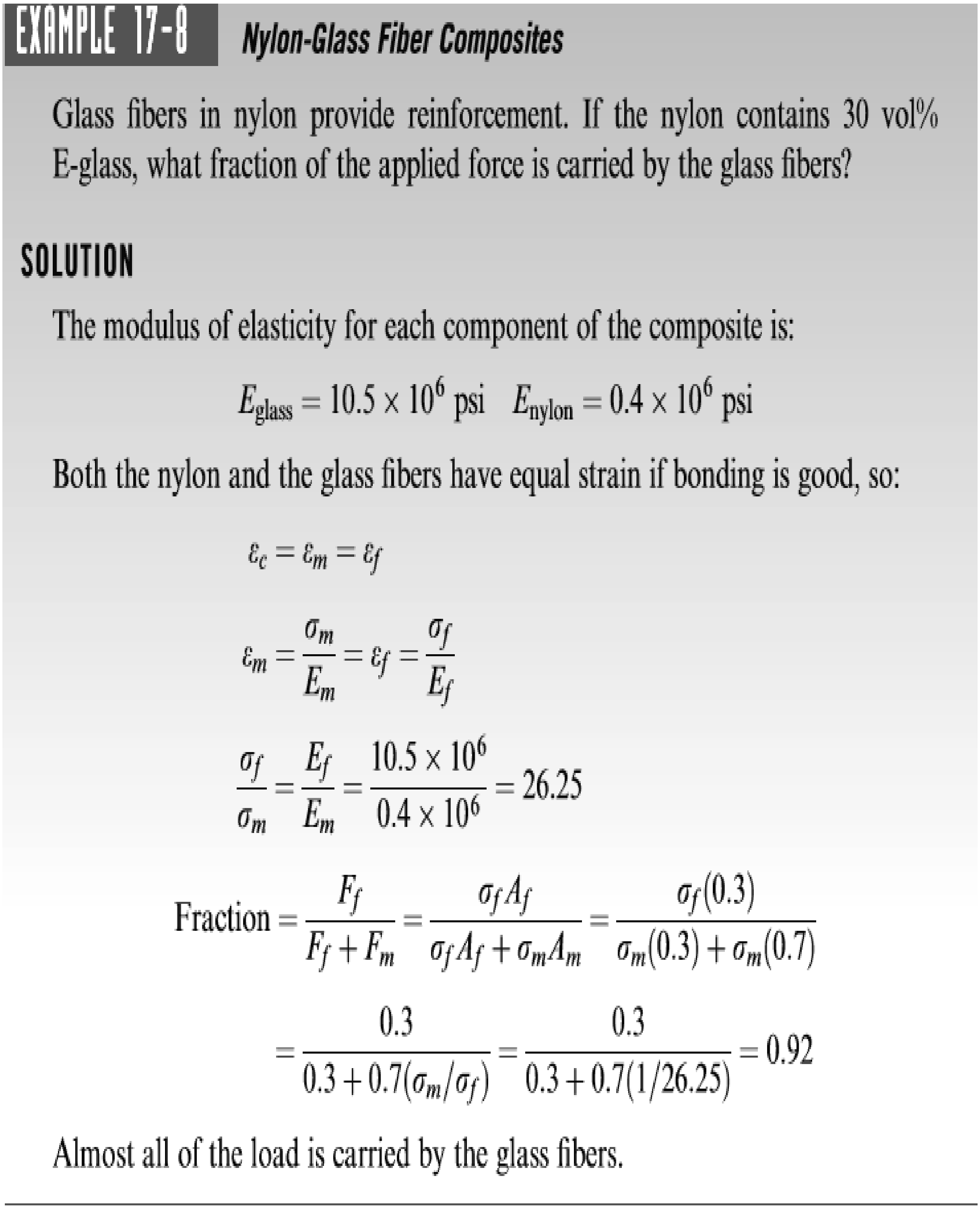
Lecture 4

Fiber-Reinforced Composites



EXAMPLE 17-8 ***Nylon-Glass Fiber Composites***

Glass fibers in nylon provide reinforcement. If the nylon contains 30 vol% E-glass, what fraction of the applied force is carried by the glass fibers?

SOLUTION

The modulus of elasticity for each component of the composite is:

$$E_{\text{glass}} = 10.5 \times 10^6 \text{ psi} \quad E_{\text{nylon}} = 0.4 \times 10^6 \text{ psi}$$

Both the nylon and the glass fibers have equal strain if bonding is good, so:

$$\varepsilon_c = \varepsilon_m = \varepsilon_f$$

$$\varepsilon_m = \frac{\sigma_m}{E_m} = \varepsilon_f = \frac{\sigma_f}{E_f}$$

$$\frac{\sigma_f}{\sigma_m} = \frac{E_f}{E_m} = \frac{10.5 \times 10^6}{0.4 \times 10^6} = 26.25$$

$$\text{Fraction} = \frac{F_f}{F_f + F_m} = \frac{\sigma_f A_f}{\sigma_f A_f + \sigma_m A_m} = \frac{\sigma_f(0.3)}{\sigma_m(0.3) + \sigma_m(0.7)}$$

$$= \frac{0.3}{0.3 + 0.7(\sigma_m/\sigma_f)} = \frac{0.3}{0.3 + 0.7(1/26.25)} = 0.92$$

Almost all of the load is carried by the glass fibers.

