Chapter 16 Composites

Bidirectional layers. 45 fiberglass. Provide torsional stiffness.

Top. ABS plastic having a low glass transition temperature. Used for containment and cosmetic purposes.

Unidirectional layers. 0 (and some 90) fiberglass. Provide longitudinal stiffness.

Side. ABS plastic having a low glass transition temperature. Containment and cosmetic.

Core wrap. Bidirectional layer of fiberglass. Acts as a torsion box and bonds outer layers to core.

Core. Polyurethane plastic. Acts as a filler.

Bidirectional layer. 45 fiberglass. Provides torsional stiffness.

Damping layer. Polyurethane. Improves chatter resistance.

Unidirectional layers. 0 (and some 90) fiberglass. Provide longitudinal stiffness.

Edge. Hardened steel. Facilitates turning by "cutting" into the snow.

Bidirectional layer. 45 fiberglass. Provides torsional stiffness.

Base. Compressed carbon (carbon particles embedded in a plastic matrix). Hard and abrasion resistant. Provides appropriate surface.
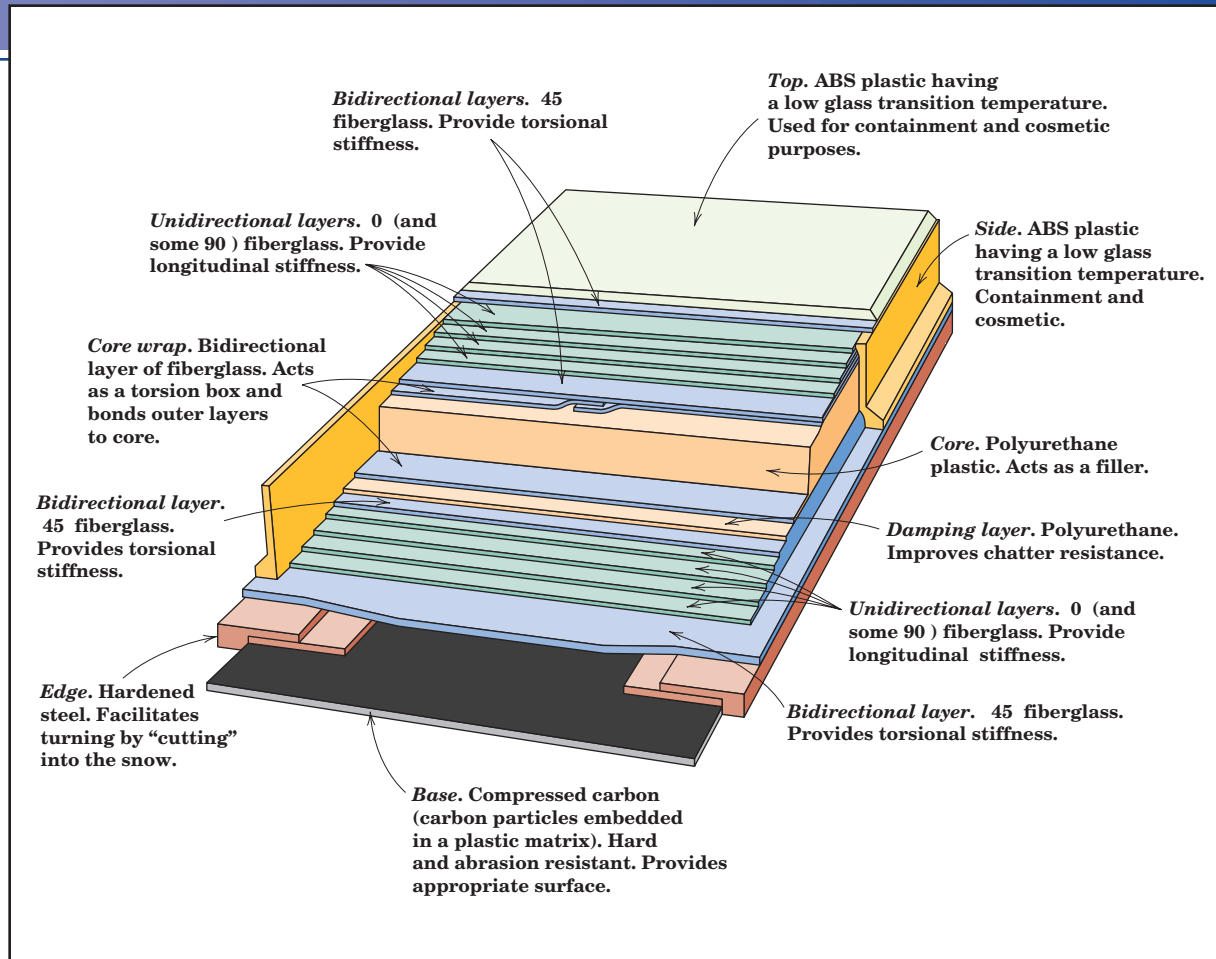
One relatively complex composite structure is the modern ski. In this illustration, a cross section of a high-performance snow ski, are shown the various components. The function of each component is noted, as well as the material that is used in its construction. (Courtesy of Evolution Ski Company, Salt Lake City, Utah.)

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 con-stituent phases, it is possible to design materials with property combinations that are better than those found in the 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 careful study of 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

Many of our modern technologies require materials with unusual combinations of properties that cannot be met by the conventional metal alloys, ceramics, and polymeric materials. This is especially true for materials that are needed for aerospace, underwater, and transportation applications. For example, aircraft engineers are increasingly searching for structural materials that have low densities, are strong, stiff, and abrasion and impact resistant, and are not easily corroded. This is a rather formidable combination of characteristics. Frequently, strong materials are relatively dense; also, increasing the strength or stiffness generally results in a decrease in impact strength.

