Composites and Powder Metallurgy
Ch 16 “Composite Materials”

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Introduction

- Composites occur naturally, examples: wood and bone
  - 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*.

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

Introduction

- 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.

- In composites: the constituent phases must be chemically dissimilar and separated by a distinct interface.

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

Introduction

- Composite: 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.

Introduction

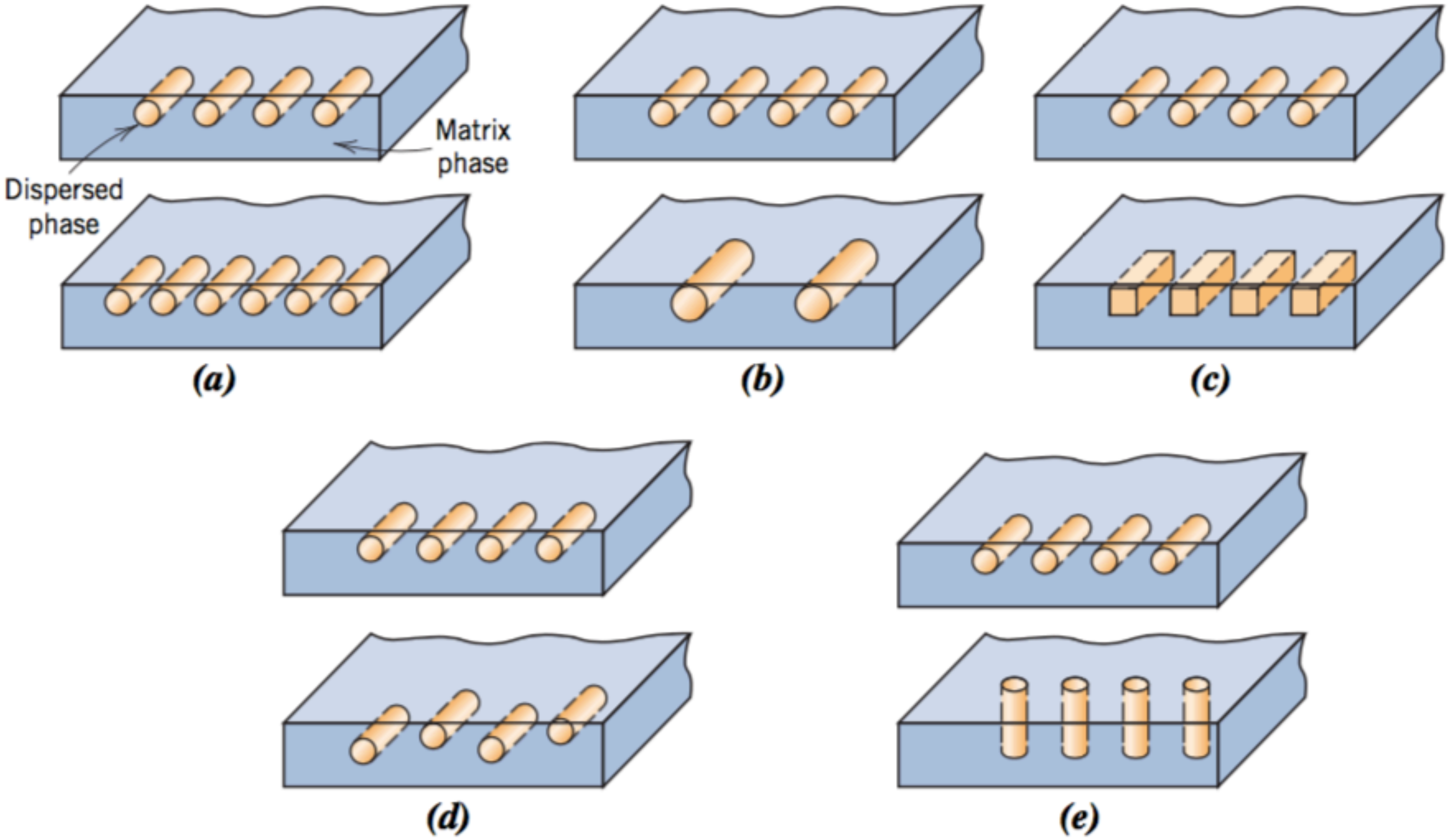


Figure 16.1 Schematic representations of the various geometrical and spatial characteristics of particles of the dispersed phase that may influence the properties of composites: (*a*) concentration, (*b*) size, (*c*) shape, (*d*) distribution, and (*e*) orientation.
(From Richard A. Flinn and Paul K.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

Introduction

- One simple scheme for the classification of composite materials is shown in Figure 16.2, which consists of four main divisions:

  - Particle-reinforced, fiber-reinforced, structural, and nanocomposites.
  - The dispersed phase for particle-reinforced composites is equiaxed
  - For fiber-reinforced composites, the dispersed phase has the geometry of a fiber.
  - Structural composites are multi-layered and designed to have low densities and high degrees of structural integrity.
  - Nanocomposites dimensions of the dispersed phase particles are on the order of nanometers.

Introduction

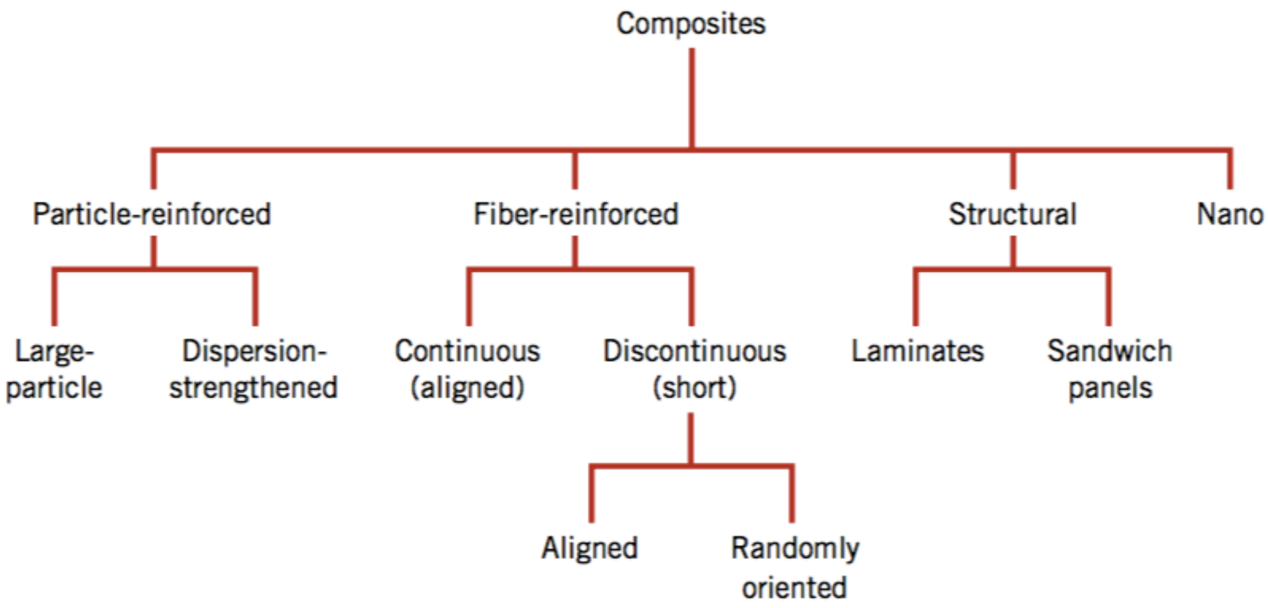


Figure 16.2 A classification scheme for the various composite types discussed in this chapter.

Particle-Reinforced Composites

- Subclassifications: **large-particle** and **dispersion-strengthened** composites.
    - The term **large** is used to indicate that particle–matrix interactions cannot be treated on the atomic or molecular level
    - 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. (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.

Particle-Reinforced Composites

- For **dispersion-strengthened** composites, particles are normally much smaller, with diameters between 10 and 100 nm.

  - Particle–matrix interactions that lead to strengthening occur on the atomic or molecular level.

  - The mechanism of strengthening: 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 strength, as well as hardness, improve.

Particle-Reinforced Composites / *Large-Particle Composites*

- A familiar large-particle composite is concrete, which is composed of cement (the matrix) and sand and gravel (the particulates).
  - Particles should be equiaxed, small and evenly distributed throughout the matrix.

  - The volume fraction of the two phases influences the behavior; mechanical properties are enhanced with increasing particulate content.

  - These rule-of-mixtures equations predict that the elastic modulus should fall between an upper and bounds.

Particle-Reinforced Composites / *Large-Particle Composites*

Upper limit

$$E_c(u) = E_m V_m + E_p V_p$$

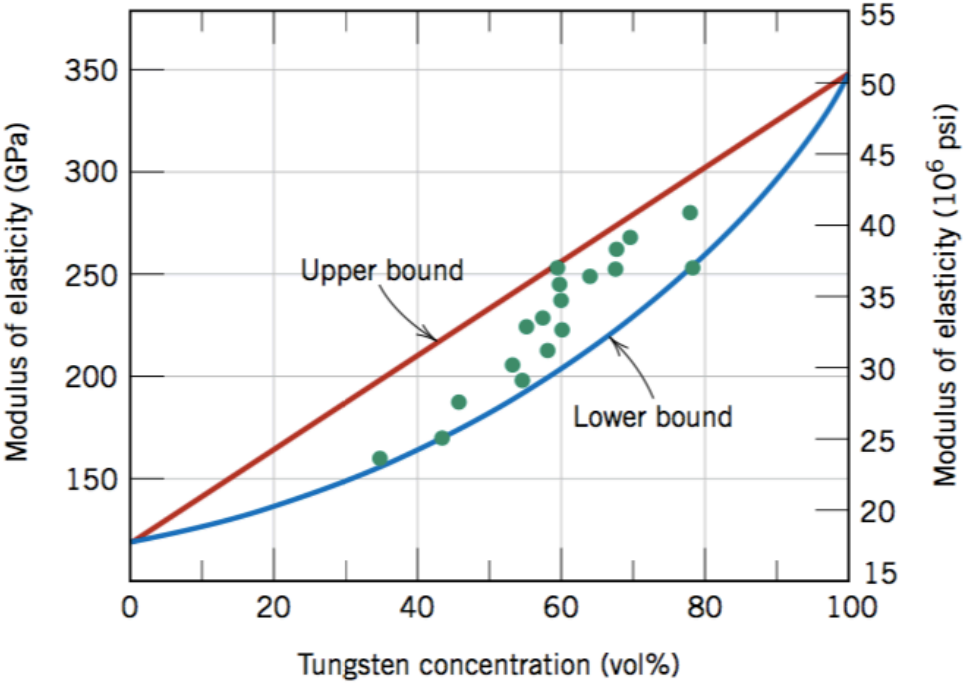
Lower limit

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

E and *V* denote the elastic modulus and volume fraction, respectively, and the subscripts *c*, *m*, and *p* represent composite, matrix, and particulate phases, respectively.

Particle-Reinforced Composites / *Large-Particle Composites*

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, respectively; experimental data points are included. (Reprinted with permission from R. H. Krock, *ASTM Proceedings*, Vol. 63, 1963. Copyright ASTM International, 100 Barr Harbor Drive, West Conschohocken, PA 19428.)