Many factors must be considered when designing a fiber-reinforced composite, including the length, diameter, orientation, amount, and properties of the fibers; the properties of the matrix; and the bonding between the fibers and the matrix.

Fiber Length and Diameter Fibers can be short, long, or even continuous. Their dimensions are often characterized by the aspect ratio defined as **l/d**, where l is the fiber length and **d** is the diameter. Typical fibers have diameters varying from 10 μm (10×10^{-4} cm) to 150 μm (150×10^{-4} cm).

The strength of a composite improves when the aspect ratio is large. Fibers often fracture because of surface imperfections. Making the diameter as small as possible gives the fiber less surface area and, consequently, fewer flaws that might propagate during processing or under a load. We also prefer long fibers. The ends of a fiber carry less of the load than the remainder of the fiber; consequently, the fewer the ends, the higher the load-carrying ability of the fibers **(Figure 17-10).**

In many fiber-reinforced systems, discontinuous fibers with an aspect ratio greater than some critical value are used to provide an acceptable compromise between processing ease and properties. A critical fiber length lc, for any given fiber diameter d can be determined:

$$l_c = \frac{TS_f d}{2\tau_i} \qquad (17\text{-}9)$$

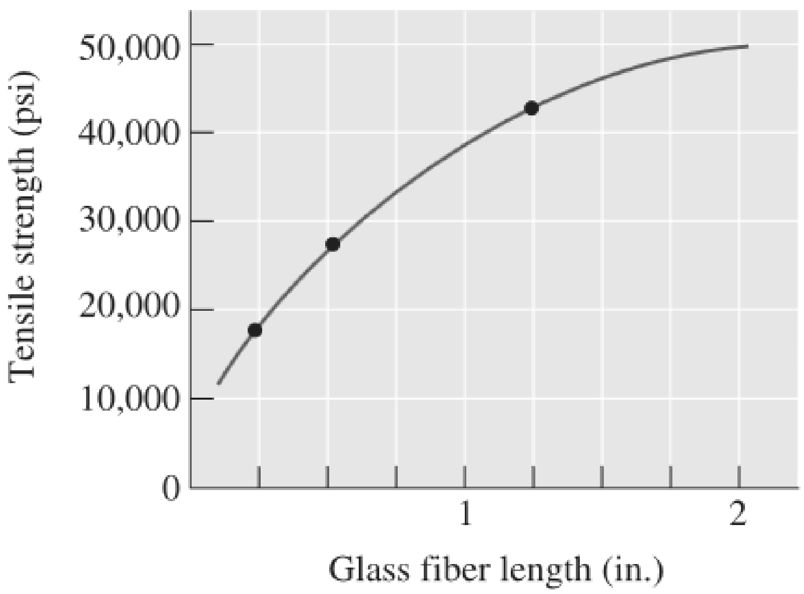


Figure 17-10
Increasing the length of chopped E-glass fibers in an epoxy matrix increases the strength of the composite. In this example, the volume fraction of glass fibers is about 0.5.

where TS_f is the strength of the fiber and τ_i is related to the strength of the bond between the fiber and the matrix, or the stress at which the matrix begins to deform. If the fiber length l is smaller than l_c, little reinforcing effect is observed; if l is greater than about $15l_c$, the fiber behaves almost as if it were continuous. The strength of the composite can be estimated from

$$\sigma_c = f_f TS_f\left(1 - \frac{l_c}{2l}\right) + f_m\sigma_m \tag{17-10}$$

where σ_m is the stress on the matrix when the fibers break.

Volume Fraction of Fiber A greater volume fraction of fibers increases the strength and stiffness of the composite, as we would expect from the rule of mixtures. However, the maximum volume fraction is about 80%, beyond which fibers can no longer be completely surrounded by the matrix.

Orientation of Fibers The reinforcing fibers may be introduced into the matrix in a number of orientations. Short, randomly oriented fibers having a small aspect ratio— typical of fiberglass—are easily introduced into the matrix and give relatively isotropic behavior in the composite.

Long, or even continuous, unidirectional arrangements of fibers produce anisotropic properties, with particularly good strength and stiffness parallel to the fibers. These fibers are often designated as 0□ plies, indicating that all of the fibers are aligned with the direction of the applied stress. However, unidirectional orientations provide poor properties if the load is perpendicular to the fibers **(Figure 17-11).** One of the unique characteristics of fiber-reinforced composites is that their properties can be tailored to meet different types of loading conditions. Long, continuous fibers can be introduced in several directions within the matrix **(Figure 17-12);** in orthogonal arrangements (0°/90° plies), good strength is obtained in two perpendicular directions. More complicated arrangements (such as 0°/- +45°/90° plies) provide reinforcement in multiple directions.