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.

principle of combined action

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. There are also a number of composites that 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. Thus, most metallic alloys and many ceramics do not fit this definition because their multiple phases are formed as a consequence of natural phenomena.

In designing composite materials, scientists and engineers have ingeniously combined various metals, ceramics, and polymers to produce a new generation of
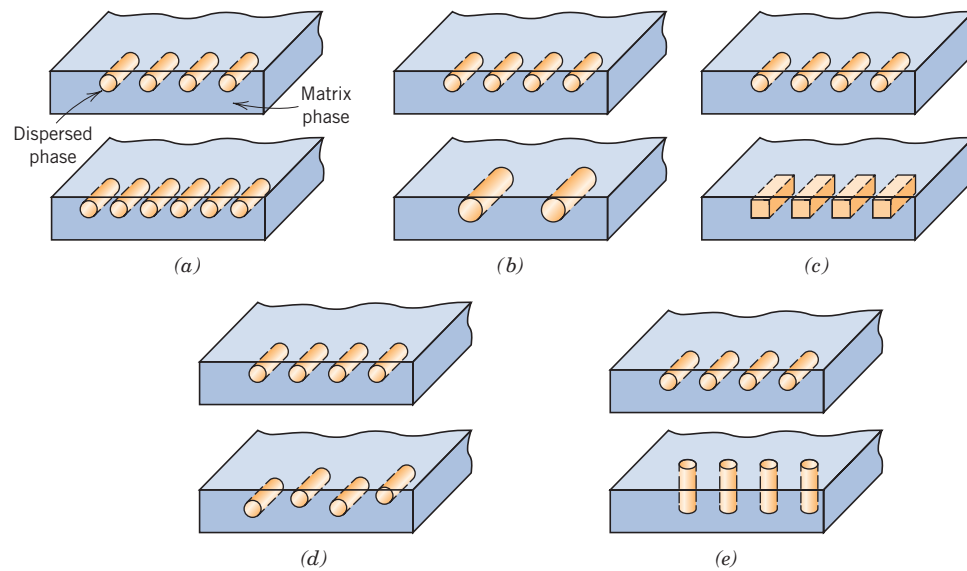
Figure 16.1 Schematic representations of the various geometrical and spatial characteristics of particles of the dispersed phase that may influence the properties of composites: (*a*) concentration, (*b*) size, (*c*) shape, (*d*) distribution, and (*e*) orientation. (From Richard A. Flinn and Paul K. Trojan, *Engineering Materials and Their Applications,* 4th edition. Copyright © 1990 by John Wiley & Sons, Inc. Adapted by permission of John Wiley & Sons, Inc.)

extraordinary materials. Most composites have been created to improve combinations of mechanical characteristics such as stiffness, toughness, and ambient and high-temperature strength.

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,

matrix phase

dispersed phase

Figure 16.2 A classification scheme for the various composite types discussed in this chapter.
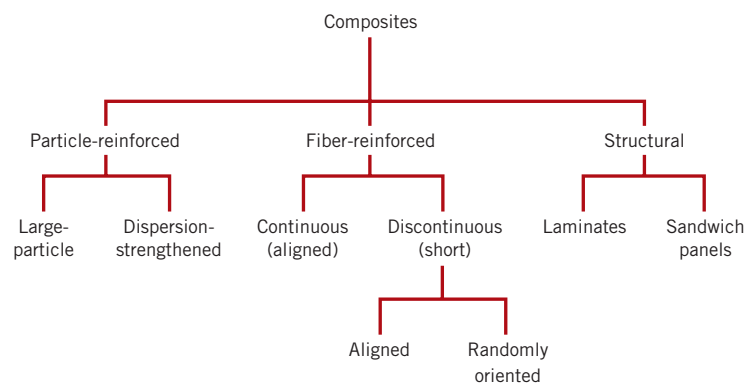
and structural composites; also, at least two subdivisions exist for each. The dispersed phase for particle-reinforced composites is equiaxed (i.e., particle dimensions are approximately the same in all directions); for fiber-reinforced composites, the dispersed phase has the geometry of a fiber (i.e., 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.

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 upon 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

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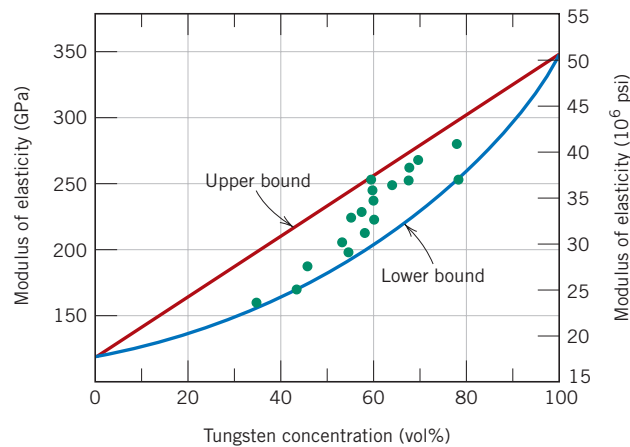
Figure 16.3   Modulus of elasticity versus volume percent tungsten for a composite of tungsten particles dispersed within a copper matrix. Upper and lower bounds are according to Equations 16.1 and 16.2; experimental data points are included. (From R. H. Krock, *ASTM Proceedings,* Vol. 63, 1963. Copyright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

