

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. Name 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.

15.1 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.

Composites of sorts have already been discussed; these include multiphase metal alloys, ceramics, and polymers. For example, pearlitic steels (Section 10.19) have a microstructure consisting of alternating layers of α ferrite and cementite (Figure 10.29). 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

bone = collagen + apatite
soft + hard

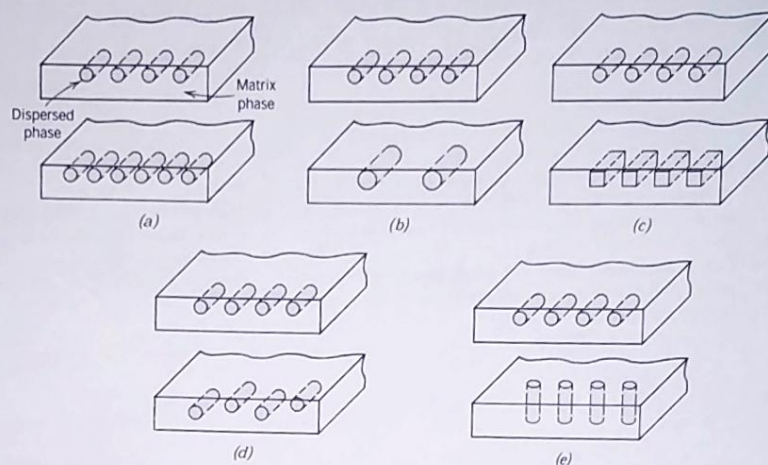


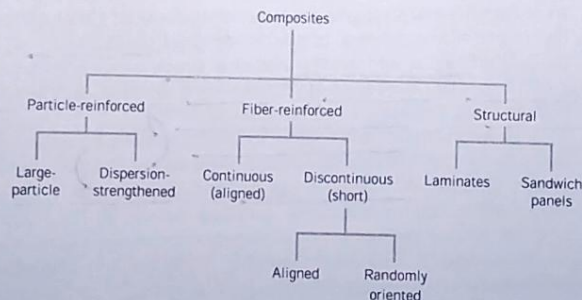
FIGURE 15.1 Schematic representations of the various geometrical and spatial characteristics of particles of the dispersed phase that may influence the properties of composites: (a) concentration, (b) size, (c) shape, (d) distribution, and (e) orientation. (From Richard A. Flinn and Paul K. Trojan, *Engineering 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 15.1.

One simple scheme for the classification of composite materials is shown in Figure 15.2, which consists of three main divisions—particle-reinforced, fiber-rein-

FIGURE 15.2 A classification scheme for the various composite types discussed in this chapter.



forced, 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

As noted in Figure 15.2, **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, having 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 11.11. 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.

15.2 LARGE-PARTICLE COMPOSITES

Some polymeric materials to which fillers have been added (Section 14.12) 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, being 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

$$E_c(u) = E_m V_m + E_p V_p \quad (15.1)$$

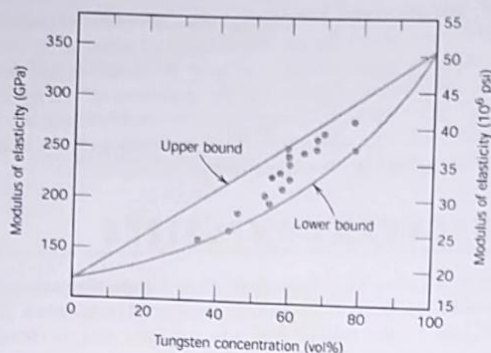


FIGURE 15.3 Modulus of elasticity versus volume percent tungsten for a composite of tungsten particles dispersed within a copper matrix. Upper and lower bounds are according to Equations 15.1 and 15.2; experimental data points are included. (From R. H. Krock, *ASTM Proceedings*, Vol. 63, 1963. Copyright ASTM. Reprinted with permission.)

and a lower bound, or limit,

$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m} \quad (15.2)$$

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 15.3 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 15.1 and 15.2 for fiber-reinforced composites are derived in Section 15.5.

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 15.4.

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

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. 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, having a low shrinkage and a low creep rate. Prestressed concretes, usually prefabricated, are commonly used for highway and railway bridges.

15.3 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 thorium (ThO_2) as finely dispersed particles; this material is known as thorium-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).