Particle-Reinforced Composites / *Large-Particle Composites (Cermets)*

- The **cermets** are examples of ceramic–metal composites.
    - Most common cermet is cemented carbide: 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 Co or Ni.
    - Used extensively as cutting tools for hardened steels. The hard carbide particles provide the cutting surface but, being extremely brittle, are not 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.

Particle-Reinforced Composites / *Large-Particle Composites*

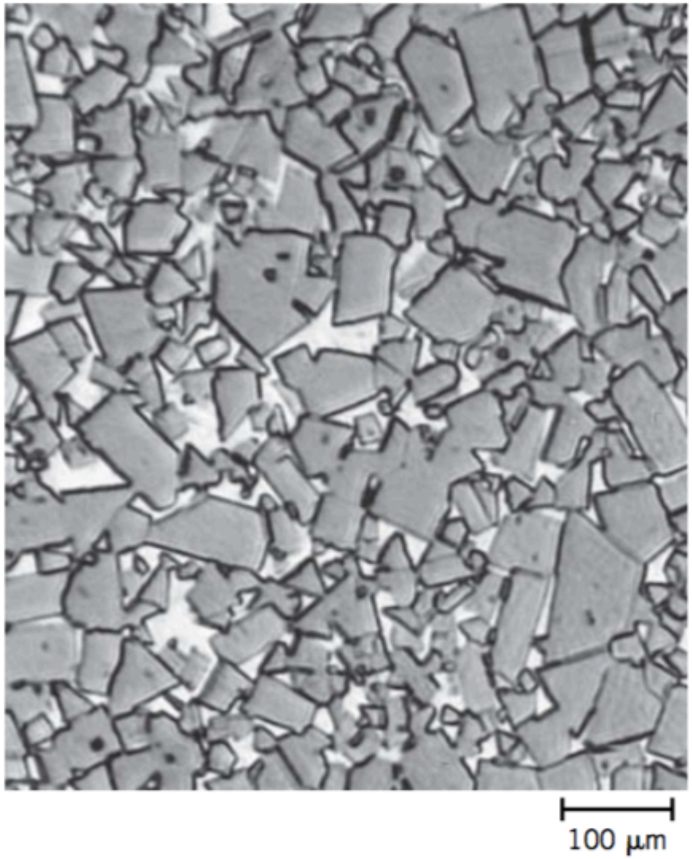
- Both elastomers and plastics are frequently reinforced with various particulate materials.

- Use of many 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 rubber, it enhances tensile strength, toughness, and tear and abrasion resistance.

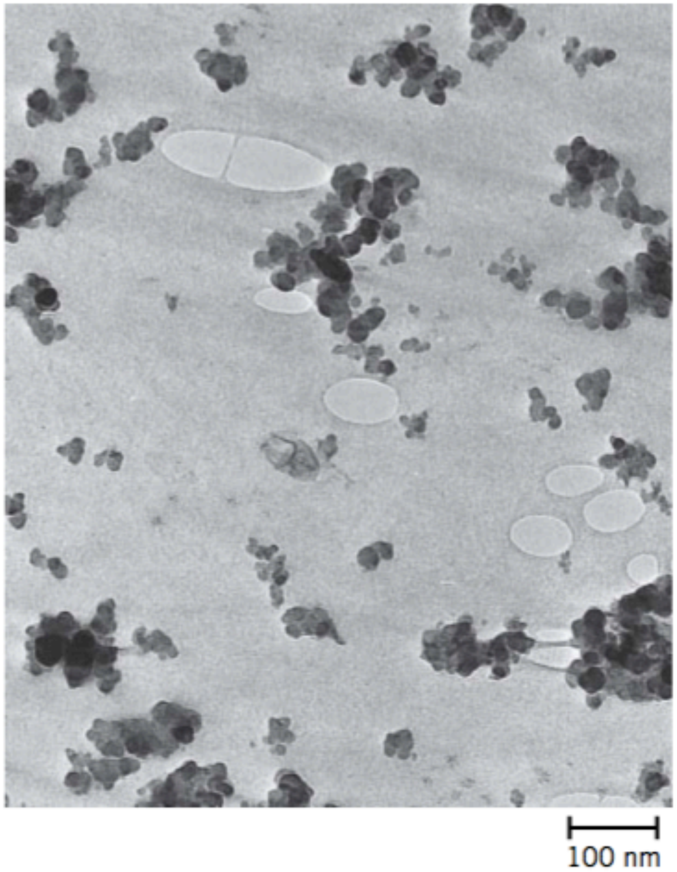
  - Automobile tires contain on the order of 15 to 30 vol% carbon black. For the carbon black to provide significant reinforcement, the particle size must be extremely small, with diameters between 20 and 50 nm; also, the particles must be evenly distributed throughout the rubber and must form a strong adhesive bond with the rubber matrix.

Particle-Reinforced Composites / *Large-Particle Composites*



Courtesy of Carboloy Systems Department, General Electric Company

Figure 16.4 Photomicrograph of a WC–Co cemented carbide. Light areas are the cobalt matrix; dark regions are the particles of tungsten carbide. 100×.



Courtesy of Goodyear Tire & Rubber Company

Figure 16.5 Electron micrograph showing the spherical reinforcing carbon black particles in a synthetic rubber tire tread compound. The areas resembling water marks are tiny air pockets in the rubber. 80,000×.

Particle-Reinforced Composites / *Large-Particle Composites (Concrete)*

- Concrete is a common large-particle composite in which both matrix and dispersed phases are ceramic materials.

  - Concrete: composite material consisting of an aggregate of particles that are bound together in a solid body by some type of binding medium, that is, a cement.

  - The two most familiar concretes are those made with Portland and asphaltic cements, in which the aggregate is gravel and sand.
    - Asphaltic concrete is widely used primarily as a paving material, whereas Portland cement concrete is employed extensively as a structural building material.

Particle-Reinforced Composites / *Large-Particle Composites (Concrete - Portland Cement)*

- Consists of: Portland cement, a fine aggregate (sand), a coarse aggregate (gravel), and water.
  - 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.
  - The ingredients must be added in the correct proportions to achieve the optimum strength.
  - 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.
  - Typically, these aggregates constitute between 60% and 80% of the total volume.

Water is added for bonding: Too much water leads to high porosity and too little leads to incomplete bonding

Particle-Reinforced Composites / *Large-Particle Composites (Concrete - Portland Cement)*

- 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.
  - Limitations and disadvantages: relatively weak and extremely brittle; its tensile strength is approximately one-fifteenth to one-tenth its compressive strength.
  - Also, large concrete structures can experience considerable thermal expansion and contraction with temperature fluctuations. In addition, water penetrates into external pores, which can cause severe cracking in cold weather.
  - Most of these inadequacies may be eliminated or at least reduced by reinforcement and/or the incorporation of additives.

Particle-Reinforced Composites / *Large-Particle Composites (Concrete - Reinforced Concrete)*

- The strength of Portland cement concrete may be increased by additional reinforcement.
    - 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.

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.

    - Fiber-reinforced composites with exceptionally high specific strengths and moduli have been produced that use low-density fiber and matrix materials.

Fiber-Reinforced Composites / *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 the figure; in other words, there is no load transmittance from the matrix at each fiber extremity.

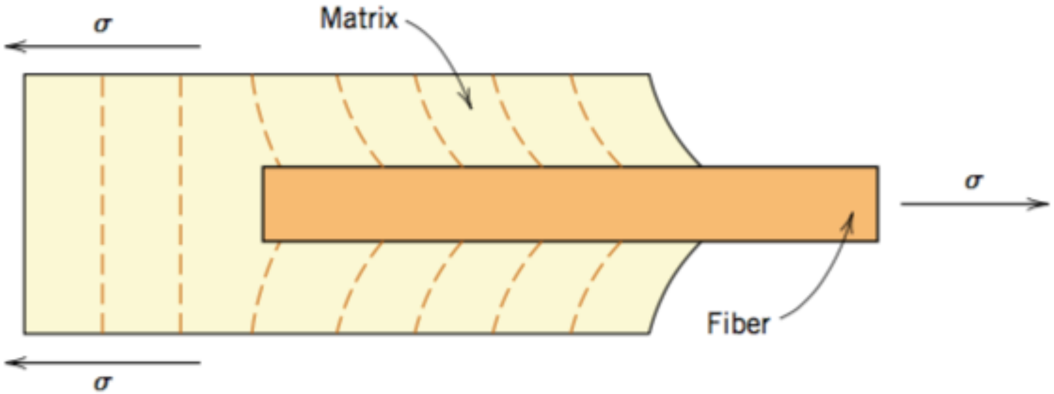


Figure 16.6 The deformation pattern in the matrix surrounding a fiber that is subjected to an applied tensile load.

Fiber-Reinforced Composites / *Influence of Fiber length*

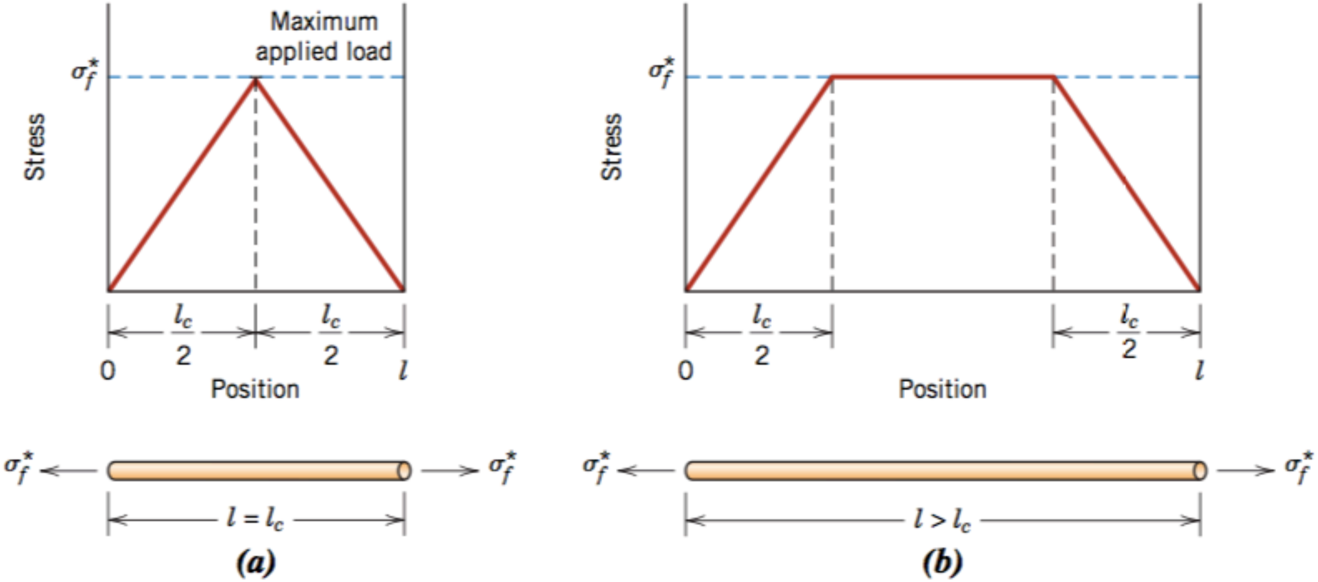
- Some critical fiber length is necessary for effective strengthening and stiffening of the composite material. This critical length l_c is dependent on the fiber diameter *d* and its ultimate (or tensile) strength σ^*_f and on the fiber–matrix bond strength (or the shear yield strength of the matrix, whichever is smaller) $\boldsymbol{\tau}_c$ according to

$$l_c = \frac{\sigma^*_f d}{2\tau_c}$$

The larger the fiber length, the more effective the reinforcement

- 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.

