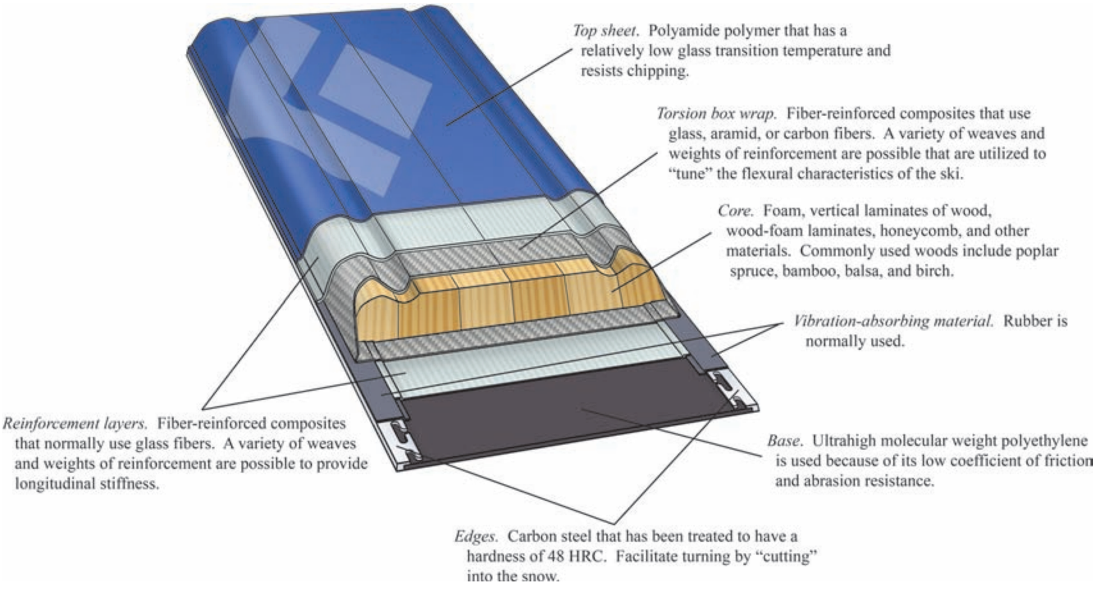
Chapter 16 Composites

Top: Photograph of a snow skier who is enjoying herself/himself in some fresh powder.

Bottom: One relatively complex composite structure is the modern ski. In this illustration, a cross section of a high-performance snow ski, are shown the various components. The function of each component is noted, as well as the material that is used in its construction. (Top photograph—iStockphoto. Bottom diagram courtesy of Black Diamond Equipment, Ltd.)



Top sheet. Polyamide polymer that has a relatively low glass transition temperature and resists chipping.

Torsion box wrap. Fiber-reinforced composites that use glass, aramid, or carbon fibers. A variety of weaves and weights of reinforcement are possible that are utilized to "tune" the flexural characteristics of the ski.

Core. Foam, vertical laminates of wood, wood-foam laminates, honeycomb, and other materials. Commonly used woods include poplar spruce, bamboo, balsa, and birch.

Vibration-absorbing material. Rubber is normally used.

Reinforcement layers. Fiber-reinforced composites that normally use glass fibers. A variety of weaves and weights of reinforcement are possible to provide longitudinal stiffness.

Base. Ultrahigh molecular weight polyethylene is used because of its low coefficient of friction and abrasion resistance.

Edges. Carbon steel that has been treated to have a hardness of 48 HRC. Facilitate turning by "cutting" into the snow.

WHY STUDY *Composites?*

With a knowledge of the various types of composites, as well as an understanding of the dependence of their behaviors on the characteristics, relative amounts, geometry/distribution, and properties of the constituent phases, it is possible to design materials with property combinations that are better than those found in any monolithic metal alloys, ceramics, and polymeric materials. For example, in Design Example 16.1, we discuss how a tubular shaft is designed that meets specified stiffness requirements.

Learning Objectives

After studying this chapter you should be able to do the following:

1. **Name the three main divisions of composite materials and cite the distinguishing feature of each.**
2. **Cite the difference in strengthening mechanism for large-particle and dispersion-strengthened particle-reinforced composites.**
3. **Distinguish the three different types of fiber-reinforced composites on the basis of fiber length and orientation; comment on the distinctive mechanical characteristics for each type.**
4. **Calculate longitudinal modulus and longitudinal strength for an aligned and continuous fiber–reinforced composite.**
5. **Compute longitudinal strengths for discontinuous and aligned fibrous composite materials.**
6. **Note the three common fiber reinforcements used in polymer-matrix composites and, for each, cite both desirable characteristics and limitations.**
7. **Cite the desirable features of metal-matrix composites.**
8. **Note the primary reason for the creation of ceramic-matrix composites.**
9. **Name and briefly describe the two subclassifications of structural composites.**

16.1 INTRODUCTION

The advent of the composites as a distinct classification of materials began during the mid-20th century with the manufacturing of deliberately designed and engineered multiphase composites such as fiberglass-reinforced polymers. Although multiphase materials, such as wood, bricks made from straw-reinforced clay, seashells, and even alloys such as steel had been known for millennia, recognition of this novel concept of combining together dissimilar materials during manufacture led to the identification of composites as a new class that was separate from the familiar metals, ceramics, and polymers. We now realize that this concept of multiphase composites provides exciting opportunities for designing an exceedingly large variety of materials with property combinations that cannot be met by any of the monolithic conventional metal alloys, ceramics, and polymeric materials.[1]

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[1] By *monolithic* we mean having a microstructure that is uniform and continuous and was formed from a single material; furthermore, more than one microconstituent may be present. Contrastingly, the microstructure of a composite is non-uniform, discontinuous, and multiphase, in the sense that it is a mixture of two or more distinct materials.

Materials that have specific and unusual properties are needed for a host of high-technology applications such as those found in the aerospace, underwater, bioengineering, and transportation industries. For example, aircraft engineers are increasingly searching for structural materials that have low densities; are strong, stiff, and abrasion and impact resistant; and do not easily corrode. This is a rather formidable combination of characteristics. Among monolithic materials, strong materials are relatively dense; increasing the strength or stiffness generally results in a decrease in toughness.

principle of combined action

Material property combinations and ranges have been, and are yet being, extended by the development of composite materials. Generally speaking, a composite is considered to be any multiphase material that exhibits a significant proportion of the properties of both constituent phases such that a better combination of properties is realized. According to this **principle of combined action,** better property combinations are fashioned by the judicious combination of two or more distinct materials. Property trade-offs are also made for many composites.

Composites of sorts have already been discussed; these include multiphase metal alloys, ceramics, and polymers. For example, pearlitic steels (Section 9.19) have a microstructure consisting of alternating layers of α-ferrite and cementite (Figure 9.27). The ferrite phase is soft and ductile, whereas cementite is hard and very brittle. The combined mechanical characteristics of the pearlite (reasonably high ductility and strength) are superior to those of either of the constituent phases. A number of composites also occur in nature. For example, wood consists of strong and flexible cellulose fibers surrounded and held together by a stiffer material called lignin. Also, bone is a composite of the strong yet soft protein collagen and the hard, brittle mineral apatite.

A composite, in the present context, is a multiphase material that is *artificially made,* as opposed to one that occurs or forms naturally. In addition, the constituent phases must be chemically dissimilar and separated by a distinct interface.

In designing composite materials, scientists and engineers have ingeniously combined various metals, ceramics, and polymers to produce a new generation of extraordinary materials. Most composites have been created to improve combinations of mechanical characteristics such as stiffness, toughness, and ambient and high-temperature strength.

matrix phase

dispersed phase

Many composite materials are composed of just two phases; one is termed the **matrix,** which is continuous and surrounds the other phase, often called the **dispersed phase.** The properties of composites are a function of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase. *Dispersed phase geometry* in this context means the shape of the particles and the particle size, distribution, and orientation; these characteristics are represented in Figure 16.1.

One simple scheme for the classification of composite materials is shown in Figure 16.2, which consists of three main divisions: particle-reinforced, fiber-reinforced, and structural composites; also, at least two subdivisions exist for each. The dispersed phase for particle-reinforced composites is equiaxed (i.e., particle dimensions are approximately the same in all directions); for fiber-reinforced composites, the dispersed phase has the geometry of a fiber (i.e., a large length-to-diameter ratio). Structural composites are combinations of composites and homogeneous materials. The discussion of the remainder of this chapter will be organized according to this classification scheme.

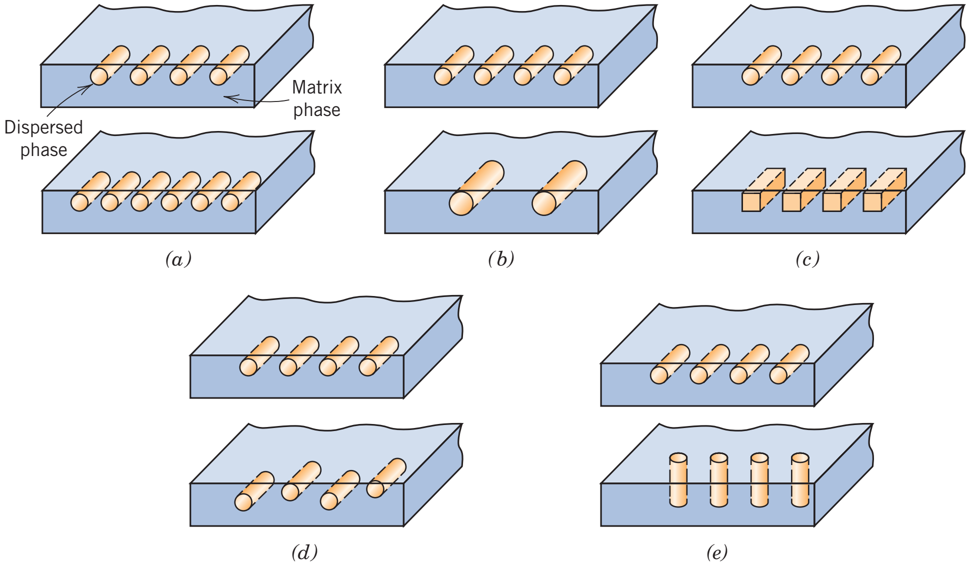
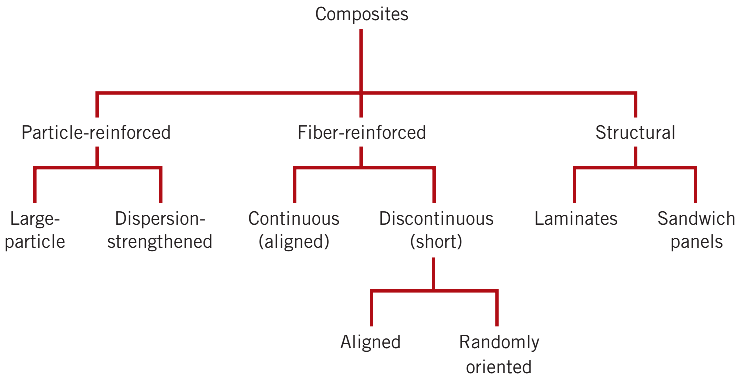


Figure 16.1 Schematic representations of the various geometrical and spatial characteristics of particles of the dispersed phase that may influence the properties of composites: (*a*) concentration, (*b*) size, (*c*) shape, (*d*) distribution, and (*e*) orientation. (From Richard A. Flinn and Paul K. Trojan, *Engineering Materials and Their Applications,* 4th edition. Copyright © 1990 by John Wiley & Sons, Inc. Adapted by permission of John Wiley & Sons, Inc.)

Figure 16.2 A classification scheme for the various composite types discussed in this chapter.



Particle-Reinforced Composites

large-particle composite

dispersion-strengthened composite

As noted in Figure 16.2, **large-particle** and **dispersion-strengthened composites** are the two subclassifications of particle-reinforced composites. The distinction between these is based on reinforcement or strengthening mechanism. The term *large* is used to indicate that particle–matrix interactions cannot be treated on the atomic or molecular level; rather, continuum mechanics is used. For most of these composites, the particulate phase is harder and stiffer than the matrix. These reinforcing particles tend to restrain movement of the matrix phase in the vicinity of each particle. In essence, the matrix transfers some of the applied stress to the particles, which bear a fraction of the load. The degree of reinforcement or improvement of mechanical behavior depends on strong bonding at the matrix–particle interface.

For dispersion-strengthened composites, particles are normally much smaller, with diameters between 0.01 and 0.1 μm (10 and 100 nm). Particle–matrix interactions that lead to strengthening occur on the atomic or molecular level. The mechanism of strengthening is similar to that for precipitation hardening discussed in Section 11.9. Whereas the matrix bears the major portion of an applied load, the small dispersed particles hinder or impede the motion of dislocations. Thus, plastic deformation is restricted such that yield and tensile strengths, as well as hardness, improve.

16.2 LARGE-PARTICLE COMPOSITES

Some polymeric materials to which fillers have been added (Section 15.21) are really large-particle composites. Again, the fillers modify or improve the properties of the material and/or replace some of the polymer volume with a less expensive material—the filler.

Another familiar large-particle composite is concrete, which is composed of cement (the matrix) and sand and gravel (the particulates). Concrete is the discussion topic of a succeeding section.

Particles can have quite a variety of geometries, but they should be of approximately the same dimension in all directions (equiaxed). For effective reinforcement, the particles should be small and evenly distributed throughout the matrix. Furthermore, the volume fraction of the two phases influences the behavior; mechanical properties are enhanced with increasing particulate content. Two mathematical expressions have been formulated for the dependence of the elastic modulus on the volume fraction of the constituent phases for a two-phase composite. These **rule-of-mixtures** equations predict that the elastic modulus should fall between an upper bound represented by

rule of mixtures

For a two-phase composite, modulus of elasticity upper-bound expression

$$E_c(u) = E_m V_m + E_p V_p \tag{16.1}$$

and a lower bound, or limit,

For a two-phase composite, modulus of elasticity lower-bound expression

$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m} \tag{16.2}$$

In these expressions, E and V denote the elastic modulus and volume fraction, respectively, whereas the subscripts c, m, and p represent composite, matrix, and particulate phases. Figure 16.3 plots upper- and lower-bound E_c-versus-V_p curves for a copper–tungsten composite, in which tungsten is the particulate phase; experimental data points fall between the two curves. Equations analogous to 16.1 and 16.2 for fiber-reinforced composites are derived in Section 16.5.

cermet

Large-particle composites are used with all three material types (metals, polymers, and ceramics). The **cermets** are examples of ceramic–metal composites. The most common cermet is cemented carbide, which is composed of extremely hard particles of a refractory carbide ceramic such as tungsten carbide (WC) or titanium carbide (TiC), embedded in a matrix of a metal such as cobalt or nickel. These composites are used extensively as cutting tools for hardened steels. The hard carbide particles provide the cutting surface but, being extremely brittle, are not themselves capable of withstanding the cutting stresses. Toughness is enhanced by their inclusion in the ductile metal matrix, which isolates the carbide particles from one another and prevents particle-to-particle crack propagation. Both matrix and particulate

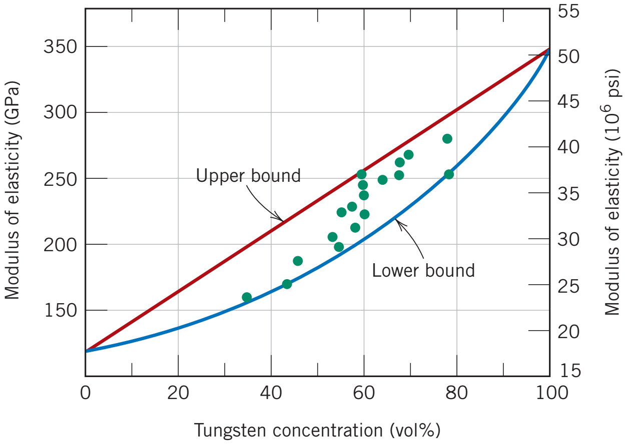


Figure 16.3 Modulus of elasticity versus volume percent tungsten for a composite of tungsten particles dispersed within a copper matrix. Upper and lower bounds are according to Equations 16.1 and 16.2; experimental data points are included. (From R. H. Krock, *ASTM Proceedings,* Vol. 63, 1963. Copyright ASTM, 1916 Race Street, Philadelphia, PA 19103. Reprinted with permission.)

phases are quite refractory, to withstand the high temperatures generated by the cutting action on materials that are extremely hard. No single material could possibly provide the combination of properties possessed by a cermet. Relatively large volume fractions of the particulate phase may be used, often exceeding 90 vol%; thus the abrasive action of the composite is maximized. A photomicrograph of a WC–Co cemented carbide is shown in Figure 16.4.