FIBER-REINFORCED COMPOSITES

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

15.4 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 15.6; 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

$$l_c = \frac{\sigma_f^* d}{2\tau_c} \quad (15.3)$$

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 15.7a results; that is, the maximum fiber load is achieved only at the axial center of the fiber. As fiber length l increases,

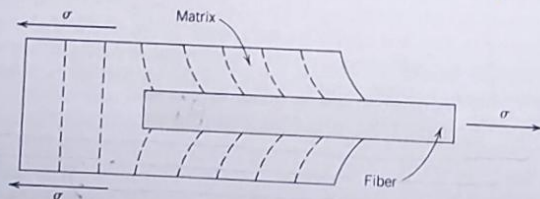


FIGURE 15.6 The deformation pattern in the matrix surrounding a fiber that is subjected to an applied tensile load.

max. load bearing
ability achieved at
if fiber

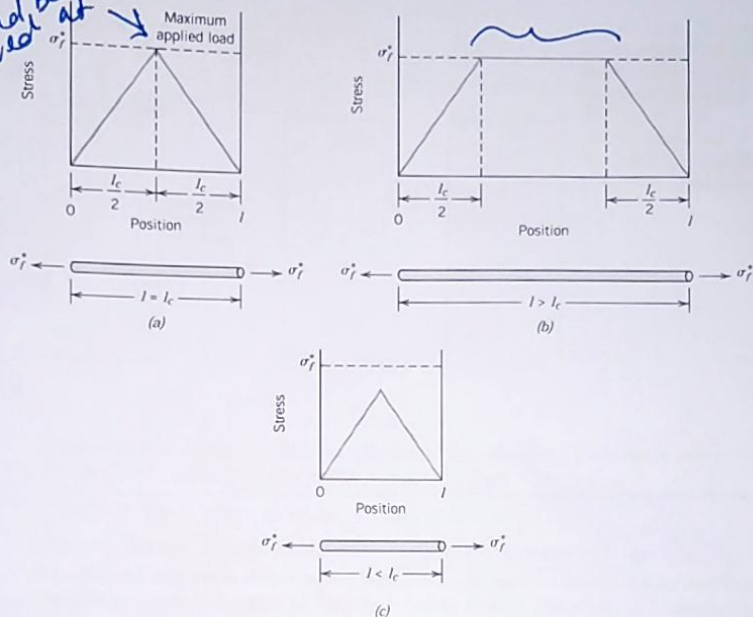


FIGURE 15.7 Stress-position profiles when fiber length l (a) is equal to the critical length l_c , (b) is greater than the critical length, and (c) is less than the critical length for a fiber-reinforced composite that is subjected to a tensile stress equal to the fiber tensile strength σ_f^* .

load bearing
capability
enhances
with $l < l_c$

the fiber reinforcement becomes more effective; this is demonstrated in Figure 15.7b, a stress-axial position profile for $l > l_c$ when the applied stress is equal to the fiber strength. Figure 15.7c 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 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.

15.5 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 15.8a), whereas discontinuous fibers may be aligned

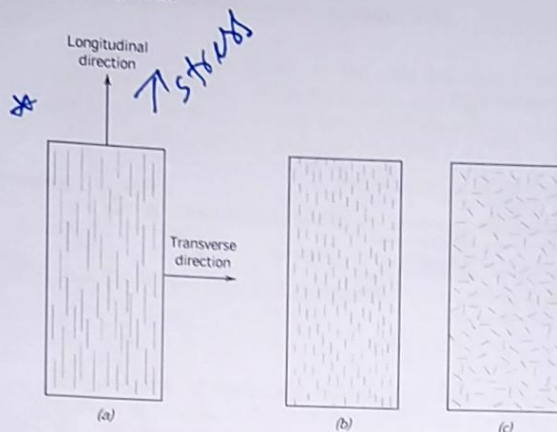


FIGURE 15.8 Schematic representations of (a) continuous and aligned, (b) discontinuous and aligned, and (c) discontinuous and randomly oriented fiber-reinforced composites.

(Figure 15.8b), randomly oriented (Figure 15.8c), 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 us first consider the stress-strain behavior for the situation wherein the stress is applied along the direction of alignment, the longitudinal direction, which direction is indicated in Figure 15.8a.

To begin, assume the stress versus strain behaviors for fiber and matrix phases that are represented schematically in Figure 15.9a; in this treatment we consider the fiber to be totally brittle and the matrix phase to be reasonably ductile. Also indicated in this figure are fracture strengths in tension for fiber and matrix, σ_f^* and σ_m^* , respectively, and their corresponding fracture strains, ϵ_f^* and ϵ_m^* ; furthermore, it is assumed that $\epsilon_m^* > \epsilon_f^*$, which is normally the case.

