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Chapter 11

Applications of Glass Fibers in 3D Preform Composites

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Abstract

E-glass three dimensional (3D) stitched preform composites have been developed for several industrial applications due to their high mechanical performance and damage tolerance properties. Although some in-plane properties of the stitched E-glass composite structure are slightly lower than in laminated composite, its mode-I delamination failure is improved. This was achieved by using the out-of-plane directional stitched fibers. Recently, some nanoparticles as single-walled nanotubes (SWNT) or multiwalled nanotubes (MWNT) or nanofibers (NF) were added to the glass fabric structure or stitched preform during consolidation process. This further enhances the thermo-mechanical impact properties of the E-glass fiber composites.

Keywords: glass fiber, nanosilicate, nanocarbon, preform, 3D fabric architecture

1. Introduction

Textile fiber composites have been used in various space-aerospace, ballistic, industrial, and medical areas due to their high stiffness to weight ratio and damage tolerance properties [1]. The most important reasons for the increased use of textile structural composites are the increased expectations for product performance and demand for lightweight materials in global markets.

Textile-based composites consist of fibers with high strength and modulus properties, and matrix materials that bond these fibers together to provide load transfer and structural integrity. Fibers provide strength and stiffness to the composite materials, while the resins basically keep the fibers together to transfer stresses between the fibers. Glass fibers are the most common of all reinforcing fibers for polymeric matrix composites, which have low cost, high tensile strength, high chemical resistance, and excellent insulating properties [1–3].

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Glass fibers are used as other reinforcement fibers in manufacturing of textile preforms for composites. The textile preform fabrication is done by weaving, braiding, knitting, and stitching and by using nonwoven techniques, and they can be chosen generally based on the end-use requirements. Originally, three dimensional (3D) preforms can be classified according to fiber interlacement types. Simple 3D preform consists of two dimensional (2D) fabrics and is stitched depending on stack sequence. More sophisticated 3D preforms are fabricated by specially designed automated loom and manufactured to near-net shape to reduce scrap [4–6].

In polymeric materials, the use of organic and inorganic fillers has become very common. Polymer composites are used commercially in various areas such as construction and civil engineering, automobile components, and sports equipment. Over the past 20 years, great importance has been attached to the development of polymeric nanocomposites. In nanocomposites where at least one of the components is in the nanometer range, the final product is in micro- or macrosize. In addition, advances in computer technology have facilitated the characterization of nanomaterials and their estimation through modeling and simulations [7].

This chapter deals with applications of glass fibers in 3D preform composites. The fabrication, classification, and properties of glass fibers were introduced. Types of matrix and properties of used nanofillers in textile-based polymeric composites in the form of sphere, tubes, and fibers were explained. 2D and 3D fabric forms of glass fibers were reviewed especially considering the 3D stitched composite. Basic fabrication methods of composites were provided. Mechanical properties and failure modes of glass fiber–reinforced 3D composites were discussed by considering the special application areas.

2. Glass fibers, matrix, and nanoadditives

2.1. Glass fibers

Glass can be finely spun into fibers that are pliable to be woven into textiles. Glassy materials, above their glass transition temperature, T_g, show Newtonian viscosity, i.e., the stress is proportional to the strain rate. This property is exploited in the drawing of glass into fiber and planar forms [8]. Glass fibers are used in manufacturing structural composites, printed circuit boards, and a wide range of special-purpose products [9]. Glass fiber manufacturing is the high-temperature conversion of various raw materials, which are predominantly borosilicate, into a homogeneous melt, followed by the fabrication of this melt into glass fibers [10]. The most important melt properties of fiberglass melts are the fiber-forming viscosity, the temperature at which fibers are formed, and the liquid temperature at which crystals can form within hours and remain in equilibrium with the melt [11]. The basic component of glass fibers is silica (silicon dioxide (SiO_2)) derived from ordinary sand, and the viscous melts can be strong melts typically containing 50–100% SiO_2 and 0–25% Al_2O_3 [12, 13]. The continuous fibers are produced using bushings, which have a few hundred to several thousand small tubes of the bushing. One fiber is produced from each tip. The temperature of the glass exiting tip is typically in the range of 1150–1300°C, depending upon the composition of the glass.

The glass will normally flow out of the bushing under the force of gravity into fibers on the order of 1 mm diameter. The final diameter of the glass fiber is a strong function of the tension applied to the fiber as it is being drawn [14]. **Figure 1** shows the manufacturing of glass fibers and some produced glass fiber tows [15, 16].

The compositions of the glass fibers vary depending on glass types (A-glass, S-glass, or E-glass). More than 99% of continuous glass fibers are spun from an E-glass [17]. The remaining glass fibers are premium special-purpose products [18]. **Table 1** presents the glass fiber types with short explanations [19].

The physical properties of glass fibers are affected by the compositions. The two types of glass fibers commonly used in the fiber-reinforced plastic industry are E-glass and S-glass [2]. Therefore, the physical properties of these fibers are generally discussed. The densities of E-glass and S2-glass fibers are 2.58 g/cm^3 and 2.46 g/cm^3, respectively. The softening points of E-glass and S2-glass are 846°C and 1056°C, respectively. The tensile strengths and modulus are 3345 MPa and 72.3 GPa for E-glass and 4890 MPa and 86.9 GPa for S2-glass, while the elongations are 4.8 and 5.7%, respectively [19]. Scanning electron microscope (SEM) views of E-glass fiber and tow are shown in **Figure 2** [20].

2.2. Matrix

Polymer-based matrix materials are basically classified into two main groups as thermoset and thermoplastic. In general, thermoset polymeric resins have a widespread use in fiber-reinforced composites. The fibers are applied with these resins using the resin transfer molding or recently vacuum-assisted resin transfer molding techniques. During processing, the viscosity of the polymer is low during the interaction of the fiber with the matrix.