Both elastomers and plastics are frequently reinforced with various particulate materials. Our use of many of the modern rubbers would be severely restricted without reinforcing particulate materials such as *carbon black*. Carbon black consists of very small and essentially spherical particles of carbon, produced by the combustion of natural gas or oil in an atmosphere that has only a limited air supply. When added to vulcanized rubber, this extremely inexpensive material enhances tensile strength, toughness, and tear and abrasion resistance. Automobile tires contain on the order of 15 to 30 vol% carbon black. For the carbon black to provide significant reinforcement, the particle size must be extremely small, with diameters between 20 and 50 nm; also, the particles must be evenly distributed throughout the

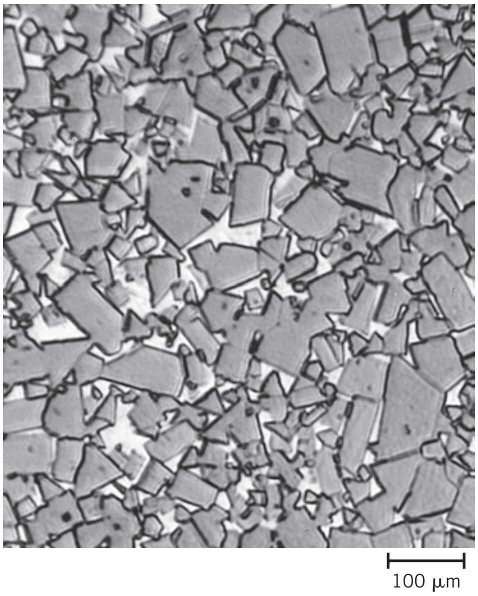


Figure 16.4 Photomicrograph of a WC–Co cemented carbide. Light areas are the cobalt matrix; dark regions, the particles of tungsten carbide. 100×. (Courtesy of Carboloy Systems Department, General Electric Company.)

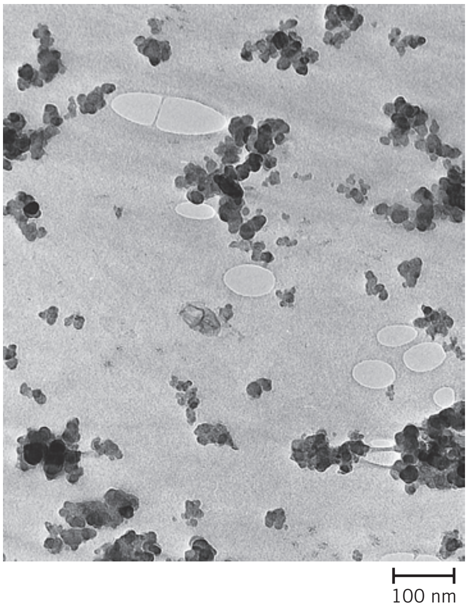


Figure 16.5 Electron micrograph showing the spherical reinforcing carbon black particles in a synthetic rubber tire tread compound. The areas resembling water marks are tiny air pockets in the rubber. 80,000×. (Courtesy of Goodyear Tire & Rubber Company.)

rubber and must form a strong adhesive bond with the rubber matrix. Particle reinforcement using other materials (e.g., silica) is much less effective because this special interaction between the rubber molecules and particle surfaces does not exist. Figure 16.5 is an electron micrograph of a carbon black–reinforced rubber.

Concrete

concrete

Concrete is a common large-particle composite in which both matrix and dispersed phases are ceramic materials. Because the terms *concrete* and *cement* are sometimes incorrectly interchanged, perhaps it is appropriate to make a distinction between them. In a broad sense, concrete implies a composite material consisting of an aggregate of particles that are bound together in a solid body by some type of binding medium, that is, a cement. The two most familiar concretes are those made with portland and asphaltic cements, in which the aggregate is gravel and sand. Asphaltic concrete is widely used primarily as a paving material, whereas portland cement concrete is employed extensively as a structural building material. Only the latter is treated in this discussion.

Portland Cement Concrete

The ingredients for this concrete are portland cement, a fine aggregate (sand), a coarse aggregate (gravel), and water. The process by which portland cement is produced and the mechanism of setting and hardening were discussed very briefly in Section 13.7. The aggregate particles act as a filler material to reduce the overall cost of the concrete product because they are cheap, whereas cement is relatively expensive. To achieve the optimum strength and workability of a concrete mixture, the ingredients must be added in the correct proportions. Dense packing of the aggregate and good interfacial contact are achieved by having particles of two different sizes; the fine particles of sand should fill the void spaces between the gravel particles. Ordinarily these aggregates constitute between 60% and 80% of the total volume. The amount of cement–water paste should be sufficient to coat all the sand and gravel particles; otherwise, the cementitious bond will be incomplete. Furthermore, all the constituents should be thoroughly mixed. Complete bonding between cement and the aggregate particles is contingent on the addition of the correct quantity of water. Too little water leads to incomplete bonding, and too much results in excessive porosity; in either case, the final strength is less than the optimum.

The character of the aggregate particles is an important consideration. In particular, the size distribution of the aggregates influences the amount of cement–water paste required. Also, the surfaces should be clean and free from clay and silt, which prevent the formation of a sound bond at the particle surface.

Portland cement concrete is a major material of construction, primarily because it can be poured in place and hardens at room temperature, and even when submerged in water. However, as a structural material, it has some limitations and disadvantages. Like most ceramics, portland cement concrete is relatively weak and extremely brittle; its tensile strength is approximately one-fifteenth to one-tenth its compressive strength. Also, large concrete structures can experience considerable thermal expansion and contraction with temperature fluctuations. In addition, water penetrates into external pores, which can cause severe cracking in cold weather as a consequence of freeze–thaw cycles. Most of these inadequacies may be eliminated or at least improved by reinforcement and/or the incorporation of additives.

Reinforced Concrete

The strength of portland cement concrete may be increased by additional reinforcement. This is usually accomplished by means of steel rods, wires, bars (rebar), or mesh, which are embedded into the fresh and uncured concrete. Thus, the reinforcement renders the hardened structure capable of supporting greater tensile, compressive, and shear stresses. Even if cracks develop in the concrete, considerable reinforcement is maintained.

Steel serves as a suitable reinforcement material because its coefficient of thermal expansion is nearly the same as that of concrete. In addition, steel is not rapidly corroded in the cement environment, and a relatively strong adhesive bond is formed between it and the cured concrete. This adhesion may be enhanced by the incorporation of contours into the surface of the steel member, which permits a greater degree of mechanical interlocking.

Portland cement concrete may also be reinforced by mixing into the fresh concrete fibers of a high-modulus material such as glass, steel, nylon, or polyethylene. Care must be exercised in using this type of reinforcement because some fiber materials experience rapid deterioration when exposed to the cement environment.

prestressed concrete

Still another reinforcement technique for strengthening concrete involves the introduction of residual compressive stresses into the structural member; the resulting material is called **prestressed concrete.** This method uses one characteristic of brittle ceramics—namely, that they are stronger in compression than in tension. Thus, to fracture a prestressed concrete member, the magnitude of the precompressive stress must be exceeded by an applied tensile stress.

In one such prestressing technique, high-strength steel wires are positioned inside the empty molds and stretched with a high tensile force, which is maintained constant. After the concrete has been placed and allowed to harden, the tension is released. As the wires contract, they put the structure in a state of compression because the stress is transmitted to the concrete via the concrete–wire bond that is formed.

Another technique, in which stresses are applied after the concrete hardens, is appropriately called *posttensioning.* Sheet metal or rubber tubes are situated inside and pass through the concrete forms, around which the concrete is cast. After the cement has hardened, steel wires are fed through the resulting holes, and tension is applied to the wires by means of jacks attached and abutted to the faces of the structure. Again, a compressive stress is imposed on the concrete piece, this time by the jacks. Finally, the empty spaces inside the tubing are filled with a grout to protect the wire from corrosion.

Concrete that is prestressed should be of a high quality, with a low shrinkage and a low creep rate. Prestressed concretes, usually prefabricated, are commonly used for highway and railway bridges.

16.3 DISPERSION-STRENGTHENED COMPOSITES

Metals and metal alloys may be strengthened and hardened by the uniform dispersion of several volume percent of fine particles of a very hard and inert material. The dispersed phase may be metallic or nonmetallic; oxide materials are often used. Again, the strengthening mechanism involves interactions between the particles and dislocations within the matrix, as with precipitation hardening. The dispersion strengthening effect is not as pronounced as with precipitation hardening; however, the strengthening is retained at elevated temperatures and for extended time periods because the dispersed particles are chosen to be unreactive with the matrix phase. For precipitation-hardened alloys, the increase in strength may disappear upon heat treatment as a consequence of precipitate growth or dissolution of the precipitate phase.

The high-temperature strength of nickel alloys may be enhanced significantly by the addition of about 3 vol% of thoria (ThO_2) as finely dispersed particles; this material is known as thoria-dispersed (or TD) nickel. The same effect is produced in the aluminum–aluminum oxide system. A very thin and adherent alumina coating is caused to form on the surface of extremely small (0.1 to 0.2 μm thick) flakes of aluminum, which are dispersed within an aluminum metal matrix; this material is termed sintered aluminum powder (SAP).

Concept Check 16.1

Cite the general difference in strengthening mechanism between large-particle and dispersion-strengthened particle-reinforced composites.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site).*]

Fiber-Reinforced Composites

fiber-reinforced composite

specific strength

specific modulus

Technologically, the most important composites are those in which the dispersed phase is in the form of a fiber. Design goals of **fiber-reinforced composites** often include high strength and/or stiffness on a weight basis. These characteristics are expressed in terms of **specific strength** and **specific modulus** parameters, which correspond, respectively, to the ratios of tensile strength to specific gravity and modulus of elasticity to specific gravity. Fiber-reinforced composites with exceptionally high specific strengths and moduli have been produced that use low-density fiber and matrix materials.

As noted in Figure 16.2, fiber-reinforced composites are subclassified by fiber length. For short fiber, the fibers are too short to produce a significant improvement in strength.

16.4 INFLUENCE OF FIBER LENGTH

The mechanical characteristics of a fiber-reinforced composite depend not only on the properties of the fiber, but also on the degree to which an applied load is transmitted to the fibers by the matrix phase. Important to the extent of this load transmittance is the magnitude of the interfacial bond between the fiber and matrix phases. Under an applied stress, this fiber–matrix bond ceases at the fiber ends,

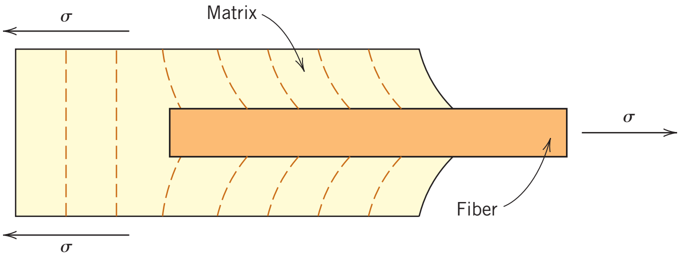


Figure 16.6 The deformation pattern in the matrix surrounding a fiber that is subjected to an applied tensile load.

yielding a matrix deformation pattern as shown schematically in Figure 16.6; in other words, there is no load transmittance from the matrix at each fiber extremity.

Some critical fiber length is necessary for effective strengthening and stiffening of the composite material. This critical length l_c is dependent on the fiber diameter d and its ultimate (or tensile) strength σ_f^*, and on the fiber–matrix bond strength (or the shear yield strength of the matrix, whichever is smaller) τ_c according to

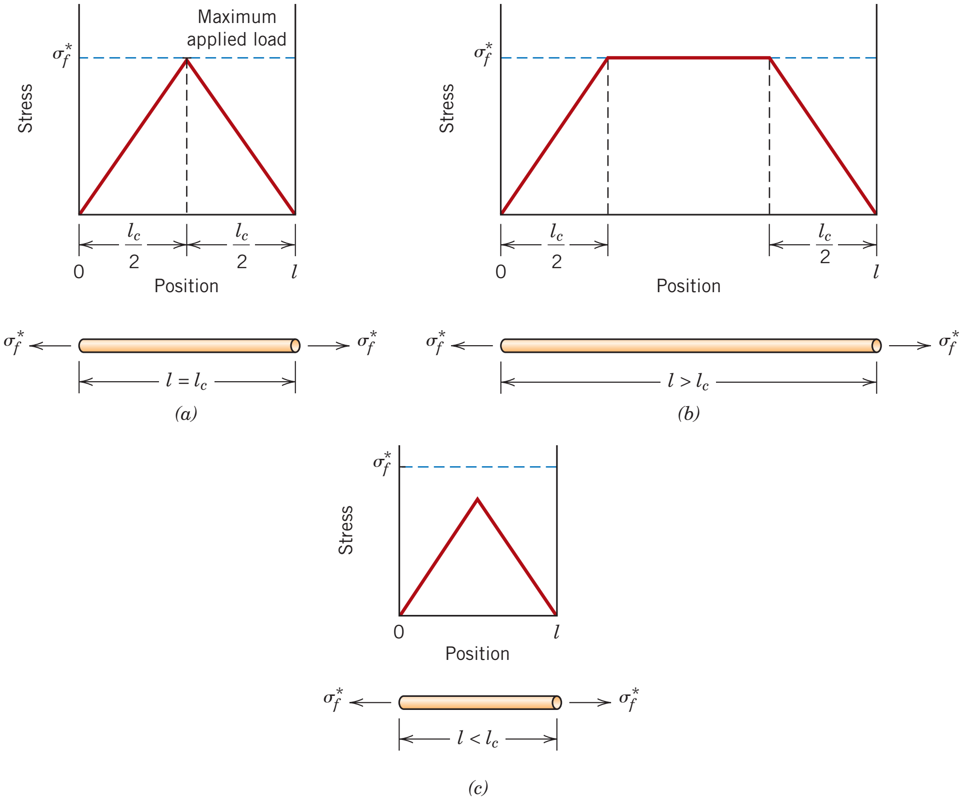
Critical fiber length—dependence on fiber strength and diameter, and fiber–matrix bond strength/matrix shear yield strength

$$l_c = \frac{\sigma_f^* d}{2\tau_c} \tag{16.3}$$

For a number of glass and carbon fiber–matrix combinations, this critical length is on the order of 1 mm, which ranges between 20 and 150 times the fiber diameter.

When a stress equal to σ_f^* is applied to a fiber having just this critical length, the stress–position profile shown in Figure 16.7*a* results; that is, the maximum fiber

Figure 16.7 Stress–position profiles when fiber length l (*a*) is equal to the critical length l_c, (*b*) is greater than the critical length, and (*c*) is less than the critical length for a fiber-reinforced composite that is subjected to a tensile stress equal to the fiber tensile strength σ_f^*.



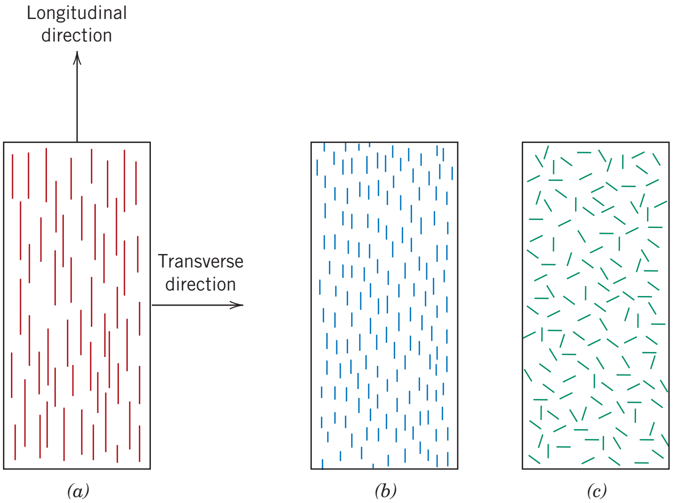


Figure 16.8 Schematic representations of (*a*) continuous and aligned, (*b*) discontinuous and aligned, and (*c*) discontinuous and randomly oriented fiber–reinforced composites.

load is achieved only at the axial center of the fiber. As fiber length l increases, the fiber reinforcement becomes more effective; this is demonstrated in Figure 16.7*b*, a stress–axial position profile for $l > l_c$ when the applied stress is equal to the fiber strength. Figure 16.7*c* shows the stress–position profile for $l < l_c$.

