11

COMPOSITES

The need for materials with properties not found in conventional materials, combined with advances in technology, have resulted in combining two or more materials to form what are called composite materials. These materials usually combine the best properties of their constituents and frequently exhibit qualities that do not even exist in their constituents. Strength, stiffness, specific weight, fracture resistance, corrosion resistance, wear resistance, attractiveness, fatigue life, temperature susceptibility, thermal insulation, thermal conductivity, and acoustical insulation can all be improved by composite materials. Of course, not all these properties are improved in the same composite, but typically a few of these properties are improved. For example, materials needed to build aircraft and space vehicles must be light, strong, and stiff and must exhibit high resistance to abrasion, impact, and corrosion. An example of a composite material that is very useful for civil engineers is fiberglass, which is strong, stiff, and corrosion resistant and can be used to make concrete reinforcing rebars to replace corrosive steel rebars. These combinations of properties are formidable and typically cannot be found in a conventional material.

Composite materials have been used throughout history, with differing levels of sophistication. For example, straw was used to strengthen the mud bricks in ancient civilizations. Swords and armor were constructed with layers of different materials to obtain unique properties. Portland cement concrete, which combines paste and aggregate with different properties to form a strong and durable construction material, has been used for many years. In recent years, fiber-reinforced concrete has been used as a building material that is strong in both tension and compression. The automobile industry has been using composite metals to build lightweight vehicles that are strong and impact resistant. Recently, a new generation of composites has been developed, such as fiber-reinforced and particle-reinforced plastics, that has revolutionized the material industry and opened new horizons for civil and construction engineering applications.

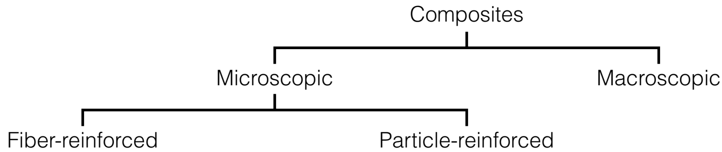


FIGURE 11.1 A classification scheme of composite materials.

Although several definitions of composites exist, it is generally accepted that a composite is a material that has two or more distinct constituent materials or phases. The constituents of a composite typically have significantly different physical properties, and thus the properties of the composite are noticeably different from those of the constituents. This definition eliminates many multiphase materials that do not have distinct properties, such as many alloys with components that are similar.

There are a number of naturally formed composites, such as wood, which consists of cellulose fibers and lignin, and bone, which consists of protein collagen and mineral appetite. However, in this chapter we discuss artificially made composites only.

Composite materials can be classified as *microscopic* or *macroscopic,* as shown in Figure 11.1. The distinction between microscopic and macroscopic depends on the type of properties being considered. This distinction seems arbitrary, but normally microscopic composites include *fibers* or *particles* in sizes up to a few hundred microns. On the other hand, macroscopic composites could have constituents of much larger size, such as aggregate particles and rebars in concrete.

11.1 Microscopic Composites

Many microscopic composite materials consist of two constituent phases: a continuous phase, or *matrix,* and the *dispersed phase* or *reinforcing phase,* which is surrounded by the matrix. In most cases, the dispersed phase is harder and stiffer than the matrix. The properties of the composite depend on the properties of both component phases, their relative properties, and the geometry of the dispersed phase, such as the particle shape, size, distribution, and orientation.

As indicated in Figure 11.1, microscopic composites fall into two basic classes: *fiber-reinforced* and *particle-reinforced*. This classification is based on the shape of the dispersed phase. Figure 11.2 shows composites with continuously aligned fibers, random fibers, and random particles. The mechanism of strengthening varies for different classes and for different sizes and orientations of the dispersed shape.

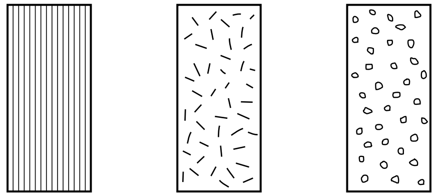


FIGURE 11.2 Schematic of microscopic composites: (a) aligned fibers, (b) random fibers, and (c) random particles.

11.1.1 Fiber-Reinforced Composites

Fiber-reinforced microscopic composites include fibers dispersed in a matrix such as metal or polymer. Fibers have a very high strength-to-diameter ratio, with near crystal-sized diameters. Because of the very small diameter of the fibers they are much stronger than the bulk material. For example, a glass plate fractures at stresses of 10 kPa to 20 kPa, yet glass fibers have strengths of 3 MPa to 5 MPa or more. Fibers are much stronger than the bulk form, because they have fewer internal defects.