(A fiber-reinforced composite consisting of these fiber and matrix materials will exhibit the uniaxial stress-strain response illustrated in Figure 15.9b) the fiber and matrix behaviors from Figure 15.9a 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 15.9b) 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, which 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 15.9b. Composite failure is not catastrophic for a couple of reasons. First of all, not all fibers fracture at the same time, since there will always be considerable variations in the fracture

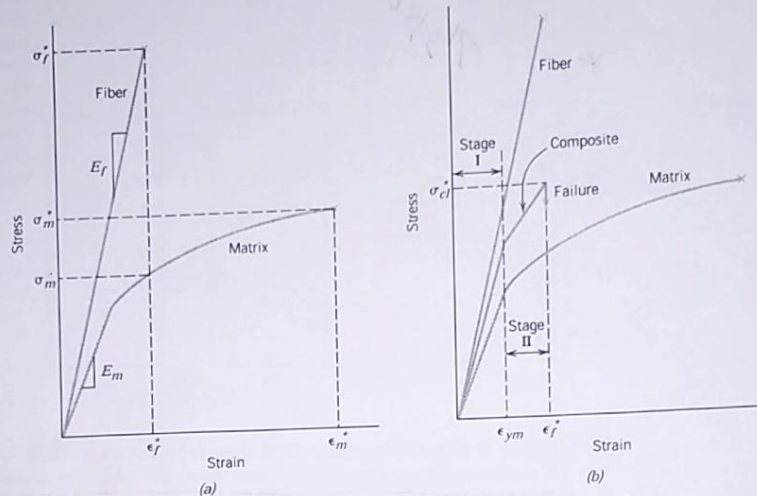


FIGURE 15.9 (a) Schematic stress-strain curves for brittle fiber and ductile matrix materials. Fracture stresses and strains for both materials are noted. (b) Schematic stress-strain curve for an aligned fiber-reinforced composite that is exposed to a uniaxial stress applied in the direction of alignment; curves for the fiber and matrix materials shown in part (a) are also superimposed.

strength of brittle fiber materials) (Section 9.6). In addition, even after fiber failure, the matrix is still intact inasmuch as $\epsilon_f^* < \epsilon_m^*$ (Figure 15.9a). 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 direction. First of all, 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 loads carried by the matrix phase F_m and the fiber phase F_f , or

$$\text{Load } F_c = F_m + F_f \quad (15.4)$$

From the definition of stress, Equation 7.1, $F = \sigma A$; 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 15.4 yields

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f \quad (15.5)$$

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

$$\sigma_c = \sigma_m \frac{A_m}{A_c} + \sigma_f \frac{A_f}{A_c} \quad (15.6)$$

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 15.6 now becomes

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \quad (15.7)$$

The previous assumption of an isostrain state means that

$$\epsilon_c = \epsilon_m = \epsilon_f \quad (15.8)$$

and when each term in Equation 15.7 is divided by its respective strain,

$$\frac{\sigma_c}{\epsilon_c} = \frac{\sigma_m}{\epsilon_m} V_m + \frac{\sigma_f}{\epsilon_f} V_f \quad (15.9)$$

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 15.9 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

$$E_{cl} = E_m V_m + E_f V_f \quad (15.10a)$$

or

$$E_{cl} = E_m (1 - V_f) + E_f V_f \quad (15.10b)$$

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 15.10a is the fiber analogue of Equation 15.1, 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

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m} \quad (15.11)$$

The demonstration is left as a homework problem.

EXAMPLE PROBLEM 15.1

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 mm² (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.

isostrain

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 15.8 in the previous development.

Elastic Behavior—Transverse Loading

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 15.8. For this situation the stress σ to which the composite as well as both phases are exposed is the same, or

$$\sigma_c = \sigma_m = \sigma_f = \sigma \quad (15.12)$$

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

$$\epsilon_c = \epsilon_m V_m + \epsilon_f V_f \quad (15.13)$$

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

$$\frac{\sigma}{E_c} = \frac{\sigma}{E_m} V_m + \frac{\sigma}{E_f} V_f \quad (15.14)$$

where E_c is the modulus of elasticity in the transverse direction. Now, dividing through by σ yields

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \quad (15.15)$$

which reduces to

$$E_c = \frac{E_m E_f}{V_m E_f + V_f E_m} = \frac{E_m E_f}{(1 - V_f) E_f + V_f E_m} \quad (15.16)$$

Equation 15.16 is analogous to the lower-bound expression for particulate composites, Equation 15.2.

EXAMPLE PROBLEM 15.2

Compute the elastic modulus of the composite material described in Example Problem 15.1, but assume that the stress is applied perpendicular to the direction of fiber alignment.

SOLUTION

According to Equation 15.16,

$$\begin{aligned} E_c &= \frac{(3.4 \text{ GPa})(69 \text{ GPa})}{(0.6)(69 \text{ GPa}) + (0.4)(3.4 \text{ GPa})} \\ &= 5.5 \text{ GPa} \quad (0.81 \times 10^6 \text{ psi}) \end{aligned}$$