CHAPTER 3

Reinforcements—Fibers

1. GENERAL

Reinforcements for composite materials can be in the form of fibers, particles, or flakes. Each has its own unique application, although fibers are the most common in composites and have the most influence on properties. The reasons for this, discussed in Chapter 1, are as follows:

- The large aspect ratio (length over diameter) of the fiber, which gives rise to effective shear stress transfer between the matrix and the reinforcement
- The ability for fibers to be bent to sharp radius, allowing them to fit into sharp radius of curvature of the parts.
- Numerous techniques to manufacture fibers such as spinning, chemical vapor deposition, or oxidation.

The fibers used in composite materials appear at different scales. The manufacturing of fiber composites involves the use of fibers from the micrometer level up to the centimeter level. Figure 3.1 shows the different scales of fiber forms. At the smaller scale (level *a*) are the individual filaments with diameters of about 10 microns. These are usually bundled together to form tows consisting of thousands of individual filaments (level *b*). There are tows of 3 k (3000) filaments, 6 k, 12 k etc. These tows can then be combined either with or without the addition of resin for adhesiveness. If resin is used, the tows can be combined to form tapes. When resin is not used, the tows can be woven together to make dry woven fabrics, or the tows can be braided or knitted together to make dry fiber preforms (level *c*). The final composite part is made by placing many of

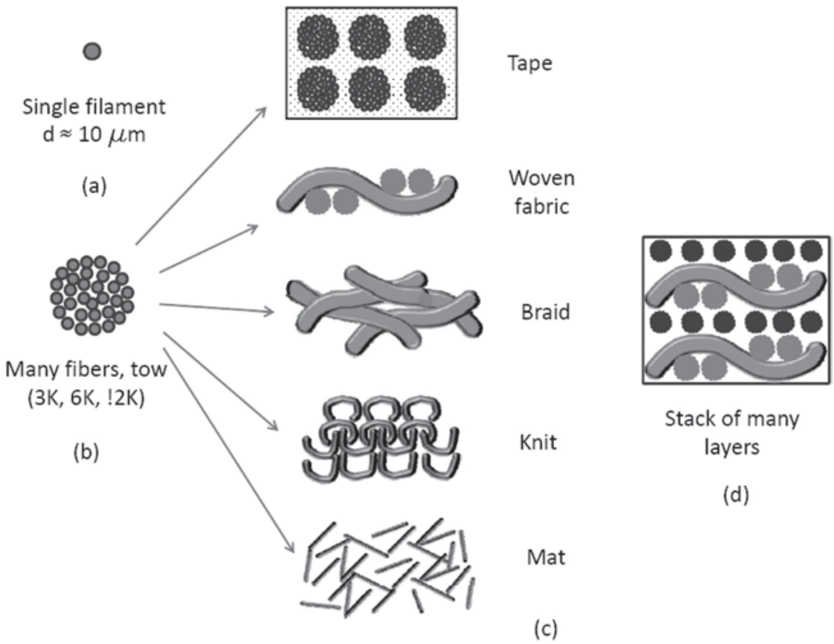


FIGURE 3.1 Fiber forms at different scales.

these layers on each other. Pressure is usually applied to press these fiber layers together (level *d*). Note that the load applied in this case is along the thickness direction (z direction) of the fiber bed. This is different from the situation where the load is applied within the plane of the fiber bed (such as along the fiber direction or transverse to the fiber direction as in normal operating conditions for load bearing composite structures). The load during the manufacturing stage is different from the loads during the operation stage and it is important to distinguish this.

The discussion on the fibers will be presented in the sequence of increasing scale level, beginning with the individual filaments.

2. INDIVIDUAL FILAMENTS

Individual filaments are normally produced by drawing from a melt of the material (such as glass) or by drawing from thermoplastic molecules and then chopping away secondary atoms from the main backbone of the fiber (such as carbon fibers). The three common fibers used for making composites are glass, carbon, Kevlar and thermoplastic fibers.

2.1. Glass Fibers

2.1.1. Glass Fiber Manufacturing Process

The raw materials for glass fibers are silica sand, boric acid, and other minor ingredients (e.g., clay, coal, and fluorospar). These are dry mixed in a high temperature refractory furnace. The temperature of this melt varies for each glass composition, but is generally about 2300°F (1260°C).

The process used for the manufacture of glass fibers from the molten glass mixture is illustrated schematically in Figure 3.2. First the mixture of silica sand and ingredients is put in a batch silo. They are then mixed and weighed. The mixture is transported to a batch charging unit where the mixture is fed into the furnace. The temperature in the furnace varies from 1540°C at the melting stage to 1425°C at the refining stage. The molten glass flows to the forehearth stage where the temperature is reduced to 1260°C. At the bottom of the forehearth station, there is a plate made of platinum which contains many tiny holes. The molten glass flows through these tiny holes and forms filaments. These filaments are then pulled mechanically to make smaller filaments. The diameter of the

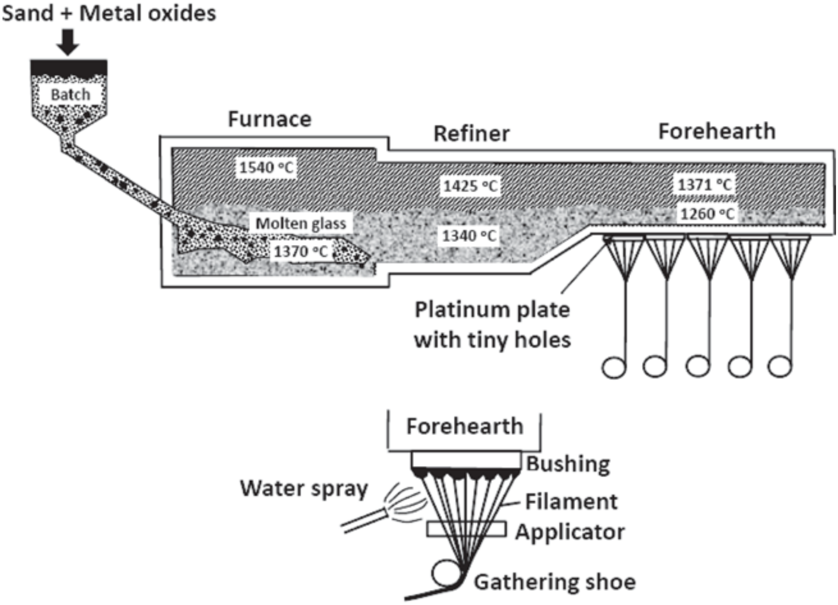


FIGURE 3.2 Fiberglass manufacturing process [4].

filaments depends on the speed of drawing. A chemical called *sizing* is applied on the surface of the fibers at this stage. The sizing is used to reduce the friction between the fibers to prevent breakage. A finish can also be applied to the fiber. Finish is a type of chemical used to protect the surface of the fibers and to provide good bonding with the matrix material when the composite is made. Many filaments are bundled together to form tows or strands. These tows or strands are then wound onto a creel for shipping purpose, or they can be cut into short fibers.

2.1.2. Types of Glass Fibers

Glass is an amorphous material that consists of a silica (SiO_2) backbone with various oxide components to give specific compositions and properties. Several types of glass fibers are manufactured but only three are used often in composites: E glass, S glass (and its variation S_2), and C glass. Table 3.1 shows the composition of the different types of glasses.

E glass (E for electrical grade) fibers have a composition of calcium aluminoborosilicate and calcium oxide, used when strength and electrical resistivity are required. The most common fiberglass used in composites, E glass is inexpensive in comparison with other types. E glass fibers are used as short fiber reinforcements for engineering thermoplastics; as fibers used with polyester or vinyl ester matrix for automotive composite components; and for fiber reinforced rods used for civil applications such as boats, seats, or trays. S glass (S for strength) is approximately

TABLE 3.1 Composition of Glasses Used in Composite Materials [3].

	E Glass Range (%)	S Glass Range (%)	C Glass Range (%)
Silicon oxide	52–56	65	64–68
Calcium oxide	16–25	—	11–15
Aluminum oxide	12–16	25	3–5
Boric oxide	5–10	—	4–6
Magnesium oxide	0–5	10	2–4
Sodium oxide and potassium oxide	0–2	—	7–10
Titanium oxide	0–15	—	—
Iron	0–1	—	—
Iron oxide	0–0.8	—	0–0.8
Barium oxide	—	—	0–1

40% higher in strength than E glass and offers better retention of properties at elevated temperatures. S glass is often used in advanced composites when strength is a premium. C glass (C for corrosion) is used in corrosive environments because of the chemical stability of its soda lime borosilicate composition.

Table 3.2 gives the physical, mechanical, thermal, electrical, and optical properties of glass fibers. Some properties, such as tensile strength and tensile modulus, are measured on the fibers directly. Other physical properties are measured on glass that has been formed into a patty or block sample and then annealed to relieve the forming stress. Note that the modulus of glass (about 70 GPa) is about the same as that of aluminum; however the strength of glass is much larger than that of aluminum.

Glass fibers normally have many defects on their surfaces. This is due to the abrasion between the fibers. The longer the fiber, the more defects there are. As such, the tensile strength of the fibers depends on their length. Figure 3.3 shows the effect of length on the tensile strengths of fibers.

Moisture has a detrimental effect on glass strength. The decrease in strength with increasing temperature is more pronounced in E glass than in S glass. However, the modulus decreases at about the same rate with increasing temperature for both E glass and S glass. The decrease is due to the rearrangement of the molecules into a less compact and hence more flexible configuration.