Fibers can be classified on the basis of their diameter and character as wiskers, fibers, and wires. Wiskers are very thin single crystals, have extremely large length-to-diameter ratios, have a high degree of crystalline perfection, and, consequently are extremely strong. Fibers have larger diameters than wiskers, while wires are even larger. Wiskers are not commonly used for reinforcement, because of their high cost, poor bond with many common matrix materials, and the difficulty of incorporating them into the matrix. Table 11.1 shows some materials used to manufacture fibers and their strength characteristics.

Fibers are manufactured from many materials, such as glass, carbon and graphite, polymer, boron, ceramic, and silicon carbide (Mallick 1993). Because of their low cost and high strength, glass fibers are the most common of all reinforcing fibers for polymer matrix composites. Glass fibers are

TABLE 11.1 Materials and Mechanical Properties of Some Fibers (Callister, 2003)

Material	Specific Gravity	Tensile Strength, GPa (psi $\times 10^6$)	Elastic Modulus, GPa (psi $\times 10^6$)
Aramid (Kevlar)	1.4	3.5 (0.5)	130 (19)
E-Glass	2.5	3.5 (0.5)	72 (10.5)
Graphite	1.4	1.7 (0.25)	255 (37)
Nylon 6,6	1.1	1.0 (0.14)	4.8 (0.7)
Asbestos	2.5	1.4 (0.2)	172 (25)

FIGURE 11.3 Common glass fibers (veil, roving, and mat). Photo courtesy of Creative Pultrusions, Inc.

commercially available in several forms suitable for different applications. Common glass fibers include veils, rovings (continuous fibers), and mats (Figure 11.3). A strand consists of about 30 or 40 fibers twisted together to form a ropelike length.

A common fiber-reinforced composite is fiberglass. Fiberglass is simply a composite consisting of glass fibers, either continuous or discontinuous, contained within a plastic matrix. Typical fiberglass applications include aircraft, automobiles, boats, storage containers, water tanks, sporting equipment, and flooring.

11.1.2 Particle-Reinforced Composites

Particle-reinforced composites consist of particles dispersed in a matrix phase. The strengthening mechanism of particle-reinforced composites varies with the size of the reinforcing particles. When the size of the particles is about 0.01 micron to 0.1 micron, the matrix bears most of the applied load, whereas the small dispersed particles hinder or impede the motion of dislocations. An example of dispersed-reinforced composite is thoria-dispersed nickel, in which about 3% of thoria (ThO_2) is finely dispersed in a nickel alloy to increase its high-temperature strength. On the other hand, when the particles are larger than 1 micron, particles act as fillers to improve the properties of the matrix phase and/or to replace some of its volume, since the filler is typically less expensive. Here, the matrix retains movement in the vicinity of the particle. Thus, the applied load is shared by the matrix and dispersed phases. The stronger the bond between the dispersed particles and the matrix, the larger is the reinforcing effect. An example of particle reinforcing is adding fillers to polymers to improve tensile and compressive strengths, abrasion resistance, toughness, dimensional and thermal properties, and other properties.

11.1.3 Matrix Phase

Typically, the matrix used in most microscopic composites is polymer (plastic) or metal. The matrix binds the dispersed materials (particles or fibers) together, transfers loads to them, and protects them against environmental attack and damage due to handling. Polymers have the advantages of low cost, easy processibility, good chemical resistance, and low specific gravity. The shortcomings of polymers are their low strength, low modulus, low operating temperatures, and low resistance to prolonged exposure to ultraviolet light and some solvents. On the other hand, metals have high strength, high modulus, high toughness and impact resistance, relative insensitivity to temperature changes, and high resistance to high temperatures and other severe environmental conditions. However, metals have high density and high processing temperatures, due to their high melting points. Metals also may react with particles and fibers and they are vulnerable to attack by corrosion (Agarwal and Broutman 1990). The metals most commonly used as the matrix phase in composites are aluminum and titanium alloys.

11.1.4 Fabrication

Fabrication of microscopic composites often combines the production of the material during the fabrication of the composite. The composite is formed by combining the matrix and dispersed material. Several methods have been used to fabricate the composites. The selection of the fabrication process typically is based on the chemical nature of the matrix and of the dispersed phases and on the temperature required to form, melt, or cure the matrix. Figure 11.4 illustrates fabrication of structural shape fiber-reinforced composites by using the pultrusion process. Pultrusion is an automated process for manufacturing fiber-reinforced composite materials into continuous, constant-cross-section profiles.