Fibers for which $l \gg l_c$ (normally $l > 15l_c$) are termed *continuous; discontinuous* or *short fibers* have lengths shorter than this. For discontinuous fibers of lengths significantly less than l_c, the matrix deforms around the fiber such that there is virtually no stress transference and little reinforcement by the fiber. These are essentially the particulate composites as described earlier. To effect a significant improvement in strength of the composite, the fibers must be continuous.

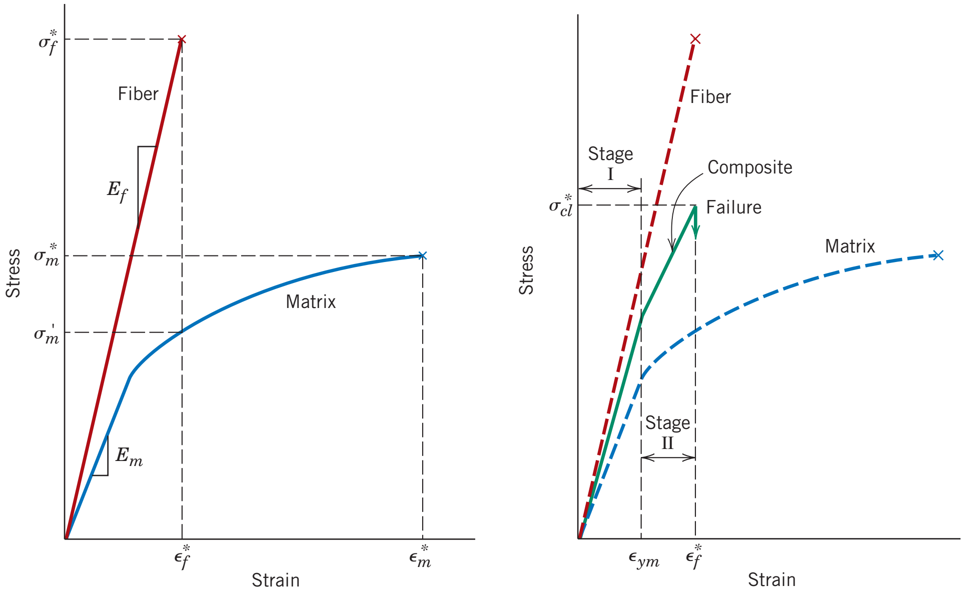
16.5 INFLUENCE OF FIBER ORIENTATION AND CONCENTRATION

The arrangement or orientation of the fibers relative to one another, the fiber concentration, and the distribution all have a significant influence on the strength and other properties of fiber-reinforced composites. With respect to orientation, two extremes are possible: (1) a parallel alignment of the longitudinal axis of the fibers in a single direction, and (2) a totally random alignment. Continuous fibers are normally aligned (Figure 16.8*a*), whereas discontinuous fibers may be aligned (Figure 16.8*b*), randomly oriented (Figure 16.8*c*), or partially oriented. Better overall composite properties are realized when the fiber distribution is uniform.

Continuous and Aligned Fiber Composites

Tensile Stress–Strain Behavior—Longitudinal Loading

Mechanical responses of this type of composite depend on several factors, including the stress–strain behaviors of fiber and matrix phases, the phase volume fractions, and the direction in which the stress or load is applied. Furthermore, the properties of a composite having its fibers aligned are highly anisotropic, that is, dependent on the direction in which they are measured. Let us first consider the stress–strain behavior for the situation wherein the stress is applied along



(*a*) (*b*)

Figure 16.9 (*a*) Schematic stress–strain curves for brittle fiber and ductile matrix materials. Fracture stresses and strains for both materials are noted. (*b*) Schematic stress–strain curve for an aligned fiber–reinforced composite that is exposed to a uniaxial stress applied in the direction of alignment; curves for the fiber and matrix materials shown in part (*a*) are also superimposed.

longitudinal direction

the direction of alignment, the **longitudinal direction,** which is indicated in Figure 16.8*a*.

To begin, assume the stress-versus-strain behaviors for fiber and matrix phases that are represented schematically in Figure 16.9*a*; in this treatment we consider the fiber to be totally brittle and the matrix phase to be reasonably ductile. Also indicated in this figure are fracture strengths in tension for fiber and matrix, σ_f^*, and σ_m^*, respectively, and their corresponding fracture strains, ϵ_f^*, and ϵ_m^*; furthermore, it is assumed that $\epsilon_m^* > \epsilon_f^*$, which is normally the case.

A fiber-reinforced composite consisting of these fiber and matrix materials will exhibit the uniaxial stress–strain response illustrated in Figure 16.9*b*; the fiber and matrix behaviors from Figure 16.9*a* are included to provide perspective. In the initial Stage I region, both fibers and matrix deform elastically; normally this portion of the curve is linear. Typically, for a composite of this type, the matrix yields and deforms plastically (at ϵ_{ym}, Figure 16.9*b*) while the fibers continue to stretch elastically, inasmuch as the tensile strength of the fibers is significantly higher than the yield strength of the matrix. This process constitutes Stage II as noted in the figure; this stage is ordinarily very nearly linear, but of diminished slope relative to Stage I. Furthermore, in passing from Stage I to Stage II, the proportion of the applied load that is borne by the fibers increases.

The onset of composite failure begins as the fibers start to fracture, which corresponds to a strain of approximately ϵ_f^* as noted in Figure 16.9*b*. Composite failure is not catastrophic for a couple of reasons. First, not all fibers fracture at the same time, because there will always be considerable variations in the fracture strength of brittle fiber materials (Section 12.8). In addition, even after fiber failure, the matrix is still intact inasmuch as $\epsilon_f^* < \epsilon_m^*$ (Figure 16.9*a*). Thus, these fractured fibers, which are shorter than the original ones, are still embedded within the intact matrix and consequently are capable of sustaining a diminished load as the matrix continues to plastically deform.

Elastic Behavior—Longitudinal Loading

Let us now consider the elastic behavior of a continuous and oriented fibrous composite that is loaded in the direction of fiber alignment. First, it is assumed that the fiber–matrix interfacial bond is very good, such that deformation of both matrix and fibers is the same (an *isostrain* situation). Under these conditions, the total load sustained by the composite F_c is equal to the sum of the loads carried by the matrix phase F_m and the fiber phase F_f, or

$$F_c = F_m + F_f \tag{16.4}$$

From the definition of stress, Equation 6.1, $F = \sigma A$; and thus expressions for F_c, F_m, and F_f in terms of their respective stresses (σ_c, σ_m, and σ_f) and cross-sectional areas (A_c, A_m, and A_f) are possible. Substitution of these into Equation 16.4 yields

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f \tag{16.5}$$

and then, dividing through by the total cross-sectional area of the composite, A_c, we have

$$\sigma_c = \sigma_m \frac{A_m}{A_c} + \sigma_f \frac{A_f}{A_c} \tag{16.6}$$

where A_m/A_c and A_f/A_c are the area fractions of the matrix and fiber phases, respectively. If the composite, matrix, and fiber phase lengths are all equal, A_m/A_c is equivalent to the volume fraction of the matrix, V_m, and likewise for the fibers, $V_f = A_f/A_c$. Equation 16.6 now becomes

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \tag{16.7}$$

The previous assumption of an isostrain state means that

$$\epsilon_c = \epsilon_m = \epsilon_f \tag{16.8}$$

and when each term in Equation 16.7 is divided by its respective strain,

$$\frac{\sigma_c}{\epsilon_c} = \frac{\sigma_m}{\epsilon_m} V_m + \frac{\sigma_f}{\epsilon_f} V_f \tag{16.9}$$

Furthermore, if composite, matrix, and fiber deformations are all elastic, then $\sigma_c/\epsilon_c = E_c$, $\sigma_m/\epsilon_m = E_m$, and $\sigma_f/\epsilon_f = E_f$, the Es being the moduli of elasticity for the respective phases. Substitution into Equation 16.9 yields an expression for the modulus of elasticity of a continuous and aligned fibrous composite *in the direction of alignment* (or *longitudinal direction*), E_{cl}, as

For a continuous and aligned fiber–reinforced composite, modulus of elasticity in the longitudinal direction

$$E_{cl} = E_m V_m + E_f V_f \tag{16.10a}$$

or

$$E_{cl} = E_m(1 - V_f) + E_f V_f \tag{16.10b}$$

because the composite consists of only matrix and fiber phases; that is, $V_m + V_f = 1$.

Thus, E_{cl} is equal to the volume-fraction weighted average of the moduli of elasticity of the fiber and matrix phases. Other properties, including density, also have this dependence on volume fractions. Equation 16.10a is the fiber analogue of Equation 16.1, the upper bound for particle-reinforced composites.

It can also be shown, for longitudinal loading, that the ratio of the load carried by the fibers to that carried by the matrix is

Ratio of load carried by fibers and the matrix phase, for longitudinal loading

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m} \tag{16.11}$$

The demonstration is left as a homework problem.

EXAMPLE PROBLEM 16.1

Property Determinations for a Glass Fiber–Reinforced Composite—Longitudinal Direction

A continuous and aligned glass fiber–reinforced composite consists of 40 vol% of glass fibers having a modulus of elasticity of 69 GPa (10×10^6 psi) and 60 vol% of a polyester resin that, when hardened, displays a modulus of 3.4 GPa (0.5×10^6 psi).

(a) Compute the modulus of elasticity of this composite in the longitudinal direction.

(b) If the cross-sectional area is 250 mm^2 (0.4 in.^{2}) and a stress of 50 MPa (7250 psi) is applied in this longitudinal direction, compute the magnitude of the load carried by each of the fiber and matrix phases.

(c) Determine the strain that is sustained by each phase when the stress in part (b) is applied.

Solution

(a) The modulus of elasticity of the composite is calculated using Equation 16.10a:

$$\begin{aligned} E_{cl} &= (3.4 \text{ GPa})(0.6) + (69 \text{ GPa})(0.4) \\ &= 30 \text{ GPa } (4.3 \times 10^6 \text{ psi}) \end{aligned}$$

(b) To solve this portion of the problem, first find the ratio of fiber load to matrix load, using Equation 16.11; thus,

$$\frac{F_f}{F_m} = \frac{(69 \text{ GPa})(0.4)}{(3.4 \text{ GPa})(0.6)} = 13.5$$

or $F_f = 13.5\, F_m$.

In addition, the total force sustained by the composite F_c may be computed from the applied stress σ and total composite cross-sectional area A_c according to

$$F_c = A_c \sigma = (250 \text{ mm}^2)(50 \text{ MPa}) = 12{,}500 \text{ N } (2900 \text{ lb}_\text{f})$$

However, this total load is just the sum of the loads carried by fiber and matrix phases; that is,

$$F_c = F_f + F_m = 12{,}500 \text{ N } (2900 \text{ lb}_\text{f})$$

Substitution for F_f from the preceding equation yields

$$13.5\,F_m + F_m = 12{,}500\text{ N}$$

or

$$F_m = 860\text{ N }(200\text{ lb}_\text{f})$$

whereas

$$F_f = F_c - F_m = 12{,}500\text{ N} - 860\text{ N} = 11{,}640\text{ N }(2700\text{ lb}_\text{f})$$

Thus, the fiber phase supports the vast majority of the applied load.

(c) The stress for both fiber and matrix phases must first be calculated. Then, by using the elastic modulus for each [from part (a)], the strain values may be determined.

For stress calculations, phase cross-sectional areas are necessary:

$$A_m = V_m A_c = (0.6)(250\text{ mm}^2) = 150\text{ mm}^2\ (0.24\text{ in.}^2)$$

and

$$A_f = V_f A_c = (0.4)(250\text{ mm}^2) = 100\text{ mm}^2\ (0.16\text{ in.}^2)$$

Thus,

$$\sigma_m = \frac{F_m}{A_m} = \frac{860\text{ N}}{150\text{ mm}^2} = 5.73\text{ MPa }(833\text{ psi})$$

$$\sigma_f = \frac{F_f}{A_f} = \frac{11{,}640\text{ N}}{100\text{ mm}^2} = 116.4\text{ MPa }(16{,}875\text{ psi})$$

Finally, strains are computed as

$$\epsilon_m = \frac{\sigma_m}{E_m} = \frac{5.73\text{ MPa}}{3.4 \times 10^3\text{ MPa}} = 1.69 \times 10^{-3}$$

$$\epsilon_f = \frac{\sigma_f}{E_f} = \frac{116.4\text{ MPa}}{69 \times 10^3\text{ MPa}} = 1.69 \times 10^{-3}$$

Therefore, strains for both matrix and fiber phases are identical, which they should be, according to Equation 16.8 in the previous development.

Elastic Behavior—Transverse Loading

transverse direction

A continuous and oriented fiber composite may be loaded in the **transverse direction;** that is, the load is applied at a 90° angle to the direction of fiber alignment as shown in Figure 16.8*a*. For this situation the stress σ to which the composite as well as both phases are exposed is the same, or

$$\sigma_c = \sigma_m = \sigma_f = \sigma \tag{16.12}$$

This is termed an *isostress* state. Also, the strain or deformation of the entire composite ϵ_c is

$$\epsilon_c = \epsilon_m V_m + \epsilon_f V_f \tag{16.13}$$

but, because $\epsilon = \sigma/E$,

$$\frac{\sigma}{E_{ct}} = \frac{\sigma}{E_m}V_m + \frac{\sigma}{E_f}V_f \tag{16.14}$$

where E_{ct} is the modulus of elasticity in the transverse direction. Now, dividing through by σ yields

$$\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \tag{16.15}$$

which reduces to

For a continuous and aligned fiber–reinforced composite, modulus of elasticity in the transverse direction

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f E_m} = \frac{E_m E_f}{(1 - V_f)E_f + V_f E_m} \tag{16.16}$$

Equation 16.16 is analogous to the lower-bound expression for particulate composites, Equation 16.2.

EXAMPLE PROBLEM 16.2

Elastic Modulus Determination for a Glass Fiber–Reinforced Composite—Transverse Direction

Compute the elastic modulus of the composite material described in Example Problem 16.1, but assume that the stress is applied perpendicular to the direction of fiber alignment.

Solution

According to Equation 16.16,

$$E_{ct} = \frac{(3.4 \text{ GPa})(69 \text{ GPa})}{(0.6)(69 \text{ GPa}) + (0.4)(3.4 \text{ GPa})}$$
$$= 5.5 \text{ GPa } (0.81 \times 10^6 \text{ psi})$$

This value for E_{ct} is slightly greater than that of the matrix phase but, from Example Problem 16.1a, only approximately one-fifth of the modulus of elasticity along the fiber direction (E_{cl}), which indicates the degree of anisotropy of continuous and oriented fiber composites.

Longitudinal Tensile Strength

We now consider the strength characteristics of continuous and aligned fiber–reinforced composites that are loaded in the longitudinal direction. Under these circumstances, strength is normally taken as the maximum stress on the stress–strain curve, Figure 16.9*b*; often this point corresponds to fiber fracture, and marks the onset of composite failure. Table 16.1 lists typical longitudinal

Table 16.1 Typical Longitudinal and Transverse Tensile Strengths for Three Unidirectional Fiber–Reinforced Composites. The Fiber Content for Each Is Approximately 50 Vol%

Material	*Longitudinal Tensile Strength (MPa)*	*Transverse Tensile Strength (MPa)*
Glass–polyester	700	20
Carbon (high modulus)–epoxy	1000	35
Kevlar–epoxy	1200	20

Source: D. Hull and T. W. Clyne, *An Introduction to Composite Materials,* 2nd edition, Cambridge University Press, New York, 1996, p. 179.

tensile strength values for three common fibrous composites. Failure of this type of composite material is a relatively complex process, and several different failure modes are possible. The mode that operates for a specific composite will depend on fiber and matrix properties, and the nature and strength of the fiber–matrix interfacial bond.

If we assume that $\epsilon_f^* < \epsilon_m^*$ (Figure 16.9*a*), which is the usual case, then fibers will fail before the matrix. Once the fibers have fractured, most of the load that was borne by the fibers is now transferred to the matrix. This being the case, it is possible to adapt the expression for the stress on this type of composite, Equation 16.7, into the following expression for the longitudinal strength of the composite, σ_{cl}^*:

For a continuous and aligned fiber–reinforced composite, longitudinal strength in tension

$$\sigma_{cl}^* = \sigma_m'(1-V_f) + \sigma_f^* V_f \tag{16.17}$$

Here σ_m' is the stress in the matrix at fiber failure (as illustrated in Figure 16.9*a*) and, as previously, σ_f^* is the fiber tensile strength.

