m = \frac{w_m}{w_c} \quad (4)$$

where $w_{f,m,c}$ = mass of fibers, matrix, and composite, respectively.

Density of the composite can be calculated using ROM:

$$\rho_c = \rho_f V_f + \rho_m V_m \quad (5)$$

where $\rho_{f,m,c}$ = density of fibers, matrix, and composite, respectively.

The volume fraction of the voids (V_v) is given by

$$V_v = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}} \quad (6)$$

where ρ_{ce} and ρ_{ct} are the experimental and theoretical density of a composite.

5.2.2. Modeling for mechanical properties

5.2.2.1. Simple micromechanical approaches

The ROM approach is particularly useful for obtaining the longitudinal modulus and major Poisson's ratio of a unidirectional composite, whereas it gives less accurate results for transverse and shear moduli. Longitudinal modulus (E_1), major Poisson's ratio (ν_{12}), transverse modulus (E_2), and in-plane shear modulus (G_{12}) can be obtained using the following relations:

$$E_1 = E_f V_f + E_m V_m \quad (7)$$

where E_f and E_m are the elastic moduli of the fiber and matrix, respectively; ν_f and ν_m are the Poisson's ratio for the fibers and matrix, respectively; and G_f and G_m are the shear moduli for fibers and matrix, respectively.

$$\nu_{12} = \nu_f V_f + \nu_m V_m \quad (8)$$

$$\frac{1}{E_2} = \frac{1}{E_f} V_f + \frac{1}{E_m} V_m \quad (9)$$

$$\frac{1}{G_{12}} = \frac{1}{G_f} V_f + \frac{1}{G_m} V_m \quad (10)$$

The Halpin-Tsai equations are a refinement of ROM. In fact, the longitudinal modulus and major Poisson's ratio are the same as those calculated by ROM approach. However, for the transverse and shear moduli, the following relation is used:

$$\frac{M}{M_m} = \frac{1 + \xi \eta V_f}{1 - \eta V_f} \quad (11)$$

$$\eta = \frac{\frac{M_f}{M_m} - 1}{\frac{M_f}{M_m} + \xi} \quad (12)$$

where $M = E_2, G_{12},$ and G_{23} for composite; $M_f =$ fiber property E_f or G_f ; $M_m =$ matrix property E_m or G_m ; and $\xi =$ a constant defining the way the load is shared between fiber and matrix.

Poisson's ratio in the transverse plane (ν_{23}) may be calculated using the following relationship:

$$\nu_{23} \cong 1 - \frac{E_2}{G_{23}} \quad (13)$$

Hashin's composite cylinder assemblage (CCA) model takes into account the fiber anisotropy. The expressions are rather lengthy, and the interested reader is referred to the work of Hashin [62].

5.2.2.2. Sophisticated models for textile-reinforced composites

The simple models presented above are for unidirectional lamina where the fibers all lie in the same direction. Textile-reinforced composites generally have complex fiber architectures, and more sophisticated analysis methods have to be used for their successful modeling. We can divide all models into two main categories such as analytical/semi-analytical and numerical models based on finite element analysis (FEA).

The simplest textile structure is non-crimp textile fabrics. Traditional angle-ply laminate procedure can be used directly since the fibers remain reasonably straight. However, woven, braided, and knitted textiles have more complex structures, and their composites require more sophisticated modeling treatments. There are various models developed for 2D and 3D woven fabric composites. Modeling methods for 2D woven composites include 1D methods such as mosaic model [63], fiber undulation model [64], and bridging model [65] developed by Ishikawa and Chou in the early 1980s. 2D models were developed by Naik and coworkers [66, 67] in 1992 by refining the fiber undulation model. The model included the fiber undulation and continuity in both warp and weft directions and the real cross-sectional geometry of the yarns. These 1D and 2D models can predict the in-plane elastic properties only. 3D models taking into account the out-of-plane elastic properties include a 3D representative volume element (RVE) proposed by Hahn and Pandey [68] and a fabric geometry model (FGM) which is originally developed by Ko and Chou [69] and used by Vandeurzen and coworkers [70, 71] for woven fabric composites. Models for 3D woven composites include orientation averaging models [72], mixed iso-stress and iso-strain models [73, 74], and finite element applications. Models for braided fabric composites include a FGM model proposed by Pastore and Goward [75], fiber inclination model [76], and finite element models. There has been limited attention to the modeling of knitted fabric composites due to their limited usage in structural applications. There are a number of models proposed to model knitted composites [77, 78].

5.2.2.3. *Prediction of strength and failure*

In general approximation, failure can occur in yarns, matrix, and fiber-matrix interface in a textile composite subject to a general type of loading. Failure strength prediction of textile-reinforced composites can be carried out by determining failure criteria for yarns, matrix, and interface using various methods. Maximum stress and maximum strain criteria and the Tsai-Wu failure criterion may be used to predict the yarn strength. Matrix failure can be predicted by standard failure criteria for a homogeneous and isotropic material. Failure that occurs along the interface may be predicted using failure criteria for predicting interlaminar delamination in composite laminates [38].

6. Applications of textile-reinforced composites

6.1. Aerospace applications

The aerospace industry is among the largest consumers of advanced composites due to the low weight and high mechanical properties of these materials such as static strength, fatigue performance, fracture toughness, damage tolerance, high impact resistance, and resistance to high temperatures. In addition, composite components can be produced with fewer joints and rivets, leading to lower susceptibility to the structural fatigue. Weight reductions of up to 40% could be achieved when aluminum is replaced by composite materials. A reduction of 1 kg in weight corresponds to \$50–500 fuel saving depending upon the type of aircraft and fuel prices. Traditionally, 2D woven fabric prepregs are the primary choice, but the trend has then shifted toward the use of unidirectional prepregs due to strength and stiffness considerations. However, the high production cost and low out-of-plane properties of 2D laminated structures are the two main driving forces for the implementation of 3D textiles in aircraft and aerospace applications. Multilayer composite laminates made up of 2D unidirectional prepregs or textile fabrics lack the through-the-thickness reinforcement resulting in low interlaminar strength and fracture resistance. In addition, laminated 2D composites are made thicker than needed to withstand residual stresses after impact which in turn increases the weight and production cost of the components. 3D fiber architectures in which a portion of the fibers are oriented in through-the-thickness or z-direction offer a way to improve the interlaminar strength and fracture resistance. 3D textile composites are also low cost due to elimination of labor-intensive laminating process. Among the 3D textile preforms, multiaxial non-crimp carbon fiber fabric is the material of choice since it provides mechanical properties similar to those of unidirectional prepregs with the added advantage of through-the-thickness reinforcement.

Today, modern aircrafts use composite materials up to 50% by their weight [79]. The composites are used in commercial and military aircrafts for several nonstructural and structural parts such as spoilers, elevators, horizontal stabilizer boxes, radomes, rocket motor castings, tail sections (Airbus), rudder (Boeing 767), fuselage (V22), antenna dishes, engine nacelles, landing gear doors, engine cowls, wings (Prototype ATF, V22), cargo liners, and so on [80]. Carbon fibers dominate the aerospace sector due to their high strength/stiffness and low density.