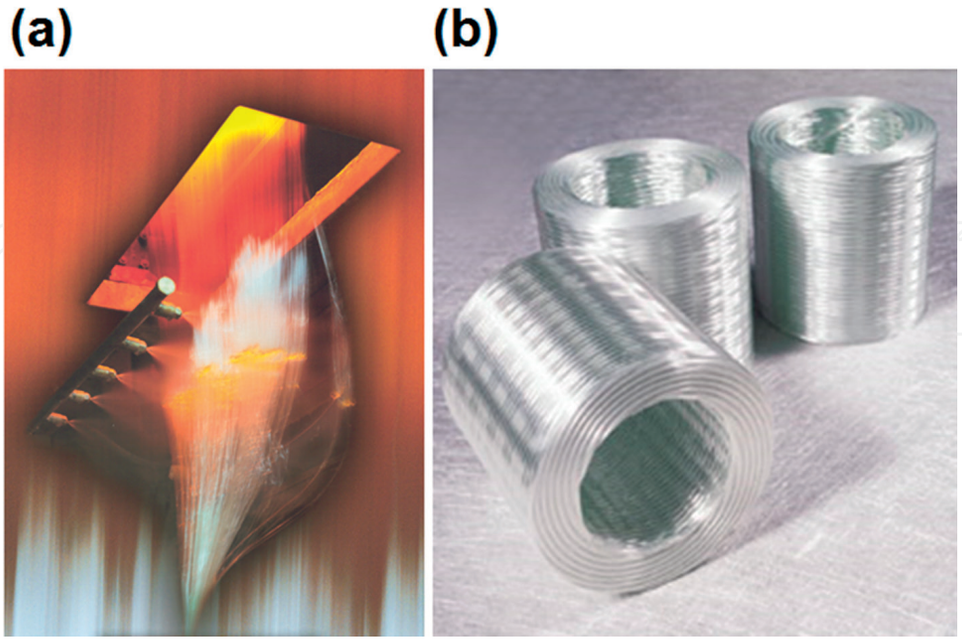


Figure 1. (a) Drawing of glass filaments and (b) glass tows [15, 16].

Type	Description
A glass	High alkali glass—72–75% silica, 0–6 alumina, and 0–6 boron oxide content. Poor resistance to heat. Used for windows, containers, light bulbs, tableware, etc.
C glass	Chemical glass—64–78% silica, 3–5% alumina, and 4–6% boron oxide content. Improved durability and corrosion resistance. Glass staple fibers for making glass mats.
D glass	Dielectric glass—72–75% silica, 0–1 alumina, and 21–24% boron oxide content. Improved dielectric strength and low density. Improved electrical performance.
E glass	Electrically resistant glass—52–56% silica, 12–16% alumina, and 5–10% boron oxide content. Used in glass reinforced plastics as general-purpose fibers where strength and high electrical resistivity are required.
ECR glass	Modified 'E' glass—54–62% silica and 9–15% alumina content. Superior long-term resistance to strain crack corrosion in acid conditions.
AR glass	Alkali-resistant glass—55–75% silica and 1–18% zirconium content. Used in cement substrates and concrete.
R glass	55–60% silica and 23–28% alumina content. High-strength, high-modulus at a lower cost than 'S' glass.
S2 glass	64–66% silica, 24–25% alumina, and 9.5–10% magnesium oxide (40% higher than E-glass) content. Developed for aerospace applications.

Table 1. Glass fiber types and some of their physical and chemical specifications [19].

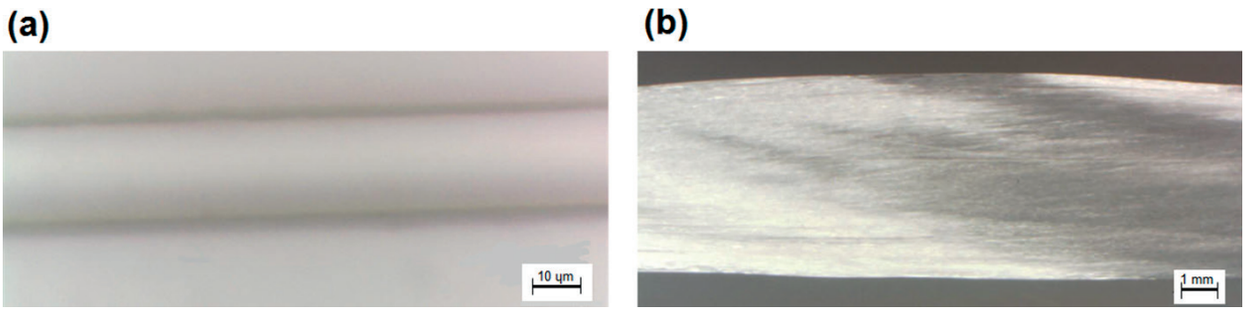


Figure 2. SEM views of E-glass fiber and tow. (a) E-glass fiber and (b) E-glass tow [20].

This provides good wetting properties between the fiber and the matrix without any additional high temperature or pressure. However, the low strain properties of thermoset resins reduce the impact strength of the composites. The most widely used thermoset resins are epoxy, polyester, phenolic, and vinyl ester [1, 2, 21].

There is a growing interest in development and production of the thermoplastic polymer–based composites. The reason of this interest is the ability of thermoplastic composites to form and remold easily in shorter process times compared to thermoset composites. Furthermore, thermoplastic composites provide high fracture toughness, damage tolerance, and microcrack resistance [22, 23]. Thermoplastic resins are about 500–1000 times more viscous than thermoset resins. This restricts the infusion tendency of resins to fibers. In addition, the need for high pressures in thermoplastic composite process is also considered as another limiting factor. Semicrystalline thermoplastic polymers such as polyether ether ketone (PEEK), polyphenylene sulfide (PPS), and liquid-crystal polymers (LCP) are mainly used in aviation due to their

mechanical and chemical resistance at relatively high temperatures. Some other thermoplastic polymers such as polypropylene(PP), acrylonitrile butadiene styrene (ABS), and polyamide (PA) find use in the automotive industry. PP has a very common use in the production of thermoplastic composites due to its low cost, high specific properties, and reusability [24, 25]. The properties of some of the thermoset and thermoplastic resins are presented in **Table 2** [21].

Polyesters are used extensively in continuous and discontinuous composites and they are relatively inexpensive with processing flexibility. They are cured by addition reactions in which unsaturated carbon-carbon double bonds (C═C) are the locations where cross-linking occurs. Typical polyester consists of at least three ingredients: a polyester, a cross-linking agent such as styrene, and an initiator, usually a peroxide, such as methyl ethyl ketone peroxide (MEKP). One of the main advantages of polyesters is that they can be formulated to cure at either room temperature or elevated temperatures, allowing great versatility in their processing. Epoxies are high-performance matrix systems for primarily continuous fiber composites and have better high-temperature performance than polyesters and vinyl esters. Epoxies are used in resin transfer molding, filament winding, pultrusion, hand layup, and other processes with various high-modulus and high-strength fibers. The properties of the resultant resins are strongly dependent on the cross-linking [2, 3]. Vinyl esters are similar to polyesters but are tougher and have better moisture resistance [2, 26].