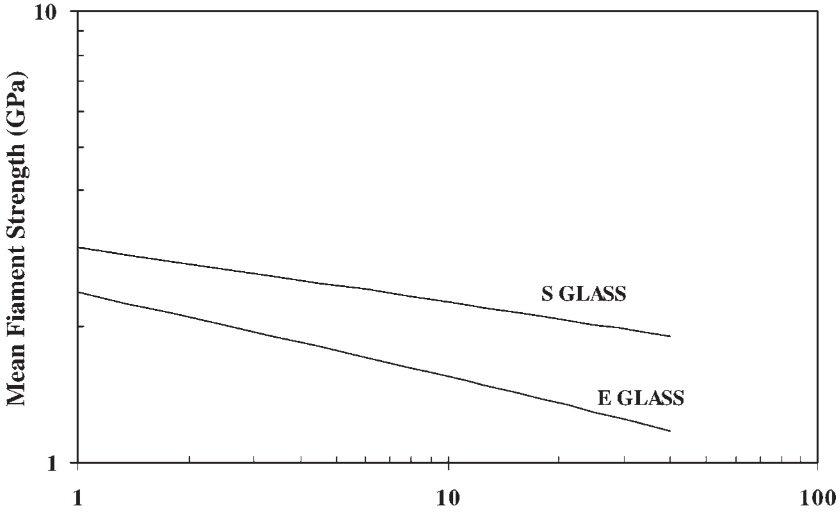


FIGURE 3.3 Effect of fiber length on tensile strength of fiber.

TABLE 3.2 Properties of Glasses [1].

Property	Type of Glass C	E	S
Density (g/cm^3)	2.49–2.50	2.54–2.62	2.48–2.50
Tensile strength (MPa)			
@22°C	3006–3280	3417	4544
@371°C	—	2597	3724–4408
@538°C	—	1708	2392
Tensile modulus (GPa)			
@22°C	68.3	71.8	84.7
@538°C	—	80.6	88.2
Elongation	0.03	0.035	0.04
Coefficient of thermal expansion (10^{-6}m/m/°C)	7.2	5.0	5.6
Heat Capacity (J/kg.C)@22°C)	800	800	800
Softening point, °C	749–750	841–846	970

2.1.3. Surface Treatment [1]

Glass fibers are extremely fragile and abrade easily during processing. The problem is especially evident in processes such as weaving, although almost any handling or moving process will cause abrasion of the glass fibers.

To guard against loss of strength, which depends strongly on surface defects that may be caused during handling, a chemical sizing (or coating) is applied to the fibers. This sizing protects the fibers during handling, and also holds the individual fibers together.

Usually sizing is temporary and after it is removed a finish is added. However in other cases the sizing also acts as the finish. The finish improves the compatibility of the fiber with the matrix. Typical finishes would be polyvinyl acetate modified with chromic chloride complex and/or organosilane coupling agents.

Coupling agents, molecules which are compatible at one end with the silane structure of the glass and at the other with the matrix, can be thought of as bridges connecting the reinforcement and the matrix. Figure 3.4 shows the bridging nature of the coupling agent between the glass fiber and the polymer matrix material. The coupling agents can combine with both the glass fiber and the polymer matrix material to form a separate phase called the *interphase*. This interphase may have different properties from either the glass or the polymer material. Figure 3.5 shows a schematic of the interphase.

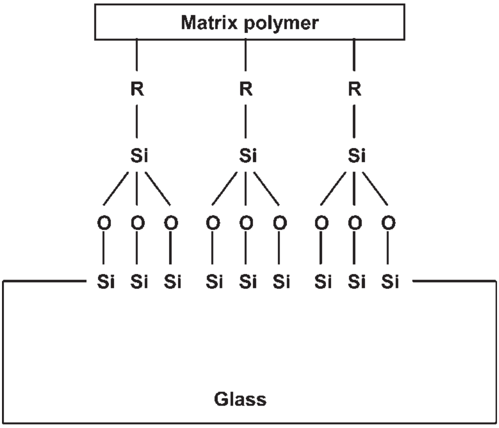


FIGURE 3.4 Idealized coupling of matrix and glass by organofunctional silane.

The use of a coupling agent can have significant effect on the mechanical properties of a composite. Changes of over 100% of the composites tensile, flexural or compressive strength with different choices of coupling agents are not uncommon for dry specimens. Because glass fibers are somewhat sensitive to moisture, the proper bonding of the glass with the matrix can also improve the mechanical properties in adverse environments. Therefore, both the application of the part and the matrix to be used should be known before specifying the fiberglass and the finish.

When glass fibers are used in pultrusion or filament winding, the strands must have high integrity, thorough wetting by the resin, and uniform processability under constant applied strain.

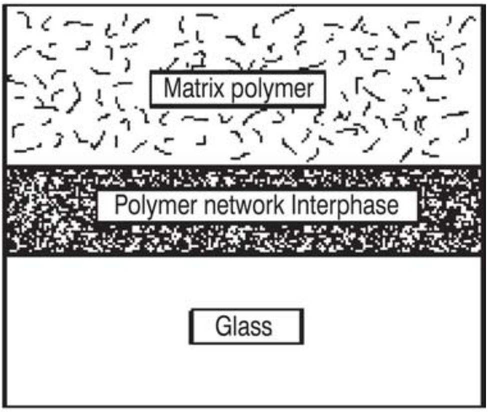


FIGURE 3.5 Silane and matrix interphase polymer network.

2.2. Carbon/Graphite Fibers [1]

Carbon/graphite fibers are used extensively in making composites for aerospace applications. Carbon and graphite are both based on layered structures of hexagonal rings of carbon. Structures of this type are called grapheme and are related to true graphite, although some differences exist in the structure.

While the terms are often used interchangeably, carbon and graphite fibers are different, at least in theory. Graphite fibers are those carbon fibers that have been subjected to heat treatment in excess of 3000°F (1650°C), possess 3-D ordering of the atoms, have carbon content in excess of 99% (although the graphite structure is still less than 75%) and have tensile modulus on the order or 344 GPa (50 Msi).

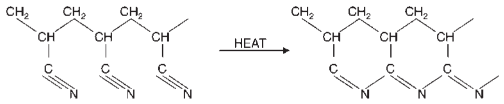
2.2.1. Fabrication Process for Carbon/Graphite Fibers

Carbon fibers are made using a raw material called the precursor. Theoretically there are three types of precursors. These are polyacrylonitrile (PAN), pitch and cellulose. However the PAN based and Pitch based precursors are more common and are discussed below.

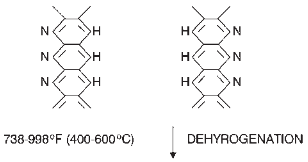
2.2.1.1. PAN Based Precursor [1]

The principle of making carbon fiber made from the PAN precursor is outlined in Figure 3.6. In this process, one begins with the polyacrylonitrile (PAN) molecules. PAN molecules are thermoplastic polymers made by addition polymerization (first row, left, in Figure 3.6). With the application of heat, the triple bond between the carbon and the nitrogen atoms is broken. This is replaced by the double bond between the carbon and nitrogen, and a single bond between the nitrogen atom and another carbon atom, forming a ring structure (first row, right). Upon heating to between 400°C–600°C, the process of dehydrogenation (removal of hydrogen atoms) takes place in which many of the hydrogen atoms are removed. The structure becomes two dimensional with many hexagons formed (second row in Figure 3.6). Upon further heating to between 600°C–1300°C, the process of denitrogenation takes place, wherein the nitrogen atoms are removed, leaving a structure consisting mainly of carbon atoms (third and fourth row in Figure 3.6). Sheets of many hexagons are stacked against each other.

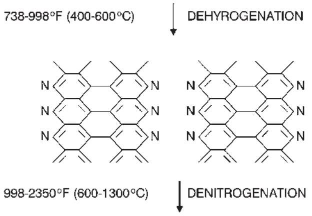
A microscopic cross section of a carbon fiber is shown in Figure 3.7. This shows about one-quarter of a carbon fiber, where the vertical direction coincides with the axis of the fiber. Note that the fiber consists of many sheets containing the hexagonal arrangement. The considerable strength and stiffness within the plane of this sheet are based on the strength and stiffness of the carbon-carbon bond, which is the same as the bond in diamond, except that diamond has bonds in three directions and the fiber only in two. The strength transverse to the sheet (normal to the axis of the fiber) is low. This is similar to onion layers, where one can peel them from each other rather easily. Carbon (or graphite) fibers, in which the strength and stiffness along the third direction is much weaker than



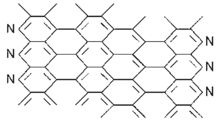
In the above, polyacrolynitrile molecule, which is a thermoplastic, is subjected to heat. This breaks the triple bond between C and N atoms and forms double bond between C and N atoms. In addition, rings are formed.



In the above, application of higher temperature removes the hydrogen atoms (dehydrogenation process)



In the above, increasing the temperature to more than 600°C removes the nitrogen (denitrogenation) and links between hexagons of carbon atoms are formed.



In the above, most nitrogen atoms are removed. What remains are sheets of hexagons of carbon atoms.

FIGURE 3.6 Formation of the carbon fibers from PAN [1].