Other fibers like aramid and glass also have a limited usage, but low strength and high density of glass fiber limit its usage in aircraft structures, whereas aramid fibers have the moisture absorption problem. Regarding the matrix systems, epoxy resin is the most preferred matrix material due to its high mechanical properties and durability. Space applications of advanced composites include launch systems and self-contained space modules such as satellites, space crafts, and space stations. Composites allowed 30% weight savings when used in expendable launch vehicles (ELV) for Atlas, Delta, and Titan rocket launch systems. Composites produced with less labor-intensive techniques such as filament winding and automated tape winding proved more economical than costly joint welding of metals. Composite motor cases from carbon fiber/epoxy with high strength and stiffness provided substantial weight reductions. Nozzles such as exit cone and throat elements are composed of carbon fiber/phenolic or carbon-carbon composites to withstand hot exhaust gases of burning propellant [80]. Hubble Space Telescope contains a carbon fiber/epoxy metering truss with near-zero coefficient of thermal expansion (CTE) which provides dimensional stability required for precise alignment of the optics aboard the telescope. These trusses are also designed to cope with various compressive loads. Composites are also used in space shuttles. Payload bay doors made of carbon fiber/epoxy (T-300) composite parts provided weight savings of over 400 kg [80].

One of the earliest applications of 3D textile composites involved the use of 3D stitching which is described in detail in previous sections. 3D stitching technique was used in a NASA-sponsored demonstrator program to manufacture low-cost and damage-tolerant composite wings. For this purpose, a 28-m-long sewing machine was developed by Boeing. This machine was able to stitch carbon fabric layers of over 25 mm in thickness at a rate of over 3000 stitches a minute. In addition to stitching the skin preform, the blade stiffener flanges made up of tubular braided fabrics are also stitched to the skin. Resin infusion technique was used for final composite production. The resulting panel was reported to be 25% lighter and 20% cheaper than an equivalent aluminum part [26].

One example of 2D layered woven structures was manufactured by Kawasaki Heavy Industries, Japan, by using twill carbon fiber fabric. The prepreg developed was used in various applications including the Embraer ERJ 170 inboard flaps, the Embraer ERJ190 outboard flaps and wing stubs, and the Boeing 737-300 winglets [81]. 3D woven preforms greatly reduce the production time by eliminating the lay-up of individual fabric layers. It is also possible to manufacture net-shape preforms that can be easily handled during the process. 3D woven fabrics can also be manufactured in complex shapes eliminating the assembling costs. The main limitation of 3D woven fabrics is that standard looms cannot introduce in-plane yarns at angles other than 0 and 90°. Therefore, the resulting structures possess very low shear and torsion properties, thus limiting their usage in most aircraft structures where high shear strength is required. 3D woven composites were first developed in the 1970s as a replacement for expensive high-temperature metal alloys in aircraft brakes. Carbon fibers were used for the production. Hollow cylindrical preforms were produced on a modified weaving loom. Carbon-carbon composites reinforced with these fabrics displayed high specific mechanical properties as well as outstanding heat resistance [82]. These composites also have low thermal expansion, good thermal conductivity, high heat capacity, and wear resistance. It was reported that carbon-carbon composite brakes exhibit nearly four times the braking power

of the forerunner steel brakes [80]. 3D woven composites are used in H-joint connectors for joining honeycomb sandwich wing panels on the Beech Starship. It was reported that the connector was crucial for the low-cost production of the wing. It also improved the stress transfer at the joint, thereby reducing the peeling stress [83]. 3D woven composites are also used by Lockheed Martin for the air inlet duct in the F35 military fighter jet. In this case, the stiffeners are integrally woven with the duct shell, reducing the need for secondary fastening. It was reported that 95% of the fasteners through the duct are eliminated, thus enhancing aerodynamic and signature performance, minimizing the risk of fasteners being ingested by the engine, and simplifying manufacturing assembly [26]. Other 3D woven composites generally include demonstration structures such as turbine engine thrust reversers, rotors, rotor blades, insulation, structural reinforcement and heat exchangers, rocket motors, nozzles and fasteners, engine mounts, T-section elements for primary fuselage frame structures, and multiblade stiffened panels [84]. 3D carbon-woven/ceramic sandwich composites are used in the combustion chamber of prototype scramjet engines [85].

2D braided composites generally display similar stiffness and strength when compared to those of equivalent 2D layered woven composites. When the damage resistance and tolerance are taken into account, 2D braided composites have proved superior to both unidirectional and 2D woven composites. This is due largely to partly 3D nature of 2D braided composites which help limit the damage growth. 2D braided composites are used in various components such as aircraft propellers, rocket launchers, aircraft fuselage frames, and helicopter rotor blade spars. The use of 3D braiding, on the other hand, has been limited due to the fact that most industrial braiding machines are only capable of producing braid preforms with small cross sections. Very large and expensive machines are necessary to manufacture preforms which are large enough for aircraft components. 3D braided fabrics were first developed around the 1960s to manufacture carbon-carbon composites as a replacement for high-temperature metal alloys in rocket motor components. With composite components, weight savings of 30–50% were attained [38]. Composite parts with holes, bends, and bifurcations can be produced with 3D braiding which allow production of junctions and complex shapes for aircraft structures [26]. Several demonstrator components have been produced using 3D braiding process such as T-section panels, I-beams, bifurcated beams, airframe spars, F-section fuselage frames, fuselage barrels, and rocket engine nozzles [26]. In general, the in-plane properties of 3D braided composites are lower compared with those of the equivalent 2D stacked laminates owing to the yarn crimp introduced during braiding process. Their out-of-plane properties and impact resistance, however, have been shown to be superior when compared to those of conventional laminates. A&P Technology, which is a leading company for braiding technology for the aerospace, manufactured various parts for aerospace applications. One example is a Vectron sock of 2 m in diameter and 3 m in length manufactured using an 800-carrier braiding machine [86]. The developed braided sock was used for a prototype airlock developed for NASA. A&P Technology also produced braid-reinforced wing flaps for Bombardier using RTM [87]. The same company produced the Honeywell jet engine stator vanes using a layer of aramid braid followed by an overlay of carbon fiber braid (**Figure 10a**) [88] and fan case of GENx jet engine which is a fuel efficient, quiet, and low-emission jet engine developed for the Boeing 787 aircraft and the Boeing 747-8 (**Figure 10b**) [89].