2.3. Nanoadditives

Nanoparticles have been identified in the last decade as an important class of materials for various emerging applications in optics, electronics, or the biomedical area. Many of the potential applications are based on two major changes when the scale of material structures decreased. These are the high surface-to-volume ratio and the improvement of the electronic properties [27]. Nanocomposites can be described as particle-filled polymers in which at least one of the components is in nanometer dimensions [28]. The investigation of fullerenes (nanosphere) and carbon nanotubes (CNT) has opened a totally new window for the development of polymer matrix composites with novel properties and applications [29]. Nanofillers have a considerable potential in improving the properties of polymeric composites [30, 31]. The stiffness, toughness, and abrasion resistance of nanocomposites depend on the size, shape, ratio, and uniform distribution of the fillers in the polymers [32]. It can be possible to obtain

Polymer	Resin	Density (g/cm^3)	Tensile modulus (GPa)	Tensile strength (MPa)
Thermoset	Epoxy	1.2–1.4	2.5–5.0	50–110
	Phenolic	1.2–1.4	2.7–4.1	35–60
	Polyester	1.1–1.4	1.6–4.1	35–95
Thermoplastic	Polyamide	1.1	1.3–3.5	55–90
	PEEK	1.3–1.35	3.5–4.4	100
	PPS	1.3–1.4	3.4	80

Table 2. The specification of thermoset and thermoplastic matrix [21].

materials with high toughness values by producing nanocomposites with high nanoparticle ratio, homogeneous alignment, and high interface strength [33]. Interfacial bond properties between nanoparticle and matrix in the composite are active research subject in the research and development societies [31]. Nanosphere, single-walled, or multiwalled tubes were applied to the composites by dispersing the nanoparticles in the resin using various techniques such as shear mixing, ultrasonication, calendering, ball milling or ultrasonication-extrusion, and transfer-printing. If nanofibers were used, they were attached, grown, or grafted onto fibers or 2D fabrics. Full deagglomeration of CNTs using mixers is difficult to achieve. High flow rates creating high-shear forces cause well distribution of agglomerated CNTs. However, their breakage is not avoided and the presence of CNT agglomerates is usually observed [34]. Various nanosized materials were developed by employing the up-to-date processing as silica is one of the most important and most studied oxide nanoparticle types. Due to its quite simple preparation, its chemical inertness, and the relatively inexpensive precursors, it became a prominent compound in academics and in commercial applications [27]. Because of its high specific component of surface energy, silica has a stronger tendency to agglomerate than carbon black [35]. **Figure 3** shows the SEM (scanning electron microscope) micrograph of nanosilica and nano- and microcarbon spheres [20].

In the past few years, novel materials such as carbon nanotubes (CNTs) and related technologies have posed a strong candidacy for providing an integrated approach toward enhanced structural integrity and multifunctionality [36]. The development of novel glass fiber–reinforced plastics (GFRPs) with electrical conductivity has opened up new opportunities for damage sensing. Adding a small amount of carbon nanotubes to form an electrically conductive network is a promising approach to monitor damage initiation and propagation for glass fiber–reinforced composites [37].

The pre-dispersed overcoating of nanotubes and the process modifications allow improvement of the interface properties of 2D woven E-glass composites since the reinforcement effect of nanotubes on z-direction [38]. The amine functionalized carbon nanotubes had improved tensile strength compared to neat [39]. The modulus of composites is enhanced by the addition of silicon carbide nanoparticles by considering dispersion of these particles in resin, which highly depends on the coupling agents and dispersants [40]. Moreover, the weak

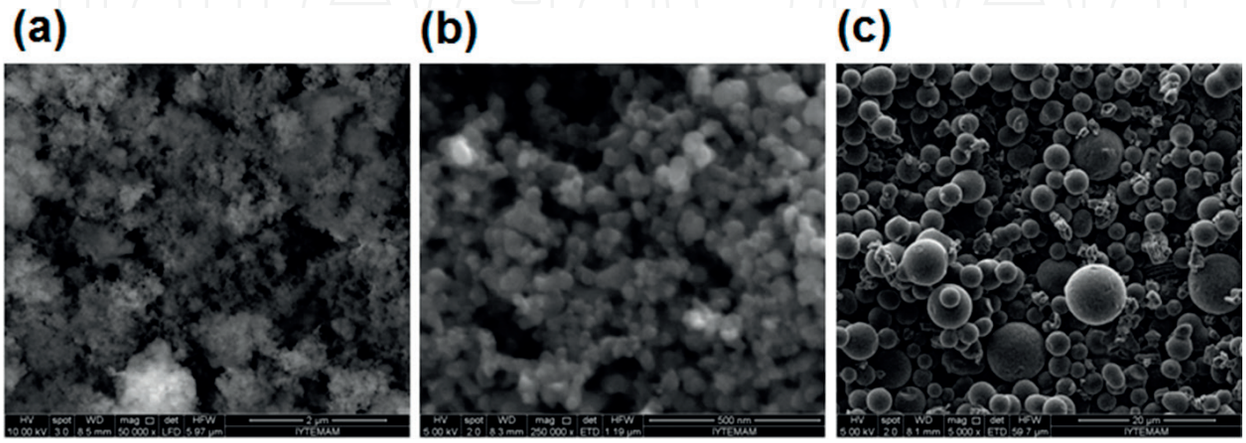


Figure 3. SEM micrograph of some nanofillers. (a) Nanosilica (magnification 50,000×); (b) nanocarbon (magnification 250,000×); and (c) nanocarbon (magnification 5000×) [20].

bonds at the interfaces of silicon carbide nanoparticles and resin lead to stress concentration rely on the particle geometry [41].

3. 2D fabrics and 3D preforms

3.1. Two dimensional (2D) fabrics

The most preferred 2D fabrics in textile structural composites are discussed as 2D woven fabric, triaxial woven fabric, braided fabric and knitted fabric, uniaxial and biaxial knitted fabrics, and nonwoven fabric. The most common fabric used in the textile structural composites is 2D woven fabric due to its more stable property compared to the knitted fabric. To form the 2D woven fabric, there are two yarn sets as warp and weft interlace each other at right angle. 2D woven fabric has three types of main patterns as plain, twill, and satin and also a lot of derivative patterns. Because the plain woven fabric is formed by more interlacement points between warp and weft, its structural characteristics become more rigid, less flexible, and more durable. Twill woven fabric has inclined paths from right to left or from left to right on the fabric surface due to its interlacements of warp and weft. In satin woven fabric, warp has long floats, which are evenly distributed through the fabric. It has low crimp ratio. The schematic views of weaves and microscopic view of E-glass plain woven fabrics are shown in **Figure 4** [20].