Fiber-Reinforced Composites / *Influence of Fiber length*



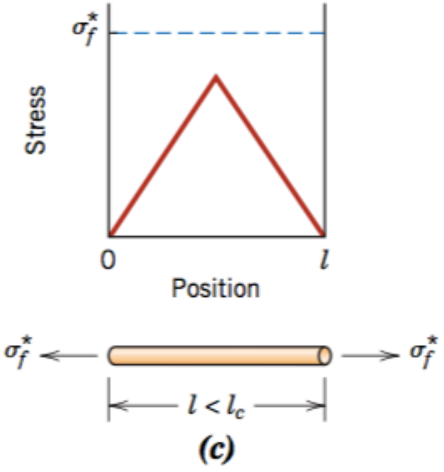


Figure 16.7 Stress–position profiles when the fiber length l (*a*) is equal to the critical length l_c, (*b*) is greater than the critical length, and (*c*) is less than the critical length for a fiber-reinforced composite that is subjected to a tensile stress equal to the fiber tensile strength σ_f^*.

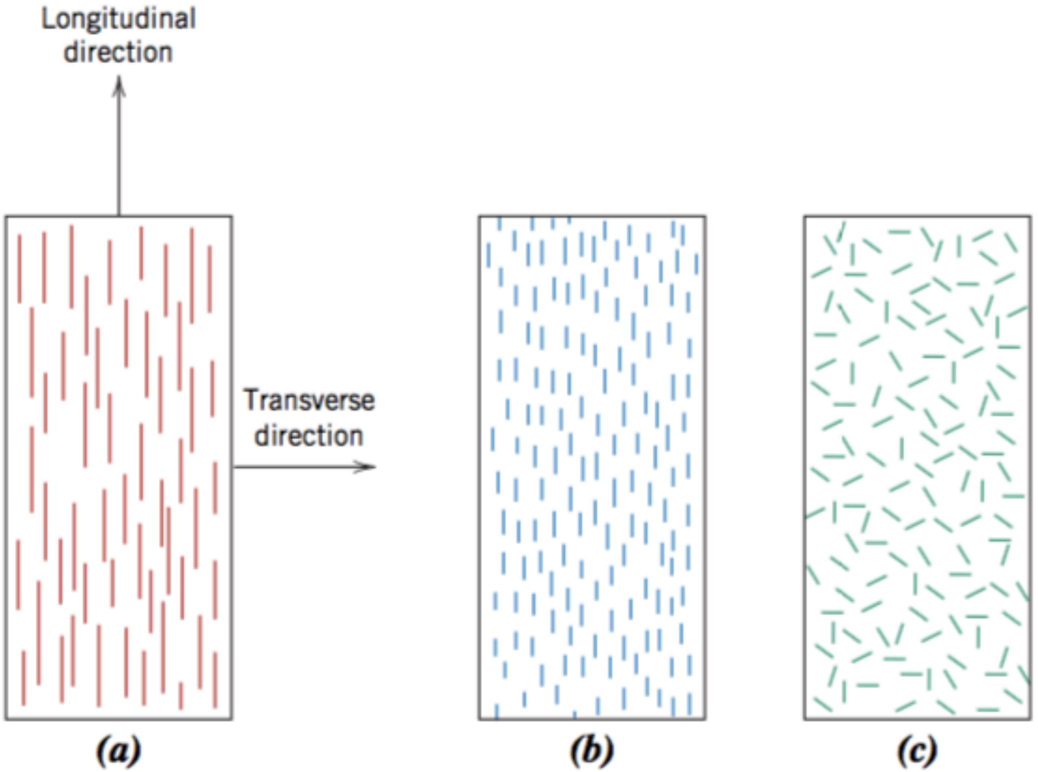
$l >> l_c$: continuous fibers

$l << l_c$: discontinuous (short) fibers

Discontinuous: the matrix deforms around the fiber such that there is virtually no stress transference and little reinforcement by the fiber.

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration*

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



Continuous fibers are normally aligned (Figure 16.8a), whereas discontinuous fibers may be aligned (Figure 16.8b), randomly oriented (Figure 16.8c), or partially oriented.

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Continuous and Aligned Fiber Composites - Tensile Stress–Strain Behavior—Longitudinal Loading)*

Composite failure is not catastrophic for a couple of reasons. First, not all fibers fracture at the same time, because there will always be considerable variations in the fracture strength of brittle fiber materials. In addition, even after fiber failure, the matrix is still intact. 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.

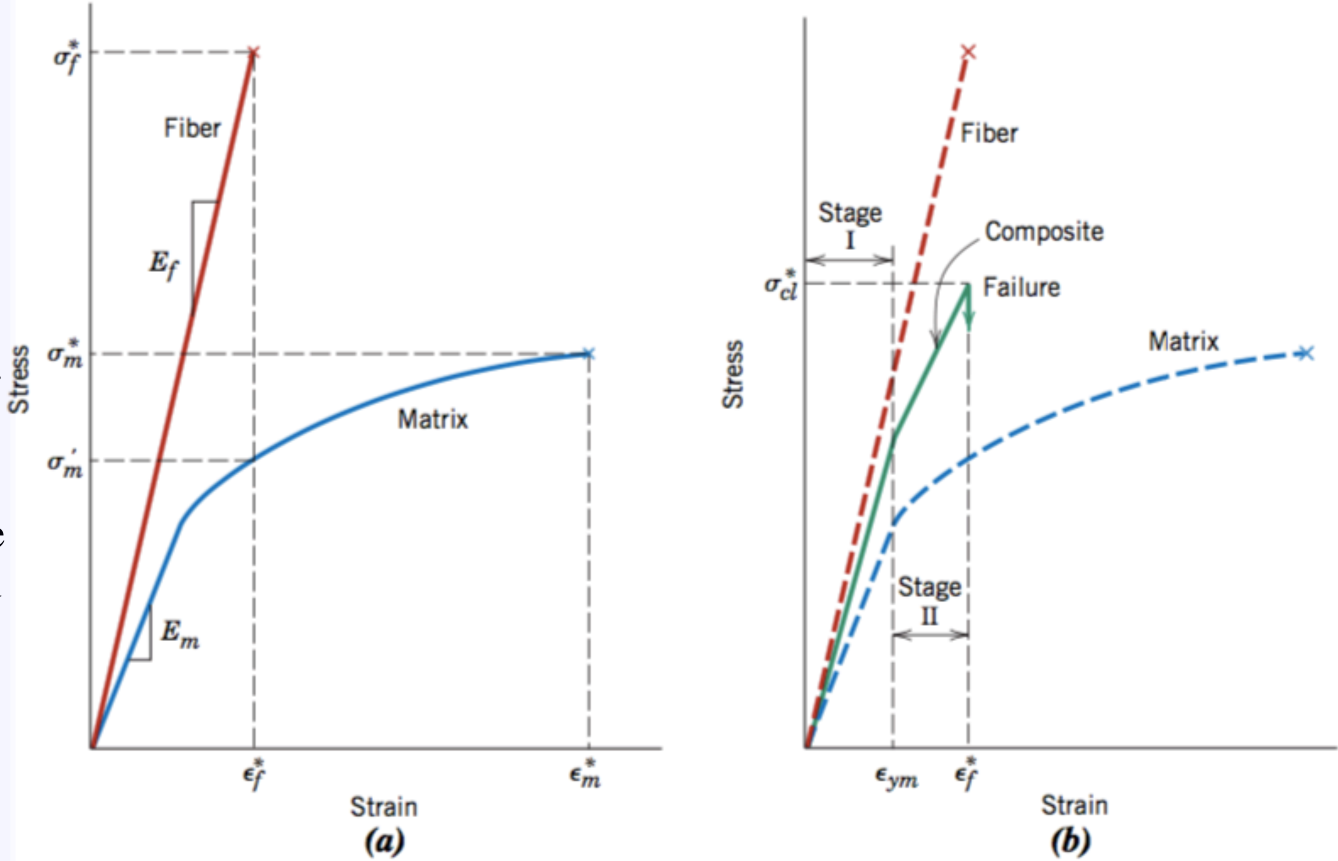


Figure 16.9 (*a*) Schematic stress–strain curves for brittle fiber and ductile matrix materials. Fracture stresses and strains for both materials are noted. (*b*) Schematic stress–strain curve for an aligned fiber–reinforced composite that is exposed to a uniaxial stress applied in the direction of alignment;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

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Continuous and Aligned Fiber Composites - 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.

$F_c = F_m + F_f$, and since $\sigma = F / A$, then

$\sigma_c \times A_c = \sigma_m \times A_m + \sigma_f \times A_f$, dividing by A_c, then

$\sigma_c = \sigma_m (A_m / A_c) + \sigma_f (A_f / A_c)$, 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, $V_f = A_f / A_c$. Then

$$\sigma_c = \sigma_m \times V_m + \sigma_f \times V_f$$

If we assume the deformation of the matrix and the fiber is the same (isostrain situation), then

$$\boldsymbol{\epsilon}_c = \boldsymbol{\epsilon}_m = \boldsymbol{\epsilon}_f$$

Dividing each term in

$\sigma_c = \sigma_m \times V_m + \sigma_f \times V_f$

by its respective strain,

$$\sigma_c / \boldsymbol{\epsilon}_c = (\sigma_m / \boldsymbol{\epsilon}_m) \times V_m + (\sigma_f / \boldsymbol{\epsilon}_f) \times V_f$$

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Continuous and Aligned Fiber Composites - Elastic Behavior—Longitudinal Loading)*

Now, if the deformations are all elastic, then

$$E_{cl} = E_m V_m + E_f V_f$$

or

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

where E_{cl} is the modulus of elasticity of a continuous and aligned fibrous composite in the direction of alignment (or longitudinal direction)

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:

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

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Continuous and Aligned Fiber Composites - Elastic Behavior—Transverse Loading)*

Let us now consider the elastic behavior of a continuous and oriented fibrous composite that is loaded in the direction perpendicular to fiber alignment.