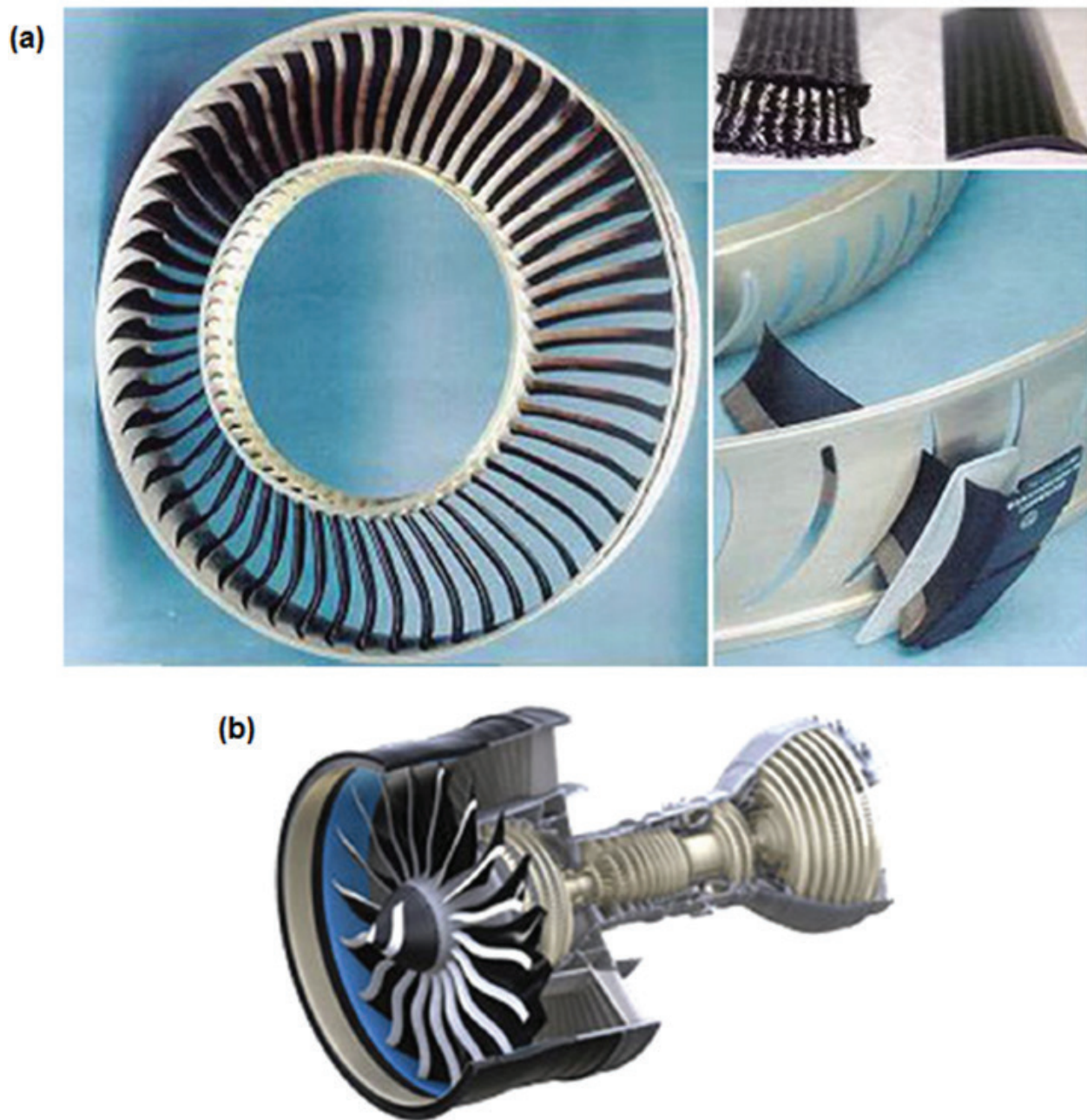


Figure 10. Braided composite components manufactured by A&P Technology: (a) jet engine stator vanes [88] and (b) fan case of GENx turbine [89].

Multiaxial warp knit (MWK) fabrics (also known as non-crimp fabrics) attracted a special attention in aerospace industry, and today it is the most common form of 3D textile structures used in aerospace applications. The main advantage of this technique, as previously mentioned, is the ability to introduce in-plane yarns without crimping which helps achieve a better yarn-to-fabric property translation efficiency. Moreover, the through-the-thickness yarns provide improved out-of-plane properties. There is a continuing effort within the aerospace industry to use MWK fabrics, and a number of demonstrator components such as wing stringers and wing panels have been produced using MWK fabric composites. One example of MWK composites is the Airbus A380 rear pressure bulkhead (RPB) shown in **Figure 11** [90].



Figure 11. Rear pressure bulkhead of the Airbus A380 [90].

This structure is produced using multiaxial carbon fiber fabrics supplied by Saertex. The part is manufactured using resin film infusion followed by autoclave process. Another successful application is the Airbus A400M cargo door which was manufactured using multiaxial carbon fiber fabrics with additional monoaxial fabrics for directional reinforcements and skin lay-up. Vacuum-assisted infusion was used for the production [91]. One of the problematic issues with MWK fabric is the stitching process which causes misalignments, fiber disruption, and so-called fish eyes in the structure which lowers the mechanical properties. These problems

can be largely eliminated by using finer polyester yarns and improving pinpointing of the stitching yarn path to avoid misplacements and yarn damage.

Novel auxetic composite structures were developed for a better sound insulation in aircraft fuselages [92]. The noises generated by the engine are generally transmitted to the cabin through the stiffeners. A novel auxetic composite consisting of an auxetic core, a damping layer, and a constraining layer was developed for stiffeners. It was stated that this new type of material could save the weight as well as enable better sound insulation when compared to conventional stiffeners with thick metallic layers.

6.2. Civil engineering applications

Textile-reinforced composites offer numerous advantages for civil engineering applications such as low weight, off-site mass production of complex-shaped components, added functionality and directional design of mechanical properties, cost reductions related to easy transportation and reduction in construction time, and also desirable aesthetic properties.

One of the earliest applications of composites is the reinforcement of concrete. Steel has traditionally been used to reinforce concrete for many years. Although steel-reinforced concrete has high strength and stiffness, the major limitation of this material is its high weight and susceptibility of steel to corrosion and subsequent deterioration. Moreover, rigid steel bars limit the possibilities of shaping concrete products. Textile materials can be used instead of steel to reinforce concrete. The outstanding durability of composites greatly extends the service life of the structure and reduces the inspection and maintenance costs, making them cost-effective [93]. Some of the advantages of composites over traditional construction materials are high strength-to-weight ratio, ability to be manufactured in complex shapes, ability to tailor their mechanical properties according to specific needs, their noncorrosive nature, low thermal conductivity, and outstanding fatigue performance. One example is the use of GFRP and CFRP reinforcement in the Wotton Bridge deck [93]. Another example of bridge construction is the pedestrian bridge in Oschatz, Germany. This bridge consisted of four layers of woven alkali-resistant (AR) glass fiber fabrics along with steel tendons. The bridge spans 8.60 m and consists of U-shaped segments (**Figure 12**) [94]. Besides bridges, very thin plates of textile-reinforced concrete are used for façades for reduced material and transport costs and an elegant appearance. Sandwich constructions consisting of two AR glass fiber concrete panels enclosing polyurethane foam can also be used for an improved sound and thermal insulation. An example of façade application is the betoShell© developed by Hering Bau (**Figure 13**) [95]. Another example is the award-winning restoration of a train station platform by Hering Bau in Walleshausen, Germany. For this purpose, two layers of carbon fiber textiles were embedded into the concrete. The concrete panels with a dimension of 2.5×1.35 m were put on a frost-proof concrete layer and fixed with two stainless steel mandrels [96].

In addition to concrete reinforcement, composites are also used for shear and flexural strengthening and the confinement of the existing concrete structural members through a process called externally bonded reinforcement (EBR). In this process, woven or nonwoven fabrics are applied



Figure 12. First segmental TRC Bridge in Oschatz, Germany [94].



Figure 13. бетоShell© façade application developed by Hering Bau [95].

on the surface of the structure through a technique similar to hand lay-up. Alternatively, composite strips consisting of unidirectional fibers embedded in an epoxy matrix can be directly bonded on the surface of the structure by using an epoxy adhesive (**Figure 14**) [93].

Other applications include the I-beams made with a 3D woven composite which is used in the roof of a ski chair-lift building as a replacement of heavy steel beams. 3D woven composite beams demonstrated lower cost and enhanced performance compared with steel and conventional composite beams [97].