The schematic views of triaxial woven fabric and braided fabric are shown in **Figure 5(a)** and **(b)**. As shown in **Figure 5(a)**, triaxial weave has three sets of yarn as +bias, −bias, and weft yarn in which these yarns take in interlacements [42]. This fabric has large gaps in the crossing region of warp and weft due to interlacements and it restricts to make dense fabrics during 2D woven fabric formation [44]. 2D braided fabric has one yarn set as braiders, which have +θ° and –θ° orientations. As shown in **Figure 5(b)**, these braider yarns are intertwined with each other to make the 2D braided fabric structure [43].

Figure 6(a–g) shows the schematic views of weft and warp knitted fabrics and uniaxial and biaxial knitted fabrics. The knitted fabric is constituted from yarn loops connected to each other and to the neighboring rows and columns by various techniques. The basic knitting types are weft knitting (**Figure 6a**) and warp knitting (**Figure 6b**) [45].

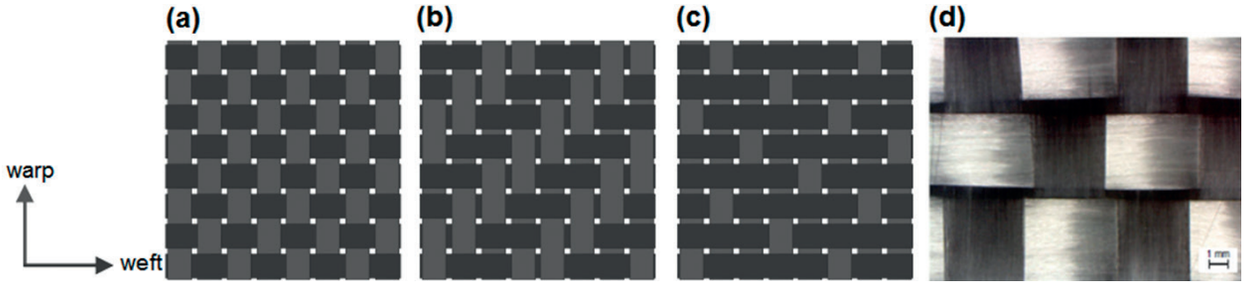


Figure 4. The schematic views of weaves and microscopic view of E-glass plain woven fabrics. (a) plain; (b) twill; (c) satin; and (d) E-glass plain woven fabric [20].

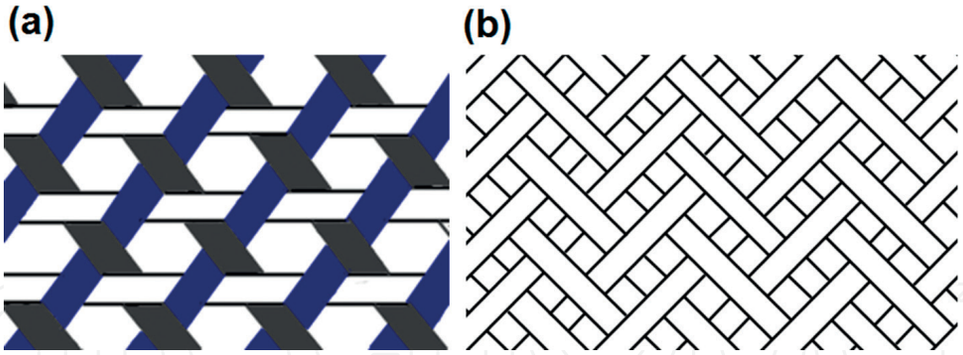


Figure 5. Schematic views of triaxial woven and braided fabrics. (a) Triaxial woven fabric and (b) braided fabric [42, 43].

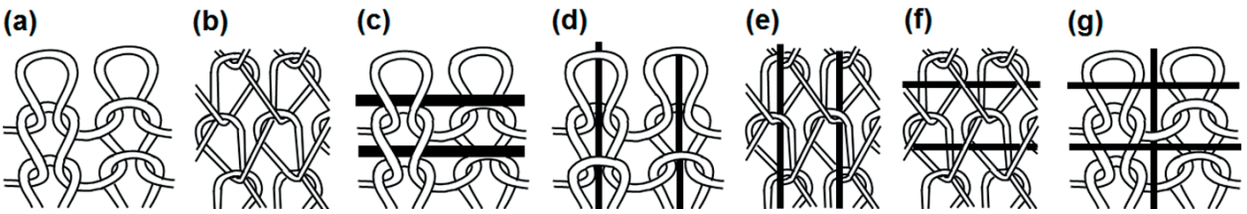


Figure 6. (a) Weft knitted fabric; (b) warp knitted fabric; (c) weft inlaid weft knitted fabric; (d) warp inlaid weft knitted fabric; (e) warp inlaid warp knitted fabric; (f) weft inlaid warp knitted fabric; and (g) 0°/90° inlaid weft knitted fabric [45–47].

The uniaxial knitted fabric is a special type looped knitted fabric. It has big gaps, which lead to low fiber-volume-fractions, high-elongation, and low stiffness. Because of these restrictions, some structural modifications were performed by adding inlay yarns either in fabric length (**Figure 6(d)** and **(e)**) or width (**Figure 6(c)** and **(f)**). The tensile strengths of uniaxial knitted fabric composites improved in the direction of inlaid [46].

Biaxial knitted fabric is manufactured by introducing the warp (0°), weft (90°), or diagonal (±45°) yarns into the weft (**Figure 6(g)**) or warp knitted fabrics, which resulted as the improved mechanical properties of composites at the inlaid directions [48]. Nonwoven fabric is a web structure made up of short fibers that are held together by various techniques [49]. Nonwoven manufacture is that it is generally done in one continuous process directly from the raw material to the finished fabric [50]. **Figure 7** shows the view of nonwoven glass mat [51].

3.2. Three dimensional (3D) fabrics

2D fabric–reinforced composites are a biaxially oriented planar structure. However, unidirectional fiber composite is an axially oriented planar structure. Both suffer from a delamination. 3D fabric preforms have been developed to make the delamination free composite.

Stitching can be used to make 3D fabrics using the 2D woven fabric [52]. 3D stitched fabric is manufactured by stitching 2D fabric layers in thickness direction. It can be stitched at one direction (0°), two directions (0° and 90°), and four directions (0°, 90°, and ±bias) as shown in **Figures 8** and **9**. Stitching can be made by sewing machine. The lock stitching is generally used in stitched preform fabrication for composites [53, 54].