11.1.5 Civil Engineering Applications

Microscopic composites have been used in many civil and construction engineering applications in the last several decades. In fact, composite materials

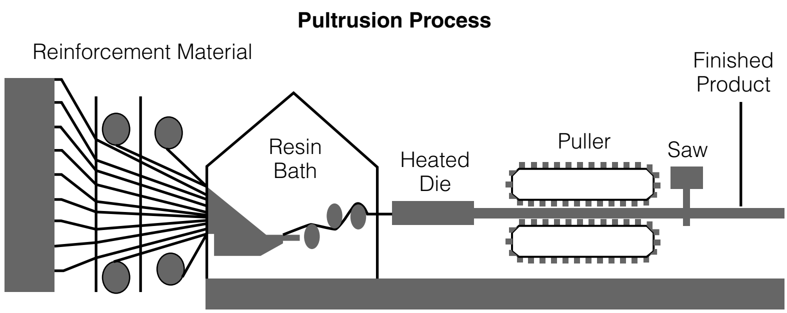


FIGURE 11.4 Pultrusion scheme used in fabricating structural shape fiber-reinforced composites. Courtesy of Creative Pultrusions, Inc.

compete with, and in many cases are preferred over, conventional building materials. Composites are used by civil engineers as structural shapes in buildings and other structures and can replace steel and aluminum structural shapes (Figure 11.5). Table 11.2 provides an example of physical properties of fiber-reinforced composite round rods and bars.

Fiber-reinforced polymer (fiberglass) rebars can also be used for concrete reinforcement instead of steel rebars. Composites have been used for tanks, industrial flooring, trusses and joists, walkways and platforms, waste treatment plants, handrailings, plastic pipes, light poles, door and window panels and frames, and electrical enclosures. Composites can also be used to strengthen and wrap columns and bridge supports that are partially damaged by earthquakes and other environmental factors (Grace 2002) (See Figures 11.6 – 11.9).

Fiber-reinforced concrete is another composite material that has been used by civil engineers in various structural applications. Different types of fibers, such as separate fibers, chopped-strands, or rovings, can be used to reinforce the concrete. If separate fibers or chopped-strands are used, they are mixed with the fresh concrete in a random order. In such a case, fibers hinder or impede the progression of cracks in concrete. Figure 11.10 shows a scanning electron micrograph of concrete mortar mixed with about 3-mm-long carbon fibers at a volume fraction of 12%. Fiber rovings, on the other hand, are placed in the direction in which the tension is applied in the structural member. In this case, fibers carry the tensile stresses. In general, fibers increase the tensile and flexure strength of concrete so that a more efficient structural member can be designed. Table 11.3 shows typical ranges of physical properties of glass fiber-reinforced concrete at 28 days. Research has shown that glass fiber-reinforced concrete offers two to three times the flexural strength of unreinforced concrete. Moreover, the material under increasing load does not fail abruptly, but yields gradually. This gradual yielding occurs because

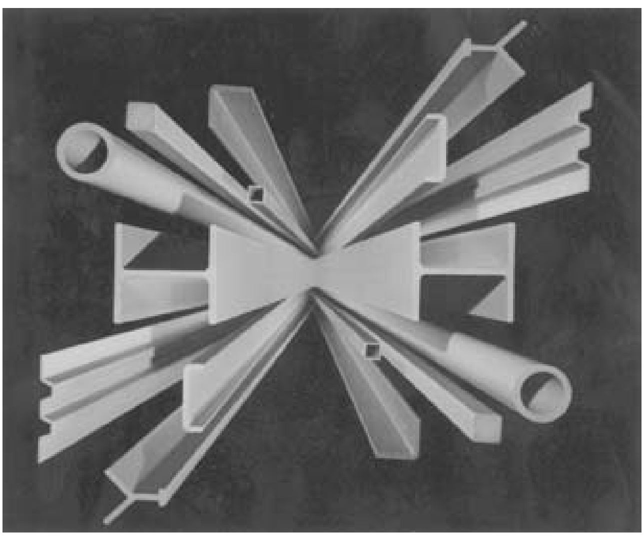


FIGURE 11.5 Structural shapes made of fiberglass composites. Courtesy of Creative Pultrusions, Inc.

TABLE 11.2 An Example of Physical Properties of Fiber-Reinforced Composite Round Rods and Bars (Creative Pultrusions, Inc., 1997)

Property	Value
Tensile strength (ASTM D638)	830 MPa (120×10^3 psi)
Tensile modulus of elasticity (ASTM D638)	45 GPa (6.5×10^6 psi)
Flexural strength (ASTM D790)	830 MPa (120×10^3 psi)
Compressive strength (ASTM D695)	480 MPa (70×10^3 psi)
Izod impact strength (ASTM D256)	2.1 kJ/m (40 ft-lb/in.)
Barcol hardness (ASTM D2583)	50
Water absorption (ASTM D570)	0.25% (maximum)
Specific gravity (ASTM D792)	2.0
Coefficient of thermal expansion (ASTM D696)	5.2×10^{-6} m/m/°C (9.4×10^{-6} in./in./°F)

FIGURE 11.6 Wrapping an old structure with glass fiber-reinforced polymer (FRP) composite (Wabash Avenue pier, Baltimore, MD).