Transverse Tensile Strength

The strengths of continuous and unidirectional fibrous composites are highly anisotropic, and such composites are normally designed to be loaded along the high-strength, longitudinal direction. However, during in-service applications transverse tensile loads may also be present. Under these circumstances, premature failure may result inasmuch as transverse strength is usually extremely low—it sometimes lies below the tensile strength of the matrix. Thus, the reinforcing effect of the fibers is negative. Typical transverse tensile strengths for three unidirectional composites are contained in Table 16.1.

Whereas longitudinal strength is dominated by fiber strength, a variety of factors will have a significant influence on the transverse strength; these factors include properties of both the fiber and matrix, the fiber–matrix bond strength, and the presence of voids. Measures that have been employed to improve the transverse strength of these composites usually involve modifying properties of the matrix.

Concept Check 16.2

The following table lists four hypothetical aligned fiber–reinforced composites (labeled A through D), along with their characteristics. On the basis of these data, rank the four composites from highest to lowest strength in the longitudinal direction, and then justify your ranking.

Composite	*Fiber Type*	*Vol. Fraction Fibers*	*Fiber Strength (MPa)*	*Ave. Fiber Length (mm)*	*Critical Length (mm)*
A	glass	0.20	3.5×10^3	8	0.70
B	glass	0.35	3.5×10^3	12	0.75
C	carbon	0.40	5.5×10^3	8	0.40
D	carbon	0.30	5.5×10^3	8	0.50

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site).*]

Discontinuous and Aligned-Fiber Composites

Even though reinforcement efficiency is lower for discontinuous than for continuous fibers, discontinuous and aligned-fiber composites (Figure 16.8*b*) are becoming increasingly more important in the commercial market. Chopped-glass fibers are used most extensively; however, carbon and aramid discontinuous fibers are also employed. These short-fiber composites can be produced having moduli of elasticity and tensile strengths that approach 90% and 50%, respectively, of their continuous-fiber counterparts.

For a discontinuous and aligned-fiber composite having a uniform distribution of fibers and in which $l > l_c$, the longitudinal strength (σ^*_{cd}) is given by the relationship

For a discontinuous ($l > l_c$,) and aligned fiber–reinforced composite, longitudinal strength in tension

$$\sigma^*_{cd} = \sigma^*_f V_f \left(1 - \frac{l_c}{2l}\right) + \sigma'_m (1 - V_f) \tag{16.18}$$

where σ^*_f and σ'_m represent, respectively, the fracture strength of the fiber and the stress in the matrix when the composite fails (Figure 16.9*a*).

If the fiber length is less than critical ($l < l_c$), then the longitudinal strength ($\sigma^*_{cd'}$) is given by

For a discontinuous ($l < l_c$) and aligned fiber–reinforced composite, longitudinal strength in tension

$$\sigma^*_{cd'} = \frac{l\tau_c}{d} V_f + \sigma'_m (1 - V_f) \tag{16.19}$$

where d is the fiber diameter and τ_c is the smaller of either the fiber–matrix bond strength or the matrix shear yield strength.

Discontinuous and Randomly Oriented–Fiber Composites

Normally, when the fiber orientation is random, short and discontinuous fibers are used; reinforcement of this type is schematically demonstrated in Figure 16.8*c*. Under these circumstances, a "rule-of-mixtures" expression for the elastic modulus similar to Equation 16.10a may be used, as follows:

For a discontinuous and randomly oriented fiber–reinforced composite, modulus of elasticity

$$E_{cd} = KE_f V_f + E_m V_m \tag{16.20}$$

Table 16.2 Properties of Unreinforced and Reinforced Polycarbonates with Randomly Oriented Glass Fibers

		Fiber Reinforcement (vol%)		
Property	*Unreinforced*	*20*	*30*	*40*
Specific gravity	1.19–1.22	1.35	1.43	1.52
Tensile strength [MPa (ksi)]	59–62 (8.5–9.0)	110 (16)	131 (19)	159 (23)
Modulus of elasticity [GPa (10^6 psi)]	2.24–2.345 (0.325–0.340)	5.93 (0.86)	8.62 (1.25)	11.6 (1.68)
Elongation (%)	90–115	4–6	3–5	3–5
Impact strength, notched Izod (lb_f/in.)	12–16	2.0	2.0	2.5

Source: Adapted from Materials Engineering's *Materials Selector,* copyright © Penton/IPC.

In this expression, K is a fiber efficiency parameter that depends on V_f and the E_f/E_m ratio. Of course, its magnitude will be less than unity, usually in the range 0.1 to 0.6. Thus, for random fiber reinforcement (as with oriented), the modulus increases in some proportion of the volume fraction of fiber. Table 16.2, which gives some of the mechanical properties of unreinforced and reinforced polycarbonates for discontinuous and randomly oriented glass fibers, provides an idea of the magnitude of the reinforcement that is possible.

By way of summary, then, aligned fibrous composites are inherently anisotropic in that the maximum strength and reinforcement are achieved along the alignment (longitudinal) direction. In the transverse direction, fiber reinforcement is virtually nonexistent: fracture usually occurs at relatively low tensile stresses. For other stress orientations, composite strength lies between these extremes. The efficiency of fiber reinforcement for several situations is presented in Table 16.3; this efficiency is taken to be unity for an oriented-fiber composite in the alignment direction, and zero perpendicular to it.

When multidirectional stresses are imposed within a single plane, aligned layers that are fastened together one on top of another at different orientations are frequently used. These are termed *laminar composites,* which are discussed in Section 16.14.

Table 16.3 Reinforcement Efficiency of Fiber-Reinforced Composites for Several Fiber Orientations and at Various Directions of Stress Application

Fiber Orientation	*Stress Direction*	*Reinforcement Efficiency*
All fibers parallel	Parallel to fibers	1
	Perpendicular to fibers	0
Fibers randomly and uniformly distributed within a specific plane	Any direction in the plane of the fibers	$\frac{3}{8}$
Fibers randomly and uniformly distributed within three dimensions in space	Any direction	$\frac{1}{5}$

Source: H. Krenchel, *Fibre Reinforcement,* Copenhagen: Akademisk Forlag, 1964 [33].

Applications involving totally multidirectional applied stresses normally use discontinuous fibers, which are randomly oriented in the matrix material. Table 16.3 shows that the reinforcement efficiency is only one-fifth that of an aligned composite in the longitudinal direction; however, the mechanical characteristics are isotropic.

Consideration of orientation and fiber length for a particular composite will depend on the level and nature of the applied stress as well as fabrication cost. Production rates for short-fiber composites (both aligned and randomly oriented) are rapid, and intricate shapes can be formed that are not possible with continuous fiber reinforcement. Furthermore, fabrication costs are considerably lower than for continuous and aligned; fabrication techniques applied to short-fiber composite materials include compression, injection, and extrusion molding, which are described for unreinforced polymers in Section 15.22.

✓ Concept Check 16.3

Cite one desirable characteristic and one less-desirable characteristic for each of (1) discontinuous-oriented and (2) discontinuous–randomly oriented fiber–reinforced composites.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site)*]

16.6 THE FIBER PHASE

An important characteristic of most materials, especially brittle ones, is that a small-diameter fiber is much stronger than the bulk material. As discussed in Section 12.8, the probability of the presence of a critical surface flaw that can lead to fracture diminishes with decreasing specimen volume, and this feature is used to advantage in the fiber–reinforced composites. Also, the materials used for reinforcing fibers have high tensile strengths.

whisker

On the basis of diameter and character, fibers are grouped into three different classifications: *whiskers, fibers,* and *wires*. **Whiskers** are very thin single crystals that have extremely large length-to-diameter ratios. As a consequence of their small size, they have a high degree of crystalline perfection and are virtually flaw-free, which accounts for their exceptionally high strengths; they are among the strongest known materials. In spite of these high strengths, whiskers are not used extensively as a reinforcement medium because they are extremely expensive. Moreover, it is difficult and often impractical to incorporate whiskers into a matrix. Whisker materials include graphite, silicon carbide, silicon nitride, and aluminum oxide; some mechanical characteristics of these materials are given in Table 16.4.

fiber

Materials that are classified as **fibers** are either polycrystalline or amorphous and have small diameters; fibrous materials are generally either polymers or ceramics (e.g., the polymer aramids, glass, carbon, boron, aluminum oxide, and silicon carbide). Table 16.4 also presents some data on a few materials that are used in fiber form.

Fine wires have relatively large diameters; typical materials include steel, molybdenum, and tungsten. Wires are used as a radial steel reinforcement in automobile tires, in filament-wound rocket casings, and in wire-wound high-pressure hoses.

Table 16.4 Characteristics of Several Fiber–Reinforcement Materials

Material	*Specific Gravity*	*Tensile Strength [GPa (10^6 psi)]*	*Specific Strength (GPa)*	*Modulus of Elasticity [GPa (10^6 psi)]*	*Specific Modulus (GPa)*
		Whiskers			
Graphite	2.2	20 (3)	9.1	700 (100)	318
Silicon nitride	3.2	5–7 (0.75–1.0)	1.56–2.2	350–380 (50–55)	109–118
Aluminum oxide	4.0	10–20 (1–3)	2.5–5.0	700–1500 (100–220)	175–375
Silicon carbide	3.2	20 (3)	6.25	480 (70)	150
		Fibers			
Aluminum oxide	3.95	1.38 (0.2)	0.35	379 (55)	96
Aramid (Kevlar 49)	1.44	3.6–4.1 (0.525–0.600)	2.5–2.85	131 (19)	91
Carbon[a]	1.78–2.15	1.5–4.8 (0.22–0.70)	0.70–2.70	228–724 (32–100)	106–407
E-glass	2.58	3.45 (0.5)	1.34	72.5 (10.5)	28.1
Boron	2.57	3.6 (0.52)	1.40	400 (60)	156
Silicon carbide	3.0	3.9 (0.57)	1.30	400 (60)	133
UHMWPE (Spectra 900)	0.97	2.6 (0.38)	2.68	117 (17)	121
		Metallic Wires			
High-strength steel	7.9	2.39 (0.35)	0.30	210 (30)	26.6
Molybdenum	10.2	2.2 (0.32)	0.22	324 (47)	31.8
Tungsten	19.3	2.89 (0.42)	0.15	407 (59)	21.1

[a] The term *carbon* instead of *graphite* is used to denote these fibers, because they are composed of crystalline graphite regions, and also of noncrystalline material and areas of crystal misalignment.

16.7 THE MATRIX PHASE

The *matrix phase* of fibrous composites may be a metal, polymer, or ceramic. In general, metals and polymers are used as matrix materials because some ductility is desirable; for ceramic-matrix composites (Section 16.10), the reinforcing component is added to improve fracture toughness. The discussion of this section will focus on polymer and metal matrices.

For fiber-reinforced composites, the matrix phase serves several functions. First, it binds the fibers together and acts as the medium by which an externally applied stress is transmitted and distributed to the fibers; only a very small proportion of an applied load is sustained by the matrix phase. Furthermore, the matrix material should be ductile. In addition, the elastic modulus of the fiber should be much higher than that of the matrix. The second function of the matrix is to protect the individual fibers from surface damage as a result of mechanical abrasion or chemical reactions with the environment. Such interactions may introduce surface flaws capable of forming cracks, which may lead to failure at low tensile stress levels. Finally, the matrix separates the fibers and, by virtue of its relative softness and plasticity, prevents the propagation of brittle cracks from fiber to fiber, which could result in catastrophic failure; in other words, the matrix phase serves as a barrier to crack propagation. Even though some of the individual fibers fail, total composite fracture will not occur until large numbers of adjacent fibers, once having failed, form a cluster of critical size.

It is essential that adhesive bonding forces between fiber and matrix be high to minimize fiber pullout. In fact, bonding strength is an important consideration in the choice of the matrix–fiber combination. The ultimate strength of the composite depends to a large degree on the magnitude of this bond; adequate bonding is essential to maximize the stress transmittance from the weak matrix to the strong fibers.

16.8 POLYMER-MATRIX COMPOSITES

polymer-matrix composite

Polymer-matrix composites (*PMC*s) consist of a polymer resin[2] as the matrix, with fibers as the reinforcement medium. These materials are used in the greatest diversity of composite applications, as well as in the largest quantities, in light of their room-temperature properties, ease of fabrication, and cost. In this section the various classifications of PMCs are discussed according to reinforcement type (i.e., glass, carbon, and aramid), along with their applications and the various polymer resins that are employed.

Glass Fiber–Reinforced Polymer (GFRP) Composites

Fiberglass is simply a composite consisting of glass fibers, either continuous or discontinuous, contained within a polymer matrix; this type of composite is produced in the largest quantities. The composition of the glass that is most commonly drawn into fibers (sometimes referred to as E-glass) is contained in Table 13.1; fiber diameters normally range between 3 and 20 μm. Glass is popular as a fiber reinforcement material for several reasons:

1. It is easily drawn into high-strength fibers from the molten state.
2. It is readily available and may be fabricated into a glass-reinforced plastic economically using a wide variety of composite-manufacturing techniques.
3. As a fiber it is relatively strong, and when embedded in a plastic matrix, it produces a composite having a very high specific strength.
4. When coupled with the various plastics, it possesses a chemical inertness that renders the composite useful in a variety of corrosive environments.

The surface characteristics of glass fibers are extremely important because even minute surface flaws can deleteriously affect the tensile properties, as discussed in Section 12.8. Surface flaws are easily introduced by rubbing or abrading the surface with another hard material. Also, glass surfaces that have been exposed to the normal atmosphere for even short time periods generally have a weakened surface layer that interferes with bonding to the matrix. Newly drawn fibers are normally coated during drawing with a *size,* a thin layer of a substance

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[2] The term *resin* is used in this context to denote a high-molecular-weight reinforcing plastic.

that protects the fiber surface from damage and undesirable environmental interactions. This size is ordinarily removed prior to composite fabrication and replaced with a *coupling agent* or finish that produces a chemical bond between the fiber and matrix.

There are several limitations to this group of materials. In spite of having high strengths, they are not very stiff and do not display the rigidity that is necessary for some applications (e.g., as structural members for airplanes and bridges). Most fiberglass materials are limited to service temperatures below 200°C (400°F); at higher temperatures, most polymers begin to flow or to deteriorate. Service temperatures may be extended to approximately 300°C (575°F) by using high-purity fused silica for the fibers and high-temperature polymers such as the polyimide resins.

Many fiberglass applications are familiar: automotive and marine bodies, plastic pipes, storage containers, and industrial floorings. The transportation industries are using increasing amounts of glass fiber–reinforced plastics in an effort to decrease vehicle weight and boost fuel efficiencies. A host of new applications are being used or currently investigated by the automotive industry.

Carbon Fiber–Reinforced Polymer (CFRP) Composites

Carbon is a high-performance fiber material that is the most commonly used reinforcement in advanced (i.e., nonfiberglass) polymer-matrix composites. The reasons for this are as follows:

1. Carbon fibers have the highest specific modulus and specific strength of all reinforcing fiber materials.
2. They retain their high tensile modulus and high strength at elevated temperatures; high-temperature oxidation, however, may be a problem.
3. At room temperature, carbon fibers are not affected by moisture or a wide variety of solvents, acids, and bases.
4. These fibers exhibit a diversity of physical and mechanical characteristics, allowing composites incorporating these fibers to have specific engineered properties.
5. Fiber and composite manufacturing processes have been developed that are relatively inexpensive and cost effective.

Use of the term *carbon fiber* may seem perplexing because carbon is an element, and, as noted in Section 12.4, the stable form of crystalline carbon at ambient conditions is graphite, having the structure represented in Figure 12.17. Carbon fibers are not totally crystalline, but are composed of both graphitic and noncrystalline regions; these areas of noncrystallinity are devoid of the three-dimensional ordered arrangement of hexagonal carbon networks that is characteristic of graphite (Figure 12.17).

Manufacturing techniques for producing carbon fibers are relatively complex and will not be discussed. However, three different organic precursor materials are used: rayon, polyacrylonitrile (PAN), and pitch. Processing technique will vary from precursor to precursor, as will also the resultant fiber characteristics.

One classification scheme for carbon fibers is by tensile modulus; on this basis the four classes are standard, intermediate, high, and ultrahigh moduli. Furthermore, fiber diameters normally range between 4 and 10 μm; both continuous and chopped forms are available. In addition, carbon fibers are normally coated with a protective epoxy size that also improves adhesion with the polymer matrix.

Carbon-reinforced polymer composites are currently being used extensively in sports and recreational equipment (fishing rods, golf clubs), filament-wound rocket motor cases, pressure vessels, and aircraft structural components—both military and commercial, fixed-wing and helicopters (e.g., as wing, body, stabilizer, and rudder components).