6.3. Automotive applications

In recent years, the depletion of petroleum resources and strict environmental regulations forced the scientists and engineers in automotive industry to search for new ways of reducing the fuel consumption and also CO₂ emission. Therefore, the automotive industry is in a constant struggle to reduce the weight of the vehicles in order to decrease the fuel consumption without sacrificing passenger safety and comfort. Lightweight and strong textile composites offer a solution to this problem. Replacing cast iron, steel, and aluminum components with composites can decrease component weight by 10–75%. It is estimated that a 10% reduction in vehicle weight corresponds to a 6–8% reduction in fuel consumption [99]. Composites are gradually replacing steel for several body parts such as bumpers, hatch doors, cabin components, spare wheel containers, and so on. Other applications of composites include underbody panels, instrument panel carriers, battery trays, front-end modules, sunroof beams, door modules, seat structures, convertible header bows, door plate carriers, roof and trunk lids, exterior claddings, skid plates, running boards, step assists, front-end carriers, bumper beams, lift gates, spare wheel tubs, and other structural parts [100]. For example, Turner et al. investigated carbon fiber composites for automotive body panel applications. They produced a full-scale front wing-fender component using two different composite manufacturing processes such as a semi-impregnated system and a novel directed fiber preforming RTM process. The semi-preg system consisted of a surface film (thin woven glass either side of an epoxy film) and a bulk ply (woven 3000 filament, 300 g/m² carbon fiber on one side, 400 g/m² woven glass on the other side, and an epoxy glass microsphere core) The resulting composite was compared with an existing stamped steel component for mechanical properties, weight



Figure 14. Strengthening of existing concrete structural members using unidirectional carbon and aramid sheets [98].

saving, and cost by employing a technical cost modeling procedure. It was demonstrated that carbon fiber composites can provide 40–50% weight saving compared with steel panels for an equivalent bending stiffness and they have greatly improved dent resistance. The steel part was shown to be more cost-effective at volumes above around 9000 parts/annum [101]. Advanced composite materials are also considered for high-performance racing cars since weight reduction is crucially important, whereas cost issues are not a primary concern in this area. Feraboli et al. investigated the performance of carbon fiber composites used in body panels and integrated chassis components for the Murciélago Roadster [102]. The laminate is made up of three plies oriented in the 0/90 direction, such as a 0.2 mm thick, 2 × 2 twill at the surface, followed by a 0.4 mm thick five-harness satin, and another 2 × 2 twill that is 0.7 mm thick. It was concluded that carbon fiber composites offer a considerable amount of weight saving as well as design flexibility [102].

3D textile-reinforced composites are also used in various applications such as floors and floor beams in trains and fast ferries; flat load trays in trucks; crash members in cars, buses, and trucks; shipping containers; and other container transport applications. 3D composites reinforced with spacer fabrics made of two parallel skins of 2D glass fabrics connected by glass yarns are used in car and truck spoilers/fairings and luggage floors of automobiles [84]. Another example of 3D textile composites is the oil pan produced using 3D woven interlock fabrics. Three different 3D woven structures were used for this purpose such as layer-to-layer, orthogonal, and through-the-thickness woven fabrics [99].

In the US, several government/private sector projects made use of composite materials in vehicles. These include Ford Motor's "all composite car," the Automotive Composites Consortium (ACC), the Partnership for the New Generation of Vehicles (PNGV) program [103], and the Sunrise™ electric vehicle (EV) program. Among these projects, Sunrise™ electric vehicle (EV) program in 1996 made the most extensive use of textile composites in a well-integrated program. This program is co-funded by the National Institute of Standards and Technology (NIST) together with a consortium of eight industry partners. Nearly all types of textile preforms such as woven, knitted, braided, and nonwoven fabrics were used for reinforcement (**Figure 15**) [104].

Other automotive applications of composites include car noses and monocoques of Formula One car bodies from carbon textile structures, aprons and spoilers of sport cars, braided carbon composites for car bumpers (e.g., BMW M6, Lotus Elise), the crash beams of the McLaren SLR which consist of foam cores overbraided with carbon rovings, and the car roof of the BMW M6 which consists of carbon-woven fabrics [105].

6.4. Applications in medicine

Composite materials are extensively used in medicine owing to their numerous advantages. Among the most important applications of composite materials in medicine is bone repair. Bone fractures can be treated by two main methods such as external fixation and internal fixation. The purpose of external fixation is to hold the bone fragments in alignment by using various materials such as splints, casts, braces, and external fixator systems. Plaster of Paris (calcium sulfate) reinforced with cotton-woven fabrics is still the most commonly used casting

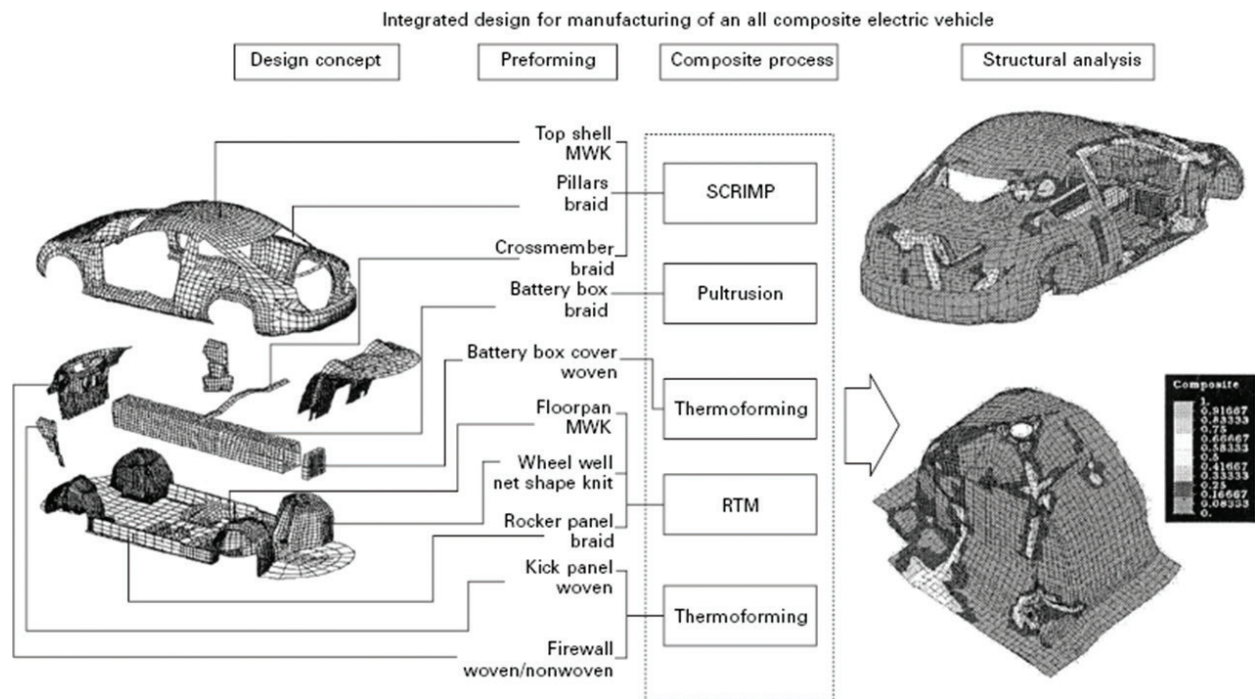


Figure 15. Composite parts breakdown of Sunrise™ BIW according to textile preforming processes and composite manufacturing processes [104].

material, but it has a high failure rate, high density, and low specific strength/stiffness and is sensitive to water. Recently, casts made of glass or polyester fiber fabrics and water-activated polyurethanes are being used to overcome these problems. An ideal splinting material must be lightweight, stiff, strong, and also comfortable. It must be also fit to the complex contours of the limbs. The fabric must be open structured to allow impregnation with a large quantity of plaster. Leno-woven structures as well as warp and weft knitted fabrics can be used [106]. In the internal fixation method, the bone fragments are held together by using wires, pins, screws, plates, and intramedullary nails. Bone plates made of stainless steel and Ti alloy are conventionally used. The stiffness of these materials is way higher than that of the bone, and this stiffness mismatch causes much of the load to be carried by the plate. This causes increased bone porosity (also known as bone atrophy), and the bone becomes less dense and weak. Less rigid plates that are more bone-like in mechanical properties can be used to overcome this problem. Various composite bone plates were developed for the usage of such as CF/epoxy, GF/epoxy, CF/PMMA, CF/PP, CF/PE, CF/nylon, and CF/PEEK [107]. **Figure 16** shows composite bone plates made of various textile composites [107].