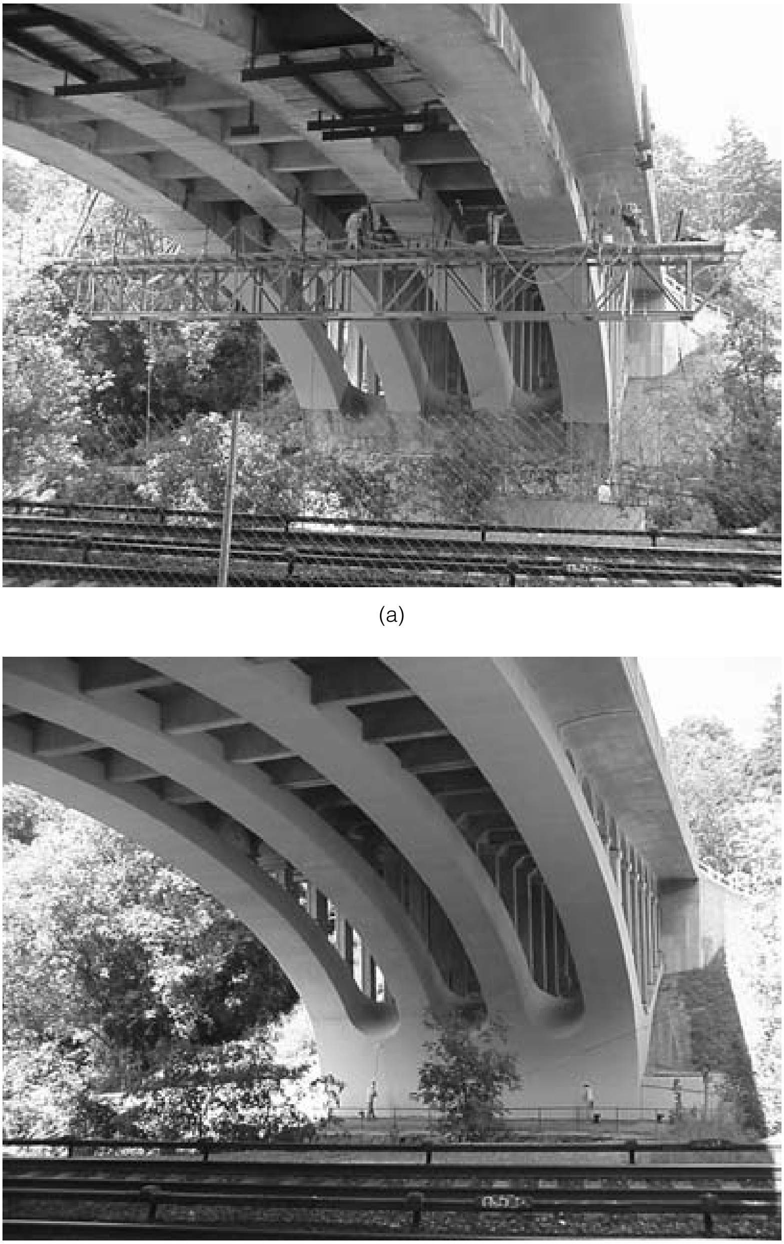
FIGURE 11.7 Wrapping columns of a bridge with FRP composites.

fibers are stronger than the matrix and, therefore, arrests cracks. Therefore, instead of a worsening of the first crack that occurs in the concrete, more cracks are developed elsewhere, and failure finally occurs when fibers pull out or break (Neal 1977).

Entrained air in concrete can also be considered as a component in a microscopic composite material. Entrained air increases the durability of concrete since it releases internal stresses due to freezing of water within the concrete. For the same water-to-cement ratio, however, air bubbles reduce the concrete strength by about 20%. Since entrained air also improves the workability of fresh concrete, the water-to-cement ratio can be reduced to compensate for some of the strength reduction.

11.2 Macroscopic Composites

Macroscopic composites are used in many engineering applications. Because macroscopic composites are relatively large, how the load is carried and how the properties of the composite components are improved vary from one composite to another. Common macroscopic composites used by civil and construction engineers include plain portland cement concrete, steel-reinforced concrete, asphalt concrete, and engineered wood such as glued–laminated timber, and structural strand board.



(a)

(b)

FIGURE 11.8 Woodland viaduct over metro north railroad in Weschester County, NY: (a) reinforcing with FRP composite and (b) finished structure.

FIGURE 11.9 Strengthening a concrete bridge with FRP bars.