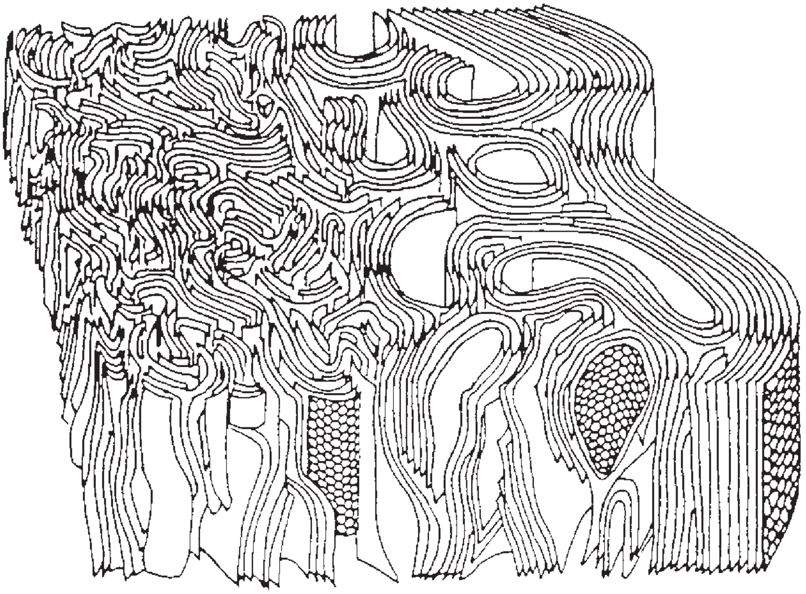


FIGURE 3.7 Configuration of a microscopic cross section of a carbon fiber (Reproduced from S.C. Bennet, D.L. Johnson, and W. Johnson, *Journal of Materials Science,* 18, 1983, p. 3337, with kind permission from Springer).

those in the in-plane directions, are therefore anisotropic, their properties depending upon direction.

The different steps in the manufacturing of carbon fibers from PAN is shown in Figure 3.8. The PAN-based precursor is first stabilized by thermosetting (crosslinking) so that the polymers do not melt in subsequent processing steps. This thermosetting step, which requires moderate heat, must be accompanied by a stretching of the fibers (or, more appropriately, a holding of the fibers at constant length against their inherent shrinkage as they become stabilized).

The fibers are then carbonized or, in other words, pyrolyzed, until they are essentially transformed into all-carbon fibers. It is during this stage that the high mechanical property levels are developed. The rapid evolution of gases up to 1800°F (982°C) requires that the heatup rate be quite slow to avoided forming voids and other defects. At about 1800°F (982°C), PAN-based fibers are approximately 94% carbon and 6% nitrogen, with further reductions in the nitrogen content until approximately 2300°F (1260°C), when the carbon content is over 99.7%.

Graphitization is carried out at temperatures in excess of 3200°F (1760°C) to improve the tensile modulus of the fiber by improving the crystalline structure and the 3-D nature of the structure. After graphitization, the fibers are surface treated, a sizing or finish is applied, and the fibers are then wound for shipment.

2.2.1.2. Pitch Precursor [1]

Pitch is the lowest grade obtained from the distillation of petroleum products. It is also the least expensive as compared to other grades. At the beginning of the fiber-making process, pitch must be converted into a suitable fiber. In the conversion process, pitch goes through a mesophase, called liquid crystal phase, in which the polymer chains are somewhat oriented even though the material is liquid. This orientation is responsible for the ease of consolidation of the pitch-based product into a carbon/graphite form. Subsequently the process follows a similar sequence as the PAN precursor, as shown in Figure 3.8.

2.2.2. Surface Treatment of Carbon Fibers [1]

Surface treatment of the carbon fibers improves the bonding between the fibers and matrix and thus improves the interlaminar shear strength (ILSS). Surface treatment can be divided into two types: oxidative and non-oxidative.

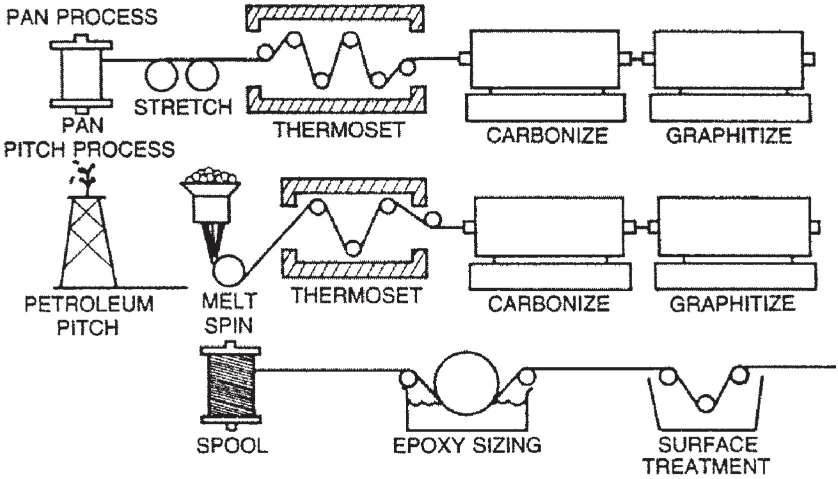


FIGURE 3.8 Process of making carbon fibers (Reproduced from Carbon/Graphite Fibers by Russell J. Diefendorf in *Engineered Materials Handbook, Vol. 1, Composites*, 1987, with permission from ASM International).

Liquid phase oxidative treatment can be done by simply drawing the fibers through a bath of some convenient oxidative agent (such as nitric acid, potassium permanganate, or sodium hypochlorite), or drawing the fiber through an acidic or alkaline electrolytic bath. The electrolytic bath is preferred since the process can be done continuously. The net result of this method is to clean the carbon fiber surface and then to attach chemical groups, such as hydroxides, which can bond with the matrix or a surface coating (sizing). Excessive oxidation, however, can result in a decrease in fiber tensile strength, presumably due to pitting of the fiber surface.

Non-oxidative treatments are of three types: whiskerization, pyrolytic surface coatings, and polymer grafting.In whiskerization, single crystals of ceramic materials (SiC, TiO_2, or Si_3N_4) are grown on the surface of the fibers. These whiskers are perpendicular to the fiber axis. The resulting improvement in interlaminar shear strength (ILSS) is excellent but the process is very expensive and is not commercially available at present. Pyrolytic coating consists of a vapor phase deposition of pyrolytic carbon on the fiber surface. This method shows good increase in ILSS but is expensive and unavailable commercially. The attachment of a polymer graft involves the preliminary attachment of some group that can be used as an anchor for the polymer. These reactive groups are generally attached by one of the oxidative methods, so the polymer graft method is really a subgroup of the oxidative method in which a polymer is introduced to act as a bridge between the fiber and the size of matrix.

The effectiveness of the fiber is often measured by the wettability of the fiber. The extent of wetting of the fiber is directly proportional to the number of chemical groups attached, and therefore the effectiveness of the surface treatment. This wettability is most often measured by looking at the contact angle of the fiber/water interface.

2.2.3. Surface Coatings (Sizing) of Carbon Fibers

In some cases organic coatings (sizings) are also added to the fibers to further improve the fiber/matrix bonding and to protect the fibers from damage during subsequent processing. These sizings are supplied to both treated and untreated fibers by passing the fibers through a heated bath of the sizing agent. The most common sizing is an epoxy, although polyvinyl alcohol and polyimides have also been used.

The value of the sizing or finish on carbon fibers is not as dramatic as it is in glass fibers in improving the mechanical properties in adverse environmental conditions. The reason for this is the inherently better moisture resistance of the carbon fibers compared to glass fibers.

2.2.4. Properties of Carbon Fibers [1]

Table 3.3 shows the properties of different types of fibers. The elastic modulus of carbon fibers can be in two categories: low modulus and high modulus. The modulus can be as low as 157 GPa for pitch based carbon fibers to as high as 383 GPa for PAN-based fibers. Tensile strength also varies from 1367 MPa for pitch based fibers to as high as 3280 MPa for PAN-based fibers. The elongation of carbon fibers is low (about 1%). The higher modulus fibers have lower elongation than the lower modulus fibers. Carbon fiber composites are therefore brittle due to the limited elongation of the fibers.

Carbon fibers are moderately good conductors of electricity. The conductivity of carbon fiber is in the order of 10^4 S/cm. This conductivity is assumed to arise from the natural conductivity of graphite and the orientation of the graphene ring, which is parallel to the axis of the fiber. Pitch fibers have better electrical conductivity than PAN-based fibers. The coefficient or thermal expansion (longitudinal) of carbon fibers is slightly negative and becomes more negative with increasing modulus. This contraction can be combined with the positive coefficient of thermal expansion of the matrix to yield a near zero coefficient of thermal expansion.

2.3. Organic Fibers

The most common organic fibers used for reinforcements are the aramids, with Kevlar, a Dupont fiber, currently being the major brand. A

TABLE 3.3 Different Types of Carbon Fibers and Their Properties [1].

PAN-Based Fibers	Low Modulus	High Modulus
Tensile modulus (GPa)	226	383
Tensile strength (MPa)	3280	2392
Elongation (%)	1.4	0.6
Density (g/cc)	1.8	1.9
Carbon assay (%)	92–97	100
Pitch-Based Fibers		
Tensile modulus (GPa)	157	376
Tensile strength (MPa)	1367	1708
Elongation (%)	0.9	0.4
Density (g/cc)	1.9	2.0
Carbon assay (%)	97	97

new ultra-high-orientation polyethylene fiber (Spectra) with some interesting and useful properties has been introduced into the market.

2.3.1. Aramid Fibers [1]

Aramid fibers are made by mixing paraphenylene diamine and terephthaloyl chloride in an organic solvent to form polyparaphenylene-terphthalamide (aramid) (Figure 3.9). After polymerization, the polymer is washed and then dissolved in sulfuric acid. At this point, the polymer is a partially oriented, liquid crystal form. Then the polymer solution is extruded through small die holes (spinnerettes) in a process known as solution spinning. The fibers are then washed, dried and wound up for shipment.