Here we have isostress situation:

$\sigma_c = \sigma_m = \sigma_f$

The strain or deformation of the entire composite $\boldsymbol{\epsilon}_c$ is

$\boldsymbol{\epsilon}_c = \boldsymbol{\epsilon}_m \times V_m + \boldsymbol{\epsilon}_f \times V_f$, but, because $\boldsymbol{\epsilon} = \sigma/E$, then

$\sigma / E_{ct} = (\sigma / E_m) \times V_m + (\sigma / E_f) \times V_f$, where E_{ct} is the modulus of elasticity in the transverse direction. Now, dividing through by σ yields

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

or

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

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Continuous and Aligned Fiber Composites - Elastic Behavior—Longitudinal Tensile Strength)*

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

the stress in the matrix at fiber failure

the fiber tensile strength

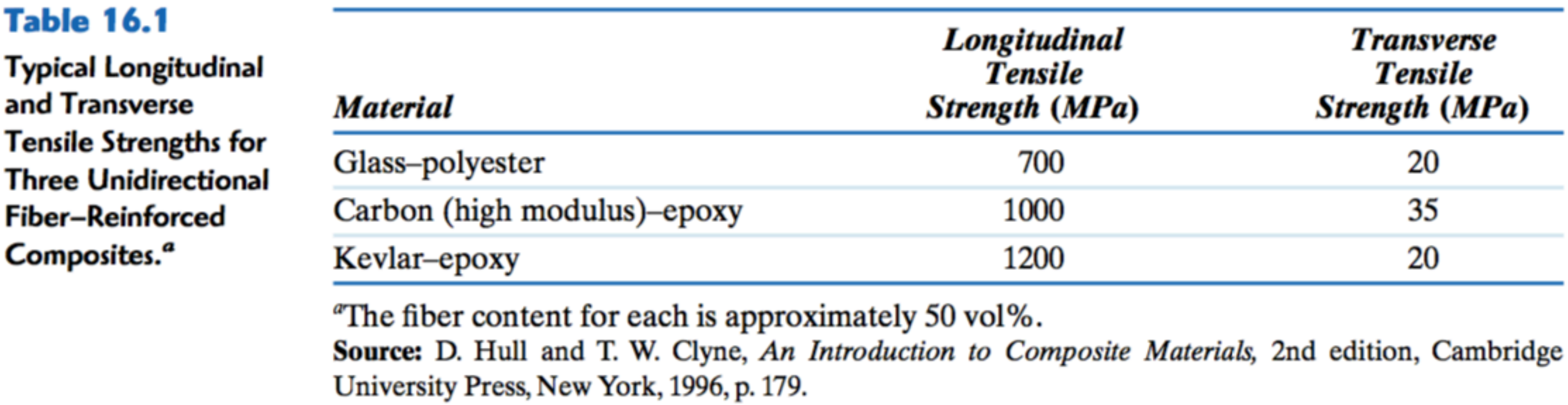


Table 16.1 Typical Longitudinal and Transverse Tensile Strengths for Three Unidirectional Fiber–Reinforced Composites.[a]

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

[a] The fiber content for each is approximately 50 vol%.

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

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Continuous and Aligned Fiber Composites - Elastic Behavior—Transverse Tensile Strength)*

- The strengths of continuous and unidirectional fibrous composites are highly anisotropic, and such composites are normally designed to be loaded along the high- strength, longitudinal direction.

  - However, during in-service applications, transverse tensile loads may also be present.

  - Under these circumstances, premature failure may result inasmuch as transverse strength is usually extremely low—it sometimes lies below the tensile strength of the matrix. Thus, the reinforcing effect of the fibers is negative.

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Continuous and Aligned Fiber Composites - Elastic Behavior—Transverse Tensile Strength)*

- 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 used to improve the transverse strength of these composites usually involve modifying properties of the matrix.

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Discontinuous and Aligned Fiber Composites)*

- Even though reinforcement efficiency is lower for discontinuous than for continuous fibers, discontinuous and aligned-fiber composites are becoming increasingly more important in the commercial market.

    - Chopped-glass fibers are used most extensively; however, carbon and aramid discontinuous fibers are also used.

    - These short-fiber composites can be produced with moduli of elasticity and tensile strengths that approach 90% and 50%, respectively, of their continuous-fiber counterparts.

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Discontinuous and Aligned Fiber Composites)*

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

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

longitudinal strength

the smaller of either the fiber–matrix bond strength or the matrix shear yield strength

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

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

fiber diameter

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Discontinuous and Randomly Oriented–Fiber Composites)*

- Normally, when the fiber orientation is random, short and discontinuous fibers are used.

$$E_{cd} = KE_fV_f + E_mV_m$$

A fiber efficiency parameter that depends on V_f and the E_f / E_m ratio

- Its magnitude will be less than unity, usually in the range 0.1 to 0.6.
    - Thus, for random- fiber reinforcement (as with oriented-fiber reinforcement), the modulus increases with increasing volume fraction of fiber.

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Discontinuous and Randomly Oriented–Fiber Composites)*

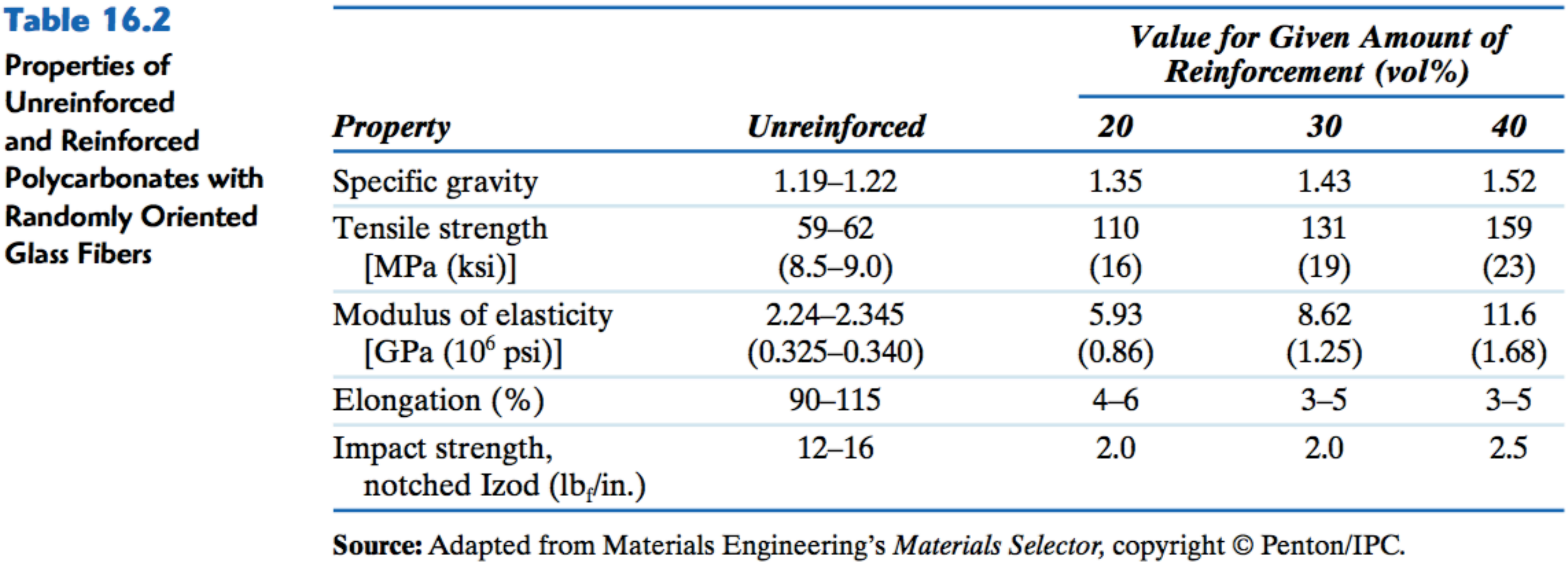


Table 16.2 Properties of Unreinforced and Reinforced Polycarbonates with Randomly Oriented Glass Fibers

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

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

Fiber-Reinforced Composites / *Influence of Fiber Orientation and Concentration (Discontinuous and Randomly Oriented–Fiber Composites)*

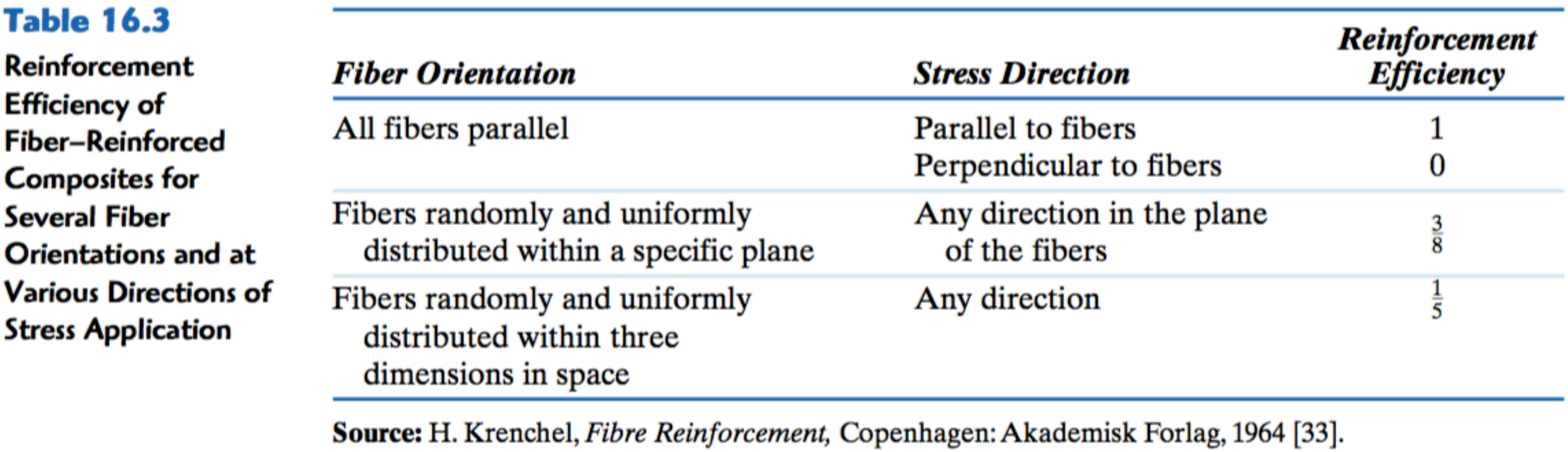


Table 16.3 Reinforcement Efficiency of Fiber–Reinforced Composites for Several Fiber Orientations and at Various Directions of Stress Application

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].

Fiber-Reinforced Composites / *The Fiber Phase*

- 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.
    - They have a high degree of crystalline perfection and are virtually flaw-free, which accounts for their exceptionally high strengths; they are among the strongest known materials.
        - In spite of these high strengths, whiskers are not used extensively as a reinforcement medium because they are extremely expensive.
        - Moreover, it is difficult and often impractical to incorporate whiskers into a matrix.
    - Whisker materials include graphite, silicon carbide, silicon nitride, and aluminum oxide.

Fiber-Reinforced Composites / *The Fiber Phase*

- On the basis of diameter and character, fibers are grouped into three different classifications: whiskers, fibers, and wires.
  - **Fibers** are either polycrystalline or amorphous and have small diameters: polymers or ceramics (e.g., the polymer aramids, glass, carbon, boron, aluminum oxide, and silicon carbide).
  - **Fine wires** have relatively large diameters; typical materials include steel, molybdenum, and tungsten.
    - Wires are used as a radial steel reinforcement in automobile tires, and in wire-wound high-pressure hoses.