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 utilized with all three material types (metals, polymers, and ceramics). The **cermets** are examples of ceramic–metal composites. The most common cermet is the 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 utilized 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 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 utilized, 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% of carbon black. For the carbon black to provide significant
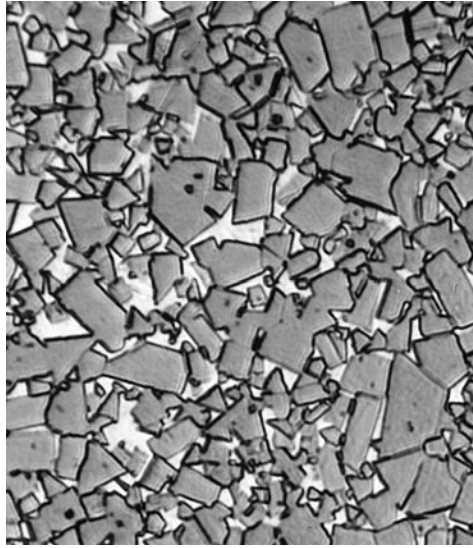
Figure 16.4 Photomicrograph of a WC–Co cemented carbide. Light areas are the cobalt matrix; dark regions, the particles of tungsten carbide. 100×. (Courtesy of Carboloy Systems Department, General Electric Company.)

reinforcement, the particle size must be extremely small, with diameters between 20 and 50 nm; also, the particles must be evenly distributed throughout the 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. Since 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
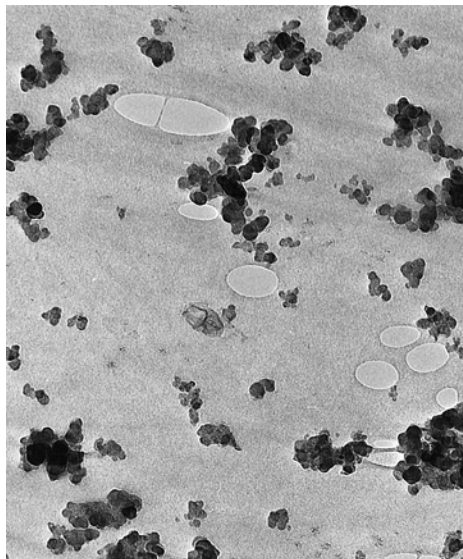
Figure 16.5 Electron micrograph showing the spherical reinforcing carbon black particles in a synthetic rubber tire tread compound. The areas resembling water marks are tiny air pockets in the rubber. 80,000×. (Courtesy of Goodyear Tire & Rubber Company.)

asphaltic cements, where 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 comprise 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 upon 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, there are some limitations and disadvantages. Like most ceramics, portland cement concrete is relatively weak and extremely brittle; its tensile strength is approximately 10 to 15 times smaller than 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, and polyethylene.

prestressed concrete

Care must be exercised in utilizing this type of reinforcement, since some fiber materials experience rapid deterioration when exposed to the cement environment.

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 utilizes 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 is also utilized in which stresses are applied after the concrete hardens; it 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 utilize 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, 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 16.7a results; that is, the maximum fiber 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 16.7b, a stress–axial position profile for $l > l_c$ when the applied stress is equal to the fiber strength. Figure 16.7c 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
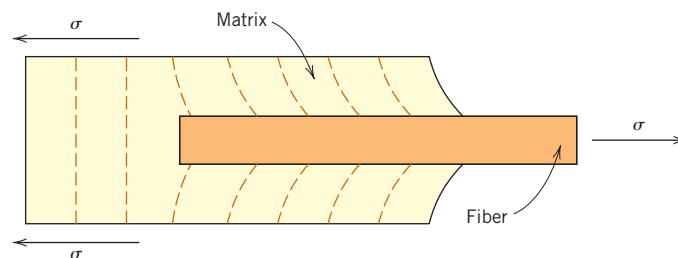

Figure 16.6 The deformation pattern in the matrix surrounding a fiber that is subjected to an applied tensile load.