Although the aramid molecule is strong due to the presence of the aromatic rings, the molecules are linked to one another only by weak hydrogen bonds, with the result that aramid fibers are strong in tension but weak in compression. When aramid fibers fail, they break into small fibrils which are like fibers within the fiber. These fibrils arise from the rod-like structure of the liquid crystals as they are being spun into fibers and from the weak intermolecular bonds. Tensile strength failure is believed to initiate at the ends of the fibrils and is propagated through the fiber by shear. This unique failure mechanism is responsible for the very high strength of aramid fibers versus conventional fibers, but is also the reason aramid composites have compression strength one-half of carbon composites. The positive point from this type of behavior is

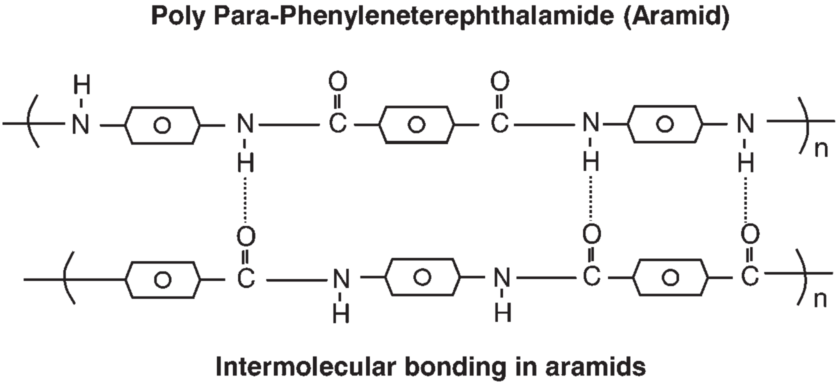


FIGURE 3.9 Formulation of aramid fibers [1].

that aramid composites can absorb a large amount of energy upon failure by impact.

2.3.1.1. Properties of Aramid Fibers [1]

Kevlar fibers are made in three different types: Kevlar 29 (high toughness), Kevlar 49 (high modulus) and Kevlar 149 (ultra high modulus). Table 3.4 gives the properties of Kevlar fibers.The modulus increases from Kevlar 29 to Kevlar 49 to Kevlar 149 and is due to changes in process conditions that promote additional crystallinity in the high modulus and ultra high modulus products. The tensile strength and modulus of aramids are substantially higher than for other organic (textile) fibers, although not as high as carbon fibers.

Aramid fibers are less brittle than carbon fibers or glass fibers. The elongation of aramid fibers is about 2% to 4%, and this combination of good strength, low weight, and toughness has led to the key applications of aramid composites. Aramid fibers have negative coefficient of thermal expansion in the fiber direction, and this has led to some applications where limited thermal expansion is a key desired property.

2.3.1.2. Bonding to Matrix [1]

Aramids do not bond as well to matrices as do glass or carbon fibers. Therefore, the ILSS is low for aramids. These low values may also arise, in part, from the relatively low shear resistance of the fiber itself. This poor bonding may give rise to good absorption of energy upon impact.

2.3.1.3. Use of Aramid Fibers [1]

Aramid fibers have been used principally as reinforcements for tires, belts, and other rubber related goods as well as for bullet proof vests, high strength cloth such as sails for racing boats, and reinforcements

TABLE 3.4 Properties of Aramid Fibers [1].

Type of Kevlar Fiber	29	49	149
Tensile modulus (GPa)	83	131	186
Tensile strength (MPa)	3.6	3.6	3.4
Elongation (%)	4	2.8	2
Density (g/cc)	1.44	1.44	1.47

for composite materials. For high load applications, they have been used in making pressure vessels where tensile strength is more important than compressive strength. Kevlar 49 with epoxy has hoop stress value of 450 ksi (307.5 MPa) which is higher than other high modulus fibers.

2.3.2. Ultra-High Orientation Polyethylene Fibers

Polyethylene is a low strength, low modulus thermoplastic polymer. It is used to make low cost items such as toys. Its microstructure is as shown in the left of Figure 3.10. When a piece of material made of this polymer is subjected to a tensile load, the molecules slide across each other, the low resistance coming from low intermolecular attraction. If the molecules can be straightened so that they are mostly aligned, as shown in the right side of Figure 3.10, the interatomic forces in the carbon-carbon backbone becomes much more resistant when a load is ap-

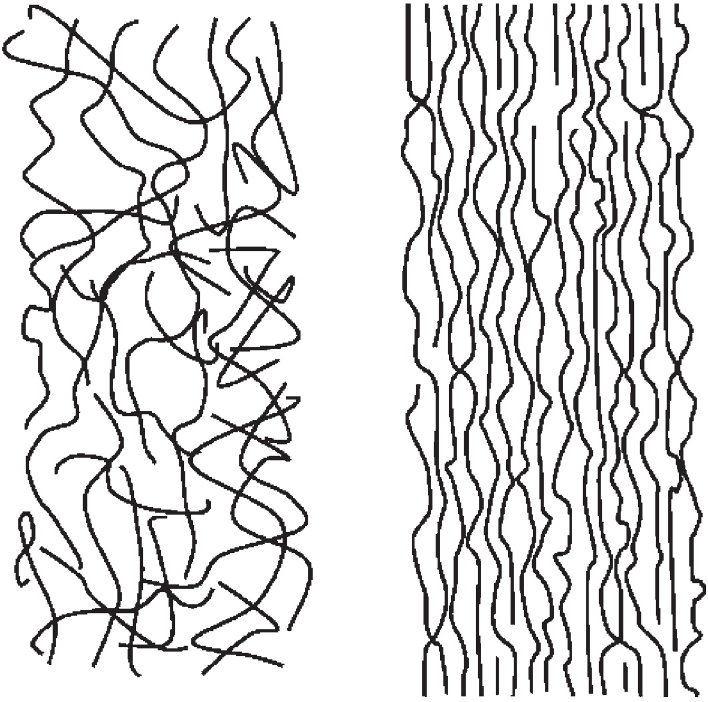


FIGURE 3.10 Formation of polyethylene fibers.

plied. A polyethylene fiber (Spectra) was developed based on this concept by Allied Corporation. It has excellent strength to weight and modulus properties.

The strength and modulus of this fiber are approximately the same as aramid but because of the lower density, its specific strength and modulus are higher than aramid and nearly as high as high modulus carbon fibers. The solvent resistance is superior to aramids, but temperature performance is inferior to aramids.

Major uses include: ballistic penetration prevention, radomes, water skis, bicycles, kayaks, and uses where the low dielectric constant is of value.

2.4. Boron and Silicon Carbide Fibers [1]

Boron and silicon carbide (SiC) are the most common of the very high modulus reinforcements. Boron is used as a reinforcement for epoxy in high performance uses. SiC is used as a reinforcement for ceramic and metal matrices. These materials are much more expensive than the other conventional reinforcement materials.

These fibers are made by chemical vapor deposition (CVD), in which a substrate filament, normally tungsten for boron and carbon for SiC, is pulled through a cleaning section and then a deposition chamber. The substrate element is heated electrically to approximately 2500°F (1370°C). In the deposition chamber, the chemicals that will give the coating are introduced and the reaction occurs on the surface of the heated filament. For boron, the reactants are boron trichloride and hydrogen, while for SiC the reactants are alkyl silanes having the Si–C–Si structure (with various side groups) and hydrogen. The tungsten filament is typically 0.5 mils (0.013 mm) in diameter and the resulting boron fibers are 4–8 mils (0.1 mm–0.2 mm) in diameter. The carbon filament is typically 1.3 mils (0.033 mm) in diameter and the resulting SiC fibers are 5–6 mils (0.13 mm–0.15 mm).

3. TOWS

Refer to Figure 3.1. The previous presentation was on individual filaments. At the end of the fiber manufacturing process, the individual filaments are normally grouped together in the form of tows consisting of thousands of filaments. The commercially available tows are in 3 k (3000 filaments), 6 k, or 12 k. The larger the number of filaments in a tow, the more efficient the deposition of the fiber to make a part (it takes less time to deposit a certain amount of material). Larger tows, however, mean more filaments are bundled together and this may make it difficult to get the liquid matrix to flow to the surface of individual filaments for wetting. The balance between the size of the tows and material deposition rate depends upon the application.

4. FABRICS AND OTHER REINFORCEMENT FORMS

Fibers are sold and used in many different forms. Rarely, if ever, are fibers used in single filament form except for laboratory testing and experimentation. Discussion of reinforcement forms will examine how fibers can be assembled together. The method of assembling the fibers (i.e., the arrangement of the fibers when they are used) often has a major effect on the manufacturing process and mechanical properties of the composite. The method to be used in the fabrication of the composite often determines the shape of the reinforcement. Following is a summary of the different forms of the reinforcement.

- *Fibers:* A general term for a material that has a long axis many times greater than its radius.
- *Filament:* A single fiber. This is the unit formed by a single hole in the spinning process.
- *Strand:* A general and somewhat imprecise term. Usually refers to a bundle or group of untwisted filaments but has also been used interchangeably with fiber and filament.
- *Tow:* An untwisted bundle of continuous filaments, usually with a specific count [such as 3k tow (3000 filaments per tow) or 6k tow (6000 filaments per tow].
- *Yarn:* A twisted bundle of continuous fibers, hence a twisted tow. Often used for weaving.
- *Roving:* A number of yarns or tows collected into a parallel bundle without twisting.
- *Tape:* A collection of parallel filaments (often made from tow) held together by a binder (usually the composite matrix). The length of the tape, in the direction of the fibers, is much greater than the width and the width is much greater than the thickness. Figure 3.11 shows a photograph of unidirectional tape.
- *Woven fabric:* A planar material made by interlacing yarns or tows in various specific patterns. Figure 3.12 shows a few common fabric forms.

FIGURE 3.11 Photograph of a roll of unidirectional tape.

- *Braid:* The interlacing of yarns or tows into a tubular shape instead of a flat fabric.
- *Mat:* A sheet like material (planar form) consisting of randomly oriented chopped fibers or swirled continuous fibers held together loosely by a binder.
-

4.1.Tows and Rovings

The simplest form of reinforcement commonly used is a tow. Tows can be laid down as parallel fibers to form a tape. Tows can also be wound around a shape, as in filament winding, or they can be chopped into short fiber segments. A tow can also be twisted into a yarn, or several tows combined into a roving. Tows are sold on spools with a particular filament count for each tow end.