Fiber-Reinforced Composites

/ *The Fiber Phase*

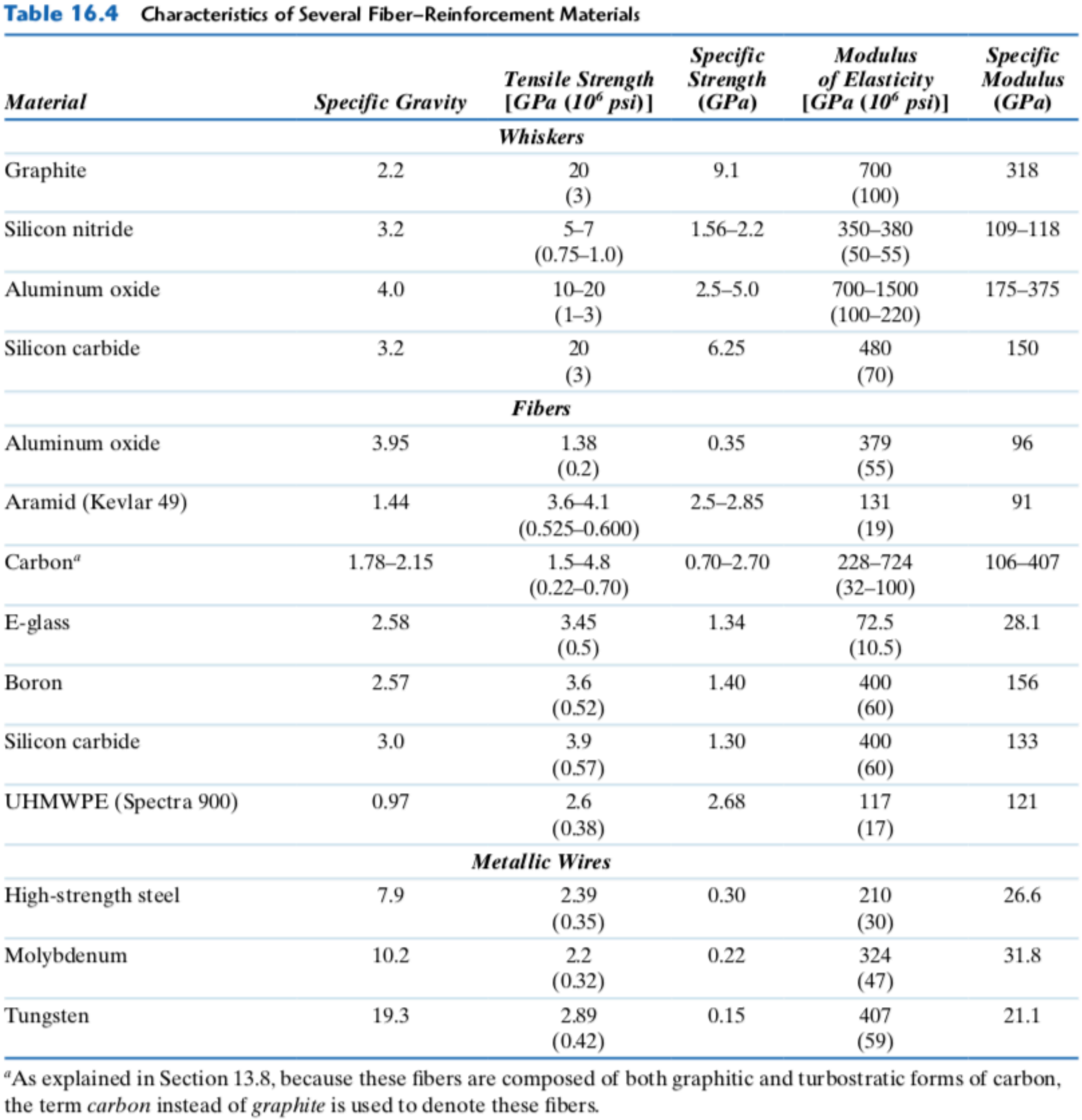


Table 16.4 Characteristics of Several Fiber–Reinforcement Materials

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] As explained in Section 13.8, because these fibers are composed of both graphitic and turbostratic forms of carbon, the term *carbon* instead of *graphite* is used to denote these fibers.

Fiber-Reinforced Composites / *The Matrix Phase*

- 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, the reinforcing component is added to improve fracture toughness.
- The matrix (<u>which should be ductile</u>):
  - 1. Binds the fibers (have much higher *E* than the matrix) together.
  - 2. Transmits and distributes stress to fibers (small portion of stress is sustained by the matrix).
  - 3. Protects fibers from abrasion and corrosion.
  - 4. Prevents the propagation of brittle cracks from fiber to fiber (barrier to crack propagation).

Fiber-Reinforced Composites / *Polymer-Matrix Composites*

- *PMCS* consist of a polymer resin (a high-molecular-weight reinforcing plastic) as the matrix and fibers as the reinforcement medium.

- 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.

Fiber-Reinforced Composites / *Polymer-Matrix Composites (Glass Fiber–Reinforced Polymer (GFRP) Composites)*

- Fiberglass: a composite consisting of glass fibers, either continuous or discontinuous, contained within a polymer matrix.

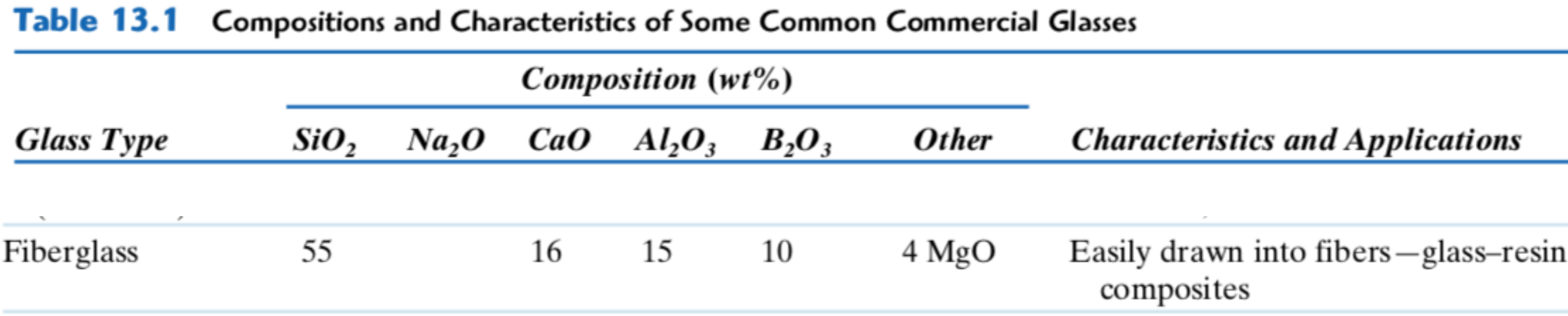


Table 13.1 Compositions and Characteristics of Some Common Commercial Glasses

	Composition (wt%)						
Glass Type	*SiO_2*	*Na_2O*	*CaO*	*Al_2O_3*	*B_2O_3*	*Other*	*Characteristics and Applications*
Fiberglass	55		16	15	10	4 MgO	Easily drawn into fibers—glass–resin composites

- The composition of the glass that is most commonly drawn into fibers (E-glass).

- Fiber diameters normally range between 3 and 20 μm.

Fiber-Reinforced Composites / *Polymer-Matrix Composites (Glass Fiber–Reinforced Polymer (GFRP) Composites)*

- Glass is popular as a fiber reinforcement material for several reasons:
  - It is easily drawn into high-strength fibers from the molten state.
  - It is readily available and may be fabricated into a glass-reinforced plastic economically.
  - As a fiber it is relatively strong, and when embedded in a plastic matrix, it produces a composite having a very high specific strength.
  - When coupled with the various plastics, it possesses a chemical inertness that renders the composite useful in a variety of corrosive environments.

Fiber-Reinforced Composites / *Polymer-Matrix Composites (Glass Fiber–Reinforced Polymer (GFRP) Composites)*

- **Limitations**:
  - 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 ºC; at higher temperatures, most polymers begin to flow or to deteriorate.
- **Applications**:
  - Automotive (decrease vehicle weight and boost fuel efficiencies) and marine bodies, plastic pipes, storage containers, and industrial floorings.

Fiber-Reinforced Composites / *Polymer-Matrix Composites (Carbon Fiber–Reinforced Polymer (CFRP) Composites)*

- Carbon is a high-performance fiber material that is the most commonly used reinforcement in advanced (i.e., *nonfiberglass*) polymer-matrix composites.
    - They have high specific moduli and specific strengths.
    - They retain their high tensile modulus and high strength at elevated temperatures; high-temperature oxidation, however, may be a problem.
    - At room temperature, carbon fibers are not affected by moisture or a wide variety of solvents, acids, and bases.
    - Are relatively inexpensive and cost effective.

Fiber-Reinforced Composites / *Polymer-Matrix Composites (Carbon Fiber–Reinforced Polymer (CFRP) Composites)*

- One classification scheme for carbon fibers is by tensile modulus; on this basis, the four classes are standard, intermediate, high, and ultrahigh moduli.

    - Fiber diameters normally range between 4 and 10 μm; both continuous and chopped forms are available.

- Applications:

    - Used extensively in sports and recreational equipment (fishing rods, golf clubs), filament-wound rocket motor cases, pressure vessels, and aircraft structural components—both military and commercial, both fixed-wing aircraft and helicopters (e.g., as wing, and body components).

Fiber-Reinforced Composites / *Polymer-Matrix Composites (Aramid Fiber–Reinforced Polymer Composites)*

- Aramid fibers are high-strength, high-modulus materials (outstanding strength-to-weight ratios, superior to those of metals)

- There are a number of aramid materials; trade names for two of the most common are Kevlar and Nomex.

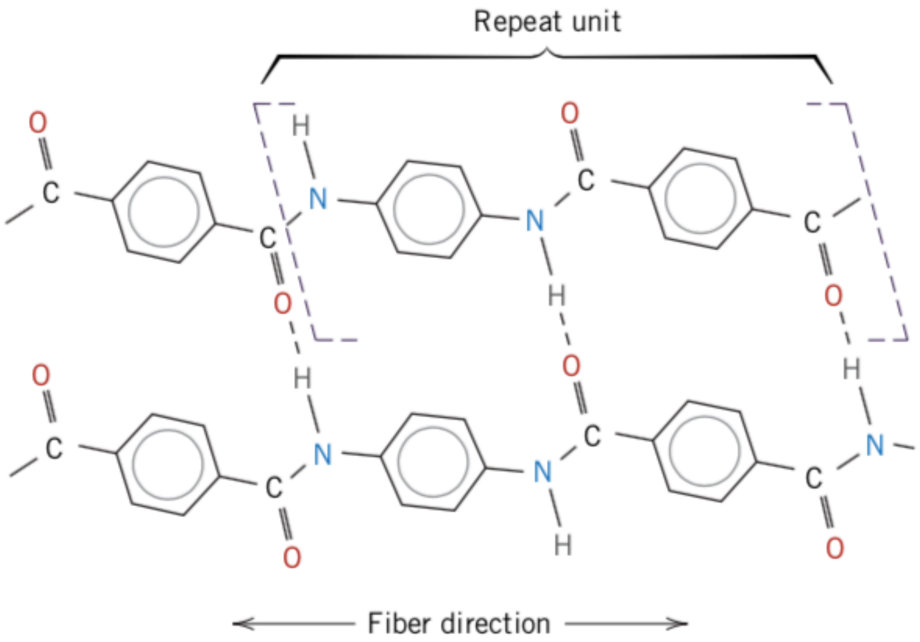


Figure 16.10 Schematic representation of repeat unit and chain structures for aramid (Kevlar) fibers. Chain alignment with the fiber direction and hydrogen bonds that form between adjacent chains are also shown. [From F. R. Jones (Editor), *Handbook of Polymer-Fibre Composites*. Copyright © 1994 by Addison-Wesley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

During synthesis, the rigid molecules are aligned in the direction of the fiber axis.