Joint replacements such as total hip replacement (THR) and total knee replacement (TKR) also employ composite materials. Conventional THRs use stainless steel, Co-Cr, and Ti alloys for the femoral shaft and neck and Co-Cr alloy or ceramics such as alumina and zirconia materials for the head or ball [107]. CF/PEEK and CF/epoxy systems and UHMWPE-based composites were used for THR and TKR with successful results (**Figure 17**) [108]. Other applications of composites include bone cement, bone grafts, dental post, dental implant and bridge, bracket and archwire, ureter prosthesis, catheters, tendons and ligaments, prosthetic limbs, and medical equipment such as walking support frames and sticks.

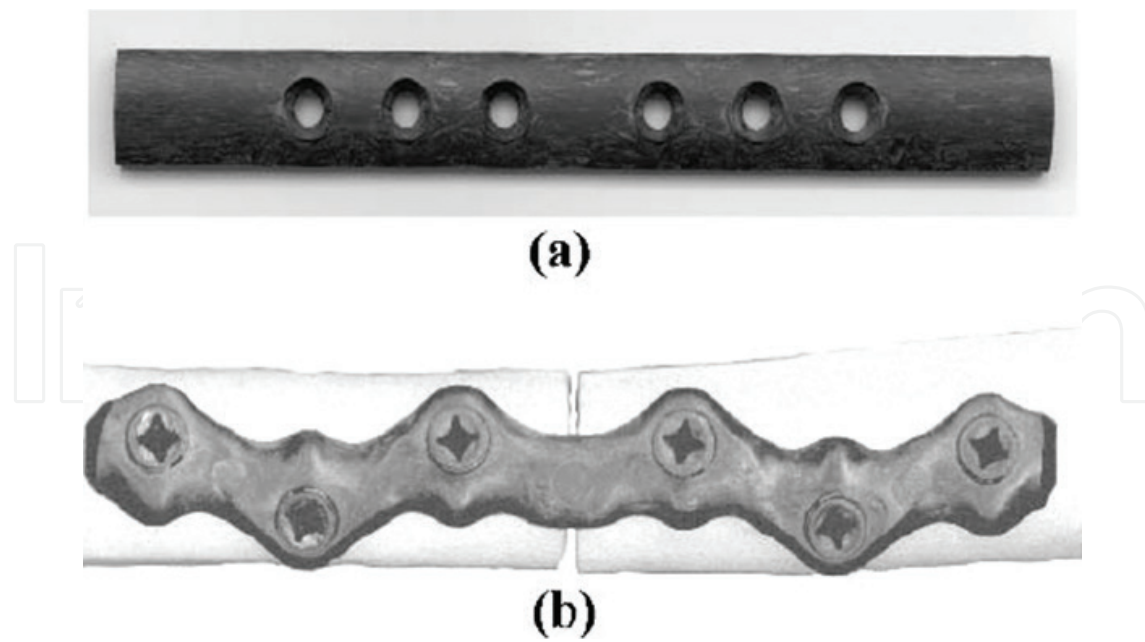


Figure 16. (a) A typical composite bone plate made using braided carbon fiber fabric and epoxy matrix and (b) composite bone plate made of carbon/PEEK material system [107].



Figure 17. Carbon fiber-reinforced thermoplastic hip prosthesis, with and without hydroxyapatite coating, shown alongside conventional titanium equivalent [108].

6.5. Sports and leisure applications

Composite materials allow for the directional design of mechanical properties which is a great advantage in various sports equipments. Lighter and stronger golf clubs made of graphite fiber-reinforced epoxy are in common use. Carbon fiber composites are used for the production of poles used in pole vaulting. The pole must be lightweight, flexible yet stiff, and torsion resistant. In order to meet these demands, a layered design is used [109]. The outer layer is made up of unidirectional carbon fiber/epoxy system, whereas the middle and inner layers are made up of glass fiber web/epoxy and wound glass fibers/epoxy, respectively. Carbon/epoxy composite layer provides maximum stiffness, while glass fiber composites ensure high torsion resistance [109]. Other applications of carbon fiber composites include bicycle frames, front forks, and seat posts. Carbon fiber composites are lightweight and provide good bending stiffness and fatigue resistance. In addition, glass fiber-reinforced nylon wheels are used as good shock absorbers. Carbon fiber composites are also used to produce tennis racket frames for high strength and stiffness. In addition, the handles can be made by wrapping multiple composite layers around a soft core such as PUR for the purpose of vibration damping [110]. Other applications include kayaks made of carbon and kevlar fibers with epoxy resin, skis and snowboards made of a soft core, and composite layers of various constructions [111].

7. Future scope

Future investigations will focus on novel fiber and matrix systems, fiber architectures and processing techniques, as well as improving the existing technologies. The successful implementation of 3D textile composites requires more work on the production economies and engineering design of these materials in order to create a cost-effective and sustainable production technology. Fabric geometry model (FGM) coupled with CAD-CAM technologies and analyzing systems such as the finite element method (FEM) can create a useful framework which can help integrate fabric design and processing parameters into structural analysis and ultimately efficiently design the required properties for a specific end use. Another interesting topic for the future research is the design of fiber-matrix interface in composites. The quality of the fiber-matrix interface is crucially important for high-standard composite properties. Increasing the fiber-matrix adhesion by using suitable coupling agents and interface modification techniques is the all-time hot topic in composite industry, and it is apparent that this trend will continue in the future. More research is also necessary on the dynamics of matrix infiltration into textile materials during composite processing as well as on the characteristics of curing process. The use of nanofibers and nanotextile structures for the reinforcement of composite materials is another area which is full of potential for future applications.

8. Summary

Composites reinforced with textile materials have attracted great attention as lightweight and strong materials for various advanced applications such as aerospace, construction,

automotive, medicine, and sports. Traditionally, multilayered structures consisting of unidirectional prepregs have been used for the production of advanced composite materials. However, these material systems lack through-the-thickness fibers and consequently exhibit poor out-of-plane properties such as interlaminar strength and damage tolerance. In addition, the layering process is labor intensive and time consuming increasing the overall cost. Textile materials in the form of short and continuous fibers as well as 2D and 3D fabric preforms offer enormous design possibilities through the proper manipulation of fiber architecture. 2D fabrics can be produced at a much lower cost compared with unidirectional prepregs and are easy to handle during composite manufacturing. However, they also require the time-consuming layering procedure similar to unidirectional laminates, and they also have poor out-of-plane properties due to lack of z-fibers. 3D woven, braided, stitched, and non-crimp fabrics possess through-the-thickness reinforcement and thus have good out-of-plane properties. In addition, the costly layering step is eliminated with these structures. They are suitable for net-shape manufacturing and inclusion of a wide range of structural details such as holes, bifurcations, and junctions which significantly reduce the production time and cost as well as eliminating the weaknesses in the resulting structures originating from these modifications. The major limitation of 3D fabric manufacture is the high production costs due to poorly developed machine technologies and economies of scale issues. These limitations can be eliminated with the implementation of more efficient production technologies and effective engineering design of 3D textile materials. New developments in fiber and matrix systems, interface modification methods, as well as in nanotechnology will increase the use of textile composites in various applications. It is expected that textile materials will continue to play an important role for the reinforcement of advanced composite materials in the future.