4.2. Weave Types

Figure 3.12 shows the most common weave types. In the weave there are two directions: the fabric, or long direction, is called the warp; and the cross, or width direction, is called the fill, weft, or woof.

The plain weave, the simplest weave form, is made by interlacing yarns in an alternating over-and-under pattern. There is one warp fiber for one fill fiber without skipping. The maximum fabric stability and firmness with minimum yarn slippage results from this weave. The pattern gives uniform strength in two directions when yarn size and count are similar in warp and fill. This weave type is the most resistant in shear and is therefore considered to be a rather stiff weave. Because the weave is stable, it is usually left moderately open so resin penetration and air removal are fair to good. Plain weave fabrics are used for flat laminates,

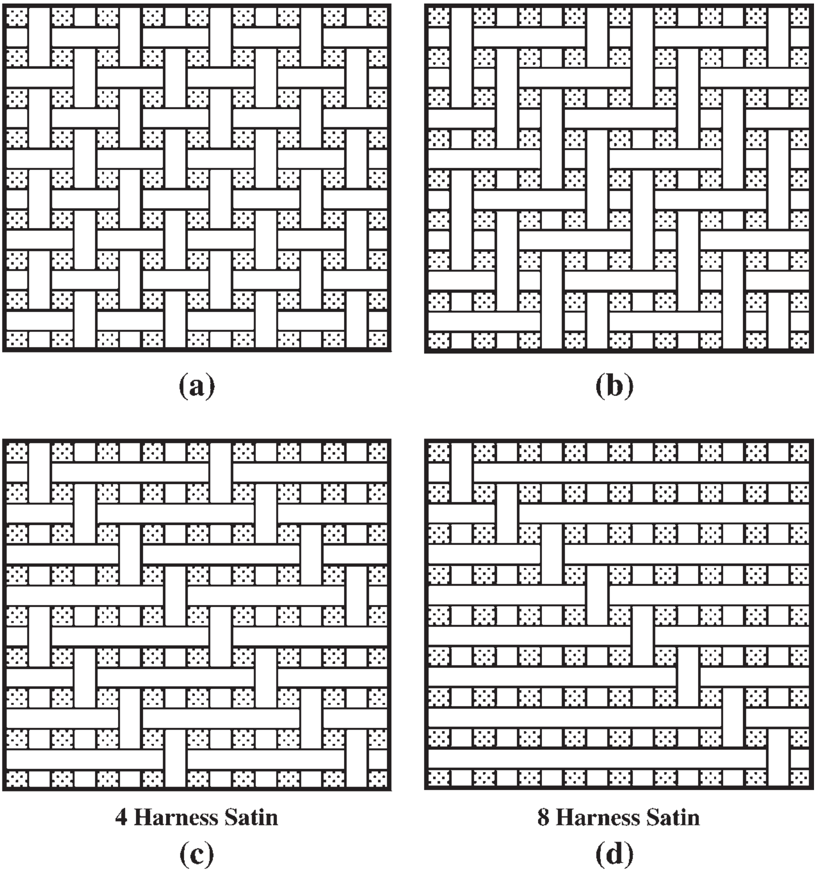


FIGURE 3.12 A few common fabric forms: (a) plain weave, (b) basket weave,(c) 4-harness-satin, (d) 8-harness-satin.

printed circuit boards, narrow fabrics, tooling, and for covering wood structures such as boats.

The basket weave is similar to the plain weave except that two warp yarns are woven as one over and under two fill yarns. This weave is less stable than plain weave so it is more pliable. This fabric is flatter and stronger than an equivalent weight and count of plain weave. The uses are similar to those for plain weave but with better drape on mild contours.

The long shaft satin weave or harness weave has one warp yarn weaving over four or more fill yarns. For example, in the 4-harness-satin weave, one warp yarn goes over three fill yarns. In the 8-harness-satin weave, one warp yarn goes over seven fill yarns, etc. This weave has high degree of drape and stretch in all directions. A high yarn density is possible. The weave is less stable than plain weave (this means that if the weave is held by hands, yarns may not keep their positions and may move). Also the weave is less open than most others so wetting and air removal can be a problem unless vacuum is used. This weave is used extensively in the aircraft industry where complex shapes are common. It is also used for housings, radomes, ducts, and other contoured surfaces.

4.3. Mats

Mat is normally made of relatively short fibers and is used in noncritical applications. Most applications for composites are noncritical, so in total consumption, mat materials are widely used. Laminates made with mats are only 33–50% as strong as fabric laminates of comparable thickness because of the lower fiber content and because the mat relies on the matrix for much of its structural integrity. Mat costs much less than woven fabrics. In general, mat requires more resin to fill interstices and more positive methods for removing the trapped air. Mat might typically be used for the inner layers of boats where thickness buildup is the critical function.

Mats can be made from continuous strands to achieve increased strength (though not as high as fabrics). This continuous mat is produced by swirling strands of continuous fibers onto a belt, spraying a binder over them, and drying the binder. This is called *swirl mat* and Figure 3.13 shows its configuration.

Some very fine mats (called surfacing mat or veil) made from glass and carbon fibers are used for the top layer in a composite and provide a smooth texture for the surface. These fine mats are also used as carriers

FIGURE 3.13 Configuration of swirl mat.

for film adhesives. Fine mats are available with almost any fiber used as a reinforcement in composites. Surface mats also prevent fiber blooming (which is the breaking of the resin surface by a fiber, usually due to environment exposure).

4.4. Braids

Interest in braids has increased because of the effort to maximize properties in all directions of a part. Braid reinforcement is intended to improve torsional load capability to contain an inner core, to provide impact resistance or damage tolerance, or to enhance product appearance. Figure 3.14 shows the configuration of a braid.

Braids can either be deposited directly onto a mandrel or wound on a spool, removed, and slipped onto a mandrel when needed. Because the speed of slipping onto a mandrel is much faster than winding directly onto a mandrel, the spool winding method is generally preferred. Mandrels can assume many shapes other than round. Generally, braided reinforcements are stronger than other types of reinforcement patterns.

4.5. 3-D Weaves

Many types of 3-D weaves are available and are used to improve the performance of shaped composite parts that can be made from preformed reinforcements. Several weaving machines are available for the fabrication of these preforms. Therefore, whenever strength in the third direction is desired and can best be given by fibers rather than by a structural member (such as I beam), 3-D woven material should be considered.

4.6. Hybrids

Reinforcement schemes that combine two or more types of reinforcements are called hybrids. Typical examples would be carbon/aramid, glass/carbon, and glass/aramid. The advantages of hybrids is that in some weaves and braids, the best properties of each of the types of reinforcements can be utilized. Figure 3.15 shows a hybrid fabric of carbon/glass.

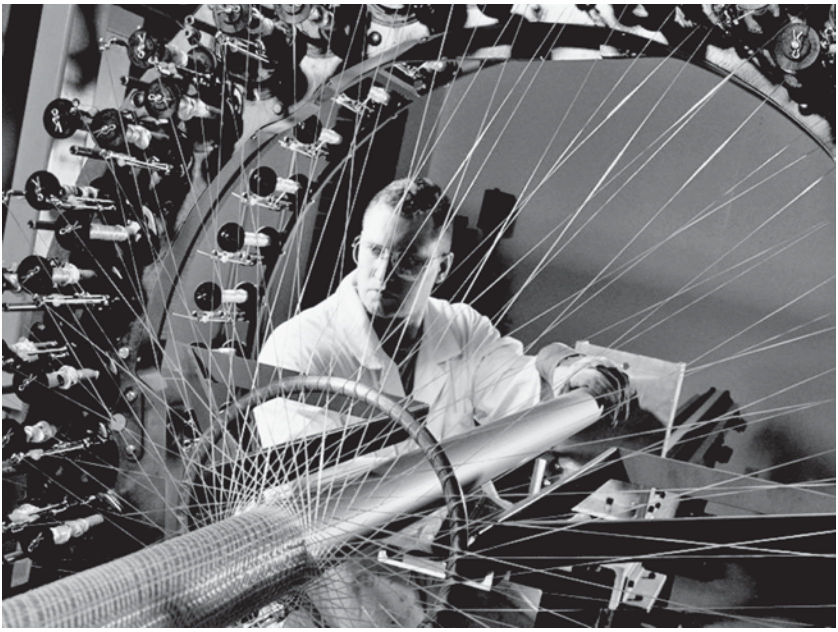


FIGURE 3.14 A braiding machine.

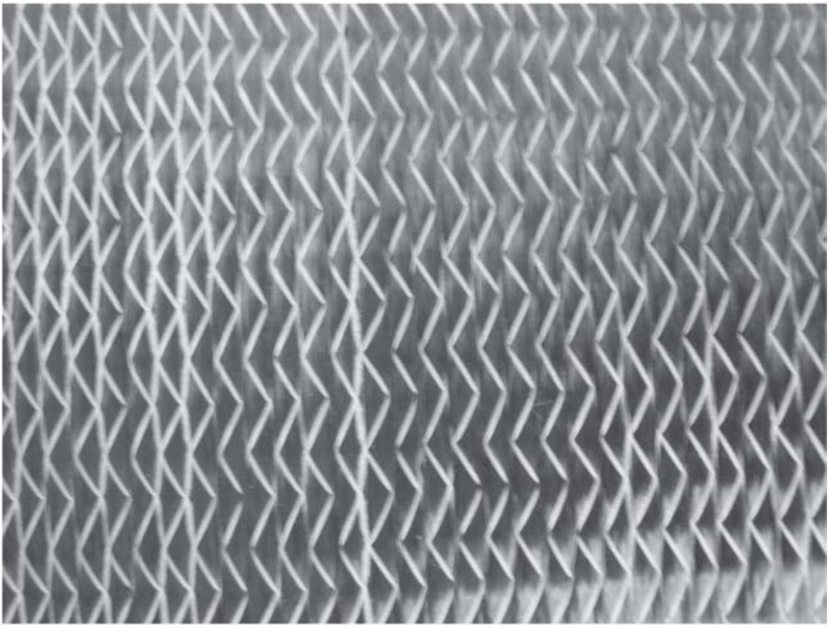


FIGURE 3.15 Hybrid fabric of carbon/glass.