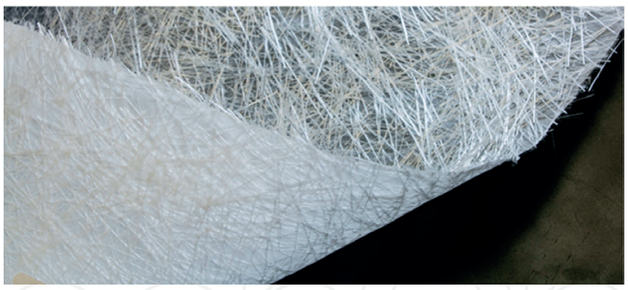


Figure 7. Nonwoven glass mat [51].

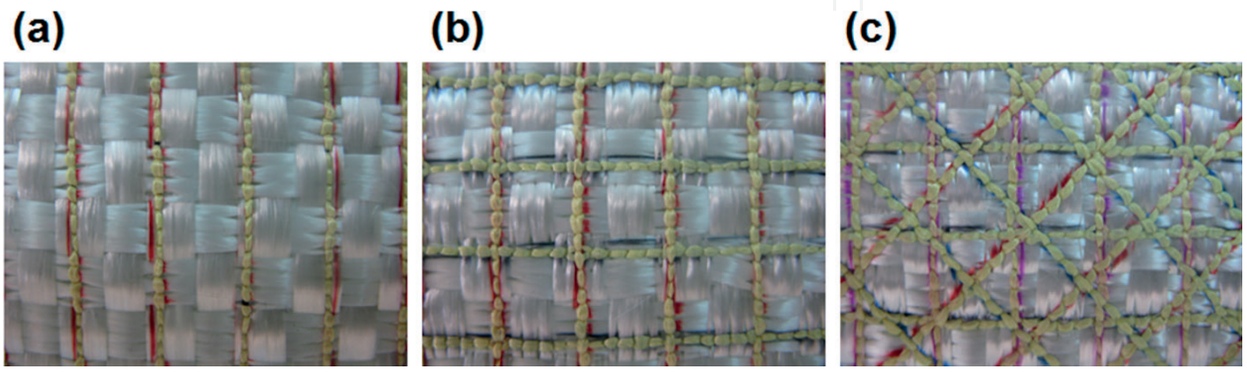


Figure 8. Top views of stitched E-glass preforms. (a) One-directional machine stitched; (b) two-directional machine stitched; and (c) four-directional machine stitched [53].

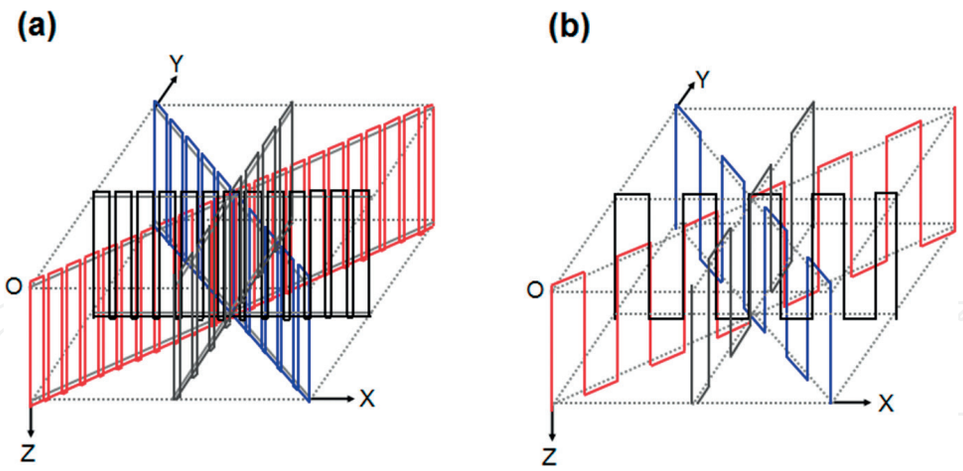


Figure 9. Schematic view of multistitched yarn paths. (a) Machine multistitched yarn path and (b) hand multistitched yarn path [54].

3D orthogonal woven fabric has three yarn sets as warp, weft, and z-yarn (**Figure 10(a)**). These yarn sets are interlaced to one another and oriented in three orthogonal directions to form the fabric [59]. Warp yarns are placed in the direction of the fabric length, while the weft yarns are inserted between the warp layers to form double picks. Z-yarns lock the other two yarn sets and provide structural integrity [48]. **Figure 10(a–d)** shows some of the 3D fabrics [55–58].

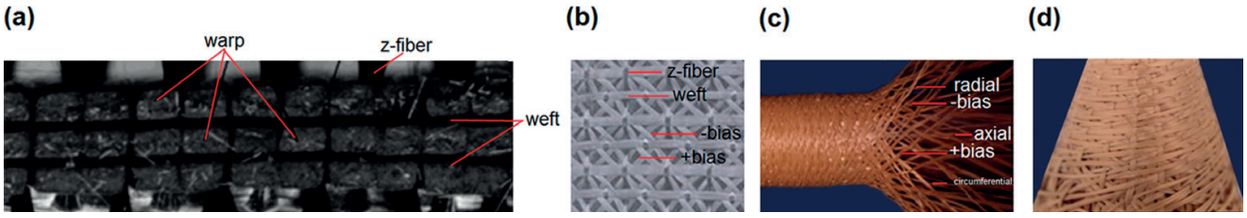


Figure 10. Some of the 3D fabrics. (a) 3D woven carbon fabric [55]; (b) multiaxis 3D woven carbon fabric [56]; (c) multiaxis 3D circular woven aramid fabric [57]; and (d) multiaxis 3D braided conical aramid fabric [58].

A multiaxis 3D woven fabric, method, and machine were developed by Mohamed and Bilisik [60]. The multiaxis 3D woven fabric has five yarn sets as +bias, −bias, warp, weft, and z-yarn. ±Bias yarns are placed on the front face and back face. These yarns are locked to the other yarn sets by the z-yarns (**Figure 10(b)**). Multiaxis 3D circular woven fabric, method, and machine were developed by Bilisik. The 3D circular woven fabric has axial and radial yarns along with circumferential and ±bias yarns (**Figure 10(c)**). Cylindrical preform can be made with thin and thick wall sections depending upon end-use requirements [61]. In multiaxis 3D braided fabric, braider yarns are intertwined with the axial yarns, whereas ±bias yarns are oriented at the surface of the structure and locked by the radial yarns to the other yarn sets (**Figure 10(d)**). The properties of the multiaxial 3D braided structure in the transverse direction can be enhanced and the nonuniformity in the directional Poisson's ratios can be decreased [58, 62].