586 • Chapter 16 / Composites

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^*.
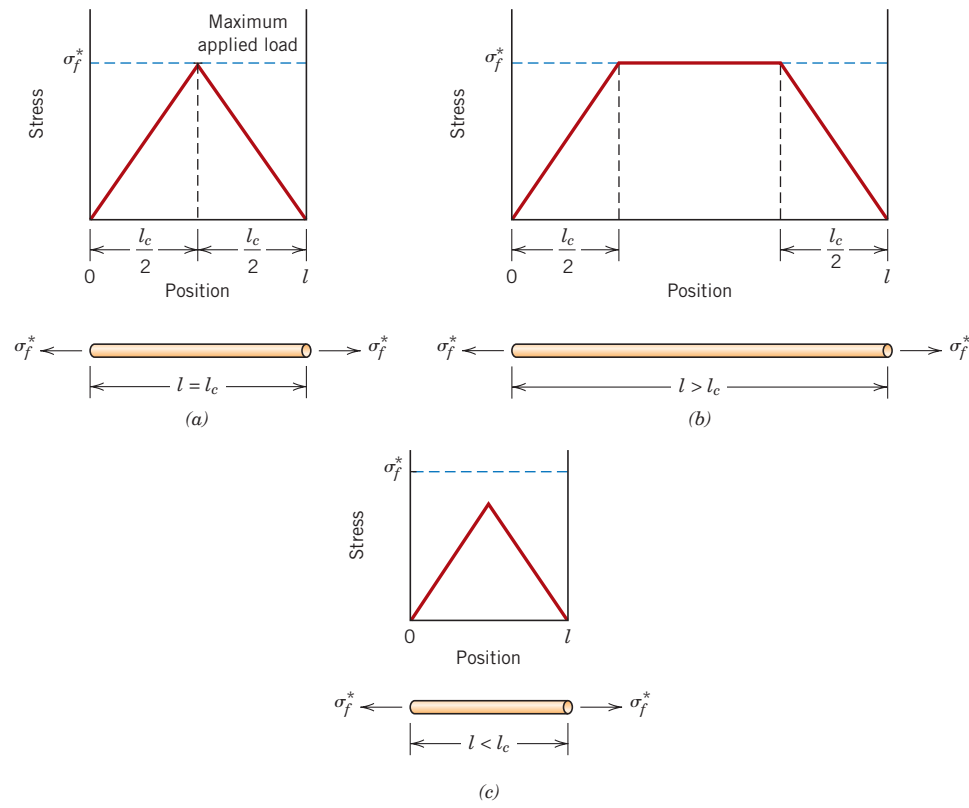
significantly less than l_c, the matrix deforms around the fiber such that there is virtually no stress transference and little reinforcement by the fiber. These are essentially the particulate composites as described above. To affect a significant improvement in strength of the composite, the fibers 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 to include the stress–strain behaviors of fiber and matrix phases, the phase volume fractions, and, in addition, 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
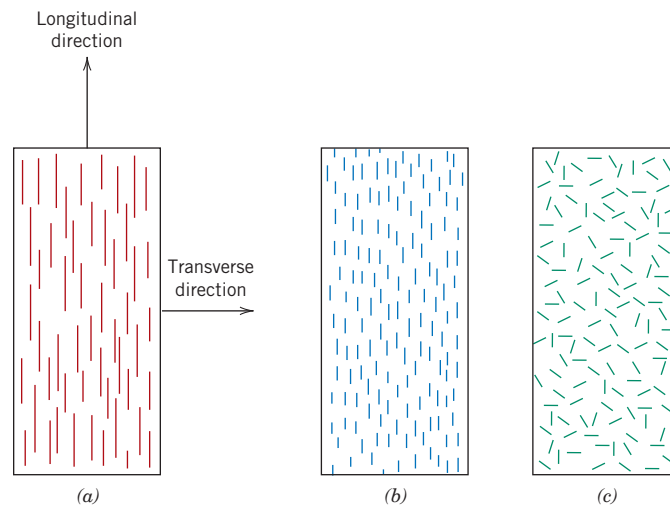
Figure 16.8   Schematic representations of (*a*) continuous and aligned, (*b*) discontinuous and aligned, and (*c*) discontinuous and randomly oriented fiber-reinforced composites.

longitudinal direction

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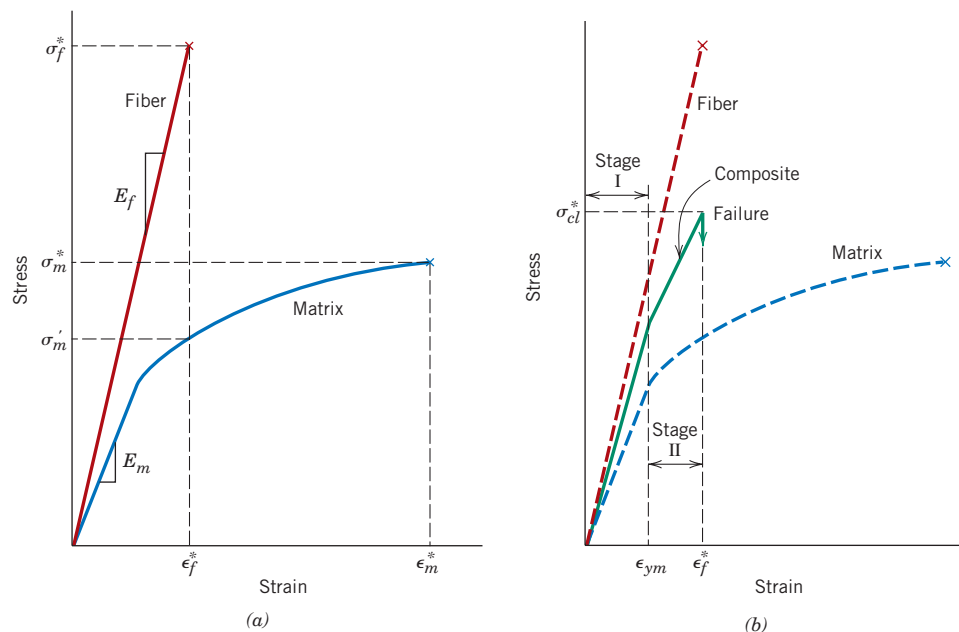
Figure 16.9   (*a*) Schematic stress–strain curves for brittle fiber and ductile matrix materials. Fracture stresses and strains for both materials are noted. (*b*) Schematic stress–strain curve for an aligned fiber-reinforced composite that is exposed to a uniaxial stress applied in the direction of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

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, since 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

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

16.5 Influence of Fiber Orientation and Concentration • 589

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

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

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 E's 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

$$E_{cl} = E_m V_m + E_f V_f \qquad (16.10a)$$

or

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

since 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 16.10*a* 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

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m} \qquad (16.11)$$

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:

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

(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

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

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

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

Substitution for F_f from the above yields

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

or

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

whereas

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

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:

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

and

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

Thus,

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

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

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.

16.5 **Influence of Fiber Orientation and Concentration** • **591**

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, since $\epsilon = \sigma/E$,

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

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

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

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

which reduces to

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

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.

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, 1996, p. 179.