5. DEFORMATION OF A BED OF FIBERS [2]

5.1. Introduction

Advanced composite materials use fibers in very high fiber volume fractions, usually in the range $0.5 \leq V_f \leq 0.7$. Two important consequences of these high fiber volume fractions are: (1) the fibers must be aligned, which leads to anisotropic behavior; and (2) the interfiber spacing is very small, which leads to significant fiber to fiber contact. The mean interfiber spacing δ_f can be calculated as:

$$\frac{\delta_f}{d} = \left(\sqrt{\frac{V_a}{V_f}} - 1 \right) \tag{3.1}$$

where V_a is the maximum allowable fiber volume fraction and d is the fiber diameter. Maximum allowable fiber volume fraction means the volume fraction when fibers touch each other.

Equation (3.1) can be derived as follows:

Assuming square packing of fibers as shown in Figure 3.16. The fiber volume fraction is calculated to be:
Let a denote the side of the square, d the fiber diameter and δ_f the interfiber spacing. The volume fraction is calculated to be:

$$V_f = \frac{n^2 \pi d^2 / 4}{[n(d+\delta_f)]^2} = \frac{\pi}{4} \frac{d^2}{(d+\delta_f)^2}$$

which can be rearranged to be:

$$\frac{\delta_f}{d} = \left(\sqrt{\frac{\pi / 4}{V_f}} - 1 \right)$$

When the fibers are touching each other, $\delta_f = d$ and $V_f = \pi/4$. $\pi/4$ can be considered as the maximum fiber volume fraction for the square packed array. For this type of array or other type of array (such as the hexagonal array), the maximum fiber volume fraction can be denoted as V_a, and Equation (3.1) can be obtained.

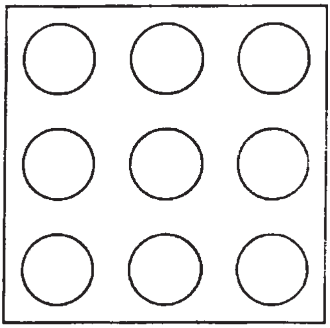


FIGURE 3.16 Square array of fibers.

For a square packing, $V_a = \pi/4$. Now if $V_f = 0.65$, then $\delta_f/d \sim 0.10$. For typical carbon fibers, $d \sim 10^{-5}$ m, which leads to a very small interfiber spacing of $\delta_f \sim 10^{-6}$ m. Given the fact that the fibers are neither perfectly aligned nor perfectly straight, these small average interfiber distances suggest that there are multiple fiber-fiber contacts. This, in fact, is the case. It has been shown that the fiber bundle can carry finite transverse loads in the volume fraction range for advanced composites. Furthermore, there are processing conditions in which the load carrying capacity of the fiber will dominate the processing behavior. Some examples of processing geometries are shown in Figure 3.17.

These suggest that the fiber bundles may be subjected to complex, 3-D state of stress during the process. (Note that the stresses considered here

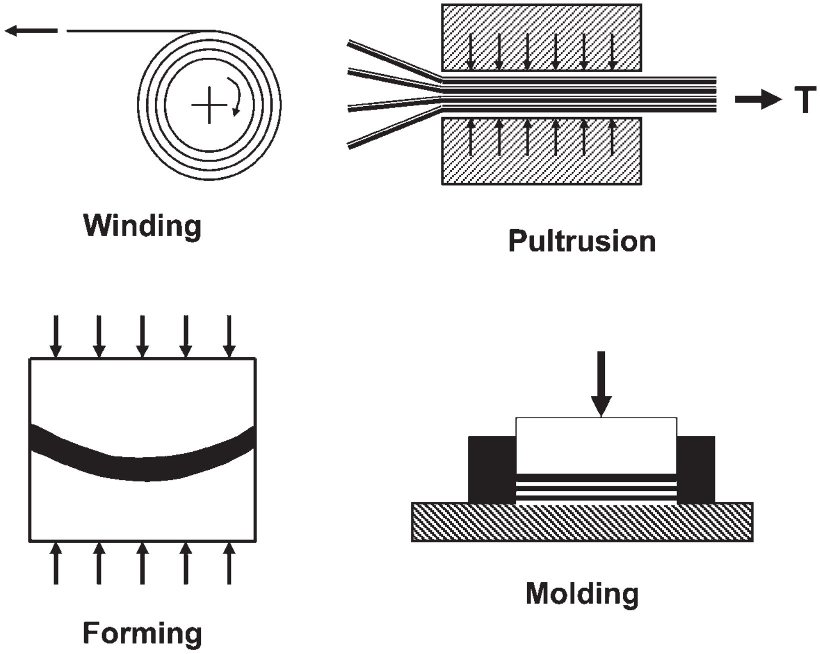


FIGURE 3.17 Examples of different loading patterns on fiber bundles [2].

are the stresses required for manufacturing, and not the stresses created due to the loading of fibers during load bearing operation).

In the case of filament winding, as the tows are being wound onto the mandrel, there is a slight tension applied on the tows. This tension serves to keep the tows tight and to compact the many layers together on the mandrel. The axial tension in the fiber bundle leads to a contracting of the fiber bundle and a corresponding increase in fiber volume fraction. This phenomenon has a large effect on the wetting behavior for the fiber bundle. In addition, the axial tension shown in winding results in a radial compression, particularly for the innermost fiber bundles. This, in turn, can reduce the axial tension in the bundles close to the mandrel and even result in axial compression.

For the case of pultrusion, the fiber bundles are pulled from the exit end. This serves to compact the many tows coming in from the creels. There can be a significant amount of shrinkage in the resin during the curing process in the die. In order to compensate for this, the amount of lateral pressure is necessary in order to avoid the formation of voids. The relation between axial tension and lateral compression needs to be understood to ensure good quality.

The molding example implies that the bundles will be subjected to a transverse compression and hence the load carrying capacity of the fiber bundle will be of utmost importance. In forming, transverse compression as well as viscous shearing will be dominant effects.

To a first approximation, the bundle of lubricated aligned fibers can respond to these applied loads either elastically or viscously. Basically the viscous loadings correspond to shear loading, while the elastic modes correspond to normal loading. A typical element of such a fiber bundle as well as the material coordinate system is shown in Figure 3.18. In general, one is interested in the average behavior of the fiber bundle and therefore will treat it as a continuum, as has been suggested by various researchers in the textile industry.

5.2. The Elastic Deformation of Fiber Bundle

5.2.1. Model Development [2]

In this section, following Gutowski [2], a general elastic deformation model for an aligned fiber bundle subjected to stresses σ_1 and σ_b was developed. It is assumed that the fibers are lubricated, but in a drained state ($p_r = 0$) and make multiple contacts with their neighbors. From earlier measurements, it was observed that the fibers have a slight waviness of a sinusoidal character. Later we will relate this waviness to the typical

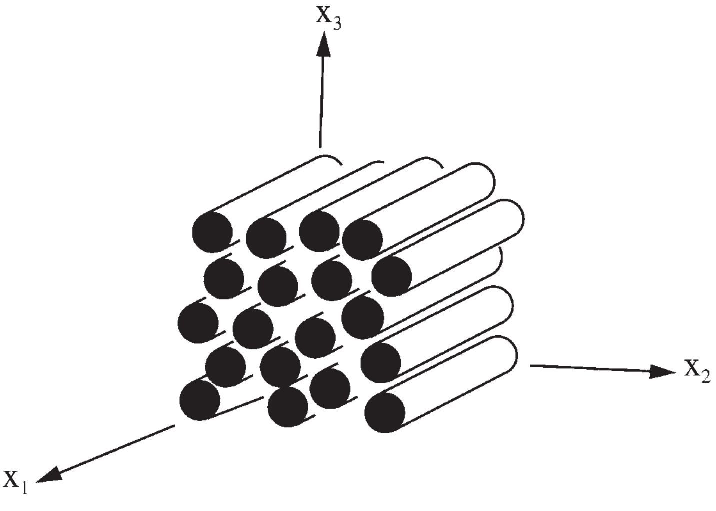


FIGURE 3.18 Representative element of an aligned fiber bundle.

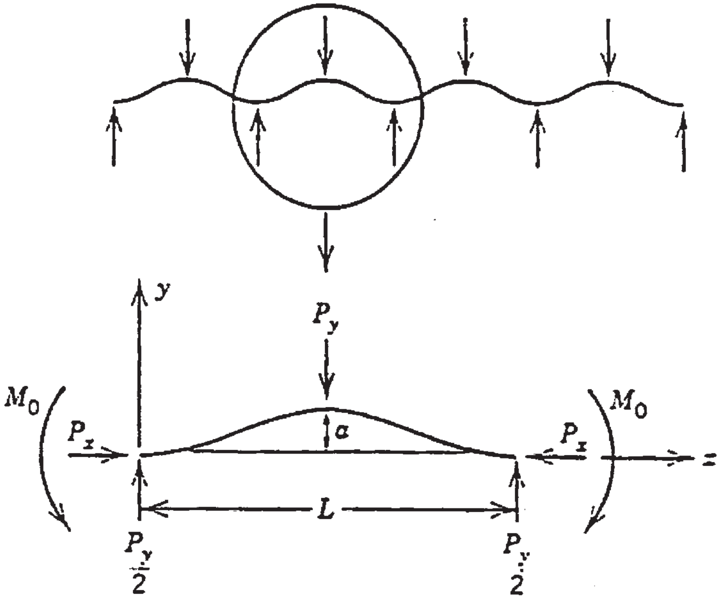


FIGURE 3.19 Slightly curved fiber with $L/a \geq 100$ and representative element for the fiber bundle [2].

length between contacts and construct a cell around a fiber, using these dimensions. First, consider the deformation behavior of a segment of a slightly curved fiber as shown in Figure 3.19.