Aramid Fiber–Reinforced Polymer Composites

Aramid fibers are high-strength, high-modulus materials that were introduced in the early 1970s. They are especially desirable for their outstanding strength-to-weight ratios, which are superior to those of metals. Chemically, this group of materials is known as poly(paraphenylene terephthalamide). There are a number of aramid materials; trade names for two of the most common are Kevlar and Nomex. For the former, there are several grades (Kevlar 29, 49, and 149) that have different mechanical behaviors. During synthesis, the rigid molecules are aligned in the direction of the fiber axis, as liquid crystal domains (Section 15.19); the repeat unit and the mode of chain alignment are represented in Figure 16.10. Mechanically, these fibers have longitudinal tensile strengths and tensile moduli (Table 16.4) that are higher than other polymeric fiber materials; however, they are relatively weak in compression. In addition, this material is known for its toughness, impact resistance, and resistance to creep and fatigue failure. Even though the aramids are thermoplastics, they are, nevertheless, resistant to combustion and stable to relatively high temperatures; the temperature range over which they retain their high mechanical properties is between −200 and 200°C (−330 and 390°F). Chemically, they are susceptible to degradation by strong acids and bases, but they are relatively inert in other solvents and chemicals.

The aramid fibers are most often used in composites having polymer matrices; common matrix materials are the epoxies and polyesters. Because the fibers are relatively flexible and somewhat ductile, they may be processed by most common textile operations. Typical applications of these aramid composites are in ballistic products (bulletproof vests and armor), sporting goods, tires, ropes, missile cases, and pressure vessels and as a replacement for asbestos in automotive brake and clutch linings and gaskets.

The properties of continuous and aligned glass, carbon, and aramid fiber–reinforced epoxy composites are included in Table 16.5. Thus, a comparison of the mechanical characteristics of these three materials may be made in both longitudinal and transverse directions.

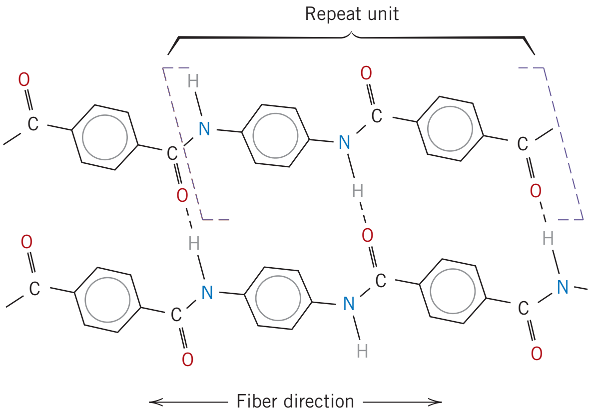

Figure 16.10 Schematic representation of repeat unit and chain structures for aramid (Kevlar) fibers. Chain alignment with the fiber direction and hydrogen bonds that form between adjacent chains are also shown. [From F. R. Jones (Editor), *Handbook of Polymer-Fibre Composites.* Copyright © 1994 by Addison-Wesley Longman. Reprinted with permission.]

Table 16.5 **Properties of Continuous and Aligned Glass, Carbon, and Aramid Fiber–Reinforced Epoxy–Matrix Composites in Longitudinal and Transverse Directions. In All Cases the Fiber Volume Fraction Is 0.60**

Property	*Glass (E-glass)*	*Carbon (High Strength)*	*Aramid (Kevlar 49)*
Specific gravity	2.1	1.6	1.4
Tensile modulus			
Longitudinal [GPa (10^6 psi)]	45 (6.5)	145 (21)	76 (11)
Transverse [GPa (10^6 psi)]	12 (1.8)	10 (1.5)	5.5 (0.8)
Tensile strength			
Longitudinal [MPa (ksi)]	1020 (150)	1240 (180)	1380 (200)
Transverse [MPa (ksi)]	40 (5.8)	41 (6)	30 (4.3)
Ultimate tensile strain			
Longitudinal	2.3	0.9	1.8
Transverse	0.4	0.4	0.5

Source: Adapted from R. F. Floral and S. T. Peters, "Composite Structures and Technologies," tutorial notes, 1989.

Other Fiber Reinforcement Materials

Glass, carbon, and the aramids are the most common fiber reinforcements incorporated in polymer matrices. Other fiber materials that are used to much lesser degrees are boron, silicon carbide, and aluminum oxide; tensile moduli, tensile strengths, specific strengths, and specific moduli of these materials in fiber form are contained in Table 16.4. Boron fiber–reinforced polymer composites have been used in military aircraft components, helicopter rotor blades, and some sporting goods. Silicon carbide and aluminum oxide fibers are used in tennis rackets, circuit boards, military armor, and rocket nose cones.

Polymer-Matrix Materials

The roles assumed by the polymer matrix are outlined in Section 16.7. In addition, the matrix often determines the maximum service temperature, because it normally softens, melts, or degrades at a much lower temperature than the fiber reinforcement.

The most widely used and least expensive polymer resins are the polyesters and vinyl esters;[3] these matrix materials are used primarily for glass fiber–reinforced composites. A large number of resin formulations provide a wide range of properties for these polymers. The epoxies are more expensive and, in addition to commercial applications, are also used extensively in PMCs for aerospace applications; they have better mechanical properties and resistance to moisture than the polyesters and vinyl resins. For high-temperature applications, polyimide resins are employed; their continuous-use, upper-temperature limit is approximately 230°C (450°F). Finally, high-temperature thermoplastic resins offer the potential to be used in future aerospace applications; such materials include polyetheretherketone (PEEK), poly(phenylene sulfide) (PPS), and polyetherimide (PEI).

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[3] The chemistry and typical properties of some of the matrix materials discussed in this section are included in Appendices B, D, and E.

DESIGN EXAMPLE 16.1

Design of a Tubular Composite Shaft

A tubular composite shaft is to be designed that has an outside diameter of 70 mm (2.75 in.), an inside diameter of 50 mm (1.97 in.), and a length of 1.0 m (39.4 in.); such is represented schematically in Figure 16.11. The mechanical characteristic of prime importance is bending stiffness in terms of the longitudinal modulus of elasticity; strength and fatigue resistance are not significant parameters for this application when filament composites are used. Stiffness is to be specified as maximum allowable deflection in bending; when subjected to three-point bending as in Figure 12.32 (i.e., support points at both tube extremities and load application at the longitudinal midpoint), a load of 1000 N (225 $\mathrm{lb_f}$) is to produce an elastic deflection of no more than 0.35 mm (0.014 in.) at the midpoint position.

Continuous fibers that are oriented parallel to the tube axis will be used; possible fiber materials are glass, and carbon in standard-, intermediate-, and high-modulus grades. The matrix material is to be an epoxy resin, and the maximum allowable fiber volume fraction is 0.60.

This design problem calls for us to do the following:

(a) Decide which of the four fiber materials, when embedded in the epoxy matrix, meet the stipulated criteria.

(b) Of these possibilities, select the one fiber material that will yield the lowest-cost composite material (assuming fabrication costs are the same for all fibers).

Elastic modulus, density, and cost data for the fiber and matrix materials are contained in Table 16.6.

Solution

(a) It first becomes necessary to determine the required longitudinal modulus of elasticity for this composite material, consistent with the stipulated criteria. This computation necessitates the use of the three-point deflection expression

$$\Delta y = \frac{FL^3}{48\,EI} \tag{16.21}$$

in which Δy is the midpoint deflection, F is the applied force, L is the support point separation distance, E is the modulus of elasticity, and I is the cross-sectional

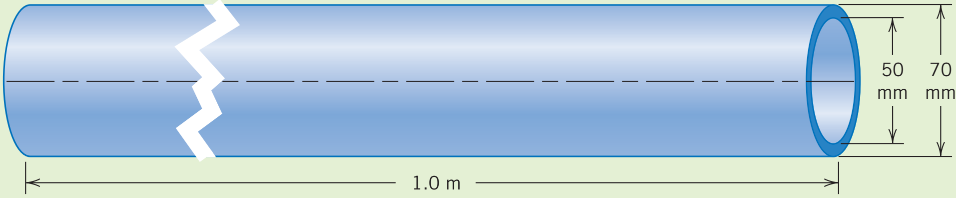

Figure 16.11 Schematic representation of a tubular composite shaft, the subject of Design Example 16.1.

Table 16.6 **Elastic Modulus, Density, and Cost Data for Glass and Various Carbon Fibers and Epoxy Resin**

Material	*Elastic Modulus (GPa)*	*Density (g/cm³)*	*Cost ($US/kg)*
Glass fibers	72.5	2.58	2.10
Carbon fibers (standard modulus)	230	1.80	60.00
Carbon fibers (intermediate modulus)	285	1.80	95.00
Carbon fibers (high modulus)	400	1.80	250.00
Epoxy resin	2.4	1.14	6.00

moment of inertia. For a tube having inside and outside diameters of d_i and d_o, respectively,

$$I = \frac{\pi}{64}(d_o^4 - d_i^4) \tag{16.22}$$

and

$$E = \frac{4FL^3}{3\pi\Delta y(d_o^4 - d_i^4)} \tag{16.23}$$

For this shaft design,

$$\begin{aligned} F &= 1000 \text{ N} \\ L &= 1.0 \text{ m} \\ \Delta y &= 0.35 \text{ mm} \\ d_o &= 70 \text{ mm} \\ d_i &= 50 \text{ mm} \end{aligned}$$

Thus, the required longitudinal modulus of elasticity for this shaft is

$$\begin{aligned} E &= \frac{4(1000 \text{ N})(1.0 \text{ m})^3}{3\pi(0.35 \times 10^{-3} \text{ m})[(70 \times 10^{-3} \text{ m})^4 - (50 \times 10^{-3} \text{ m})^4]} \\ &= 69.3 \text{ GPa } (9.9 \times 10^6 \text{ psi}) \end{aligned}$$

The next step is to determine the fiber and matrix volume fractions for each of the four candidate fiber materials. This is possible using the rule-of-mixtures expression, Equation 16.10b:

$$E_{cs} = E_m V_m + E_f V_f = E_m(1 - V_f) + E_f V_f$$

Table 16.7 lists the V_m and V_f values required for $E_{cs} = 69.3$ GPa; Equation 16.10b and the moduli data in Table 16.6 were used in these computations. Only the three carbon-fiber types are possible candidates because their V_f values are less than 0.6.

(b) At this point it becomes necessary to determine the volume of fibers and matrix for each of the three carbon types. The total tube volume V_c in centimeters is

$$V_c = \frac{\pi L}{4}(d_o^2 - d_i^2) \tag{16.24}$$

$$= \frac{\pi(100 \text{ cm})}{4}[(7.0 \text{ cm})^2 - (5.0 \text{ cm})^2]$$

$$= 1885 \text{ cm}^3 (114 \text{ in.}^3)$$

Table 16.7 Fiber and Matrix Volume Fractions for Three Carbon-Fiber Types as Required to Give a Composite Modulus of 69.3 GPa

Fiber Type	V_f	V_m
Glass	0.954	0.046
Carbon (standard modulus)	0.293	0.707
Carbon (intermediate modulus)	0.237	0.763
Carbon (high modulus)	0.168	0.832

Thus, fiber and matrix volumes result from products of this value and the V_f and V_m values cited in Table 16.7. These volume values are presented in Table 16.8, which are then converted into masses using densities (Table 16.6), and finally into material costs, from the per unit mass cost (also given in Table 16.6).

As may be noted in Table 16.8, the material of choice (i.e., the least expensive) is the standard-modulus carbon-fiber composite; the relatively low cost per unit mass of this fiber material offsets its relatively low modulus of elasticity and required high volume fraction.

Table 16.8 Fiber and Matrix Volumes, Masses, and Costs and Total Material Cost for Three Carbon-Fiber Epoxy–Matrix Composites

Fiber Type	*Fiber Volume (cm^3)*	*Fiber Mass (kg)*	*Fiber Cost ($US)*	*Matrix Volume (cm^3)*	*Matrix Mass (kg)*	*Matrix Cost ($US)*	*Total Cost ($US)*
Carbon (standard modulus)	552	0.994	59.60	1333	1.520	9.10	68.70
Carbon (intermediate modulus)	447	0.805	76.50	1438	1.639	9.80	86.30
Carbon (high modulus)	317	0.571	142.80	1568	1.788	10.70	153.50

16.9 METAL-MATRIX COMPOSITES

metal-matrix composite

As the name implies, for **metal-matrix composites** (*MMC*s) the matrix is a ductile metal. These materials may be used at higher service temperatures than their base-metal counterparts; furthermore, the reinforcement may improve specific stiffness, specific strength, abrasion resistance, creep resistance, thermal conductivity, and dimensional stability. Some of the advantages of these materials over the polymer-matrix composites include higher operating temperatures, nonflammability, and greater resistance to degradation by organic fluids. Metal-matrix composites are much more expensive than PMCs, and, therefore, MMC use is somewhat restricted.

The superalloys, as well as alloys of aluminum, magnesium, titanium, and copper, are employed as matrix materials. The reinforcement may be in the form of particulates, both continuous and discontinuous fibers, and whiskers; concentrations normally range between 10 and 60 vol%. Continuous-fiber materials include carbon, silicon carbide, boron, aluminum oxide, and the refractory metals. On the other hand, discontinuous reinforcements consist primarily of silicon carbide whiskers, chopped fibers of aluminum oxide and carbon, and particulates of silicon carbide and aluminum oxide. In a sense, the cermets (Section 16.2) fall within this MMC scheme. Table 16.9 presents the properties of several common metal-matrix, continuous and aligned fiber–reinforced composites.

Some matrix–reinforcement combinations are highly reactive at elevated temperatures. Consequently, composite degradation may be caused by high-temperature processing or by subjecting the MMC to elevated temperatures during service. This problem is commonly resolved either by applying a protective surface coating to the reinforcement or by modifying the matrix alloy composition.

Normally the processing of MMCs involves at least two steps: consolidation or synthesis (i.e., introduction of reinforcement into the matrix), followed by a shaping operation. A host of consolidation techniques are available, some of which are relatively sophisticated; discontinuous fiber MMCs are amenable to shaping by standard metal-forming operations (e.g., forging, extrusion, rolling).

Automobile manufacturers have recently begun to use MMCs in their products. For example, some engine components have been introduced consisting of an aluminum-alloy matrix that is reinforced with aluminum oxide and carbon fibers; this MMC is light in weight and resists wear and thermal distortion. Metal-matrix composites are also employed in driveshafts (that have higher rotational speeds and reduced vibrational noise levels), extruded stabilizer bars, and forged suspension and transmission components.

The aerospace industry also uses MMCs. Structural applications include advanced aluminum-alloy metal-matrix composites; boron fibers are used as the reinforcement for the space shuttle orbiter, and continuous graphite fibers for the Hubble Space Telescope.

Table 16.9 **Properties of Several Metal-Matrix Composites Reinforced with Continuous and Aligned Fibers**

Fiber	*Matrix*	*Fiber Content (vol%)*	*Density* (g/cm^3)	*Longitudinal Tensile Modulus (GPa)*	*Longitudinal Tensile Strength (MPa)*
Carbon	6061 Al	41	2.44	320	620
Boron	6061 Al	48	—	207	1515
SiC	6061 Al	50	2.93	230	1480
Alumina	380.0 Al	24	—	120	340
Carbon	AZ31 Mg	38	1.83	300	510
Borsic	Ti	45	3.68	220	1270

Source: Adapted from J. W. Weeton, D. M. Peters, and K. L. Thomas, *Engineers' Guide to Composite Materials,* ASM International, Materials Park, OH, 1987.

The high-temperature creep and rupture properties of some of the superalloys (Ni- and Co-based alloys) may be enhanced by fiber reinforcement using refractory metals such as tungsten. Excellent high-temperature oxidation resistance and impact strength are also maintained. Designs incorporating these composites permit higher operating temperatures and better efficiencies for turbine engines.

16.10 CERAMIC-MATRIX COMPOSITES

As discussed in Chapters 12 and 13, ceramic materials are inherently resilient to oxidation and deterioration at elevated temperatures; were it not for their disposition to brittle fracture, some of these materials would be ideal candidates for use in high-temperature and severe-stress applications, specifically for components in automobile and aircraft gas turbine engines. Fracture toughness values for ceramic materials are low and typically lie between 1 and 5 $\text{MPa}\sqrt{\text{m}}$ (0.9 and 4.5 $\text{ksi}\sqrt{\text{in.}}$); see Table 8.1 and Table B.5 in Appendix B. By way of contrast, K_{Ic} values for most metals are much higher [15 to greater than 150 $\text{MPa}\sqrt{\text{m}}$ (14 to >140 $\text{ksi}\sqrt{\text{in.}}$)].

ceramic-matrix composite

The fracture toughnesses of ceramics have been improved significantly by the development of a new generation of **ceramic-matrix composites** (*CMC*s)—particulates, fibers, or whiskers of one ceramic material that have been embedded into a matrix of another ceramic. Ceramic-matrix composite materials have extended fracture toughnesses to between about 6 and 20 $\text{MPa}\sqrt{\text{m}}$ (5.5 and 18 $\text{ksi}\sqrt{\text{in.}}$).