Fiber-Reinforced Composites / *Polymer-Matrix Composites (Aramid Fiber–Reinforced Polymer Composites)*

- They have longitudinal tensile strengths and tensile moduli that are higher than those of other polymeric fiber materials.
    - However, they are relatively weak in compression.
- Known for its toughness, impact resistance, and resistance to creep and fatigue failure.
- Wide working range (between -200 ºC and 200 ºC).
- Chemically, they are susceptible to degradation by strong acids and bases, but they are relatively inert in other solvents and chemicals.

Fiber-Reinforced Composites / *Polymer-Matrix Composites (Aramid Fiber–Reinforced Polymer Composites)*

- Applications of these aramid composites are in ballistic products (bulletproof vests and armor), sporting goods, tires, ropes, missile cases, and pressure vessels.

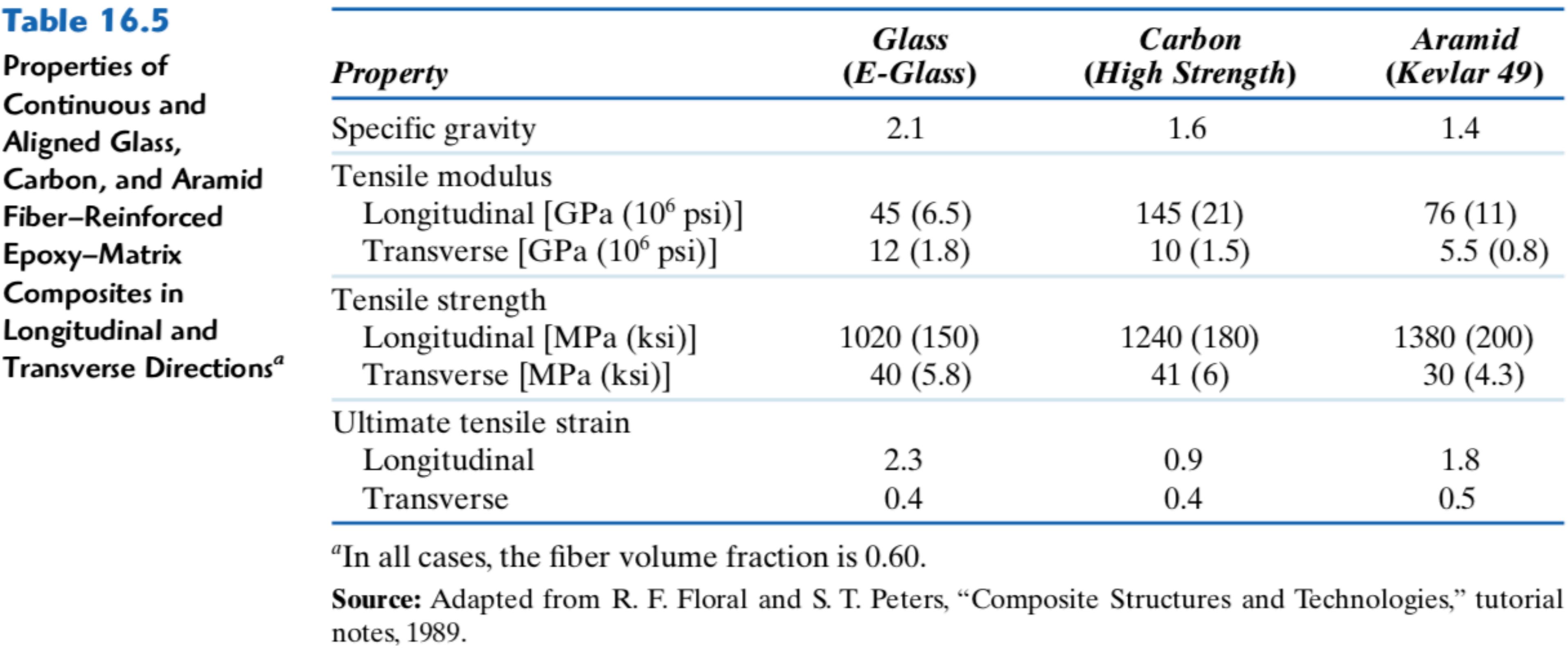


Table 16.5 Properties of Continuous and Aligned Glass, Carbon, and Aramid Fiber–Reinforced Epoxy–Matrix Composites in Longitudinal and Transverse Directions[a]

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

[a] In all cases, the fiber volume fraction is 0.60.

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

Fiber-Reinforced Composites / *Polymer-Matrix Composites (Polymer-Matrix Materials)*

- The most widely used and least expensive polymer resins are the polyesters and vinyl esters.
- These matrix materials are used primarily for glass fiber–reinforced composites.
- The epoxies are more expensive and, in addition to commercial applications, are also used extensively in PMCs for aerospace applications;
- they have better mechanical properties and resistance to moisture than the polyesters and vinyl resins.
- For high-temperature applications, polyimide resins are employed; their upper-temperature limit is approximately 230 ºC.

Fiber-Reinforced Composites / *Metal-Matrix Composites*

- *MMCs*: the matrix is a ductile metal.
    - These materials may be used at higher service temperatures than their base-metal counterparts;
    - Also, the reinforcement may improve specific stiffness, specific strength, abrasion resistance, creep resistance, thermal conductivity, and dimensional stability.
- Advantages over PMCs: higher operating temperatures, nonflammability, and greater resistance to degradation by organic fluids.
- MMCs are much more expensive than PMCs, and, therefore, MMC use is somewhat restricted.

Fiber-Reinforced Composites / *Metal-Matrix Composites*

- Matrix: superalloys, alloys of aluminum, magnesium, titanium, and copper.

- Reinforcement: may be in the form of particulates, both continuous and discontinuous fibers, and whiskers; concentrations normally range between 10 and 60 vol%.

    - Continuous-fiber materials include carbon, silicon carbide, boron, aluminum oxide, and the refractory metals.
    - Discontinuous reinforcements: silicon carbide whiskers, chopped fibers of aluminum oxide and carbon, or particulates of silicon carbide and aluminum oxide.

Fiber-Reinforced Composites / *Metal-Matrix Composites*

- Applications:
  - Automobile (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).
  - The aerospace industry also employs MMCs in the form of advanced aluminum- alloy metal-matrix composites.

Fiber-Reinforced Composites / *Metal-Matrix Composites*

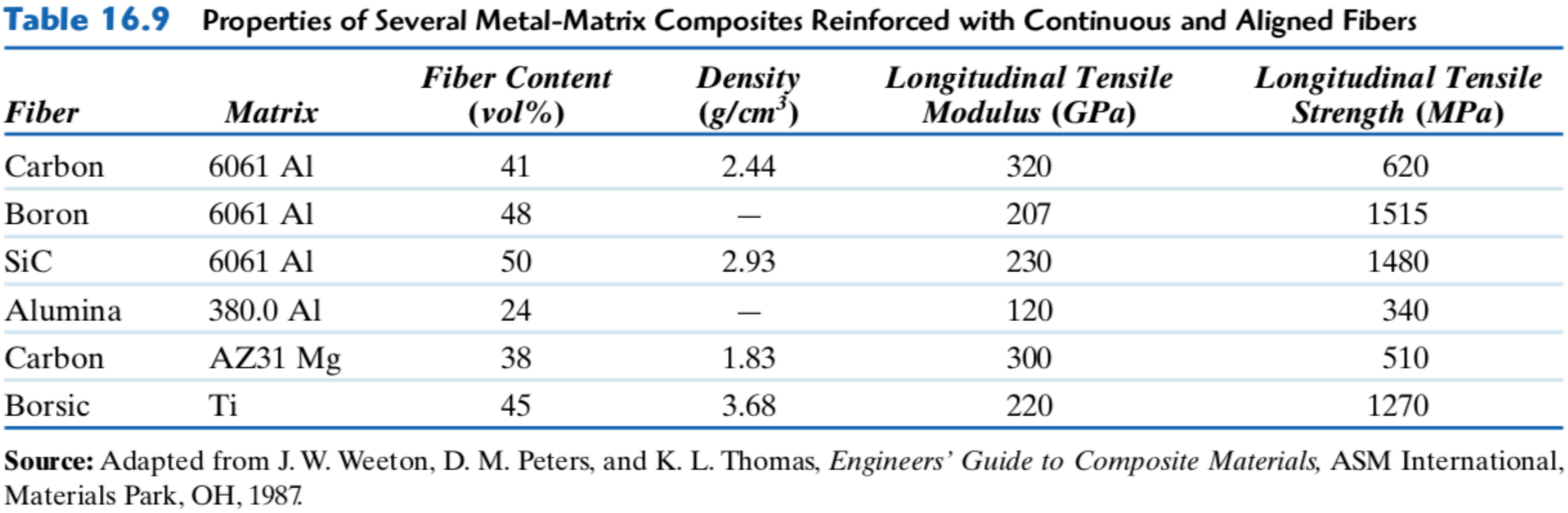


Table 16.9 Properties of Several Metal-Matrix Composites Reinforced with Continuous and Aligned Fibers

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.

Fiber-Reinforced Composites / *Ceramic-Matrix Composites*

- CMSs: particulates, fibers, or whiskers of one ceramic material that have been embedded into a matrix of another ceramic.

- CMCs: developed to improve the fracture toughnesses of ceramics.

  - Ceramics fracture toughness = 1 to 5 MPa√m.
  - CMCs fracture toughness = 6 to 20 MPa√m.

- This improvement 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.

Fiber-Reinforced Composites / *Ceramic-Matrix Composites*

- *Transformation toughening*: a technique used to arrest crack propagation through phase transformation.
  - Small particles of partially stabilized zirconia 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
  - The stress field in front of a propagating crack causes these metastably retained tetragonal particles to undergo transformation to the stable monoclinic phase.

Fiber-Reinforced Composites / *Ceramic-Matrix Composites*

- 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.