Author details

Nesrin Sahbaz Karaduman^{1*}, Yekta Karaduman¹, Huseyin Ozdemir² and Gokce Ozdemir³

*Address all correspondence to: nesrin38@gmail.com

1 Department of Textile, Clothing, Footwear and Leather, Akdagmadeni Vocational High School, Bozok University, Akdagmadeni, Yozgat, Turkey

2 Department of Textile, Clothing, Footwear and Leather, Vocational High School of Technical Sciences, Gaziantep University, Gaziantep, Turkey

3 Department of Fashion and Textile Design, Faculty of Fine Arts, Gaziantep University, Gaziantep, Turkey

References

- [1] Ko FK. 3-D textile reinforcements in composite materials. In: Miravete A, editor. 3-D Textile Reinforcements in Composite Materials. Cambridge: Woodhead Publishing Limited; 1999. pp. 9-42

- [2] Lavin JG. Carbon fibers. In: Hearle JWS, editor. *High-Performance Fibers*. Cambridge: Woodhead Publishing Limited; 2001. pp. 156-190
- [3] Shambaugh RL. A macroscopic view of the melt-blowing process for producing micro-fibers. *Industrial & Engineering Chemistry Research*. 1988;**27**:2363-2372. DOI: 10.1021/ie00084a021
- [4] Mochida I, Korai Y, Ku CH, Watanabe F, Sakai Y. Chemistry of synthesis, structure, preparation and application of aromatic-derived mesophase pitch. *Carbon*. 2000;**38**:305-328. DOI: 10.1016/S0008-6223(99)00176-1
- [5] Edie DD. The effect of processing on the structure and properties of carbon fibers. *Carbon*. 1998;**36**:345-362. DOI: 10.1016/S0008-6223(97)00185-1
- [6] Kwolek SL, Morgan PW, Sorenson WR, inventors. Process of making wholly aromatic polyamides. 1962. US Patent 3063966 A
- [7] Kwolek SL, inventor. Optically anisotropic aromatic polyamide dopes. 1972. US Patent 3671542 A
- [8] Rebouillat S. Aramids. In: Hearle JWS, editor. *High-performance Fibres*. Cambridge: Woodhead Publishing Limited; 2001. pp. 23-61
- [9] Morgan PW, Kwolek SL. Interfacial polycondensation 2. Fundamentals of polymer formation at liquid interfaces. *Journal of Polymer Science*. 1959;**40**:299-327
- [10] Morgan PW, Kwolek SL. Interfacial polycondensation XII. Variables affecting stirred polycondensation reactions. *Journal of Polymer Science*. 1962;**62**:33-58. DOI: 10.1002/pol.1962.1206217304
- [11] Jassal M, Ghosh S. Aramid fibres—An overview. *Indian Journal of Fibre & Textile Research*. 2002;**27**:290-306
- [12] History of the Owens-Corning Fiberglas Corporation. [Internet]. 2016. Available from: <http://media.owenscorning.com/history> [Accessed: 08 January 2016]
- [13] Kumar S, Gupta VB. Manufactured fibres for high performance, industrial and non-conventional applications. In: Gupta VB, Kothari VK, editors. *Manufactured Fibre Technology*. London: Chapman & Hall; 1997. pp. 514-559
- [14] Wallenberger FT. Structural silicate and silica glass fibers. In: Wallenberger FT, editor. *Advanced Inorganic Fibers Processes, Structures, Properties, Applications*. Dordrecht: Kluwer Academic Publishers; 1999. pp. 129-168
- [15] Jones FR. Glass fibres. In: Hearle JWS, editor. *High-Performance Fibres*. Cambridge: Woodhead Publishing Limited; 2001. pp. 191-238
- [16] Deitzel JM, McDaniel P, Gillespie JW. High performance polyethylene fibers. In: Bhat G, editor. *Structure and Properties of High-Performance Fibers*. Cambridge: Woodhead Publishing Limited; 2016

- [17] Barham PJ, Keller A. High-strength polyethylene fibres from solution and gel spinning. *Journal of Materials Science*. 1985;**20**:2281-2302. DOI:10.1007/BF00556059
- [18] Kavesh S, Prevorsek DC, inventors. High tenacity, high modulus polyethylene and polypropylene fibers and intermediates therefore. 1982. US Patent 4413110
- [19] Wilson DM. Ceramic fibers. In: Miracle DB, Donaldson SL, editors. *ASM Handbook Volume 21: Composites*. Ohio: ASM International; 2001
- [20] Chung DDL. *Composite Materials: Science and Applications*. London: Springer; 2010. 371 p
- [21] Lord PR, Mohamed MH. *Weaving: Conversion of Yarn to Fabric*. Durham: Merrow Publishing Company; 1982. 368 p
- [22] Tan P, Tong L, Steven GP. Modelling for predicting the mechanical properties of textile composites-A review. *Composites Part A: Applied Science and Manufacturing*. 1997;**28**:903-922. DOI: 10.1016/S1359-835X(97)00069-9
- [23] Chou TW. *Microstructural Design of Fiber Composites*. New York: Cambridge University Press; 1992. 592 p
- [24] Spencer DJ. *Knitting Technology: A Comprehensive Handbook and Practical Guide*. Cambridge: Woodhead Publishing Limited; 2001. 386 p
- [25] Wray GR, Vitols R. Advances in stitch-bonding, warp- and weft-knitting systems, and automated knitwear manufacture. In: Happey F, editor. *Contemporary Textile Engineering*. London: Academic Press; 1982. pp. 375-409
- [26] Baker A, Dutton S, Kelly D. *Composite Materials for Aircraft Structures*. Reston, Virginia: American Institute of Aeronautics and Astronautics, Inc.; 2004. 599 p
- [27] Pastore C, Gowayed Y. Structure and mechanics of 2D and 3D textile composites. In: Schwartz P, editor. *Structure and Mechanics of Textile Fibre Assemblies*. Cambridge: Woodhead Publishing Limited; 2008. pp. 141-189
- [28] Wilson A. The formation of dry, wet, spunlaid and other types of nonwovens. In: Chapman RA, editor. *Applications of Nonwovens in Technical Textiles*. Cambridge: Woodhead Publishing Limited; 2010. pp. 3-17
- [29] Bluck RM, inventor. High speed bias weaving and braiding. 1969. US Patent 3426804
- [30] Florentine RA, inventor. Apparatus for weaving a three dimensional article. 1982. US Patent 4312261
- [31] Bilisik K, Sahbaz Karaduman N, Bilisik NE, Bilisik HE. Three dimensional fully interlaced woven preforms for composites. *Textile Research Journal*. 2013;**83**:2060-2084. DOI: 10.1177/0040517513487791
- [32] Stig F, Hallström S. Spatial modelling of 3D-woven textiles. *Composite Structures* 2012;**94**: 1495-1502. DOI: 10.1016/j.compstruct.2011.12.003

- [33] Bilisik K, Sahbaz Karaduman N, Bilisik NE, Bilisik HE. Three dimensional (3D) circular various weave patterns in woven preform structures. *Textile Research Journal*. 2014;**84**:638-654. DOI: 10.1177/0040517513499437
- [34] Bilisik K. Three-dimensional braiding for composites: A review. *Textile Research Journal*. 2013;**83**:1414-1436. DOI: 10.1177/0040517512450766
- [35] Tada M, Uozumi T, Nakai A, Hamada H. Structure and machine braiding procedure of coupled square braids with various cross sections. *Composites Part A: Applied Science and Manufacturing*. 2001;**32**:1485-1489. DOI: 10.1016/S1359-835X(01)00047-1
- [36] Bilisik K, Sahbaz N. Structure-unit cell base approach on three dimensional (3D) representative braided preforms from 4-step braiding: Experimental determination of effect of structure-process parameters on predetermined yarn path. *Textile Research Journal*. 2012;**82**:220-241. DOI: 10.1177/0040517511404597
- [37] Cox BN, Flanagan G. *Handbook of Analytical Methods for Textile Composites*. Washington: NASA Contractor Report 4750; March 1997
- [38] Tong L, Mouritz AP, Bannister MK. *3D Fibre Reinforced Polymer Composites*. Oxford: Elsevier; 2002. 254 p
- [39] Ko FK. Three-dimensional fabrics for composites. In: Chou TW, Ko F, editors. *Composite Materials Series Vol. 3: Textile Structural Composites*. Amsterdam: Elsevier Science Publishers; 1989. pp. 129-171
- [40] Williams DJ. New knitting methods offer continuous structures. *Advance Composite Engineering*. 1978; Summer: 12-13
- [41] Fanguero R, Soutinho F. Textile structures. In: Fanguero R, editor. *Fibrous and Composite Materials for Civil Engineering Applications*. Cambridge: Woodhead Publishing Limited; 2011. pp. 62-91
- [42] Roye A, Gries T, Peled A. Spacer fabrics for thin walled concrete elements. In: 6th RILEM Symposium on Fiber-Reinforced Concrete (FRC); 20-22 September 2004; Varenna, Italy. pp. 1505-1514
- [43] Roye A, Gries T. 3-D textiles for advanced cement based matrix reinforcement. *Journal of Industrial Textiles*. 2007;**37**:163-173. DOI: 10.1177/1528083707078136
- [44] Schnabel A., Gries T. Production of non-crimp fabrics for composites. In: Lomov SV, editor. *Non-crimp Fabric Composites*. Cambridge: Woodhead Publishing Limited; 2011. pp. 3-41
- [45] Hu J. *3-D Fibrous Assemblies: Properties, Applications and Modelling of Three-Dimensional Textile Structures*. Cambridge: Woodhead Publishing Limited; 2008. 280 p
- [46] Bilisik AK, Turhan Y. Multidirectional stitched layered aramid woven fabric structures and their experimental characterization of ballistic performance. *Textile Research Journal*. 2009;**79**:1331-1343. DOI: 10.1177/0040517509104275