In essence, this improvement in the fracture properties results from interactions between advancing cracks and dispersed phase particles. Crack initiation normally occurs with the matrix phase, whereas crack propagation is impeded or hindered by the particles, fibers, or whiskers. Several techniques are used to retard crack propagation, which are discussed as follows.

One particularly interesting and promising toughening technique employs a phase transformation to arrest the propagation of cracks and is aptly termed *transformation toughening.* Small particles of partially stabilized zirconia (Section 12.7) are dispersed within the matrix material, often Al_2O_3 or ZrO_2 itself. Typically, CaO, MgO, Y_2O_3, and CeO are used as stabilizers. Partial stabilization allows retention of the metastable tetragonal phase at ambient conditions rather than the stable monoclinic phase; these two phases are noted on the ZrO_2–$CaZrO_3$ phase diagram in Figure 12.26. The stress field in front of a propagating crack causes these metastably retained tetragonal particles to undergo transformation to the stable monoclinic phase. Accompanying this transformation is a slight particle volume increase, and the net result is that compressive stresses are established on the crack surfaces near the crack tip that tend to pinch the crack shut, thereby arresting its growth. This process is demonstrated schematically in Figure 16.12.

Other recently developed toughening techniques involve the use of ceramic whiskers, often SiC or Si_3N_4. These whiskers may inhibit crack propagation by (1) deflecting crack tips, (2) forming bridges across crack faces, (3) absorbing energy during pullout as the whiskers debond from the matrix, and/or (4) causing a redistribution of stresses in regions adjacent to the crack tips.

In general, increasing fiber content improves strength and fracture toughness; this is demonstrated in Table 16.10 for SiC whisker-reinforced alumina. Furthermore, there is a considerable reduction in the scatter of fracture strengths for whisker-reinforced ceramics relative to their unreinforced counterparts. In addition, these CMCs exhibit improved high-temperature creep behavior and resistance to thermal shock (i.e., failure resulting from sudden changes in temperature).

Ceramic-matrix composites may be fabricated using hot pressing, hot isostatic pressing, and liquid-phase sintering techniques. Relative to applications, SiC

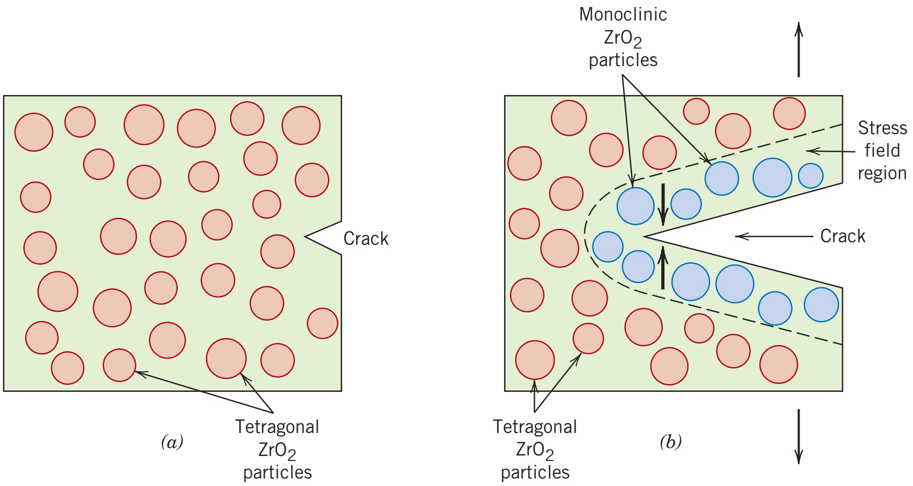

Figure 16.12 Schematic demonstration of transformation toughening. (*a*) A crack prior to inducement of the ZrO_2 particle phase transformation. (*b*) Crack arrestment due to the stress-induced phase transformation.

whisker-reinforced aluminas are being used as cutting-tool inserts for machining hard metal alloys; tool lives for these materials are greater than for cemented carbides (Section 16.2).

16.11 CARBON–CARBON COMPOSITES

carbon–carbon composite

One of the most advanced and promising engineering materials is the carbon fiber–reinforced carbon-matrix composite, often termed a **carbon–carbon composite;** as the name implies, both reinforcement and matrix are carbon. These materials are relatively new and expensive and, therefore, are not currently being used extensively. Their desirable properties include high-tensile moduli and tensile strengths that are retained to temperatures in excess of 2000°C (3630°F), resistance to creep, and relatively large fracture toughness values. Furthermore, carbon–carbon composites have low coefficients of thermal expansion and relatively high thermal conductivities; these characteristics, coupled with high strengths, give rise to a relatively low susceptibility to thermal shock. Their major drawback is a propensity to high-temperature oxidation.

The carbon–carbon composites are employed in rocket motors, as friction materials in aircraft and high-performance automobiles, for hot-pressing molds, in components for advanced turbine engines, and as ablative shields for re-entry vehicles.

Table 16.10 Room Temperature Fracture Strengths and Fracture Toughnesses for Various SiC Whisker Contents in Al_2O_3

Whisker Content (vol%)	*Fracture Strength (MPa)*	*Fracture Toughness ($MPa\sqrt{m}$)*
0	—	4.5
10	455 ± 55	7.1
20	655 ± 135	7.5–9.0
40	850 ± 130	6.0

Source: Adapted from *Engineered Materials Handbook,* Vol. 1, *Composites,* C. A. Dostal (Senior Editor), ASM International, Materials Park, OH, 1987.

The primary reason that these composite materials are so expensive is the relatively complex processing techniques that are employed. Preliminary procedures are similar to those used for carbon-fiber, polymer-matrix composites. That is, the continuous carbon fibers are laid down having the desired two- or three-dimensional pattern; these fibers are then impregnated with a liquid polymer resin, often a phenolic; the workpiece is next formed into the final shape, and the resin is allowed to cure. At this time the matrix resin is *pyrolyzed,* that is, converted into carbon by heating in an inert atmosphere; during pyrolysis, molecular components consisting of oxygen, hydrogen, and nitrogen are driven off, leaving behind large carbon-chain molecules. Subsequent heat treatments at higher temperatures will cause this carbon matrix to densify and increase in strength. The resulting composite, then, consists of the original carbon fibers that remained essentially unaltered, which are contained in this pyrolyzed carbon matrix.

16.12 HYBRID COMPOSITES

hybrid composite

A relatively new fiber-reinforced composite is the **hybrid,** which is obtained by using two or more different kinds of fibers in a single matrix; hybrids have a better all-around combination of properties than composites containing only a single fiber type. A variety of fiber combinations and matrix materials are used, but in the most common system, both carbon and glass fibers are incorporated into a polymeric resin. The carbon fibers are strong and relatively stiff and provide a low-density reinforcement; however, they are expensive. Glass fibers are inexpensive and lack the stiffness of carbon. The glass–carbon hybrid is stronger and tougher, has a higher impact resistance, and may be produced at a lower cost than either of the comparable all-carbon or all-glass reinforced plastics.

The two different fibers may be combined in a number of ways, which will ultimately affect the overall properties. For example, the fibers may all be aligned and intimately mixed with one another, or laminations may be constructed consisting of layers, each of which consists of a single fiber type, alternating one with another. In virtually all hybrids the properties are anisotropic.

When hybrid composites are stressed in tension, failure is usually noncatastrophic (i.e., does not occur suddenly). The carbon fibers are the first to fail, at which time the load is transferred to the glass fibers. Upon failure of the glass fibers, the matrix phase must sustain the applied load. Eventual composite failure concurs with that of the matrix phase.

Principal applications for hybrid composites are lightweight land, water, and air transport structural components, sporting goods, and lightweight orthopedic components.

16.13 PROCESSING OF FIBER-REINFORCED COMPOSITES

To fabricate continuous fiber–reinforced plastics that meet design specifications, the fibers should be uniformly distributed within the plastic matrix and, in most instances, all oriented in virtually the same direction. In this section several techniques (pultrusion, filament winding, and prepreg production processes) by which useful products of these materials are manufactured will be discussed.

Pultrusion

Pultrusion is used for the manufacture of components having continuous lengths and a constant cross-sectional shape (rods, tubes, beams, etc.). With this technique,

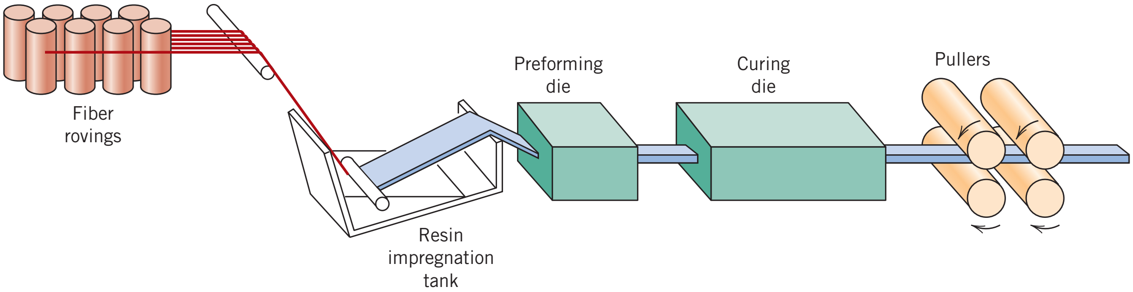

Figure 16.13 Schematic diagram showing the pultrusion process.

illustrated schematically in Figure 16.13, continuous-fiber *rovings,* or *tows,*[4] are first impregnated with a thermosetting resin; these are then pulled through a steel die that preforms to the desired shape and also establishes the resin/fiber ratio. The stock then passes through a curing die that is precision machined so as to impart the final shape; this die is also heated to initiate curing of the resin matrix. A pulling device draws the stock through the dies and also determines the production speed. Tubes and hollow sections are made possible by using center mandrels or inserted hollow cores. Principal reinforcements are glass, carbon, and aramid fibers, normally added in concentrations between 40 and 70 vol%. Commonly used matrix materials include polyesters, vinyl esters, and epoxy resins.

Pultrusion is a continuous process that is easily automated; production rates are relatively high, making it very cost effective. Furthermore, a wide variety of shapes are possible, and there is really no practical limit to the length of stock that may be manufactured.

Prepreg Production Processes

prepreg

Prepreg is the composite industry's term for continuous-fiber reinforcement preimpregnated with a polymer resin that is only partially cured. This material is delivered in tape form to the manufacturer, which then directly molds and fully cures the product without having to add any resin. It is probably the composite material form most widely used for structural applications.

The prepregging process, represented schematically for thermoset polymers in Figure 16.14, begins by collimating a series of spool-wound continuous-fiber tows. These tows are then sandwiched and pressed between sheets of release and carrier paper using heated rollers, a process termed *calendering.* The release paper sheet has been coated with a thin film of heated resin solution of relatively low viscosity so as to provide for its thorough impregnation of the fibers. A *doctor blade* spreads the resin into a film of uniform thickness and width. The final prepreg product—the thin tape consisting of continuous and aligned fibers embedded in a partially cured resin—is prepared for packaging by winding onto a cardboard core. As shown in Figure 16.14, the release paper sheet is removed as the impregnated tape is spooled. Typical tape thicknesses range between 0.08 and 0.25 mm (3×10^{-3} and 10^{-2} in.) and tape widths range between 25 and 1525 mm (1 and 60 in.), whereas resin content usually lies between about 35 and 45 vol%.

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[4] A roving, or tow, is a loose and untwisted bundle of continuous fibers that are drawn together as parallel strands.

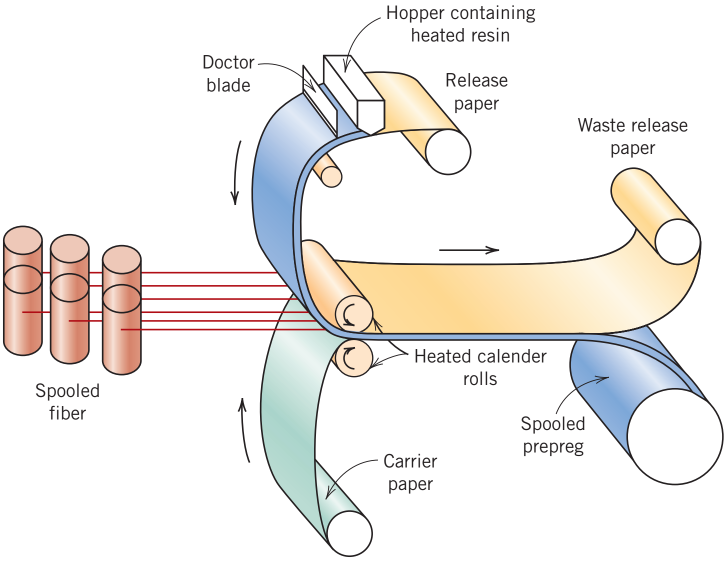

Figure 16.14 Schematic diagram illustrating the production of prepreg tape using a thermoset polymer.

At room temperature the thermoset matrix undergoes curing reactions; therefore, the prepreg is stored at 0°C (32°F) or lower. Also, the time in use at room temperature (or *out-time*) must be minimized. If properly handled, thermoset prepregs have a lifetime of at least six months and usually longer.

Both thermoplastic and thermosetting resins are used; carbon, glass, and aramid fibers are the common reinforcements.

Actual fabrication begins with the *lay-up*—laying of the prepreg tape onto a tooled surface. Normally a number of plies are laid up (after removal from the carrier backing paper) to provide the desired thickness. The lay-up arrangement may be unidirectional, but more often the fiber orientation is alternated to produce a cross-ply or angle-ply laminate. Final curing is accomplished by the simultaneous application of heat and pressure.

The lay-up procedure may be carried out entirely by hand (hand lay-up), wherein the operator both cuts the lengths of tape and then positions them in the desired orientation on the tooled surface. Alternately, tape patterns may be machine cut, then hand laid. Fabrication costs can be further reduced by automation of prepreg lay-up and other manufacturing procedures (e.g., filament winding, as discussed next), which virtually eliminates the need for hand labor. These automated methods are essential for many applications of composite materials to be cost effective.

Filament Winding

Filament winding is a process by which continuous reinforcing fibers are accurately positioned in a predetermined pattern to form a hollow (usually cylindrical) shape. The fibers, either as individual strands or as tows, are first fed through a resin bath and then are continuously wound onto a mandrel, usually using automated winding equipment (Figure 16.15). After the appropriate number of layers have been applied, curing is carried out either in an oven or at room temperature, after which the mandrel is removed. As an alternative, narrow and thin prepregs (i.e., tow pregs) 10 mm or less in width may be filament wound.

Various winding patterns are possible (i.e., circumferential, helical, and polar) to give the desired mechanical characteristics. Filament-wound parts have very high strength-to-weight ratios. Also, a high degree of control over winding uniformity

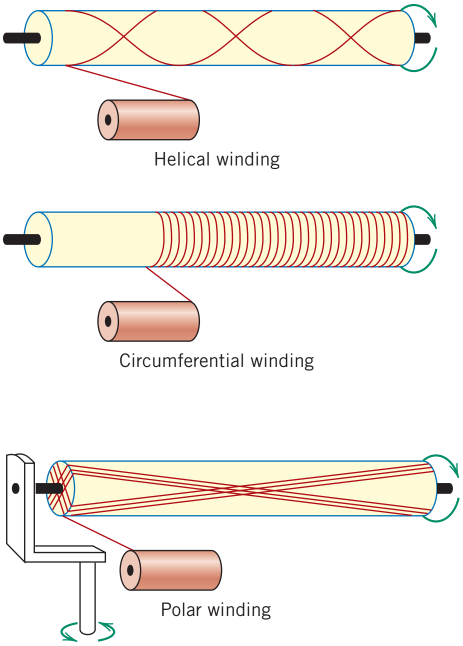

Figure 16.15 Schematic representations of helical, circumferential, and polar filament winding techniques. [From N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials*, The Macmillan Company, New York, 1981.]

and orientation is afforded with this technique. Furthermore, when automated, the process is most economically attractive. Common filament-wound structures include rocket motor casings, storage tanks and pipes, and pressure vessels.

Manufacturing techniques are now being used to produce a wide variety of structural shapes that are not necessarily limited to surfaces of revolution (e.g., I-beams). This technology is advancing very rapidly because it is very cost effective.