4. Composite

Several methods are developed in order to make composite based on 2D fabric and 3D preforms. The fiber properties, type of fabric formation and matrix, end-use requirement, and shape/size characteristics of the part influence the composite fabrication processes. **Figure 11** shows the schematic views of some of the composite fabrication techniques [20, 63].

Hand layup is the most commonly used composite fabrication method. It is still preferred because of highly flexible in design and suitable for the production of a wide variety of raw materials. The fabric layers are laid according to the desired thickness, and after each layer is laid, the resin is added by brush to spread the resin to wet the fibers. Then, the part is usually cured at room temperature and removed from the mold (**Figure 11(a)**). Resin transfer mold (RTM) is a recently introduced composite fabrication method to produce near-net shape parts.

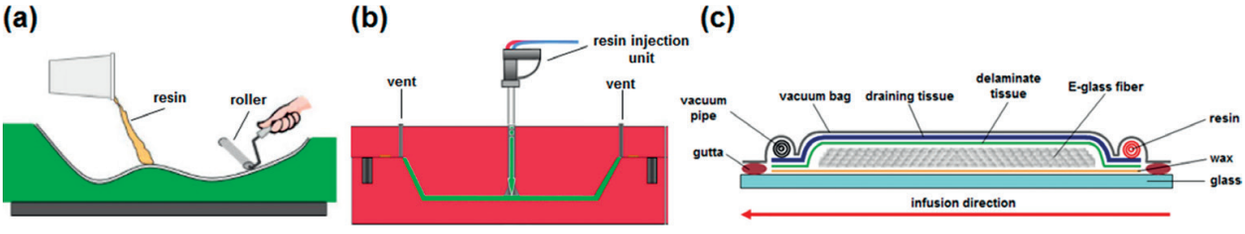


Figure 11. Schematic views of some of the composite fabrication techniques. (a) Hand layup; (b) resin transfer molding [63]; and (c) vacuum-assisted resin transfer molding [20].

The preform is placed in the gap between the molds. Then, the mold is closed and the gaps in the preform are filled by wetting all the fibers with resin. This process usually takes place under high pressure. The part is removed from the molds after curing (**Figure 11(b)**). The vacuum-assisted resin transfer molding (VARTM) method is more cost-effective since it does not require a metallic mold. The preform is placed on the mold and covered with sealing tape with flexible vacuum film. The resin passes through the structure under vacuum and it is possible to produce high performance composite structures with high fiber volume fractions (**Figure 11(c)**) [1–3].

5. Properties of preforms and composites

3D glass woven preforms improve the out-of-plane properties of the composites. 3D stitched woven preforms also enhance the out-of-plane properties without decreasing the in-plane properties of the composite [64]. It is pointed out that the fracture mechanism of the stitched composite plates is affected by the loading direction in tensile test, but the stiffness of the structure is not significantly affected by the stitching [65]. The tensile strengths of stitched composite, in which twisted stitching yarns are utilized, is lower compared to the stitched composite having with untwisted stitching yarns [66]. It is demonstrated that stitching prevents the crack propagation [66, 67]. The stitching causes local irregularities and undulation in the preform, which leads to a nonuniform fiber volume fractions and reduces the in-plane properties of the composite [68, 69]. In unstitched composites, delamination-based cracks are observed as a form of layer separation. However, in stitched composites, mode-I failure is improved and catastrophic delamination is eliminated in which the composite becomes damage tolerance material. It is stated that the tensile strength of stitched composites is dependent on the parameters as stitching yarn type and stitching density. The ±45° directional off-axis tensile strengths of the 2D unstitched woven E-glass/polyester composites are 84.1 MPa and 75.4 MPa, while the ±45° directional off-axis tensile strengths of the 3D stitched woven E-glass/polyester composites vary from 86.5 to 70.0 MPa and from 83.5 to 64.1 MPa. The tensile strengths of four directional densely stitched composite is almost 15 and 6% lower than those of the unstitched composites at +45 and −45 directions, respectively. The similar trend is obtained for the ±45° directional off-axis tensile modulus of composite structures. The ±45° directional off-axis tensile modulus of the 2D unstitched woven E-glass/polyester composites is 5.9 GPa and 6.2 GPa, while the ±45° directional off-axis tensile modulus of the 3D stitched woven E-glass/polyester composites vary from 6.4 to 4.0 GPa and from 6.3 to 3.7 GPa. The tensile modulus of four directional densely stitched composite is almost 32 and 40% lower than those of the unstitched composites at +45 and −45 directions, respectively. These results show that when the stitching direction and stitching density in structures increase, their off-axis tensile strengths and modulus decrease since the multi-stitching process causes more filament breakages [70]. The warp and weft directional specific tensile strengths of the unstitched composites are higher than those in the multistitched composites due to stitching that causes filament breakages during insertion of the z-yarn. The stitching yarn types, stitch directions, and the stitch density generally influence the in-plane tensile properties of the multistitched E-glass/polyester woven composites. The warp-weft directional tensile strengths of the 2D unstitched woven E-glass/polyester composites are

303 MPa and 285 MPa, while the warp-weft directional tensile strengths of the 3D stitched woven E-glass/polyester composites vary from 353 to 229 MPa and from 345 to 209 MPa. The tensile strength of four directional densely stitched composite is almost 25 and 27% lower than those of the unstitched composites at warp and weft directions, respectively. The warp-weft tensile modulus of four directional densely stitched composite is almost 35 and 35% lower than those of the unstitched composites at warp and weft directions, respectively. However, the warp-weft damaged areas of four directional densely stitched composite after tensile failure are almost 70 and 82% lower than those of the unstitched composites at warp and weft directions, respectively. The warp and weft directional damaged areas of multistitched composites decrease when the stitching directions in the out-of-plane of the structure increased. Therefore, the stitching yarns lock the in-plane directional warp and weft yarns in the layered woven structure and confine the damage areas at narrow regions, which considers as damage tolerant materials [71]. Furthermore, the off-axis tensile modulus of the multistitched composites decreases with the increase of the stitching direction and stitching density [70].