- [47] Bilisik K, Yolacan G. Short beam strength properties of multistitched biaxial woven E-glass/polyester nano composites. *Journal of Industrial Textiles*. 2015;**45**:199-221. DOI: 10.1177/1528083714528017
- [48] Dow MB, Smith DL. Damage tolerant composite materials produced by stitching carbon fabrics. In: *Proceedings of the 21st International SAMPE Technical Conference*; 25-28 September 1989; Atlantic City, NJ. pp. 595-605
- [49] Bilisik K, Karaduman NS, Bilisik NE. 3D fabrics for technical textile applications. In: Jeon HY, editor. *Non-woven Fabrics*. Rijeka: InTech; 2016. pp. 81-141. DOI: 10.5772/61224
- [50] Wang Z, Hu H. Auxetic materials and their potential applications in textiles. *Textile Research Journal*. 2014;**84**:1600-1611. DOI: 10.1177/0040517512449051
- [51] Sloan MR, Wright JR, Evans KE. The helical auxetic yarn—A novel structure for composites and textiles; geometry, manufacture and mechanical properties. *Mechanics of Materials*. 2011;**43**:476-486. DOI: 10.1016/j.mechmat.2011.05.003
- [52] Ugbolue SC, Kim YK, Warner SB, Fan Q, Yang CL, Kyzymchuk O, Feng Y. The formation and performance of auxetic textiles. Part I: theoretical and technical considerations. *The Journal of The Textile Institute*. 2010;**101**:660-667. DOI: 10.1080/00405000902733790
- [53] Steffens F, Rana S, Figueiro R. Development of novel auxetic textile structures using high performance fibres. *Materials and Design*. 2016;**106**:81-89. DOI: 10.1016/j.matdes.2016.05.063
- [54] Wang Z, Zulifqar A, Hu H. Auxetic composites in aerospace engineering. In: Rana S, Figueiro R, editors. *Advanced Composite Materials for Aerospace Engineering*. Cambridge: Woodhead Publishing Limited; 2016. pp. 213-240
- [55] Ge Z, Hu H. Innovative three-dimensional fabric structure with negative Poisson's ratio for composite reinforcement. *Textile Research Journal*. 2013;**83**:543-550. DOI: 10.1177/0040517512454185
- [56] Groover ME. *Fundamentals of Modern Manufacturing- Materials, Processes, and Systems*. New Jersey: Prentice-Hall; 1996. 1128 p.
- [57] Campbell FC. *Manufacturing Processes For Advanced Composites*. Oxford: Elsevier; 2004. 532 p
- [58] Islam MS, Roy AK. Surface preparation of fibres for composite applications. In: Rana S, Figueiro R, editors. *Fibrous and Textile Materials for Composite Applications*. Singapore: Springer; 2016. pp. 301-315
- [59] Adams DF, Carlsson LA, Pipes RB. *Experimental Characterization of Advanced Composite Materials*. Boca Raton, FL: CRC Press; 2003. 256 p
- [60] Daniel IM, Ishai O. *Engineering Mechanics of Composite Materials*. New York: Oxford University Press; 2006
- [61] Kaw AK. *Mechanics of Composite Materials*. Boca Raton, FL: CRC Press; 2006

- [62] Hashin Z. Theory of Fibre Reinforced Materials. CR-1974. Washington: NASA; 1972
- [63] Ishikawa T, Chou TW. Elastic behavior of woven hybrid composites. *Journal of Composite Materials*. 1982;**16**:2-19. DOI: 10.1177/002199838201600101
- [64] Ishikawa T, Chou TW. One-dimensional micromechanical analysis of woven fabric composites. *AIAA Journal*. 1983;**21**:1714-1721. DOI: 10.2514/3.8314
- [65] Ishikawa T, Chou TW. Nonlinear behavior of woven fabric composites. *Journal of Composite Materials*. 1983;**17**:399-413. DOI: 10.1177/002199838301700502
- [66] Naik NK, Shembekar PS. Elastic behavior of woven fabric composites: I—Lamina analysis. *Journal of Composite Materials*. 1992;**26**:2196-2225. DOI: 10.1177/002199839202601502
- [67] Shembekar PS, Naik NK. Elastic behavior of woven fabric composites: II—Laminate analysis. *Journal of Composite Materials*. 1992;**26**:2226-2246. DOI: 10.1177/002199839202601503
- [68] Hahn HT, Pandey R. A micromechanics model for thermoelastic properties of plain weave fabric composites. *Journal of Engineering Materials and Technology*. 1994;**116**:517-523. DOI: 10.1115/1.2904322
- [69] Ko FK, Chou TW. *Composite Materials Series 3—Textile Structural Composites*. Amsterdam: Elsevier Science; 1989
- [70] Vandeurzen P, Ivens J, Verpoest I. A three-dimensional micromechanical analysis of woven-fabric composites: I. Geometric analysis. *Composites Science and Technology*. 1996;**56**:1303-1315. DOI: 10.1016/S0266-3538(96)00092-9
- [71] Vandeurzen P, Ivens J, Verpoest I. A three-dimensional micromechanical analysis of woven-fabric composites: II. Elastic analysis. *Composites Science and Technology*. 1996;**56**:1317-1327. DOI: 10.1016/S0266-3538(96)00091-7
- [72] Cox BN, Dadkhah MS. The macroscopic elasticity of 3D woven composites. *Journal of Composite Materials*. 1995;**29**:785-819. DOI: 10.1177/002199839502900606
- [73] Tan P, Tong L, Steven GP. Models for predicting thermomechanical properties of three-dimensional orthogonal woven composites. *Journal of Reinforced Plastics and Composites*. 1999;**18**:151-185. DOI: 10.1177/073168449901800204
- [74] Tan P, Tong L, Steven GP. Micromechanics models for mechanical and thermomechanical properties of 3D through-the-thickness angle interlock woven composites. *Composites Part A: Applied Science and Manufacturing*. 1999;**30**:637-648. DOI: 10.1016/S1359-835X(98)00176-6
- [75] Pastore C, Gawayed Y. A self-consistent fabric geometry model: Modification and application of a fabric geometry model to predict the elastic properties of textile composites. *Journal of Composites, Technology and Research*. 1994;**16**:32-36. DOI: 10.1520/CTR10392J
- [76] Yang JM, Ma CL, Chou TW. Fiber inclination model of three-dimensional textile structural composites. *Journal of Composite Materials*. 1986;**20**:472-484. DOI: 10.1177/002199838602000505