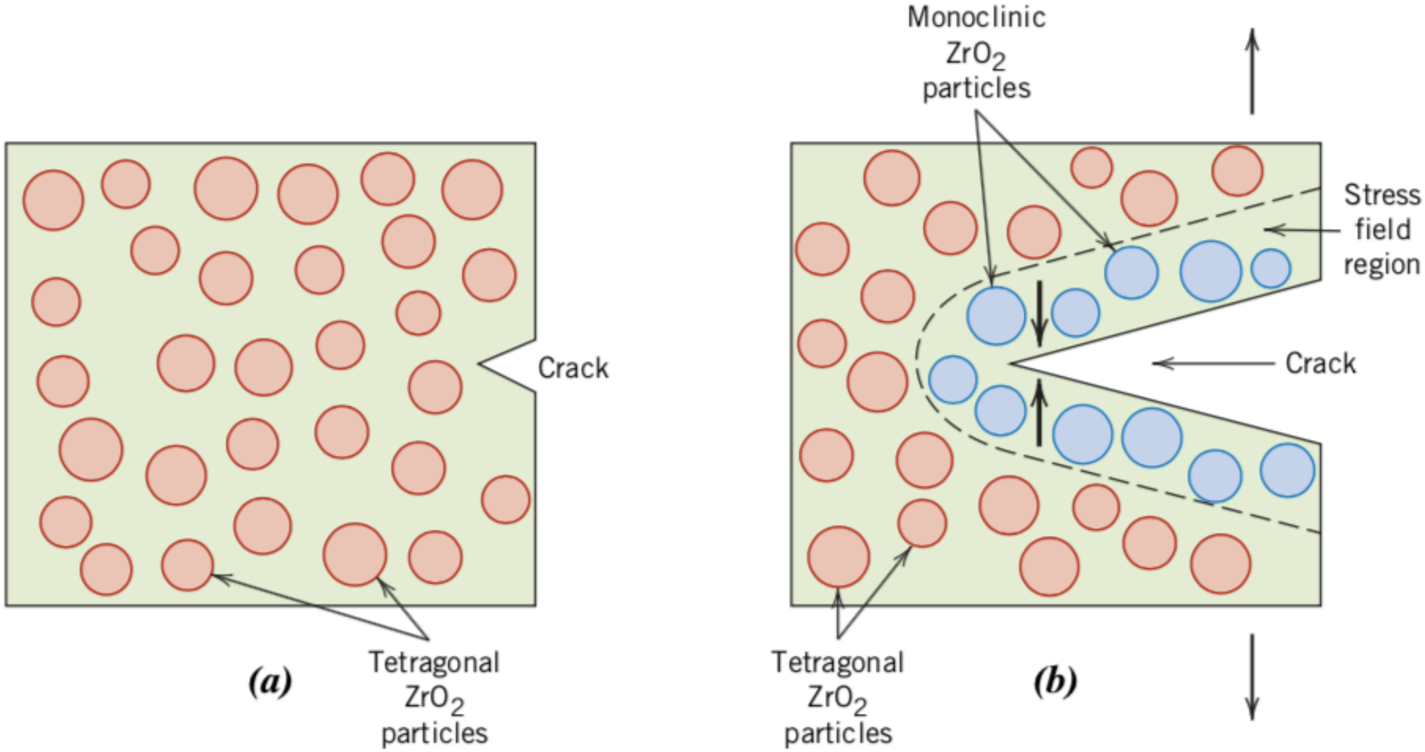


Figure 16.12 Schematic demonstration of transformation toughening. (*a*) A crack prior to inducement of the ZrO_2 particle phase transformation. (*b*) Crack arrestment due to the stress-induced phase transformation.

Fiber-Reinforced Composites / *Processing of Fiber-Reinforced Composites (Pultrusion)*

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

  - Here, continuous-fiber rovings, or tows (loose and untwisted bundle of continuous fibers that are drawn together as parallel strands), 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 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.

Fiber-Reinforced Composites / *Processing of Fiber-Reinforced Composites (Pultrusion)*

- Matrix: polyesters, vinyl esters, and epoxy resins.
- Reinforcement: glass, carbon, and aramid fibers, (40 and 70 vol%).

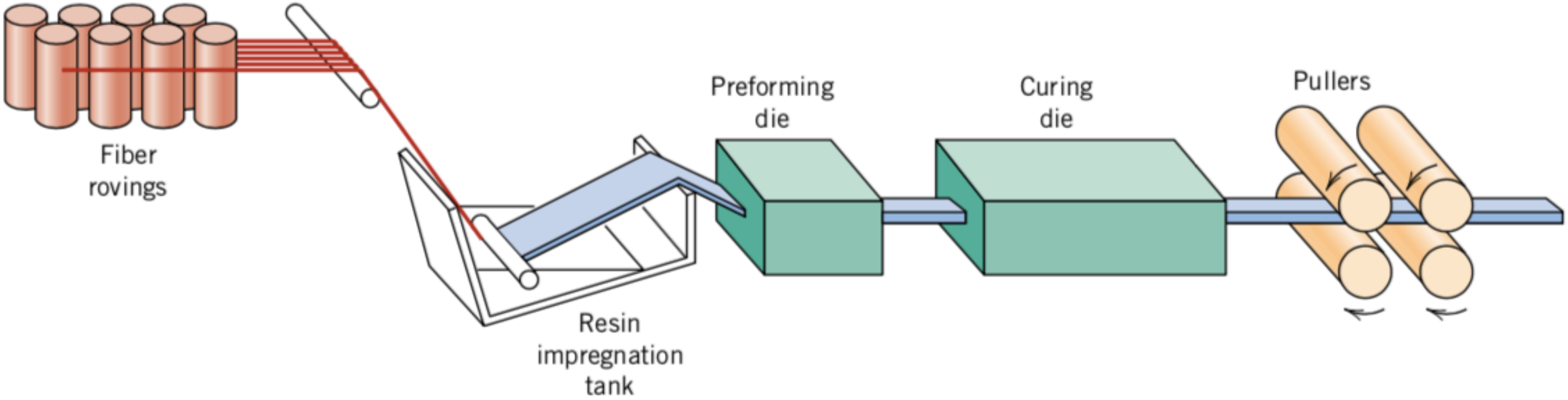


Figure 16.13 Schematic diagram showing the pultrusion process.

Fiber-Reinforced Composites / *Processing of Fiber-Reinforced Composites (Filament Winding)*

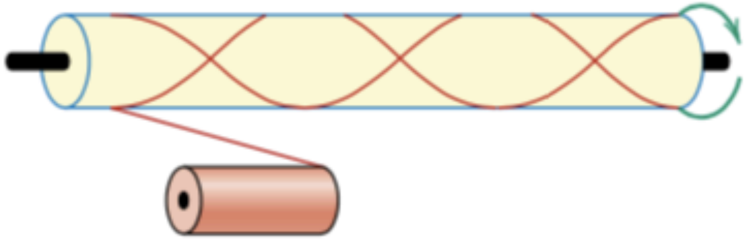
- Filament winding is a process by which continuous reinforcing fibers are accurately positioned in a predetermined pattern to form a hollow (usually cylindrical) shape.

- 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.

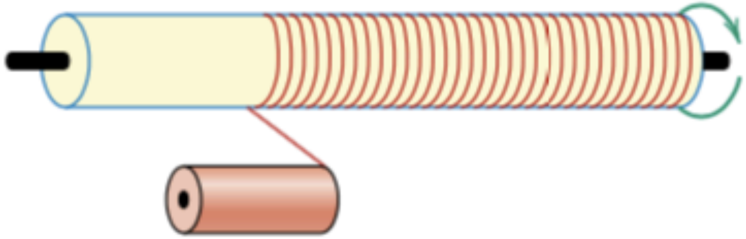
- After the appropriate number of layers have been applied, curing is carried out either in an oven or at room temperature, after which the mandrel is removed.

- Common filament-wound structures include rocket motor casings, storage tanks and pipes, and pressure vessels.

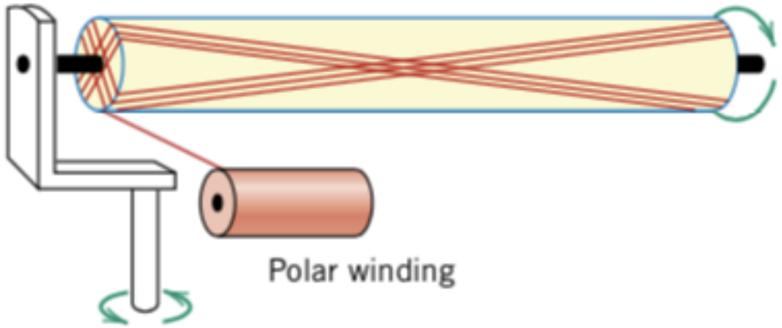
Fiber-Reinforced Composites / *Processing of Fiber-Reinforced Composites (Filament Winding)*



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.]

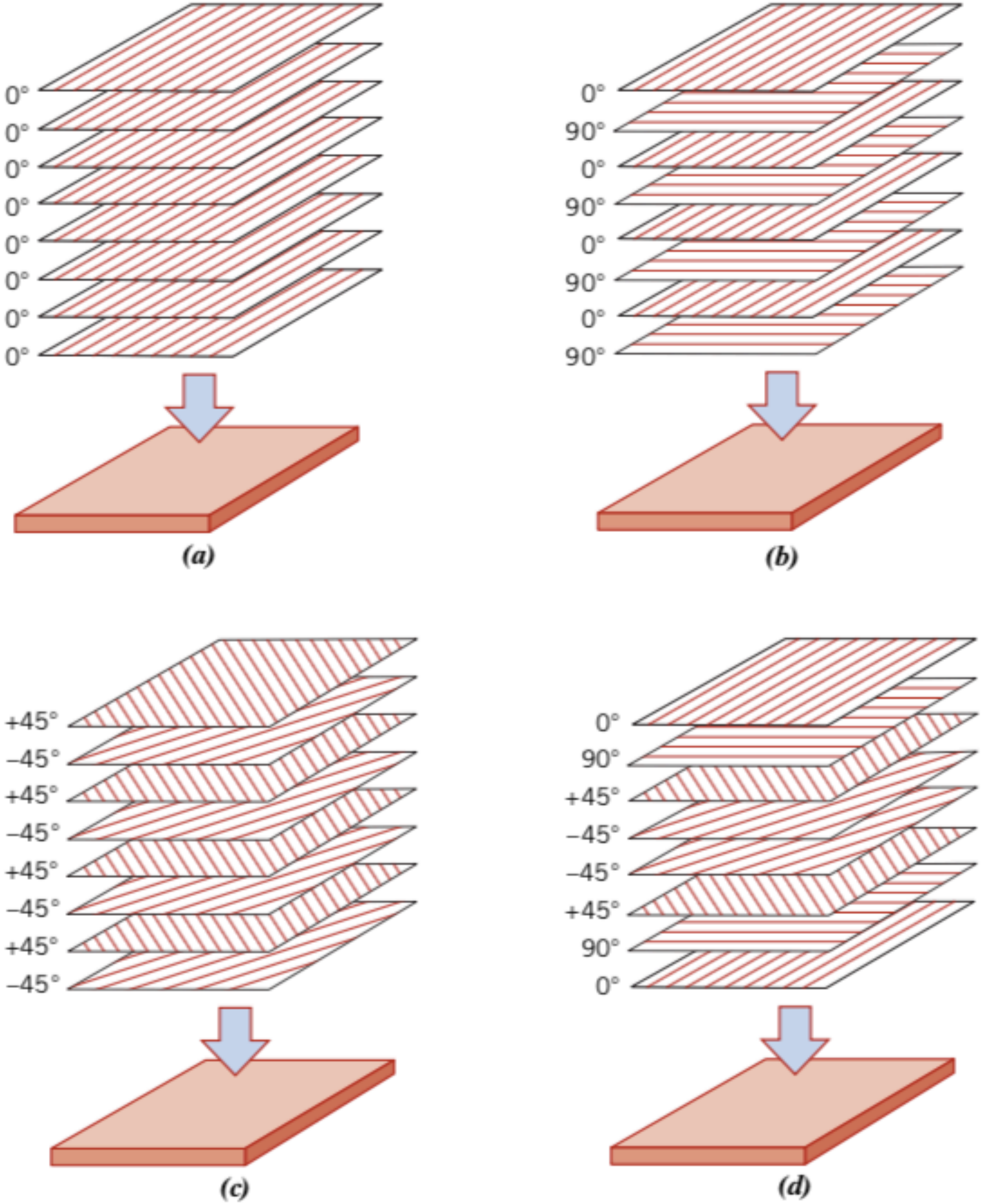
Structural Composites

- A structural composite: a multi-layered and normally low-density composite.
    - Used in applications requiring structural integrity (high tensile, compressive, and torsional strengths and stiffnesses).
- The properties depend on the properties of the constituent materials, and on the geometrical design of the structural elements.
- Two types: Laminar composites and sandwich panels

Structural Composites / *Laminar Composites*

- Composed of two-dimensional sheets or panels (plies or laminae) bonded to one another.
    - Each ply has a preferred high-strength direction.
    - A multi-layered structure such as this is termed a *laminate*.
- Four classes of laminar composites: *unidirectional, cross-ply, angle-ply* and *multidirectional.*
- In-plane properties (e.g., modulus of elasticity and strength) of unidirectional laminates are highly anisotropic. Cross-, angle-, and multidirectional laminates are designed to increase the degree of in-plane isotropy; multidirectional can be fabricated to be most isotropic.