FIGURE 11.10 Scanning electron micrograph of concrete mortar mixed with carbon fibers.

TABLE 11.3 Typical Ranges of Physical Properties at 28 Days of Glass Fiber Reinforced Concrete (Neal, 1977)

Property	Value
Flexural strength	21–32 MPa (3.0–4.6 ksi)
Tensile strength	7–11 MPa (1.0–1.6 ksi)
Compressive strength	50–79 MPa (7.2–11.4 ksi)
Impact strength	10–25 kN/m (57–143 in. lb/in.^{2})
Elastic modulus	10.5–20.5 GPa (1.5–3.0 × 10^6 psi)
Density	1.70–2.10 Mg/m^3 (105–130 lb/ft^3

11.2.1 Plain Portland Cement Concrete

Plain portland cement concrete is a composite material consisting of cement paste and aggregate particles with different physical and mechanical properties, as discussed in Chapter 7 (Figure 11.11). Aggregate particles in concrete act as a filler material, since it is cheaper than the portland cement. In addition, since cement paste shrinks as it cures, aggregate increases the volume stability of the concrete. When the concrete structure is loaded, both cement paste and aggregate share the load. Both the strength of aggregate particles and the bond between the aggregate and cement paste play an important role in determining the strength of the concrete composite, which is limited by the weaker of the two. The bond between cement paste and aggregate is affected by roughness and absorption of the aggregate particles, as well as by other physical and chemical properties of aggregate.

11.2.2 Reinforced Portland Cement Concrete

Steel-reinforced concrete can be viewed as a composite material, consisting of plain concrete and steel rebars, as shown in Figure 11.12. Since concrete has a very low tensile strength, which is typically ignored in designing concrete structures, steel rebars are usually placed in areas within the structure

FIGURE 11.11 Cross section of portland cement concrete showing cement paste and aggregate particles.

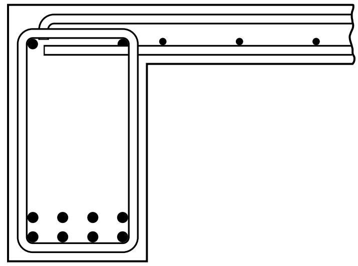


FIGURE 11.12 An example of steel-reinforced concrete beam and slab details.

that are subjected to tension. When the concrete structure is loaded, the concrete carries compressive stresses and steel carries tensile stresses. In such cases steel allows concrete to be used as structural members carrying tension. Steel rebars are also used in areas subjected to compression, such as columns, to share the load support. In such cases, steel reduces the required cross-sectional area of the compressive member, since the compressive strength of steel is larger than that of concrete. Steel reinforcing is also used in prestressed concrete, where the reinforcement is prestressed under tension so that the concrete remains under compression even when it is externally loaded. In such cases, a smaller cross-sectional area of the concrete member is required. Steel rebars can also be used to control cracking in concrete due to temperature change. For example, concrete pavement is sometimes reinforced by placing longitudinal and transverse steel bars at the midheight of the concrete slab. In this case, when the concrete shrinks due to reduction in ambient temperature, many cracks will develop; these cracks are uniformly distributed within the pavement section, but each crack will be tight. Typically, tight cracks are not harmful to concrete pavement, since they transfer the load from one side of the crack to the other by interlocking. In all applications of steel reinforced concrete, the bond between the rebars and the concrete is important in order to allow the composite to work as one unit. Therefore, bars have a deformed surface to prevent slipping between steel and concrete.

11.2.3 Asphalt Concrete

Asphalt concrete used in pavements is another composite material. It consists of two materials with distinct properties, as presented in Chapter 9. Asphalt concrete consists of approximately 95% aggregate and 5% asphalt binder, by weight. When the traffic loads are applied on the asphalt concrete composite, most of the compressive stresses are supported by the aggregate-to-aggregate contact. The asphalt acts as a binder that prevents slipping of aggregate particles relative to each other. When tensile stresses are applied due to bending of the asphalt concrete layer or due to thermal contraction, the aggregate particles are supported by the asphalt binder. One important property of asphalt is that it gets soft at high temperatures and brittle at low temperatures, whereas aggregate does not change its properties with temperature fluctuation. It is important, therefore, to properly select the asphalt grade that will perform properly within the temperature range of the region in which it is being used. Also, since aggregate represents a major portion of the mixture, it is important to use aggregate with proper gradation and other properties. The asphalt binder content must be carefully designed in order to ensure that aggregate particles are fully coated, without excessive lubrication. When the asphalt concrete mixture is appropriately designed and compacted, it should last for a long time without failure.