The arch length over height L/a is on the order of 300. The fiber shown is just one small segment of the continuous fiber so the slopes at the ends are zero. When needed, it is assumed that the fiber has a shape as given by:

$$y = \frac{a}{2}\left[1 - \cos\left(\frac{2\pi x}{L}\right)\right] \tag{3.2}$$

Note that other reasonable assumed shapes for the fiber can be used; these will give similar results, with similar scaling but slightly different constants. Since these constants are adjusted experimentally for the final model, the exact shape is not critical.

The fiber will be deformed by the application of two loads, one along the axis P_x and the other transverse to axis x, in the plane of the arch P_y. The deflection of this fiber in both x and y directions (Δx and Δy) can be obtained by direct calculation as:

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = \begin{bmatrix} \frac{a^2 L}{8EI} + \frac{L}{EA} & -\frac{aL^2}{4\pi^2 EI} \\ -\frac{aL^2}{4\pi^2 EI} & \frac{L^3}{192EI} \end{bmatrix} \begin{bmatrix} P_x \\ P_y \end{bmatrix} \tag{3.3}$$

Here, E and I correspond to the bending modulus and the moment of inertia of the fiber, respectively.

This result can be related to the deformation behavior of a fiber bundle if one constructs a suitable unit cell around the fiber and then modify Equation (3.3) to represent the deformation of this unit cell. For example, a square cell is shown in Figure 3.20. The dimensions L and h will change during deformation. Because the fiber is only slightly arched, the actual length of the fiber and the cell length L will be almost identical. In the transverse direction, one can make the height and the width of the box equal. Hence, even though fibers may be thought of as simple arches, this assumption will give the bundle transverse isotropy in the 2-3 plane. This assumption is rooted in the earlier assumption that the bundle has no shear strength in the 2-3 plane. Having established these dimensions, one can now define the cell stresses, which are the same as the bundle stresses:

$$\sigma_1 = \frac{P_x}{h^2} \tag{3.4}$$

$$\sigma_b = \frac{P_y}{hL} \tag{3.5}$$

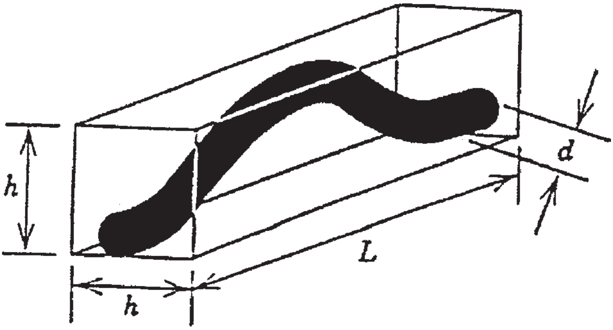


FIGURE 3.20 Representative fiber cell [2].

and two measures of deformation of the bundle:

$$e_1 = \frac{\Delta_x}{L} \tag{3.6}$$

$$e_b = \frac{\Delta_y}{h} \tag{3.7}$$

Note that these quantities are normalized by the current values of the cell dimensions. An expression for e_b may be directly related to the cross-sectional area, and the fiber volume fraction of the fiber bundle as:

$$e_b = \frac{h - h_o}{h} = 1 - \frac{h_o}{h}$$

Assuming constant volume, one has:

$$e_b = 1 - \sqrt{\frac{A_o}{A}} = 1 - \sqrt{\frac{V_f}{V_o}} \tag{3.8}$$

where the subscript *o* represents an initial state, and the subscript *f* represents the instantaneous state.

In order to relate the forces and the deflections for a single fiber to the deformation of a cell and hence the fiber bundle, two other relationships are needed.

The first relation is derived as follows:

$$\frac{a}{d} = \frac{h - d}{d} = \frac{h}{d} - 1$$

In order to obtain the expression *h*/*d*, one can consider the case of square packing. It can be shown that for this fiber arrangement, the fiber volume fraction can be expressed as:

$$V_f = \frac{\pi d^2 / 4}{h^2} = \frac{\pi}{4}\left(\frac{d}{h}\right)^2$$

from which

$$\frac{h}{d} = \sqrt{\frac{\pi / 4}{V_f}}$$

In the extreme case where $h = d$, we have $V_f = \pi/4$. This maximum fiber volume fraction can be denoted with a more general name as V_a. If one assumes some other form of array (such as the hexagonal array), V_a can have a different value. For the general case of maximum allowable fiber volume fraction V_a, one has:

$$\frac{h}{d} = \sqrt{\frac{V_a}{V_f}}$$

This gives:

$$\frac{a}{d} = \sqrt{\frac{V_a}{V_f}} - 1 \tag{3.9}$$

The second relationship is:

$$\frac{L}{d} = \frac{L}{a}\frac{a}{d} = \beta\left(\sqrt{\frac{V_a}{V_f}} - 1\right) \tag{3.10}$$

Where the coefficient β is defined as:

$$\beta = \frac{L}{a} \tag{3.11}$$

This quantity, assumed to be constant, can be termed the *waviness ratio* and it is determined empirically. Equation (3.10) relates the contact frequency, or length between contacts to transverse compression.

Now applying Equations (3.4)–(3.8) to Equation (3.3), one may obtain the functional relationship between the applied stresses and the deformations for a fiber bundle as:

$$\begin{bmatrix} Le_1 \\ he_b \end{bmatrix} = \begin{bmatrix} \dfrac{a^2L}{8EI} + \dfrac{L}{EA} & -\dfrac{aL^2}{4\pi^2 EI} \\ -\dfrac{aL^2}{4\pi^2 EI} & \dfrac{L^3}{192EI} \end{bmatrix} \begin{bmatrix} \sigma_1 h^2 \\ \sigma_b hL \end{bmatrix}$$

or

$$\begin{bmatrix} e_1 \\ e_b \end{bmatrix} = \begin{bmatrix} \dfrac{a^2h^2}{8EI} + \dfrac{h^2}{EA} & -\dfrac{aL^2h}{4\pi^2 EI} \\ -\dfrac{aL^2h}{4\pi^2 EI} & \dfrac{L^4}{192EI} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_b \end{bmatrix} \tag{3.12}$$

One now defines a new variable, which is related to the maximum allowable fiber volume fraction and the instantaneous fiber volume fraction (called the fiber volume parameter), as:

$$\varsigma = \sqrt{\frac{V_a}{V_f}}$$

Equation (3.12) can be shown to be,

$$\begin{bmatrix} e_1 \\ e_b \end{bmatrix} = \begin{bmatrix} F_{11} & F_{1b} \\ F_{b1} & F_{bb} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_b \end{bmatrix} \tag{3.13}$$

where

$$F_{11} = \frac{4}{\pi}\frac{1}{E}\varsigma^2[1 + 2(\varsigma - 1)^2] \tag{3.14a}$$

$$F_{1b} = F_{b1} = -\frac{16}{\pi^3}\frac{\beta^2}{E}\varsigma(\varsigma - 1)^3 \tag{3.14b}$$

and

$$F_{bb} = \frac{\beta^4}{3\pi E}(\varsigma - 1)^4 \tag{3.14c}$$

These equations give the 3-D elastic behavior of a fiber bundle. Since both the F_{ij} values and e_b are functions of V_f, Equation (3.13) represents two equations and two unknowns: e_1 and V_f. From this expression, the deformation behavior of a fiber bundle can be obtained for any applied stresses σ_{01} and σb.

The solution procedure is to first write:

$$e_b = F_{b1}\sigma_1 + F_{bb}\sigma_b \tag{3.15}$$

and then use Equation (3.13) to solve for V_f. The solution, say V_f^* is then substituted into Equation (3.13) to obtain the axial strain:

$$e_1 = F_{11}(V_f^*)\sigma_1 + F_{1b}(V_f^*)\sigma_b \tag{3.16}$$

Note that the subscript o used in Equation (3.8) for the definition of e_b refers to some original value. This means a specific reference value corresponding to the condition when the unstressed fibers can just begin carrying transverse loads. More specifically, $V_f = V_o$ would indicate the maximum fiber volume fraction for which $\sigma_1 = 0$ and $\sigma_b = 0$. The cell dimension h_o and cell or bundle area A_o then correspond to V_o. The term V_o is experimentally determined.

The relationships given in Equation (3.13) represent the elastic deformation of fiber bundles. As $V_f \rightarrow V_a$, the "bundle" nature of the fibers is lost. For example, when $V_f = V_a = \pi/4$, one obtains:

$$F_{11} = \frac{1}{V_f E_f} \tag{3.17}$$

which is a familiar result corresponding to a composite with zero matrix stiffness. For the same conditions:

$$F_{1b} = F_{b1} = F_{bb} = 0 \tag{3.18}$$

which implies that there is no functional relationship between the stresses and the deformations in this region. Hence in this region the deformation of the fibers does not depend on their "bundle" nature. Probably a better model for the fibers in this region would be based on their bulk properties. Of course, fibers are not used in this region in real composites. From Equation (3.13) several useful results with practical implications can be derived.