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 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, the majority 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, in actual fact, the reinforcing effect of the fibers is a negative one. 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*

In the table below are listed 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

$$\sigma_{cd}^* = \sigma_f^* V_f \left(1 - \frac{l_c}{2l}\right) + \sigma_m'(1 - V_f) \qquad (16.18)$$

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

$$\sigma_{cd'}^* = \frac{l\tau_c}{d} V_f + \sigma_m'(1 - V_f) \qquad (16.19)$$

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 16.10*a* may be utilized, as follows:

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

$$E_{cd} = KE_f V_f + E_m V_m \qquad (16.20)$$

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

Property	Unreinforced	Fiber Reinforcement (vol%)		
		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 utilized. 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 utilized 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 utilized as a radial steel reinforcement in automobile tires, in filament-wound rocket casings, and in wire-wound high-pressure hoses.

596 • **Chapter 16** / **Composites**

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, since they are composed of crystalline graphite regions, and also of noncrystalline material and areas of crystal misalignment.

16.7 THE MATRIX PHASE

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 pull-out. 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[1] 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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[1] 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 inter-actions. 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 tem-peratures 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 utilizing 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 rein-forcement 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 tempera-tures; 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 since carbon is an ele-ment, and, as noted in Section 12.4, the stable form of crystalline carbon at ambi-ent conditions is graphite, having the structure represented in Figure 12.17. Carbon fibers are not totally crystalline, but are composed of both graphitic and noncrys-talline 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.
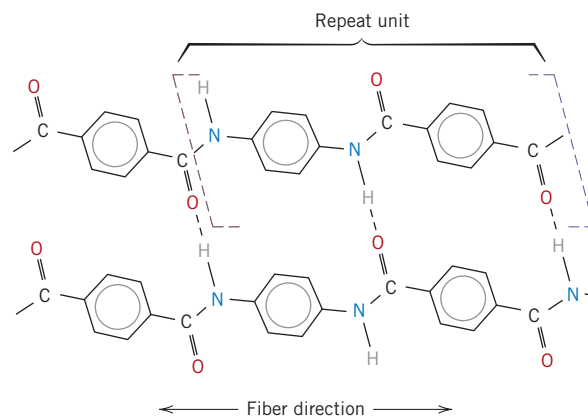
Table 16.5 **Properties of Continuous and Aligned Glass–, Carbon–, and Aramid–Fiber Reinforced Epoxy–Matrix Composites in Longitudinal and Transverse Directions. In All Cases the Fiber Volume Fraction Is 0.60**

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 utilized 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, since it normally softens, melts, or degrades at a much lower temperature than the fiber reinforcement.

The most widely utilized and least expensive polymer resins are the polyesters and vinyl esters;[2] 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 utilized 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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[2] The chemistry and typical properties of some of the matrix materials discussed in this section are included in Appendices B, D, and E.
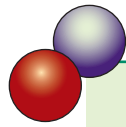
DESIGN EXAMPLE 16.1

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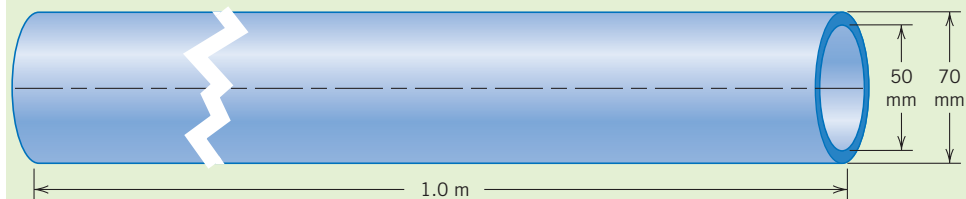
Elastic modulus, density, and cost data for the fiber and matrix materials are contained in Table 16.6.

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

50 mm 70 mm

1.0 m

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 ($/kg)
Glass fibers	72.5	2.58	2.50
Carbon fibers (standard modulus)	230	1.80	35.00
Carbon fibers (intermediate modulus)	285	1.80	70.00
Carbon fibers (high modulus)	400	1.80	175.00
Epoxy resin	2.4	1.14	9.00

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,

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

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

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

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:

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

In Table 16.7 is given a tabulation of 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. Here it may be noted that only the three carbon fiber types are possible candidates since 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 (cm³)*	*Fiber Mass (kg)*	*Fiber Cost ($)*	*Matrix Volume (cm³)*	*Matrix Mass (kg)*	*Matrix Cost ($)*	*Total Cost ($)*
Carbon (standard modulus)	552	0.994	34.80	1333	1.520	13.70	48.50
Carbon (intermediate modulus)	447	0.805	56.35	1438	1.639	14.75	71.10
Carbon (high modulus)	317	0.571	99.90	1568	1.788	16.10	116.00

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 utilized at higher service temperatures than their base metal counterparts; furthermore, the reinforcement may improve specific

stiffness, specific strength, abrasion resistance, creep resistance, thermal conductiv-
ity, 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, their (MMC) use is somewhat
restricted.

The superalloys, as well as alloys of aluminum, magnesium, titanium, and cop-
per, 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 car-
bon, 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. In Table 16.9 are presented the properties of several common metal-matrix,
continuous and aligned fiber-reinforced composites.

Some matrix–reinforcement combinations are highly reactive at elevated tem-
peratures. 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 rela-
tively 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 prod-
ucts. 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 reinforce-
ment for the Space Shuttle Orbiter, and continuous graphite fibers for the Hubble
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 MPa$\sqrt{m}$ (0.9 and 4.5 ksi$\sqrt{in.}$), Table 8.1 and Table B.5, Appendix B. By way of contrast, K_{Ic} values for most metals are much higher (15 to greater than 150 MPa$\sqrt{m}$ [14 to > 140 ksi$\sqrt{in.}$])

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 MPa$\sqrt{m}$ (5.5 and 18 ksi$\sqrt{in.}$).