11.2.4 Engineered Wood

Engineered wood is manufactured by bonding together wood strands, veneers, or lumber with different grain orientations to produce large and integral units. Since engineered wood consists of components of the same material, it does not qualify as a composite according to our definition. However, engineered wood is presented in this chapter because it follows a strengthening mechanism similar to that of composites. Since wood has anisotripic properties due to the existence of grains, engineered wood produces specific and consistent mechanical behavior and thus has consistent design properties. For example, alternating the grain orientation of the plies of plywood provides nearly identical properties along the length and width and provides resistance to dimensional change under varying moisture conditions. The plywood composite has about one-tenth of the dimensional change of solid lumber under any temperature or moisture condition. As discussed in Chapter 10, engineered wood products include plywood, oriented strand boards, composite panels, glued–laminated timber (glulam), laminated veneer lumber, parallel strand lumber, oriented strand lumber, and wood I-joists.

11.3 Properties of Composites

The properties of composite materials are affected by the component properties, volume fractions of components, type and orientation of the dispersed phase, and the bond between the dispersed phase and the matrix. The properties of the composite can be viewed as the weighted average of the properties of the components (Shackelford 1996). Equations can be derived to estimate the composite properties under certain idealized material properties, loading patterns, and geometrical conditions. Assumptions that can be used to simplify the analysis include the following:

- Each component has linear, elastic, and isotropic properties.
- A perfect bond exists between the dispersed and matrix phases without slipping.
- The composite geometry is idealized and the loading pattern is parallel or perpendicular to reinforcing fibers.

11.3.1 Loading Parallel to Fibers

When load is applied to an aligned fiber-reinforced composite parallel to the fibers, as seen in Figure 11.13(a), both matrix and fiber phases will deform equally. Thus, the strains of both phases will be the same (known as an *isostrain condition*) and are given by

$$\varepsilon_c = \varepsilon_m = \varepsilon_f = \varepsilon \qquad (11.1)$$

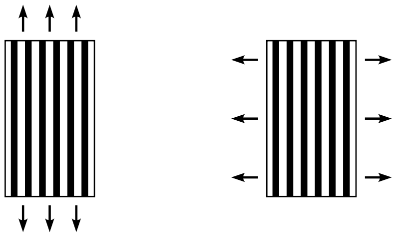


FIGURE 11.13 Patterns of loading continuously aligned fiber-reinforced composites: (a) loading parallel to fibers and (b) loading perpendicular to fibers.

where

ε = total strain
ε_c = composite
ε_m = matrix strain
ε_f = fiber strain

Also, the force applied to the composite F_c is the sum of the force carried by the matrix F_m and the force carried by the fibers F_f:

$$F_c = F_m + F_f \tag{11.2}$$

Thus,

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f \tag{11.3}$$

where

σ_i = stress of component i
A_i = area of component i

Replacing σ with $E\varepsilon$ for each material, we can write Equation 11.3 as

$$E_c \varepsilon A_c = E_m \varepsilon A_m + E_f \varepsilon A_f \tag{11.4}$$

where E is the modulus of elasticity. Canceling ε and dividing by A_c, we have

$$E_c = E_m \frac{A_m}{A_c} + E_f \frac{A_f}{A_c} \tag{11.5}$$

or

$$E_c = \nu_m E_m + \nu_f E_f \tag{11.6}$$

where ν is the volume fraction of each component and $\nu_m + \nu_f = 1$.

Equation 11.6 shows that the composite's modulus of elasticity is the weighted average of the component moduli.

The share of the load carried by the fibers can be determined as follows:

$$\frac{F_f}{F_c} = \frac{\sigma_f A_f}{\sigma_c A_c} = \frac{E_f \varepsilon A_f}{E_c \varepsilon A_c} = \frac{E_f}{E_c}\nu_f \tag{11.7}$$

Sample Problem 11.1

Calculate the modulus of elasticity of fiberglass under isostrain condition if the fiberglass consists of 70% E-glass fibers and 30% epoxy by volume. Also, calculate the percentage of load carried by the glass fibers. The modulus of elasticity of the glass fibers and the epoxy are 70.5 GPa and 6.9 GPa, respectively.

Solution
From Equation 11.6,

$$E_c = (0.3)(6.9) + (0.7)(70.5) = 51.4 \text{ GPa}$$

From Equation 11.7,

$$\frac{F_f}{F_c} = \frac{70.5}{51.4}(0.7) = 0.96 = 96\%$$

This example shows that, under the given conditions, 96% of the load is carried by the fibers.

Equation 11.6 can be generalized to cover other composite properties as a function of the properties of the components as

$$X_c = \nu_m X_m + \nu_f X_f \tag{11.8}$$

where X is a property such as Poisson's ratio, thermal conductivity, electrical conductivity, or diffusivity.