5.2.2. Axial Extension of a Fiber Bundle

The axial extension behavior of a fiber bundle is of interest during such operations as prepregging, pultrusion and filament winding. If one applies only axial tension to the fiber bundle ($\sigma_b = 0$), then Equation (3.13) reveals a slightly nonlinear relationship between the applied force P_1, and the axial extension e_1 due to the straightening of the fibers. Of more interest, however, is the coupling behavior, or the induced fiber volume fraction increase due to this tension. This relationship can be derived by setting $\sigma_b = 0$ and solving for a relationship between P_1 and V_f, where the force P_1 is defined as:

$$P_1 = A\sigma_1 = \frac{A_o V_o}{V_f} \frac{e_b}{f_{b1}} \tag{3.19}$$

This leads to:

$$P_1 = -\frac{A_o V_o}{V_f} \frac{1 - \sqrt{\dfrac{V_f}{V_o}}}{\dfrac{16}{\pi^3} \dfrac{\beta^2}{E} \sqrt{\dfrac{V_a}{V_f}} \left(\sqrt{\dfrac{V_a}{V_f}} - 1 \right)^2} \tag{3.20}$$

This equation shows that tensioning of the bundle has a strong effect on increasing the fiber volume fraction.

5.2.3. Bulk Compressive Stresses

During many advanced composite processes (e.g., autoclave molding, compression molding), bulk compressive stresses are applied to the fiber bundle. One particular case of interest is the bulk compressive stresses that are applied in the absence of any axial stress ($\sigma_1 = 0$). This may be similar to conditions during autoclave processing. In this case, an expression can be obtained that relates the bulk compressive stress with the fiber volume fraction

$$\sigma_b = \frac{e_b}{F_{bb}} = \frac{3\pi E}{\beta^4} \frac{1 - \sqrt{\dfrac{V_f}{V_o}}}{\left(\sqrt{\dfrac{V_a}{V_f}} - 1 \right)^4} \tag{3.21}$$

This equation, or slightly modified versions of it, has been used extensively for modeling the transverse compression of graphite and glass fiber bundles in thermoplastics, thermosets and oils. It reveals a rapid stiffening effect that can lead to load transfer from the resin to the fibers during processing. The importance of this effect is that the reduced resin pressure can, in turn, lead to voids in the composite.

A variety of other important loading conditions can also be modeled using equation (3.13). One worth noting is the axial extension ($e_1 > 0$) induced by transverse compression. If this axial extension is constrained, then the applied compression bulk stress would lead to an induced axial compression. This, in turn, could lead to fiber buckling and fiber waviness.

Example 3.1

Consider the case of autoclave processing. A bed of fibers is being compressed. The initial fiber volume fraction is $V_o = 0.50$. The final fiber volume fraction is $V_f = 0.68$. Assume that the maximum allowable fiber volume fraction is $V_a = 0.785$. Assume also that $E = 234$ GPa and $L/a = 200$. What would be the compressive stress to reach this final fiber volume fraction?

Solution

Using Equation (3.21), we have:

$$\beta = L / a = 200$$

$$\frac{3\pi E}{\beta^4} = (3)(\pi)(234\ \text{Gpa}) / 200^4 = 1378\ \text{Pa}$$

$$1 - \left(\frac{V_f}{V_o}\right)^{0.5} = 1 - \left(\frac{0.68}{0.50}\right)^{0.5} = -1.66$$

$$\left[\left(\frac{V_a}{V_f}\right)^{0.5} - 1\right]^4 = \left[\left(\frac{0.785}{0.68}\right)^{0.5} - 1\right]^4 = 0.000031$$

The required compressive stress is:

$$\sigma_b = \frac{(1378\ \text{Pa})(-0.166)}{0.000031} = 7.38\ \text{MPa} = 1071\ \text{psi} \tag{a}$$

This stress is fairly high compared to normal autoclave pressure.

It can be seen from Equation (3.21) that apart from the volume fractions, the two parameters affecting the value of the compressive stress are the modulus E and the waviness ratio $\beta = L/a$.

If one were to use the value of $L/a = 350$, and the modulus of $E = 181$ GPa, the result would be:

$$\frac{3\pi E}{\beta^4} = (3)(\pi)(181\ \text{GPa}) / 350^4 = 113.6\ \text{Pa}$$

The compressive stress is now:

$$\sigma_b = \frac{(113.6\ \text{Pa})(-0.166)}{0.000031} = 0.608\ \text{MPa} = 88.3\ \text{psi} \tag{b}$$

If $L/a = 400$ and the modulus is $E = 181$ GPa, one has:

$$\frac{3\pi E}{\beta^4} = (3)(\pi)(181\ \text{GPa}) / 400^4 = 66.6\ \text{Pa}$$

and the compressive stress is:

$$\sigma_b = \frac{(66.6\ \text{Pa})(-0.166)}{0.000031} = 0.357\ \text{MPa} = 51.8\ \text{psi} \tag{c}$$

5.2. Experimental Values

A number of experiments were performed by a number of researchers on different types of fabrics. The results are shown in Figure 3.21. This figure shows the variation of the compressive stress with the fiber volume fraction. It can be seen that even though the experimental results follow curves of similar shape, there is a significant degree of variation between the data. Equation (3.21) shows that the compression stress depends on the modulus of the fiber *E*, the aspect ratio β (= *L*/*a*) and the three fiber volume fractions V_o, V_f and V_a. Among the three fiber volume fractions, V_f is the fiber volume fraction of the final laminate to be manufactured. V_o represents the initial fiber volume fraction, and may depend on how tight or how loose the fiber bundles are in their initial state. The maximum fiber volume fraction, V_a, is the value at which fluid cannot flow across the fiber bundle. This may have relation with the theoretical maximum value of fiber volume fraction.

By fitting Equation (3.21) to the individual data sets shown in Figure 3.21, Gutowski [2] showed that there are good fits shown in the figure. Also by shifting all of these curves along the V_f axis, a "universal" curve can be obtained to describe the bulk compression of carbon fibers. This is shown in Figure 3.22.

In the above derivations, the concept of maximum fiber volume fraction V_a is used. This maximum fiber volume fraction depends on the following factors:

- *The state of lubrication of the fiber beds.* Dry fiber beds may have lower V_a than lubricated fiber beds.

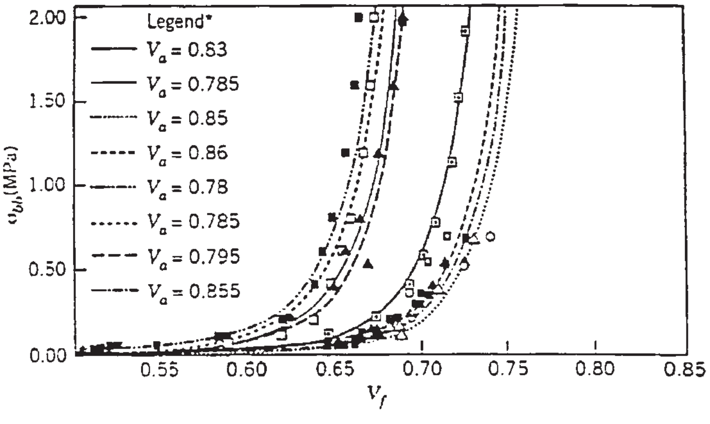


FIGURE 3.21 Fitting the experimental points with the equations [2].

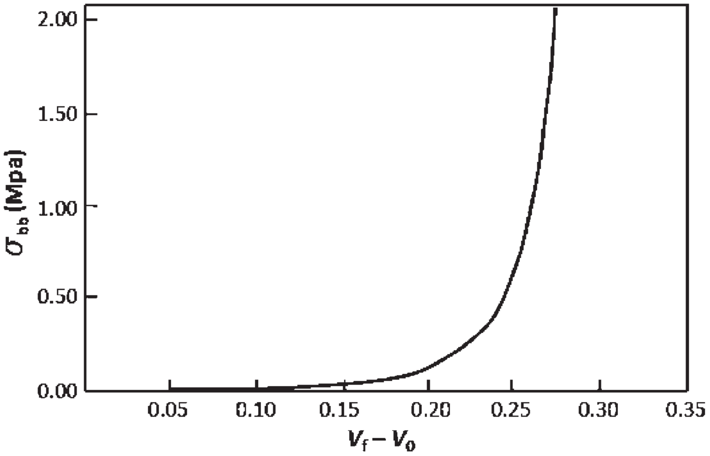


FIGURE 3.22 Master curve between compression stress and adjusted fiber volume fraction.

- *The rate of loading.* Faster rate of loading will produce lower V_a.
- *Repeat loading.* The maximum fiber volume fraction V_a can increase after a first cycle of loading. This increase will taper off after three or four cycles of loading.
- *Type of fabrics to be compressed.* Mats will show different values of V_a as compared to fabrics. Fabrics of different weave types will also show different V_a values.
- *The stacking sequence.* A fiber bed consisting of different combinations of fiber type or fabric type will show different values for V_a when the stacking sequence is different.
- *The fiber bed will also exhibit creep behavior* (deformation under constant load after some time).

Equations (3.13), (3.20) and (3.21) should be validated with a number of experiments on the specific type of fiber beds before use.

5.4. Summary and Conclusions

A number of experiments were performed by various researchers on different types of fabrics. They found that the compressive stress versus fiber volume fraction of the fiber bundles follows exponential curves after a certain critical fiber volume fraction. Different types of fabric and wetting systems follow different curves. Gutowski [2] showed that by plotting the compressive stress versus the difference between the fiber volume fraction and the initial fiber volume fraction, the curves from the different material systems fall along one single line.

6. REFERENCES

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2. Gutsowksi T.G., ed. *Advanced Composites Manufacturing,* John Wiley and Sons, 1997.
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4. Watson, J. C. and N Raguhathi, in *Engineered Materials Handbook Composites,* ASM International, 1987.

7. HOMEWORK

1. A bed of fibers is compressed. The dimensions of the bed of fibers are 0.5 m × 0.4 m. The initial fiber volume fraction is 0.50. The maximum allowable fiber volume fraction is 0.80. Determine the compressive load required to compress the bed of fibers so that the fiber volume fraction reaches the following values:
    a. 0.60
    b. 0.65
    c. 0.70
    d. 0.75