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 utilized 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–$ZrCaO_3$ phase diagram, 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 utilization 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 pull-out 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.
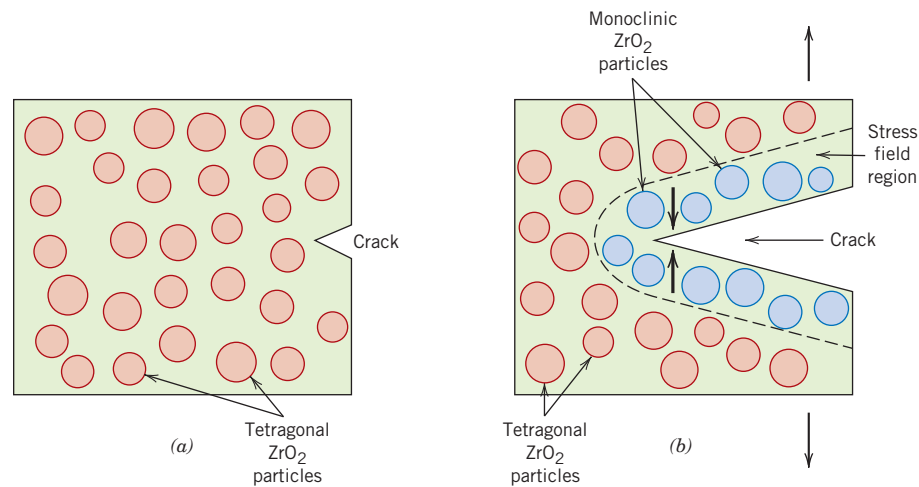
whisker-reinforced aluminas are being utilized as cutting tool inserts for machining hard metal alloys; tool lives for these materials are greater than for cemented carbides (Section 16.2).

16.11 CARBON–CARBON COMPOSITES

carbon–carbon composite

One of the most advanced and promising engineering material 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 utilized 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.

There are a number of ways in which the two different fibers may be combined, 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 (i.e., rods, tubes, beams, etc.). With this technique,
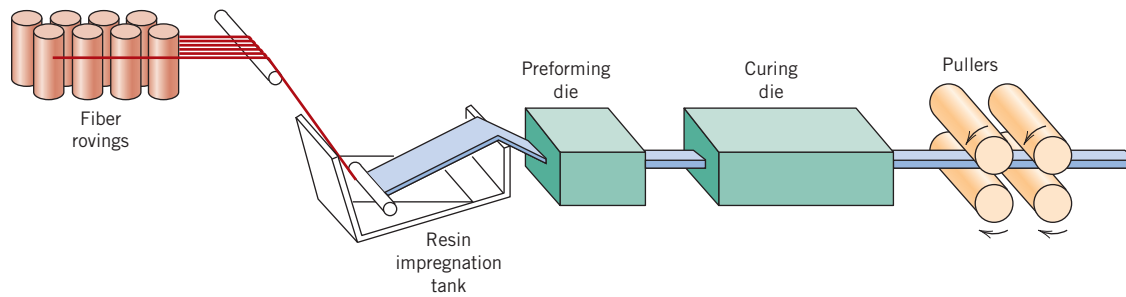
Figure 16.13 Schematic diagram showing the pultrusion process.

illustrated schematically in Figure 16.13, continuous fiber *rovings,* or *tows,*[3] 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, who 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.), 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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[3] 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.
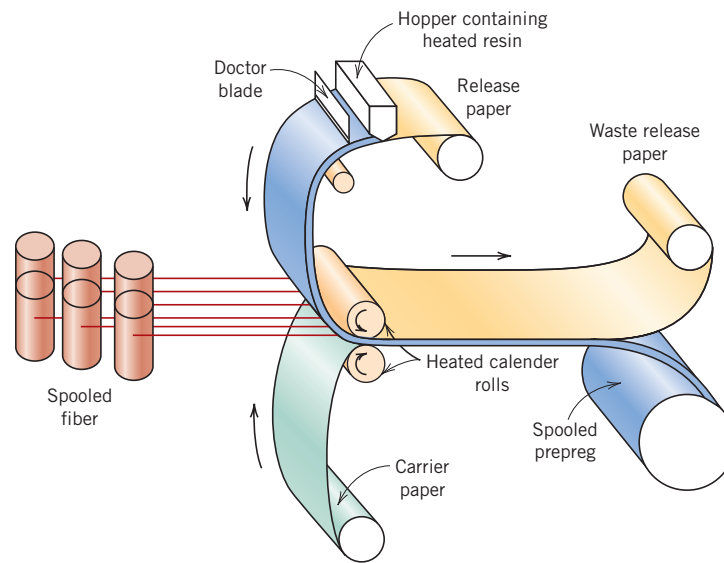
At room temperature the thermoset matrix undergoes curing reactions; therefore, the prepreg is stored at 0°C (32°F) or lower. Also, the time in use at room temperature (or "out-time") must be minimized. If properly handled, thermoset prepregs have a lifetime of at least six months and usually longer.