11.3.2 Loading Perpendicular to Fibers

When load is applied to an aligned fiber-reinforced composite perpendicular to the fibers [Figure 11.13(b)], both matrix and fiber phases will be subjected to the same stress (isostress condition). In other words,

$$\sigma_c = \sigma_m = \sigma_f = \sigma \tag{11.9}$$

The elongation of the composite in the direction of the applied stress is the sum of the elongations of the matrix and fibers:

$$\Delta L_c = \Delta L_m + \Delta L_f \tag{11.10}$$

Dividing Equation 11.10 by the composite length L_c in the stress direction gives

$$\frac{\Delta L_c}{L_c} = \frac{\Delta L_m}{L_c} + \frac{\Delta L_f}{L_c} \tag{11.11}$$

Assuming that the fibers are uniform in thickness, the cumulative length of each component in the direction of the stress is proportional to its volume fraction. Thus,

$$L_m = \nu_m L_c \tag{11.12}$$

and

$$L_f = \nu_f L_c \tag{11.13}$$

Substituting the values of L_c from Equations 11.12 and 11.13 in Equation 11.11 yields

$$\frac{\Delta L_c}{L_c} = \frac{\nu_m \Delta L_m}{L_m} + \frac{\nu_f \Delta L_f}{L_f} \tag{11.14}$$

Since $\varepsilon = \dfrac{\Delta L}{L}$, Equation 11.14 can be rewritten as

$$\varepsilon_c = \nu_m \varepsilon_m + \nu_f \varepsilon_f \tag{11.15}$$

Replacing ε with $\dfrac{\sigma}{E}$ gives

$$\frac{\sigma}{E_c} = \nu_m \frac{\sigma}{E_m} + \nu_f \frac{\sigma}{E_f} \tag{11.16}$$

or

$$\frac{1}{E_c} = \frac{\nu_m}{E_m} + \frac{\nu_f}{E_f} \tag{11.17}$$

Equation 11.17 can be rewritten as

$$E_c = \frac{E_m E_f}{\nu_m E_f + \nu_f E_m} \tag{11.18}$$

As with Equation 11.8, Equation 11.18 can be generalized as

$$X_c = \frac{X_m X_f}{\nu_m X_f + \nu_f X_m} \tag{11.19}$$

where X is a property such as thermal conductivity, electrical conductivity, or diffusivity.

The moduli in Equations 11.6 and 11.18 can be plotted as functions of the volume fraction of the fiber, as shown in Figure 11.14. Clearly, the fibers are more effective in raising the modulus of the composite when loading parallel to fibers than when loading perpendicular to fibers.

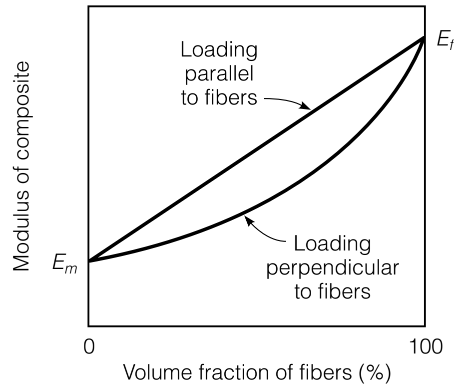


FIGURE 11.14 Modulus of elasticity of the composite versus fiber volume fraction.

11.3.3 Randomly Oriented Fiber Composites

Unlike continuously aligned fiber composites, the mechanical properties of randomly oriented fiber composites are isotropic. The modulus of elasticity of randomly oriented fiber composites falls between the moduli of loading parallel to fibers and perpendicular to fibers. To estimate the modulus of elasticity of randomly oriented fiber composites, Equation 11.6 can be rewritten as

$$E_c = \nu_m E_m + K \nu_f E_f \tag{11.20}$$

where K is a fiber efficiency parameter (Callister 1985). For fibers randomly and uniformly distributed within three dimensions in space, K has a value of 0.2.

Sample Problem 11.2

A fiberglass composite consists of epoxy matrix reinforced with randomly oriented and uniformly distributed E-glass fibers. The modulus of elasticity of the glass fibers and the epoxy are 65 GPa and 7 GPa, respectively. If the volume percentage of fibers is 30%, and the fiber efficiency is 0.2, calculate the modulus of elasticity of the fiberglass.

Solution
From Equation 11.20, we have

$$E_c = 0.67 \times 7 + 0.2 \times 0.33 \times 65 = 9.0 \text{ GPa}$$

11.3.4 Particle-Reinforced Composites

The analysis of loading a particle-reinforced composite depends on the specific nature of the dispersed and matrix phases. A rigorous analysis of loading a particle-reinforced composite can become quite complex. Equations 11.6 and 11.18 serve as upper and lower bounds for the particle-reinforced properties.