Figure 16.16 Lay-ups (schematics) for laminar composites. (*a*) Undirectional; (*b*) cross-ply; (*c*) angle-ply; and (*d*) multidirectional. (Adapted from *ASM Handbook*, Vol. 21, *Composites*, 2001. Reproduced with permission from ASM International, Materials Park, OH, 44073.)



Structural Composites / *Laminar Composites*

- Most laminate fiber materials are carbon, glass, and aramid.
- Applications that use laminate composites are primarily in aircraft, automotive, marine, and building/civil-infrastructure sectors.
- Specific applications include the following: aircraft— landing-gear, floors, and rotor blades for helicopters; automotive— sports car bodies, and drive shafts; building/civil-infrastructure—bridge components, beams, and roof panels.

Structural Composites / *Sandwich Panels*

- a class of structural composites designed to be lightweight beams or panels having relatively high stiffnesses and strengths.
    - A sandwich panel consists of two outer sheets, faces, or skins that are separated by and adhesively bonded to a thicker core.
        - The outer sheets are made of a relatively stiff and strong material, typically aluminum alloys, steel and stainless steel, fiber-reinforced plastics, and ply- wood;
    - they carry bending loads that are applied to the panel. When a sandwich panel is bent, one face experiences compressive stresses, the other tensile stresses.

Structural Composites / *Sandwich Panels*

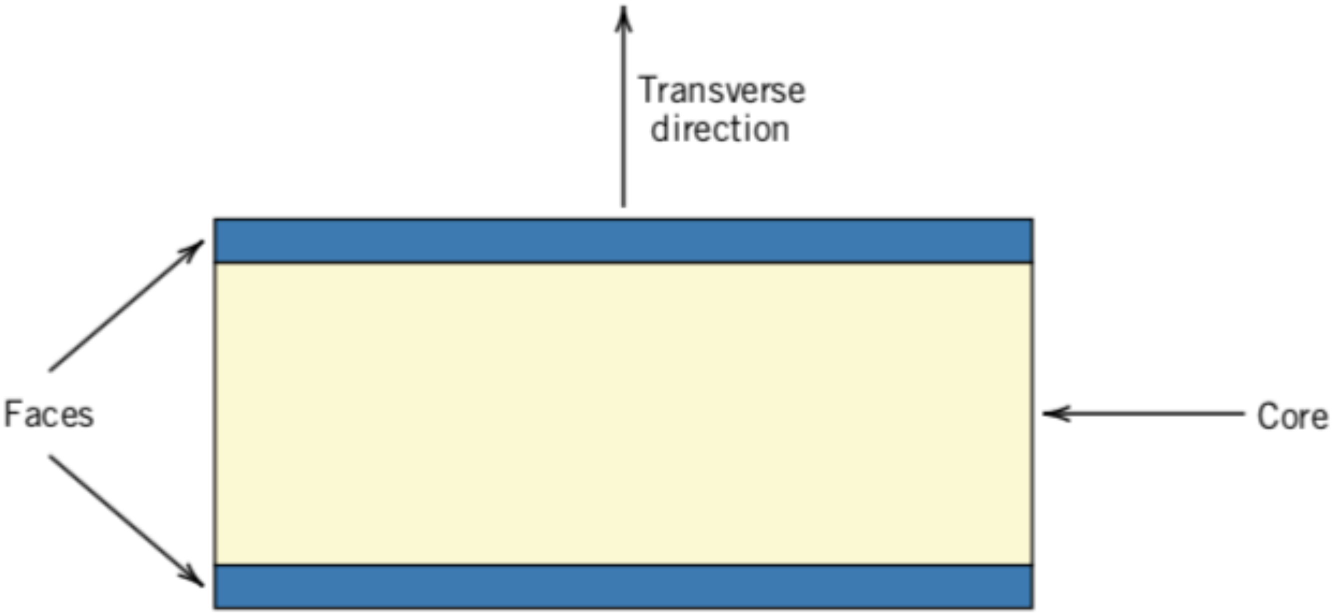


Figure 16.17 Schematic diagram showing the cross section of a sandwich panel.

Structural Composites / *Sandwich Panels*

- The core material is lightweight and normally has a low modulus of elasticity.
  - Structurally, it serves several functions.
    - First, it provides continuous support for the faces and holds them together.
    - In addition, it must have sufficient shear strength to withstand transverse shear stresses.
- Tensile and compressive stresses on the core are much lower than on the faces.
- Panel stiffness depends primarily on the properties of the core material and core thickness; bending stiffness increases significantly with increasing core thickness.

Structural Composites / *Sandwich Panels*

- The sandwich panel is a cost-effective composite because core materials are less expensive than materials used for the faces.

- Core materials typically fall within three categories: rigid polymeric foams, wood, and honeycombs.

    - Both thermoplastic and thermosetting polymers are used as rigid foam materials; these include polystyrene, phenol- formaldehyde (phenolic), polyurethane, poly(vinyl chloride), polypropylene, polyetherimide, and polymethacrylimide.

    - Balsa wood is also commonly used as a core material for several reasons: (1) Its density is extremely low (0.10 to 0.25 g/cm^3), (2) it is relatively inexpensive; and (3) it has relatively high compression and shear strengths.

Structural Composites / *Sandwich Panels*

- Core materials typically fall within three categories: rigid polymeric foams, wood, and honeycombs.
    - Another popular core consists of a “honeycomb” structure—thin foils that have been formed into interlocking cells (having hexagonal as well as other configurations), with axes oriented perpendicular to the face planes.
    - Mechanical properties of honeycombs are anisotropic: tensile and compressive strengths are greatest in a direction parallel to the cell axis; shear strength is highest in the plane of the panel.

Structural Composites / *Sandwich Panels*

- Core materials typically fall within three categories: rigid polymeric foams, wood, and honeycombs.
    - Strength and stiffness of honeycomb structures depend on cell size, cell wall thickness, and the material from which the honeycomb is made.
    - Honeycomb structures also have excellent sound and vibration damping characteristics because of the high volume fraction of void space within each cell.
    - Honeycombs are fabricated from thin sheets. Materials used for these core structures include metal alloys—aluminum, titanium, nickel-based, and stainless steels; and polymers—polypropylene, polyurethane, kraft paper (a tough brown paper used for heavy-duty shopping bags and cardboard), and aramid fibers.

Structural Composites / *Sandwich Panels*

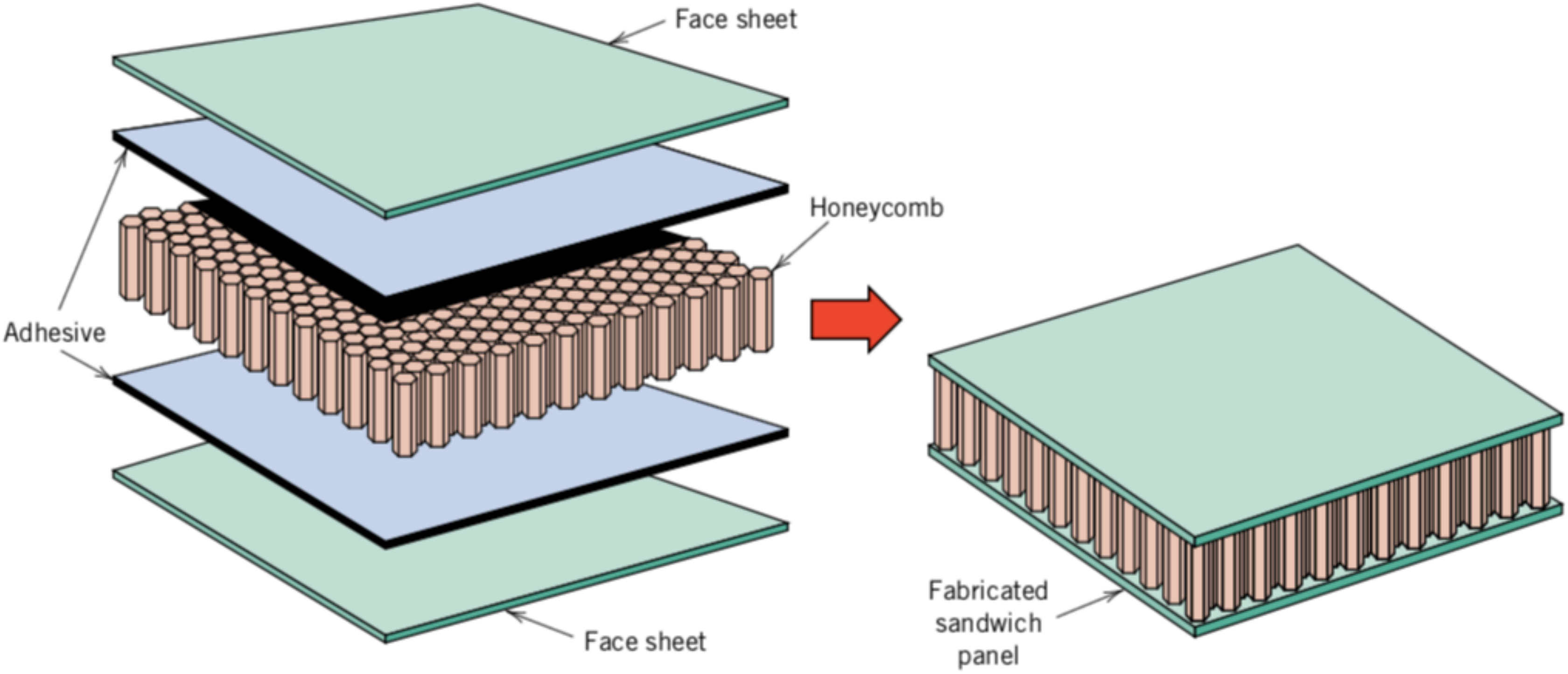


Figure 16.18 Schematic diagram showing the construction of a honeycomb core sandwich panel. (Reprinted with permission from *Engineered Materials Handbook,* Vol. 1, *Composites,* ASM International, Materials Park, OH, 1987.)

Structural Composites / *Sandwich Panels*

- Sandwich panels are used in a wide variety aircraft, construction, automotive, and marine applications,
- Including the following: aircraft—rotor blades for helicopters; construction—decorative facades and interior surfaces, insulated roof and wall systems; automotive—luggage compartment floors, spare wheel covers, and cabin floors; marine—furniture, and wall, ceiling, and partition panels.