Structural Composites

structural composite

A **structural composite** is normally composed of both homogeneous and composite materials, the properties of which depend not only on the properties of the constituent materials but also on the geometrical design of the various structural elements. Laminar composites and sandwich panels are two of the most common structural composites; only a relatively superficial examination is offered here for them.

16.14 LAMINAR COMPOSITES

laminar composite

A **laminar composite** is composed of two-dimensional sheets or panels that have a preferred high-strength direction, such as is found in wood and continuous and aligned fiber–reinforced plastics. The layers are stacked and subsequently cemented together such that the orientation of the high-strength direction varies with each successive layer (Figure 16.16). For example, adjacent wood sheets in plywood are aligned with the grain direction at right angles to each other. Laminations may also be constructed using fabric material such as cotton, paper, or woven glass fibers embedded in a plastic matrix. Thus a laminar composite has relatively high strength in a number of directions in the two-dimensional plane; however, the strength in any given direction is, of course, lower than it would be if all the fibers were oriented in that direction. One example of a relatively complex laminated structure is the modern ski (see the chapter-opening illustration for this chapter).

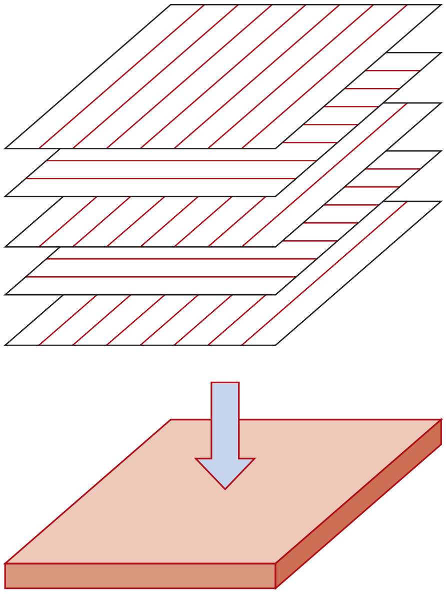

Figure 16.16 The stacking of successive oriented fiber–reinforced layers for a laminar composite.

16.15 SANDWICH PANELS

sandwich panel

Sandwich panels, considered to be a class of structural composites, are designed to be lightweight beams or panels having relatively high stiffnesses and strengths. A sandwich panel consists of two outer sheets, or faces, that are separated by and adhesively bonded to a thicker core (Figure 16.17). The outer sheets are made of a relatively stiff and strong material, typically aluminum alloys, fiber-reinforced plastics, titanium, steel, or plywood; they impart high stiffness and strength to the structure and must be thick enough to withstand tensile and compressive stresses that result from loading. The core material is lightweight and normally has a low modulus of elasticity. Core materials typically fall within three categories: rigid polymeric foams (i.e., phenolics, epoxy, polyurethanes), wood (i.e., balsa wood), and honeycombs (discussed shortly).

Structurally, the core serves several functions. First of all, it provides continuous support for the faces. In addition, it must have sufficient shear strength to withstand transverse shear stresses and also be thick enough to provide high shear stiffness (to resist buckling of the panel). (Tensile and compressive stresses on the core are much lower than on the faces.)

Another popular core consists of a "honeycomb" structure—thin foils that have been formed into interlocking hexagonal cells, with axes oriented perpendicular to

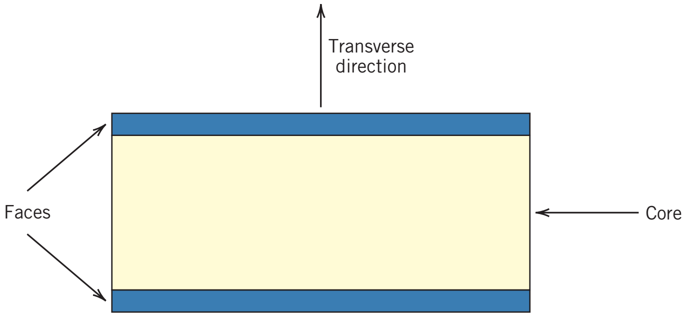

Figure 16.17 Schematic diagram showing the cross section of a sandwich panel.

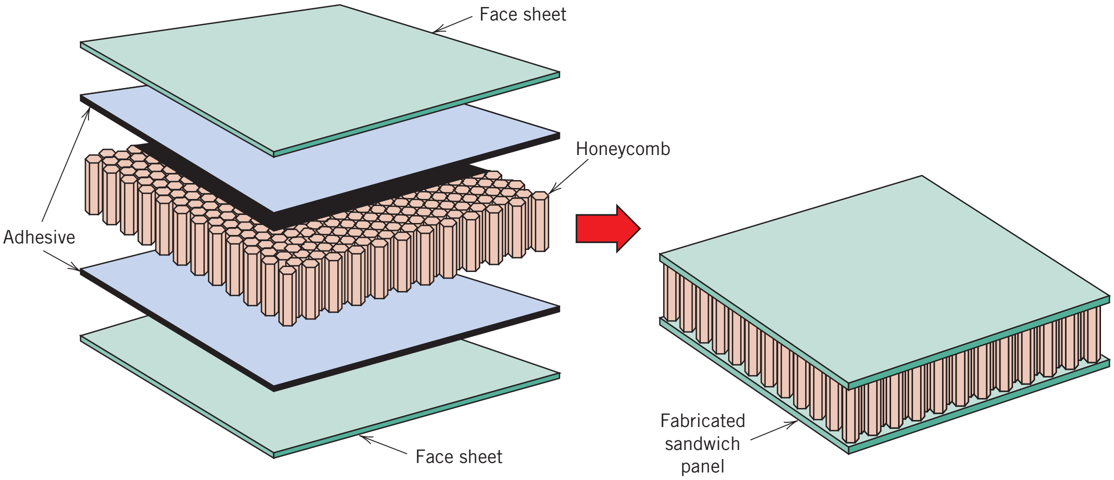

Figure 16.18 Schematic diagram showing the construction of a honeycomb core sandwich panel. (Reprinted with permission from *Engineered Materials Handbook,* Vol. 1, *Composites,* ASM International, Metals Park, OH, 1987.)

the face planes; Figure 16.18 shows a cutaway view of a honeycomb core sandwich panel. The honeycomb material is normally either an aluminum alloy or aramid polymer. Strength and stiffness of honeycomb structures depend on cell size, cell wall thickness, and the material from which the honeycomb is made.

Sandwich panels are used in a wide variety of applications including roofs, floors, and walls of buildings and in aerospace and aircraft (i.e., for wings, fuselage, and tailplane skins).

MATERIALS OF IMPORTANCE

Nanocomposites in Tennis Balls

Nanocomposites—composites that consist of nanosized particles embedded in some type of matrix—are a group of promising new materials that will undoubtedly become infused with some of our modern technologies. In fact, one type of nanocomposite is currently being used in high-performance tennis balls. These balls retain their original pressure and bounce twice as long as conventional ones. Air permeation through the walls of the ball is inhibited by a factor of two due to the presence of a flexible and very thin (10 to 50 μm) nanocomposite barrier coating that covers the inner core;[5] a schematic diagram of the cross-section of one of these tennis balls is shown in Figure 16.19. Because of their outstanding characteristics, these Double Core balls have recently been selected as the official balls for some of the major tennis tournaments.

This nanocomposite coating consists of a matrix of butyl rubber, within which is embedded thin platelets of vermiculite,[6] a natural clay mineral. The vermiculite platelets exist as single-molecule thin sheets—on the order of a nanometer thick—that have a very large aspect ratio (of about 10,000); *aspect ratio* is the ratio of the lateral dimensions of a platelet to its thickness. Furthermore, the vermiculite platelets are *exfoliated*—that is,

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[5] This coating was developed by InMat Inc., and is called Air D-Fense. Wilson Sporting Goods has incorporated this coating in its Double Core tennis balls.

[6] Vermiculite is one member of the layered silicates group that is discussed in Section 12.3.

they remain separated from one another. Also, within the butyl rubber, the vermiculite platelets are aligned such that all their lateral axes lie in the same plane; and throughout this barrier coating are multiple layers of these platelets (per the inset of Figure 16.19).

The presence of the vermiculite platelets accounts for the ability of the nanocomposite coating to more effectively retain air pressure within the tennis balls. These platelets act as multilayer barriers to the diffusion of air molecules and slow down the diffusion rate; that is, the diffusion path length of air molecules is enhanced significantly because the air molecules must bypass these particles as they diffuse through the coating. Also, the addition of the particles to the butyl rubber does not diminish its flexibility.

It is anticipated that this type of coating can also be applied to other kinds of sporting equipment (i.e., soccer balls, footballs, bicycle tires), as well as to automobile tires (which would be lighter in weight and more recyclable).

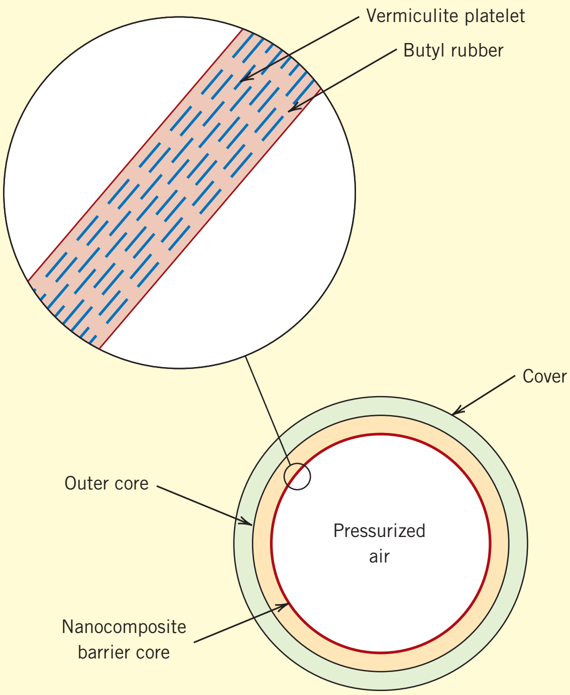

Figure 16.19 Schematic diagram showing the cross-section of a high-performance Double Core tennis ball. The inset drawing presents a detailed view of the nanocomposite coating that acts as a barrier to air permeation.

Photograph of a can of Double Core tennis balls and an individual ball. (Photograph courtesy of Wilson Sporting Goods Company.)

SUMMARY

Introduction

- Composites are artificially produced multiphase materials having desirable combinations of the best properties of the constituent phases.
- Usually, one phase (the matrix) is continuous and completely surrounds the other (the dispersed phase).
- In this discussion, composites were classified as particle-reinforced, fiber-reinforced, and structural.

Large-Particle Composites
Dispersion-Strengthened Composites

- Large-particle and dispersion-strengthened composites fall within the particle-reinforced classification.
- For dispersion strengthening, improved strength is achieved by extremely small particles of the dispersed phase, which inhibit dislocation motion.
- The particle size is normally greater with large-particle composites, whose mechanical characteristics are enhanced by reinforcement action.
- For large-particle composites, upper and lower elastic modulus values depend on the moduli and volume fractions of matrix and particulate phases according to the rule-of-mixtures expressions Equations 16.1 and 16.2.
- Concrete, a type of large-particle composite, consists of an aggregate of particles bonded together with cement. In the case of portland cement concrete, the aggregate consists of sand and gravel; the cementitious bond develops as a result of chemical reactions between the portland cement and water.
- The mechanical strength of concrete may be improved by reinforcement methods (e.g., embedment into the fresh concrete of steel rods, wires, etc.).

Influence of Fiber Length

- Of the several composite types, the potential for reinforcement efficiency is greatest for those that are fiber-reinforced.
- With fiber-reinforced composites, an applied load is transmitted to and distributed among the fibers via the matrix phase, which in most cases is at least moderately ductile.
- Significant reinforcement is possible only if the matrix–fiber bond is strong. Because reinforcement discontinues at the fiber extremities, reinforcement efficiency depends on fiber length.
- For each fiber–matrix combination, there exists some critical length (l_c), which depends on fiber diameter and strength, and fiber–matrix bond strength according to Equation 16.3.
- The length of continuous fibers greatly exceeds this critical value (i.e., $l > 15l_c$), whereas shorter fibers are discontinuous.

Influence of Fiber Orientation and Concentration

- On the basis of fiber length and orientation, three different types of fiber-reinforced composites are possible:
  - Continuous and aligned (Figure 16.8*a*)—mechanical properties are highly anisotropic. In the alignment direction, reinforcement and strength are a maximum; perpendicular to the alignment, they are a minimum.
  - Discontinuous and aligned (Figure 16.8*b*)—significant strengths and stiffnesses are possible in the longitudinal direction.
  - Discontinuous and randomly oriented (Figure 16.8*c*)—despite some limitations on reinforcement efficiency, properties are isotropic.
- For continuous and aligned, rule-of-mixtures expressions for the modulus in both longitudinal and transverse orientations were developed (Equations 16.10 and 16.16). In addition, an equation for longitudinal strength was also cited (Equation 16.17).
- For discontinuous and aligned, composite strength equations were presented for two different situations:

When $l > l_c$, Equation 16.18 is valid.
When $l < l_c$, it is appropriate to use Equation 16.19.

- The elastic modulus for discontinuous and randomly oriented fibrous composites may be determined using Equation 16.20.

The Fiber Phase

- On the basis of diameter and material type, fiber reinforcements are classified as follows:
  Whiskers—extremely strong single crystals that have very small diameters
  Fibers—normally polymers or ceramics that may be either amorphous or polycrystalline
  Wires—metals/alloys that have relatively large diameters

The Matrix Phase

- Although all three basic material types are used for matrices, the most common are polymers and metals.
- The matrix phase normally performs three functions:
  It binds the fibers together and transmits an externally applied load to the fibers.
  It protects the individual fibers from surface damage.
  It prevents the propagation of cracks from fiber to fiber.
- Fibrous reinforced composites are sometimes classified according to matrix type; within this scheme are three classifications: polymer-, metal-, and ceramic-matrix.

Polymer-Matrix Composites

- Polymer-matrix composites are the most common; they may be reinforced with glass, carbon, and aramid fibers.

Metal-Matrix Composites

- Service temperatures are higher for metal-matrix composites than for polymer-matrix composites. MMCs also use a variety of fiber and whisker types.

Ceramic-Matrix Composites

- With ceramic-matrix composites, the design goal is increased fracture toughness. This is achieved by interactions between advancing cracks and dispersed phase particles.
- Transformation toughening is one such technique for improving K_{Ic}.

Carbon–Carbon Composites

- Carbon–carbon composites are composed of carbon fibers embedded in a pyrolyzed carbon matrix.
- These materials are expensive and used in applications requiring high strengths and stiffnesses (that are retained at elevated temperatures), resistance to creep, and good fracture toughnesses.

Hybrid Composites

- The hybrid composites contain at least two different fiber types. Using hybrids it is possible to design composites having better all-around sets of properties.

Processing of Fiber-Reinforced Composites

- Several composite processing techniques have been developed that provide a uniform fiber distribution and a high degree of alignment.
- With pultrusion, components of continuous length and constant cross section are formed as resin-impregnated fiber tows are pulled through a die.
- Composites used for many structural applications are commonly prepared using a lay-up operation (either hand or automated), wherein prepreg tape plies are laid down on a tooled surface and are subsequently fully cured by the simultaneous application of heat and pressure.
- Some hollow structures may be fabricated using automated filament winding procedures, whereby resin-coated strands or tows or prepreg tape are continuously wound onto a mandrel, followed by a curing operation.

Structural Composites

- Two general kinds of structural composites were discussed: laminar composites and sandwich panels.

  Laminar composites are virtually isotropic in a two-dimensional plane. This is made possible with several sheets of a highly anisotropic composite, which are cemented onto one another such that the high-strength direction is varied with each successive layer.

  Sandwich panels consist of two strong and stiff sheet faces that are separated by a core material or structure. These structures combine relatively high strengths and stiffnesses with low densities.