- [77] Rudd CD, Owen MJ, Middleton V. Mechanical properties of weft knit glass fibre/polyester laminates. *Composites Science and Technology*. 1990;**39**:261-277. DOI: 10.1016/0266-3538(90)90045-7
- [78] Ramakrishna S, Hull D. Tensile behaviour of knitted carbon-fibre-fabric/epoxy laminates—part II: Prediction of tensile properties. *Composites Science and Technology*. 1994;**50**:249-258. DOI: 10.1016/0266-3538(94)90146-5
- [79] Brown G. The use of composites in aircraft construction. [Internet]. 2014. Available from: <https://vandaair.com/2014/04/14/the-use-of-composites-in-aircraft-construction/> [Accessed: 29 January 2017]
- [80] Pilato LA, Michno MJ. *Advanced Composite Materials*. Heidelberg: Springer; 1994. 208 p
- [81] Liu Y, Araujo M, Hu H. Advanced fibrous architectures for composites in aerospace engineering. In: Rana S, Figueiro R, editors. *Advanced Composite Materials for Aerospace Engineering: Processing, Properties and Applications*. Oxford: Elsevier; 2016. pp. 17-58
- [82] Mullen CK, Roy PJ. Fabrication and properties description of Avco 3D carbon-carbon cylindrical composites. In: *National SAMPE Symposium*; 11-13 April 1972; Los Angeles, California. pp. III-A-Two-I-8
- [83] Wong R. Sandwich construction in the Starship. In: *Proceedings of the 37th International SAMPE Symposium*; 9-12 March 1992; Anaheim, California. pp. 186-197
- [84] Mouritz AP, Bannister MK, Falzon PJ, Leong KH. Review of applications for advanced three-dimensional fibre textile composites. *Composites Part A: Applied Science and Manufacturing*. 1999;**30**:1445-1461. DOI: 10.1016/S1359-835X(99)00034-2
- [85] Kadero SW. France, Russia to join in scramjet flight tests. *Aviation Week and Space Technology*. 2001 60-62
- [86] Potluri P, Nawaz S. Developments in braided fabrics. In: Gong RH, editor. *Specialist Yarn and Fabric Structures*. Cambridge: Woodhead Publishing Limited; 2011. pp. 333-353
- [87] Technology A. Bombardier Wing Flap. [Internet]. 2017. Available from: <http://www.braider.com/Case-Studies/Bombardier-Wing-Flap.aspx> [Accessed: 29 January 2017]
- [88] Technology A. Honeywell Jet Engine Stator Vane. [Internet]. 2017. Available from: <http://www.braider.com/Case-Studies/Jet-Engine-Stator-Vane.aspx> [Accessed: 29 January 2017]
- [89] Technology A. GENx Engine. [Internet]. 2017. Available from: <http://www.braider.com/Case-Studies/GENx-Engine.aspx> [Accessed: 29 January 2017]
- [90] Lowe J. Aerospace applications. In: Long AC, editor. *Design and Manufacture of Textile Composites*. Cambridge: Woodhead Publishing Limited; 2005. pp. 405-423
- [91] Middendorf P, Metzner C. Aerospace applications of non-crimp fabric composites. In: Lomov SV, editor. *Non-crimp Fabric Composites*. Cambridge: Woodhead Publishing Limited; 2011. pp. 441-448

- [92] Liguore SL, Montgomery JM, inventors. Systems and Methods for Reducing Noise in Aircraft Fuselages and Other Structures. 2012. US Patent 8297555
- [93] Motavalli M, Czaderski C, Schumacher A, Gsell D. Fibre reinforced polymer composite materials for building and construction. In: Pohl G, editor. *Textiles, Polymers and Composites for Buildings*. Cambridge: Woodhead Publishing Limited; 2010. pp. 69-128
- [94] Ehlig D, Schladith F, Frenzel M, Curbach M. Textilbeton—ausgeführte projekte im überblick. *Beton-und Stahlbetonbau*. 2012;**107**:777-785. DOI: 10.1002/best.201200034
- [95] Hering. BetoShell: Textile-reinforced concrete as curtain facade. [Internet]. 2017. Available from: <https://www.heringinternational.com/en/products-services/architectural-concrete/material-concepts/textile-reinforced-concrete/> [Accessed: 29 January 2017]
- [96] Raupach M, Cruz CM. Textile-reinforced concrete: Selected case studies. In: Triantafillou T, editor. *Textile Fibre Composites in Civil Engineering*. Duxford: Elsevier; 2016. pp. 275-299
- [97] Müller J, Zulliger A, Dorn M. Economic production of composite beams with 3D fabric tapes. *Textile Month*. 1994; September: 9-13
- [98] S&P. FRP strengthening systems. [Internet]. 2017. Available from: <http://www.sp-reinforcement.eu/en-CH/products> [Accessed: 29 January 2017]
- [99] Dufour C, Pineau P, Wang P, Soulat D, Boussu F. Three-dimensional textiles in the automotive industry. In: Chen X, editor. *Advances in 3D Textiles*. Cambridge: Woodhead Publishing Limited; 2015. pp. 265-291. DOI: 10.1016/B978-1-78242-214-3.00010-3
- [100] Vaidya U. *Composites for Automotive, Truck and Mass Transit-Materials, Design, Manufacturing*. Lancaster, PA: DEStech Publications, Inc.; 2011. 419 p
- [101] Turner TA, Harper LT, Warrior NA, Rudd CD. Low-cost carbon-fibre-based automotive body panel systems: A performance and manufacturing cost comparison. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*. 2008;**222**:53-63. DOI: 10.1243/09544070JAUTO406
- [102] Feraboli P, Masini A, Bonfatti A. Advanced composites for the body and chassis of a production high performance car. *International Journal of Vehicle Design*. 2007;**44**:233-246. DOI: 10.1504/IJVD.2007.013641
- [103] Chapman GB. The need and requirements driving the development of polymer composites for automotive applications. In: *Proceedings of ICCM-11; 1997; Gold Coast, Australia*
- [104] Ko FK. Textile composites for automotive structural components. In: Shishoo R, editor. *Textile Advances in the Automotive Industry*. Cambridge: Woodhead Publishing Limited; 2008. pp. 320-343

- [105] Gries T, Stueve J, Grundmann T, Veit D. Textile structures for load-bearing applications in automobiles. In: Shishoo R, editor. *Textile Advances in the Automotive Industry*. Cambridge: Woodhead Publishing Limited; 2008. pp. 301-319
- [106] Ellis JG. Textile reinforced composites in medicine. In: Long AC, editor. *Design and Manufacture of Textile Composites*. Cambridge: Woodhead Publishing Limited; 2005. pp. 436-443
- [107] Ramakrishna S, Huang ZM, Kumar GV, Batchelor AW, Mayer J. *An Introduction to Biocomposites*. London: Imperial College Press; 2004. 223 p
- [108] Evans SL, Gregson PJ. Composite technology in load-bearing orthopaedic implants. *Biomaterials*. 1998;**19**:1329-1342. DOI: 10.1016/S0142-9612(97)00217-2
- [109] McCormick M. Soaring to new heights: The evolution of pole vaulting and pole materials. *Illumin*. 2010;**12**:1-5
- [110] Froes FH. Is the use of advanced materials in sports equipment unethical? *Journal of the Minerals, Metals, and Materials Society*. 1997;**49**:15-19. DOI: 10.1007/BF02915473
- [111] Van de Velde K. Textile composites in sports products. In: Long AC, editor. *Design and Manufacture of Textile Composites*. Cambridge: Woodhead Publishing Limited; 2005. pp. 444-457