The warp and weft direction specific bending strengths and modulus of the unstitched/nanocomposites are higher than those of the stitched composites since the stitching perhaps causes filament breakages during needle piercing action. The warp-weft specific strengths of four directional densely stitched composite are almost 25 and 31% lower than those of the unstitched composites at warp and weft directions, respectively. On the other hand, the warp and weft directional damaged areas of the unstitched composites are higher than multistitched and multistitched/nanocomposites. The addition of the nanosilica to the stitched structures increases the damage tolerance [72]. One of the critical property of the stitched composite is also through-the-thickness directional shearing. The short-beam strengths of hand-stitched composites in the warp and weft direction increase slightly as the stitching direction increased from two directions to four directions. In addition, the warp and weft directional short-beam strengths of machine-stitched structures with high-modulus stitching yarns (Kevlar® 129) are higher than those of the machine-stitched structures stitched with low-modulus stitching yarns (Nylon 6.6) [73]. The tensile and impact behaviors of stitched E-glass/polypropylene woven composites are studied. The stitching in the through-the-thickness direction increases impact damage tolerance especially at low temperatures. It is claimed that there is a relation between stitching fiber fracture work and energy absorption based on fiber volume fraction in stitched composites [74]. The mechanical properties such as the tensile and compression and compression-after-impact (CAI) strength of noncrimped fabric are not degraded by the stitching parameters, whereas the tensile and compression strength and the tensile fatigue behavior are reduced as a result of pronounced localized fiber undulations due to stitching [68]. Stitched layered composite has slightly higher compression and CAI strengths than the integrally woven composite [75]. In addition, it is found that the strength of overlap joint during preforming is improved by using high-density chain stitching [76]. The damage initiation force for 3D noninterlaced stitched composite is lower than for the 2D unstitched woven composite due to weak resin-rich regions around the stitch loops. Densely stitched composite with more stitched-induced matrix cracks upon impact loading is due to the presence of weak resin-rich pockets around the stitching yarns [77–80]. The noncrimp stitched carbon fabric composite shows a quasi-isotropic behavior, while 2D woven composite demonstrated an anisotropic behavior. Stitching in the noncrimp carbon fabric has only a minor effect on its strength properties. Damage sites are mainly observed in the resin-rich

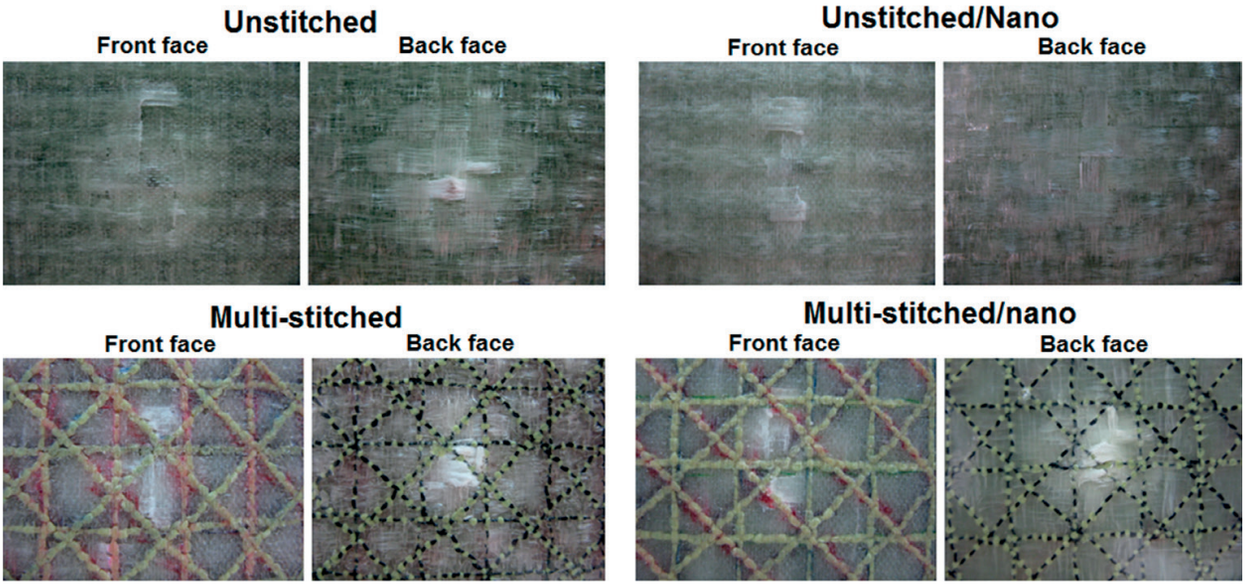


Figure 12. Damaged areas of composite after low-velocity impact test [82].

zones created by the stitching [81]. The low-velocity impact properties of the multistitched/micro-/nano-E-glass/polyester woven composites are studied. It is observed that the material type (silicate or carbon or metal), the material particle size (nano or micro), amount of materials (weight, %), stitching density (step/cm), and stitching type (hand or machine) influence the damaged areas of composites. **Figure 12** shows the damaged areas of composite after low-velocity impact test. The damaged areas of multistitched/nanosilica (5 wt.%) composite after low-velocity impact test are almost 60 and 48% lower than those of the unstitched composites on front and back faces, respectively [82].

The multistitched and multistitched/nano-E-glass/polyester woven composite show a better damage resistance performance compared to those of the unstitched or unstitched/nano-composites. The multistitching suppresses the impact energy relatively at a small area of the composite. In addition, adding the nanomaterial to the multistitched structure can further enhance the damage resistance performance [82].

6. Glass fabric and glass composite applications

The glass fiber–reinforced composites are used in a variety of forms to assure the required properties of usage areas as space, aerospace, automobile, energy, marine, electronic components, and defense-related special areas. The composites are designed according to service environments of usage areas in mechanical, impact, flammability, and electrical properties.

6.1. Aviation and aerospace

Although the volumes of fiber-reinforced polymer composites used for aircraft applications were a relatively small percentage, they found their most advanced applications in the fabrication of civil or military aircrafts [83]. For instance, the Boeing 787 made large use of composite materials in its airframe and primary structure. The use of composites, especially in the highly tension-loaded

part of the fuselage, greatly reduced maintenance labor and cost. **Figure 13** shows the percentages of used composite materials along with metals in commercial civilian airplane (Boeing 787) [84]. Typical glass fiber–reinforced composite applications in aircraft were engine cowlings, luggage racks, instrument enclosures, bulkheads, ducting, storage bins, and antenna enclosures. In addition, it was also widely used in ground-handling equipment [85].

6.2. Automotive

Glass fiber composite used in automotive is primarily driven by the demand for lightweight components, fuel efficiency, and recycling [86]. The two most common types of glass fibers used in automotive composites were the E-glass, which was cost-effective and had good tensile properties. Second one was S-glass, which had 40% higher tensile properties compared to the E-glass. But, it was expensive [87]. All glass fiber–based composites were used in automotive as primary or secondary structural parts of interior headliner, underbody system, and air intake manifold, instrument panel, bumper beam, and engine cover [88]. **Figure 14** shows the glass fiber–based composite panels in car and trucks [63].