Equation Summary

Equation Number	*Equation*	*Solving for*	*Page Number*
16.1	$E_c(u) = E_m V_m + E_p V_p$	Rule-of-mixtures expression—lower bound	630
16.2	$E_c(l) = \dfrac{E_m E_p}{V_m E_p + V_p E_m}$	Rule-of-mixtures expression—upper bound	630
16.3	$l_c = \dfrac{\sigma_f^* d}{2\tau_c}$	Critical fiber length	635
16.10a	$E_{cl} = E_m V_m + E_f V_f$	Modulus of elasticity for continuous and aligned fibrous composite in the longitudinal direction	638
16.16	$E_{ct} = \dfrac{E_m E_f}{V_m E_f + V_f E_m}$	Modulus of elasticity for continuous and aligned fibrous composite in the transverse direction	641
16.17	$\sigma_{cl}^* = \sigma_m'(1 - V_f) + \sigma_f^* V_f$	Longitudinal tensile strength for continuous and aligned fibrous composite	642
16.18	$\sigma_{cd}^* = \sigma_f^* V_f\left(1 - \dfrac{l_c}{2l}\right) + \sigma_m'(1 - V_f)$	Longitudinal tensile strength for discontinuous and aligned fibrous composite, and $l > l_c$	643
16.19	$\sigma_{cd'}^* = \dfrac{l\tau_c}{d} V_f + \sigma_m'(1 - V_f)$	Longitudinal tensile strength for discontinuous and aligned fibrous composite, and $l < l_c$	643

List of Symbols

Symbol	*Meaning*
d	Fiber diameter
E_f	Modulus of elasticity of fiber phase
E_m	Modulus of elasticity of matrix phase
E_p	Modulus of elasticity of particulate phase
l	Fiber length
l_c	Critical fiber length
V_f	Volume fraction of fiber phase
V_m	Volume fraction of matrix phase
V_p	Volume fraction of particulate phase
σ_f^*	Fiber tensile strength
σ'_m	Stress in matrix at composite failure
τ_c	Fiber-matrix bond strength or matrix shear yield strength

Important Terms and Concepts

carbon–carbon composite
ceramic-matrix composite
cermet
concrete
dispersed phase
dispersion-strengthened composite
fiber
fiber-reinforced composite
hybrid composite
laminar composite
large-particle composite
longitudinal direction
matrix phase
metal-matrix composite
polymer-matrix composite
prepreg
prestressed concrete
principle of combined action
reinforced concrete
rule of mixtures
sandwich panel
specific modulus
specific strength
structural composite
transverse direction
whisker

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QUESTIONS AND PROBLEMS

Large-Particle Composites

16.1 The mechanical properties of aluminum may be improved by incorporating fine particles of aluminum oxide (Al_2O_3). Given that the moduli of elasticity of these materials are, respectively, 69 GPa (10×10^6 psi) and 393 GPa (57×10^6 psi), plot modulus of elasticity versus the volume percent of Al_2O_3 in Al from 0 to 100 vol%, using both upper- and lower-bound expressions.

16.2 Estimate the maximum and minimum thermal conductivity values for a cermet that contains 85 vol% titanium carbide (TiC) particles in a cobalt matrix. Assume thermal conductivities of 27 and 69 W/m · K for TiC and Co, respectively.

16.3 A large-particle composite consisting of tungsten particles within a copper matrix is to be prepared. If the volume fractions of tungsten and copper are 0.60 and 0.40, respectively, estimate the upper limit for the specific stiffness of this composite given the data that follow.

	Specific Gravity	*Modulus of Elasticity (GPa)*
Copper	8.9	110
Tungsten	19.3	407

16.4 **(a)** What is the distinction between cement and concrete?

(b) Cite three important limitations that restrict the use of concrete as a structural material.

(c) Briefly explain three techniques that are used to strengthen concrete by reinforcement.

Dispersion-Strengthened Composites

16.5 Cite one similarity and two differences between precipitation hardening and dispersion strengthening.

Influence of Fiber Length

16.6 For a glass fiber–epoxy matrix combination, the critical fiber length–fiber diameter ratio is 50. Using the data in Table 16.4, determine the fiber-matrix bond strength.

16.7 **(a)** For a fiber-reinforced composite, the efficiency of reinforcement η is dependent on fiber length l according to

$$\eta = \frac{l - 2x}{l}$$

where x represents the length of the fiber at each end that does not contribute to the load transfer. Make a plot of η versus l to $l = 40$ mm (1.6 in.), assuming that $x = 0.75$ mm (0.03 in.).

(b) What length is required for a 0.80 efficiency of reinforcement?

Influence of Fiber Orientation and Concentration

16.8 A continuous and aligned fiber–reinforced composite is to be produced consisting of 30 vol% aramid fibers and 70 vol% of a polycarbonate matrix; mechanical characteristics of these two materials are as follows:

	Modulus of Elasticity [GPa (psi)]	*Tensile Strength [MPa (psi)]*
Aramid fiber	131 (19×10^6)	3600 (520,000)
Polycarbonate	2.4 (3.5×10^5)	65 (9425)

Also, the stress on the polycarbonate matrix when the aramid fibers fail is 45 MPa (6500 psi).

For this composite, compute

(a) the longitudinal tensile strength, and

(b) the longitudinal modulus of elasticity

16.9 Is it possible to produce a continuous and oriented aramid fiber–epoxy matrix composite having longitudinal and transverse moduli of elasticity of 57.1 GPa (8.28×10^6 psi) and 4.12 GPa (6×10^5 psi), respectively? Why or why not? Assume that the modulus of elasticity of the epoxy is 2.4 GPa (3.50×10^5 psi).

16.10 For a continuous and oriented fiber–reinforced composite, the moduli of elasticity in the longitudinal and transverse directions are 19.7 and 3.66 GPa (2.8×10^6 and 5.3×10^5 psi), respectively. If the volume fraction of fibers is 0.25, determine the moduli of elasticity of fiber and matrix phases.

16.11 **(a)** Verify that Equation 16.11, the expression for the fiber load–matrix load ratio (F_f/F_m), is valid.

(b) What is the F_f/F_c ratio in terms of E_f, E_m, and V_f?

16.12 In an aligned and continuous glass fiber–reinforced nylon 6,6 composite, the fibers are to carry 94% of a load applied in the longitudinal direction.

(a) Using the data provided, determine the volume fraction of fibers that will be required.

(b) What will be the tensile strength of this composite? Assume that the matrix stress at fiber failure is 30 MPa (4350 psi).

	Modulus of Elasticity [GPa (psi)]	***Tensile Strength [MPa (psi)]***
Glass fiber	72.5 (10.5×10^6)	3400 (490,000)
Nylon 6,6	3.0 (4.35×10^5)	76 (11,000)

16.13 Assume that the composite described in Problem 16.8 has a cross-sectional area of 320 mm^2 (0.50 in.^{2}) and is subjected to a longitudinal load of 44,500 N (10,000 lb$_f$).

(a) Calculate the fiber–matrix load ratio.

(b) Calculate the actual loads carried by both fiber and matrix phases.

(c) Compute the magnitude of the stress on each of the fiber and matrix phases.

(d) What strain is experienced by the composite?

16.14 A continuous and aligned fiber–reinforced composite having a cross-sectional area of 1130 mm^2 (1.75 in.^{2}) is subjected to an external tensile load. If the stresses sustained by the fiber and matrix phases are 156 MPa (22,600 psi) and 2.75 MPa (400 psi), respectively; the force sustained by the fiber phase is 74,000 N (16,600 lb$_f$); and the total longitudinal strain is 1.25×10^{-3}, determine

(a) the force sustained by the matrix phase,

(b) the modulus of elasticity of the composite material in the longitudinal direction, and

(c) the moduli of elasticity for fiber and matrix phases.

16.15 Compute the longitudinal strength of an aligned carbon fiber–epoxy matrix composite having a 0.25 volume fraction of fibers, assuming the following: (1) an average fiber diameter of 10×10^{-3} mm (3.94×10^{-4} in.), (2) an average fiber length of 5 mm (0.20 in.), (3) a fiber fracture strength of 2.5 GPa (3.625×10^5 psi), (4) a fiber-matrix bond strength of 80 MPa (11,600 psi), (5) a matrix stress at fiber failure of 10.0 MPa (1450 psi), and (6) a matrix tensile strength of 75 MPa (11,000 psi).

16.16 It is desired to produce an aligned carbon fiber–epoxy matrix composite having a longitudinal tensile strength of 750 MPa (109,000 psi). Calculate the volume fraction of fibers necessary if (1) the average fiber diameter and length are 1.2×10^{-2} mm (4.7×10^{-4} in.) and 1 mm (0.04 in.), respectively; (2) the fiber fracture strength is 5000 MPa (725,000 psi); (3) the fiber-matrix bond strength is 25 MPa (3625 psi); and (4) the matrix stress at fiber failure is 10 MPa (1450 psi).

16.17 Compute the longitudinal tensile strength of an aligned glass fiber–epoxy matrix composite in which the average fiber diameter and length are 0.010 mm (4×10^{-4} in.) and 2.5 mm (0.10 in.), respectively, and the volume fraction of fibers is 0.40. Assume that (1) the fiber-matrix bond strength is 75 MPa (10,900 psi), (2) the fracture strength of the fibers is 3500 MPa (508,000 psi), and (3) the matrix stress at fiber failure is 8.0 MPa (1160 psi).

16.18 **(a)** From the moduli of elasticity data in Table 16.2 for glass fiber–reinforced polycarbonate composites, determine the value of the fiber efficiency parameter for each of 20, 30, and 40 vol% fibers.

(b) Estimate the modulus of elasticity for 50 vol% glass fibers.

The Fiber Phase
The Matrix Phase

16.19 For a polymer-matrix fiber-reinforced composite:

(a) List three functions of the matrix phase.

(b) Compare the desired mechanical characteristics of matrix and fiber phases.

(c) Cite two reasons why there must be a strong bond between fiber and matrix at their interface.

16.20 **(a)** What is the distinction between matrix and dispersed phases in a composite material?

(b) Contrast the mechanical characteristics of matrix and dispersed phases for fiber-reinforced composites.

Polymer-Matrix Composites

16.21 **(a)** Calculate the specific longitudinal strengths of the glass fiber, carbon fiber, and aramid fiber–reinforced epoxy composites in Table 16.5 and compare them with those of the following alloys: tempered (315°C) 440A martensitic stainless steel, normalized 1020 plain-carbon steel, 2024-T3 aluminum alloy, cold-worked (HO2 temper) C36000 free-cutting brass, rolled AZ31B magnesium alloy, and annealed Ti-6Al-4V titanium alloy.

(b) Compare the specific moduli of the same three fiber-reinforced epoxy composites with the same metal alloys. Densities (i.e., specific gravities), tensile strengths, and moduli of elasticity for these metal alloys may be found in Tables B.1, B.4, and B.2, respectively, in Appendix B.

16.22 **(a)** List four reasons why glass fibers are most commonly used for reinforcement.

(b) Why is the surface perfection of glass fibers so important?

(c) What measures are taken to protect the surface of glass fibers?

16.23 Cite the distinction between carbon and graphite.

16.24 **(a)** Cite several reasons why fiberglass-reinforced composites are used extensively.

(b) Cite several limitations of this type of composite.

Hybrid Composites

16.25 **(a)** What is a hybrid composite?

(b) List two important advantages of hybrid composites over normal fiber composites.

16.26 **(a)** Write an expression for the modulus of elasticity for a hybrid composite in which all fibers of both types are oriented in the same direction.

(b) Using this expression, compute the longitudinal modulus of elasticity of a hybrid composite consisting of aramid and glass fibers in volume fractions of 0.30 and 0.40, respectively, within a polyester resin matrix [E_m = 2.5 GPa (3.6×10^5 psi)].

16.27 Derive a generalized expression analogous to Equation 16.16 for the transverse modulus of elasticity of an aligned hybrid composite consisting of two types of continuous fibers.

Processing of Fiber-Reinforced Composites

16.28 Briefly describe pultrusion, filament winding, and prepreg production fabrication processes; cite the advantages and disadvantages of each.

Laminar Composites
Sandwich Panels

16.29 Briefly describe laminar composites. What is the prime reason for fabricating these materials?

16.30 **(a)** Briefly describe sandwich panels.

(b) What is the prime reason for fabricating these structural composites?

(c) What are the functions of the faces and the core?

Spreadsheet Problems

16.1SS For an aligned polymer-matrix composite, develop a spreadsheet that will allow the user to compute the longitudinal tensile strength after inputting values for the following parameters: volume fraction of fibers, average fiber diameter, average fiber length, fiber fracture strength, fiber-matrix bond strength, matrix stress at composite failure, and matrix tensile strength.

16.2SS Generate a spreadsheet for the design of a tubular composite shaft (Design Example 16.1)—that is, which of available fiber materials provide the required stiffness, and, of these possibilities, which will cost the least. The fibers are continuous and are to be aligned parallel to the tube axis. The user is allowed to input values for the following parameters: inside and outside tube diameters, tube length, maximum deflection at the axial midpoint for some given applied load, maximum fiber volume fraction, elastic moduli of matrix and all fiber materials, densities of matrix and fiber materials, and cost per unit mass for the matrix and all fiber materials.

DESIGN PROBLEMS

16.D1 Composite materials are now being used extensively in sports equipment.

(a) List at least four different sports implements that are made of, or contain composites.

(b) For one of these implements, write an essay in which you do the following: (1) Cite the materials that are used for matrix and dispersed phases, and, if possible, the proportions of each phase; (2) note the nature of the dispersed phase (i.e., continuous fibers); and (3) describe the process by which the implement is fabricated.

Influence of Fiber Orientation and Concentration

16.D2 It is desired to produce an aligned and continuous fiber–reinforced epoxy composite having a maximum of 50 vol% fibers. In addition, a minimum longitudinal modulus of elasticity of 50 GPa (7.3×10^6 psi) is required, as well as a minimum tensile strength of 1300 MPa (189,000 psi). Of E-glass, carbon (PAN standard modulus), and aramid fiber materials, which are possible candidates and why? The epoxy has a modulus of elasticity of 3.1 GPa (4.5×10^5 psi) and a tensile strength of 75 MPa (11,000 psi). In addition, assume the following stress levels on the epoxy matrix at fiber failure: E-glass—70 MPa (10,000 psi); carbon (PAN standard modulus)—30 MPa (4350 psi); and aramid—50 MPa (7250 psi). Other fiber data are contained in Tables B.2 and B.4 in Appendix B. For aramid and carbon fibers, use average strengths computed from the minimum and maximum values provided in Table B.4.

16.D3 It is desired to produce a continuous and oriented carbon fiber–reinforced epoxy having a modulus of elasticity of at least 83 GPa (12×10^6 psi) in the direction of fiber alignment. The maximum permissible specific gravity is 1.40. Given the following data, is such a composite possible? Why or why not? Assume that composite specific gravity may be determined using a relationship similar to Equation 16.10a.

	Specific Gravity	*Modulus of Elasticity [GPa (psi)]*
Carbon fiber	1.80	260 (37×10^6)
Epoxy	1.25	2.4 (3.5×10^5)

16.D4 It is desired to fabricate a continuous and aligned glass fiber–reinforced polyester having a tensile strength of at least 1400 MPa (200,000 psi) in the longitudinal direction. The maximum possible specific gravity is 1.65. Using the following data, determine whether such a composite is possible. Justify your decision. Assume a value of 15 MPa for the stress on the matrix at fiber failure.

	Specific Gravity	*Tensile Strength [MPa (psi)]*
Glass fiber	2.50	3500 (5×10^5)
Polyester	1.35	50 (7.25×10^3)

16.D5 It is necessary to fabricate an aligned and discontinuous carbon fiber–epoxy matrix composite having a longitudinal tensile strength of 1900 MPa (275,000 psi) using 0.45 volume fraction of fibers. Compute the required fiber fracture strength assuming that the average fiber diameter and length are 8×10^{-3} mm (3.1×10^{-4} in.) and 3.5 mm (0.14 in.), respectively. The fiber-matrix bond strength is 40 MPa (5800 psi), and the matrix stress at fiber failure is 12 MPa (1740 psi).

16.D6 A tubular shaft similar to that shown in Figure 16.11 is to be designed that has an outside diameter of 80 mm (3.15 in.) and a length of 0.75 m (2.46 ft). The mechanical characteristic of prime importance is bending stiffness in terms of the longitudinal modulus of elasticity. Stiffness is to be specified as maximum allowable deflection in bending; when subjected to three-point bending as in Figure 12.32, a load of 1000 N (225 lb_f) is to produce an elastic deflection of no more than 0.40 mm (0.016 in.) at the midpoint position.

Continuous fibers that are oriented parallel to the tube axis will be used; possible fiber materials are glass, and carbon in standard-, intermediate-, and high-modulus grades. The matrix material is to be an epoxy resin, and fiber volume fraction is 0.35.

(a) Decide which of the four fiber materials are possible candidates for this application, and for each candidate determine the required inside diameter consistent with the preceding criteria.

(b) For each candidate, determine the required cost, and on this basis, specify the fiber that would be the least expensive to use.

Elastic modulus, density, and cost data for the fiber and matrix materials are contained in Table 16.6.