SUMMARY

Combining different materials to produce a composite that has properties superior to the component materials has been practiced since ancient times. In fact, many of the conventional materials currently used in civil engineering are composites, including portland cement concrete, reinforced concrete, asphalt concrete, and engineered woods. Composites are generally classified as either fiber or particle reinforced, depending on the nature of the dispersed phase material. The properties of composites depend on the characteristics of the component materials, the bonding between the dispersed and matrix phases, and the orientation of the dispersed phase.

QUESTIONS AND PROBLEMS

11.1 What is a composite material? List some composite materials that you use in your daily life.

11.2 List five different advantages of composite materials over conventional materials.

11.3 Define microscopic composites. What are the two phases of microscopic composites?

11.4 What are the two types of microscopic composites? Show the mechanism for strengthening of each type.

11.5 Why are fibers much stronger than the bulk material? Give an example of a material that is relatively weak in the bulk form and very strong in the fiber form.

11.6 Compare the desired properties of the matrix and the fiber phases of the fiber-reinforced composite.

11.7 Name three functions of the matrix phase in fiber-reinforced composites. State the reason for the need for a strong bond between the fibers and the matrix.

11.8 What are the functions of aggregate used in portland cement concrete?

11.9 How is the load supported by asphalt concrete in the cases of tension and compression. Under what conditions is the asphalt concrete layer subjected to tension?

11.10 Briefly describe why engineered wood is stronger and has better properties than natural wood.

11.11 Calculate the modulus of elasticity of carbon–epoxy composite under isostrain condition if the composite consists of 30% carbon fibers and 70% epoxy by volume. Also, calculate the percentage of load carried by the carbon fibers. The modulus of elasticity of the carbon fibers and the epoxy are 50×10^6 psi and 0.5×10^6 psi, respectively.

11.12 Repeat problem 11.11 for 40% carbon fibers by volume.

11.13 Repeat problem 11.11 under isostress condition.

11.14 Calculate the modulus of elasticity of carbon–epoxy composite under isostrain condition if the composite consists of 50% carbon fibers and 50% epoxy by volume. Also, calculate the percentage of load carried by the carbon fibers. The modulus of elasticity of the carbon fibers and the epoxy are 350 GPa and 3.5 GPa, respectively.

11.15 Repeat problem 11.14 for 30% carbon fibers by volume.

11.16 Repeat problem 11.14 under isostress condition.

11.17 A fiberglass composite consists of epoxy matrix reinforced with randomly oriented and uniformly distributed E-glass fibers. The modulus of elasticity of the glass fibers and the epoxy are 70 GPa and 6 GPa, respectively. Calculate the modulus of elasticity of the fiberglass if the volume percentage of fibers is (a) 25%, (b) 50%, and (c) 75%. Plot a graph showing the relationship between the modulus of elasticity of the fiberglass and the percent of fibers. Comment on the effect of the percent of glass fibers on the modulus of elasticity of fiberglass.

11.18 A fiberglass composite consists of epoxy matrix reinforced with randomly oriented and uniformly distributed E-glass fibers. The modulus of elasticity of the glass fibers and the epoxy are 10×10^6 psi and 1×10^6 psi, respectively. Calculate the modulus of elasticity of the fiberglass if the volume percentage of fibers is (a) 30%, (b) 50%, and (c) 70%. Plot a graph showing the relationship between the modulus of elasticity of the fiberglass and the percent of fibers. Comment on the effect of the percent of glass fibers on the modulus of elasticity of fiberglass.

11.19 A short reinforced concrete column is subjected to a 1000 kN axial compressive load. The moduli of elasticity of plain concrete and steel are 25 GPa and 207 GPa, respectively, and the cross-sectional area of steel is 2% of that of the reinforced concrete. Considering the column as a structural member made of a composite material and subjected to load parallel to the steel rebars, calculate the following:

a. the modulus of elasticity of the reinforced concrete
b. the load carried by each of the steel and plain concrete
c. the minimum required cross-sectional area of the column given that the allowable compressive stress of plain concrete is 20 MPa and that the allowable compressive stress of plain concrete will be reached before that of steel.

11.20 A short reinforced concrete column is subjected to a 500 kips axial compressive load. The moduli of elasticity of plain concrete and steel are 4.5×10^6 psi and 30×10^6 psi, respectively, and the cross-sectional area of steel is 1.8% of that of the reinforced concrete. Considering the column as a structural member made of a composite material and subjected to load parallel to the steel rebars, calculate the following:
a. the modulus of elasticity of the reinforced concrete
b. the load carried by each of the steel and plain concrete
c. the minimum required cross-sectional area of the column, given that the allowable compressive stress of plain concrete is 5000 psi and that the allowable compressive stress of plain concrete will be reached before that of steel.

11.4 References

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