6.3. Boats and marine

Glass fiber both continuous TOW or discontinuous short forms has been the main material for the recreational boating industry, which was employed as hulls with a minimum number of assembled parts. Glass fiber–based composites have gained acceptance in pleasure craft because of light weight, vibration damping, corrosion resistance, impact resistance, low construction costs, and ease of fabrication, maintenance, and repair. Current leading-edge manufacturing technologies were driven by racing vessels, both power and sail [85, 89].

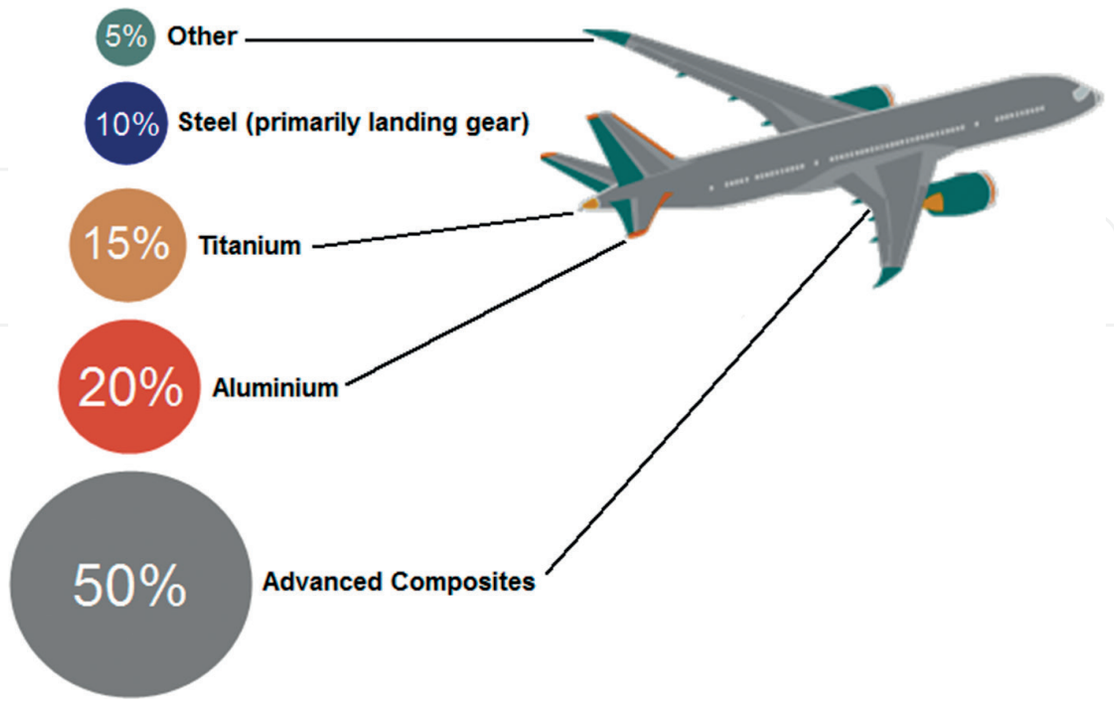


Figure 13. Composite materials used in civilian aircraft (Boeing 787) [84].



Figure 14. Glass fiber–reinforced composite body panels for truck and car [63].

6.4. Electronics

Glass fiber/epoxy composites have been the foundational structural substrate in printed circuit boards since 1980. They supported the transistors, resistors, and integrated circuits at all digital technologies. Glass composite board connected them electrically via conductive pathways etched or printed on their surfaces [90]. They were also used as insulators for high-voltage energy cabin components, a cable, or cable-coated material to transit the electrical energy [91].

6.5. Wind energy

In the sector of energy generation, glass fiber composites were utilized in manufacturing wind generators. The blades of the generators were generally made of epoxy resins reinforced with glass or carbon fibers. Their high mechanical strength and modulus made them attractive material for the wind blade in turbine generators [26]. **Figure 15** shows the wind blades placed in the sea [92].

6.6. Ballistic

2D S2-glass fabric and 3D S2-glass preform composites were employed in ballistic armor. 3D S2-glass ballistic plate has better energy absorption properties due to z-yarn insertion in the through-the-thickness direction. This provided additional energy absorbing as a mechanism of high-strain interlayer deformations. In addition, 2D S2-glass fabric plate with or without



Figure 15. Wind blades placed in the sea [92].



Figure 16. Glass fiber–based ballistic plate and bulletproof jacket [93].

stitching or 3D S2-glass preform composite plate has certain specific energy-absorbing advantages over the ceramic or metal armor plate. **Figure 16** shows the glass fiber–based ballistic plate and bulletproof jacket [26, 93, 94].

7. Future trends

Biaxial 2D woven fabrics have been widely used as simple and complex-shaped structural composite parts in various technical areas. In addition, biaxial weaving methods and techniques are well developed. 3D glass fabrics have multiple layers and show no delamination. 3D woven glass preform as well as multilayered stitched fabrics will be expanded in the field of especially marine and industrial applications as a form of composite structure. However, the multiaxis 3D weaving technique is at an early stage of development and needs to be fully automated. This will be a future technological challenge in the area of multiaxis 3D weaving.

8. Conclusion

In this chapter, two dimensional glass fabric (2D) and three dimensional (3D) glass preforms, fabrication methods, and application areas were reviewed. Glass fabrics were readily available and important, but they were specific segmented basic materials. 2D E-glass fabrics were traditionally employed in various industrial areas. 3D glass fabrics have multiple layers and no delamination due to out-of-plane directional fibers. Various techniques were also developed for 3D glass preforms. 3D orthogonal and stitched as well as multiaxis 3D knitted and 3D braided glass preforms are commercially available. On the other hand, various unit cell base models on 3D glass preform and composites were developed to define their geometrical and mechanical properties. Multiaxis 3D glass fabrics have multiple layers, and their in-plane properties are enhanced due to the bias yarn layers. However, the multiaxis

3D woven preform technique is at an early stage of development. Recently, 3D woven and stitched glass preforms were made by adding single or multiwalled nanotubes and nanofibers to enhance their mechanical, thermal, and electrical properties. This will open up new material classes as well as application areas for near future.

9. Sources of further information and advice

Many studies have been carried out on the characterization and modeling of 2D and 3D glass preform composite structures, but limited information is available on the 3D fabric architecture and nanoadded glass fiber composites. Recent literature and books can be useful for having more information on these areas as indicated in Refs. [95–97].

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