Both thermoplastic and thermosetting resins are utilized; 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 below), 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

Helical winding

Circumferential winding
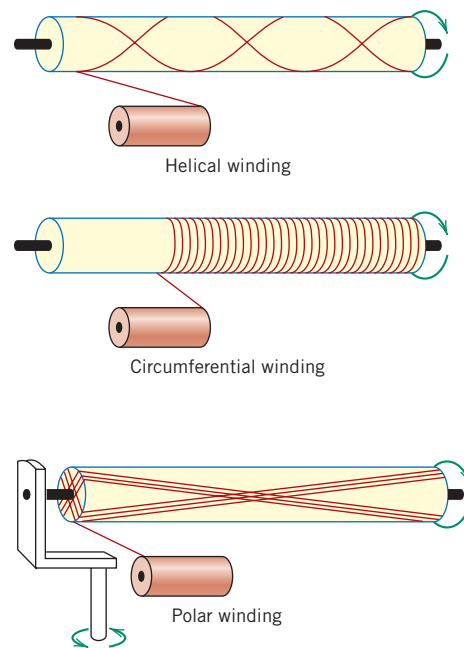
Polar winding

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.
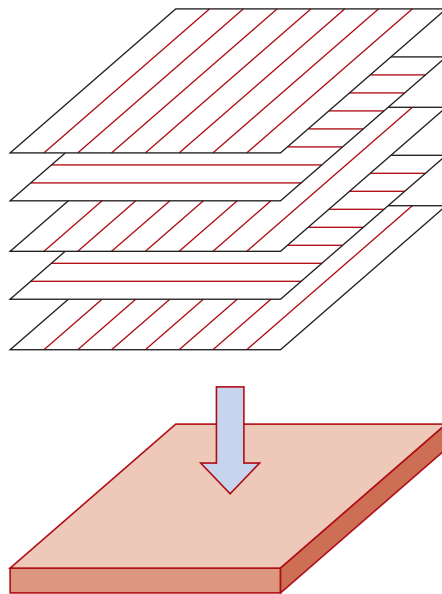
Structural Composites

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 light-weight 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 (see below).

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). (It should be noted that 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
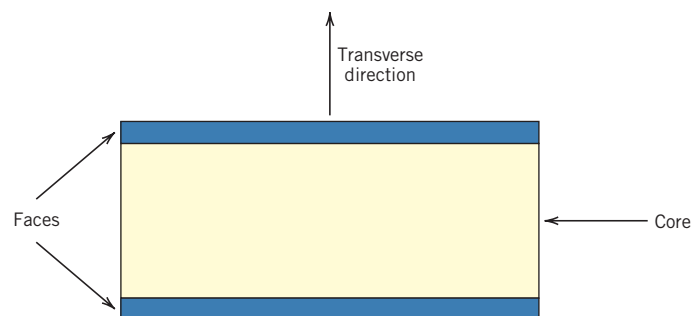
Figure 16.17 Schematic diagram showing the cross section of a sandwich panel.

Transverse direction

Faces
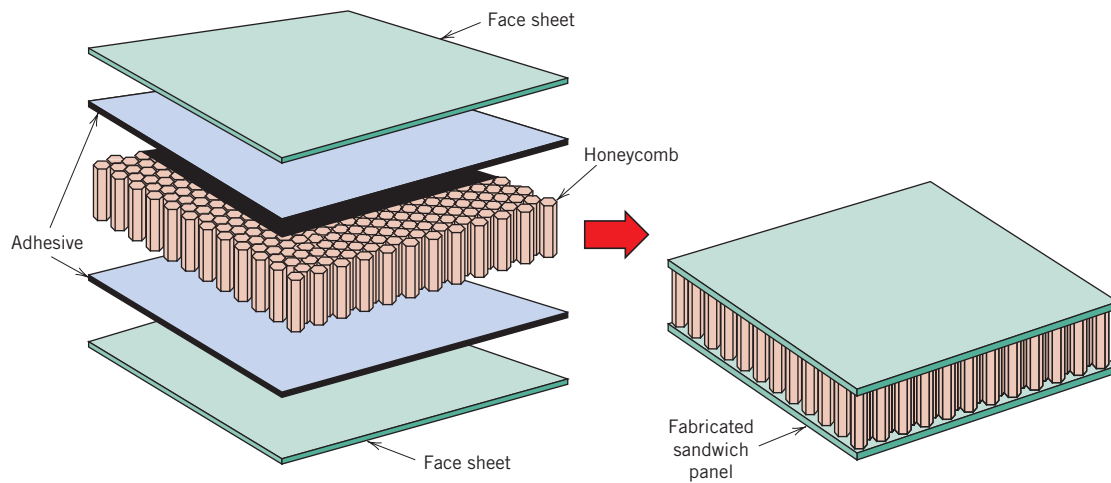
Core

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;[4] 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,[5] 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,

[4] 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.
[5] Vermiculite is one member of the layered silicates group that is discussed in Section 12.3.

the vermiculite platelets are *exfoliated*—that is, 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 there 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 multi-layer 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 since they (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).
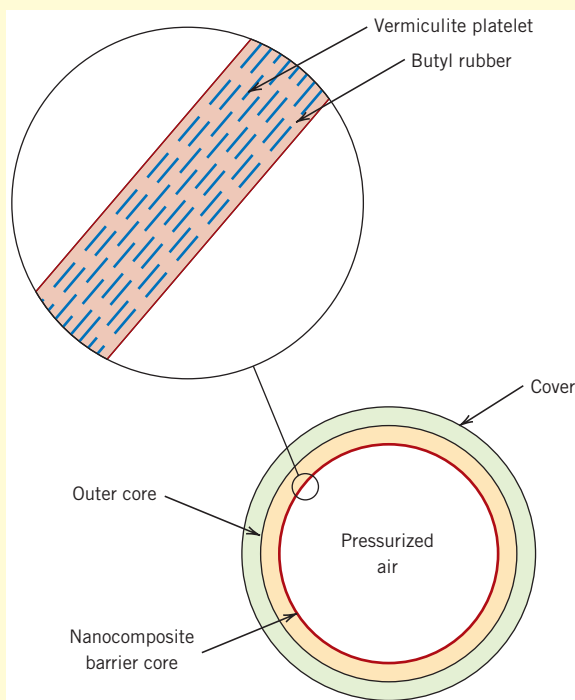
Figure 16.19 Schematic diagram showing the cross-section of a high-performance Double Core™ tennis ball. The inset drawing presents a detailed view of the nanocomposite coating that acts as a barrier to air permeation.

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 a desirable combination 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; that is, the strengthening mechanism involves interactions that may be treated on the atomic level. The particle size is normally greater with large-particle composites, whose mechanical characteristics are enhanced by reinforcement action.

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 this concrete may be improved by reinforcement methods (e.g., embedment into the fresh concrete of steel rods, wires, etc.). Additional reinforcement is possible by the imposition of residual compressive stresses using prestressing and posttensioning techniques.

Influence of Fiber Length
The Fiber Phase

Of the several composite types, the potential for reinforcement efficiency is greatest for those that are fiber reinforced. With these 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. On the basis of diameter, fiber reinforcements are classified as whiskers, fibers, or wires. Since reinforcement discontinues at the fiber extremities, reinforcement efficiency depends on fiber length. For each fiber–matrix combination, there exists some critical length; the length of continuous fibers greatly exceeds this critical value, whereas shorter fibers are discontinuous.

Influence of Fiber Orientation and Concentration

Fiber arrangement is also crucial relative to composite characteristics. The mechanical properties of continuous and aligned fiber composites are highly anisotropic. In the alignment direction, reinforcement and strength are a maximum; perpendicular to the alignment, they are a minimum. The stress–strain behavior for longitudinal loading was discussed. Composite rule-of-mixture expressions for the modulus in both longitudinal and transverse orientations were developed; in addition, an equation for longitudinal strength was also cited.

For short and discontinuous fibrous composites, the fibers may be either aligned or randomly oriented. Significant strengths and stiffnesses are possible for aligned short-fiber composites in the longitudinal direction. Despite some limitations on reinforcement efficiency, the properties of randomly oriented short-fiber composites are isotropic.

Polymer-Matrix Composites
Metal-Matrix Composites
Ceramic-Matrix Composites
Carbon–Carbon Composites
Hybrid Composites

Fibrous-reinforced composites are sometimes classified according to matrix type; within this scheme are three classifications: polymer-, metal-, and ceramic-matrix.

Polymer-matrix are the most common, which may be reinforced with glass, carbon, and aramid fibers. Service temperatures are higher for metal-matrix composites, which also utilize a variety of fiber and whisker types. The objective of many polymer- and metal-matrix composites is a high specific strength and/or specific modulus, which requires matrix materials having low densities. 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}. Other more advanced composites are carbon–carbon (carbon fibers embedded in a pyrolyzed carbon matrix) and the hybrids (containing at least two different fiber types).

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 utilized 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.

Laminar Composites
Sandwich Panels

Two general kinds of structural composites were discussed: the laminar composites and sandwich panels. The properties of 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.

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 cobalt may be improved by incorporating fine particles of tungsten carbide (WC). Given that the moduli of elasticity of these materials are, respectively, 200 GPa (30×10^6 psi) and 700 GPa (102×10^6 psi), plot modulus of elasticity versus the volume percent of WC in Co 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 90 vol% titanium carbide (TiC) particles in a nickel matrix. Assume thermal conductivities of 27 and 67 W/m-K for TiC and Ni, 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 0.70 and 0.30, 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 utilized 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 some glass fiber–epoxy matrix combination, the critical fiber length–fiber diameter ratio is 40. 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 $l = 50$ mm (2.0 in.) assuming that $x = 1.25$ mm (0.05 in.).

(b) What length is required for a 0.90 efficiency of reinforcement?

Influence of Fiber Orientation and Concentration

16.8 A continuous and aligned fiber-reinforced composite is to be produced consisting of 45 vol% aramid fibers and 55 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 35 MPa (5075 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 35 GPa (5×10^6 psi) and 5.17 GPa (7.5×10^5 psi), respectively? Why or why not? Assume that the elastic modulus of the epoxy is 3.4 GPa (4.93×10^5 psi).

16.10 For a continuous and oriented fiber-reinforced composite, the moduli of elasticity in the longitudinal and transverse directions are 33.1 and 3.66 GPa (4.8×10^6 and 5.3×10^5 psi), respectively. If the volume fraction of fibers is 0.30, 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 carbon fiber-reinforced nylon 6,6 composite, the fibers are to carry 97% 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 50 MPa (7250 psi).

	Modulus of Elasticity [GPa (psi)]	Tensile Strength [MPa (psi)]
Carbon fiber	260 (37×10^6)	4000 (580,000)
Nylon 6,6	2.8 (4.0×10^5)	76 (11,000)

16.13 Assume that the composite described in Problem 16.8 has a cross-sectional area of 480 mm^2 (0.75 in.^{2}) and is subjected to a longitudinal load of 53,400 N (12,000 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 fibrous reinforced composite having a cross-sectional area of 970 mm^2 (1.5 in.^{2}) is subjected to an external tensile load. If the stresses sustained by the fiber and matrix phases are 215 MPa (31,300 psi) and 5.38 MPa (780 psi), respectively, the force sustained by the fiber phase is 76,800 N (17,265 lb$_f$), and the total longitudinal composite strain is 1.56×10^{-3}, then 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 0.20 volume fraction of fibers, assuming the following: (1) an average fiber diameter of 6×10^{-3} mm (2.4×10^{-4} in.), (2) an average fiber length of 8.0 mm (0.31 in.), (3) a fiber fracture strength of 4.5 GPa (6.5×10^5 psi), (4) a fiber–matrix bond strength of 75 MPa (10,900 psi), (5) a matrix stress at composite failure of 6.0 MPa (870 psi),