Fibers can also be arranged in three-dimensional patterns. In even the simplest of fabric weaves, the fibers in each individual layer of fabric have some small degree of orientation in a third direction. Better three-dimensional reinforcement occurs when the fabric layers are knitted or stitched together. More complicated three-dimensional weaves **(Figure 17-13)** can also be used.

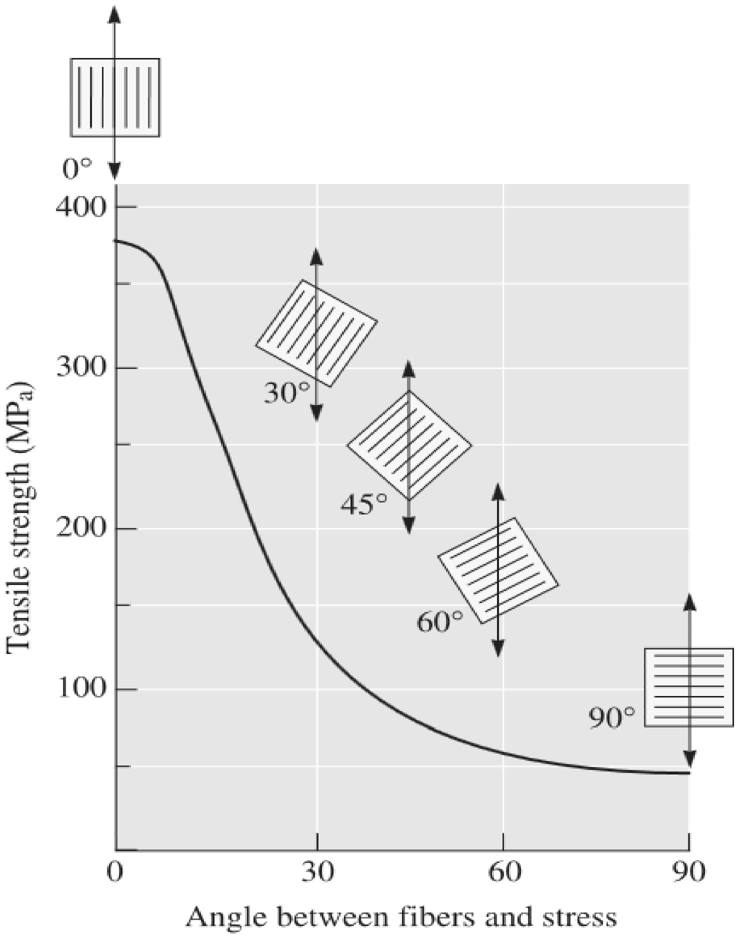


Figure 17-11
Effect of fiber orientation on the tensile strength of E-glass fiber-reinforced epoxy composites.

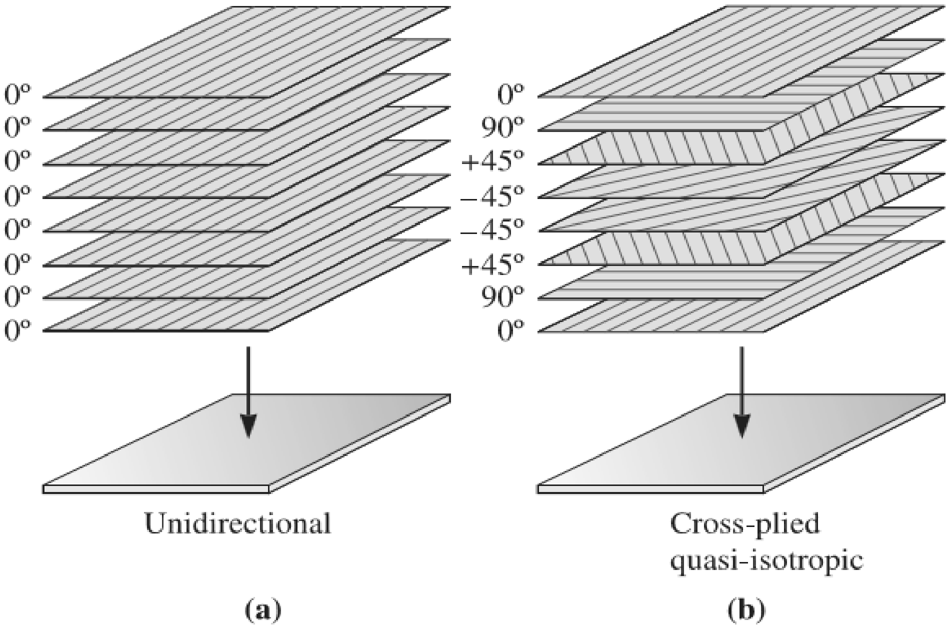


Figure 17-12 (a) Tapes containing aligned fibers can be joined to produce a multi-layered unidirectional composite structure. (b) Tapes containing aligned fibers can be joined with different orientations to produce a quasi-isotropic composite. In this case, a 0°/±45°/90° composite is formed.

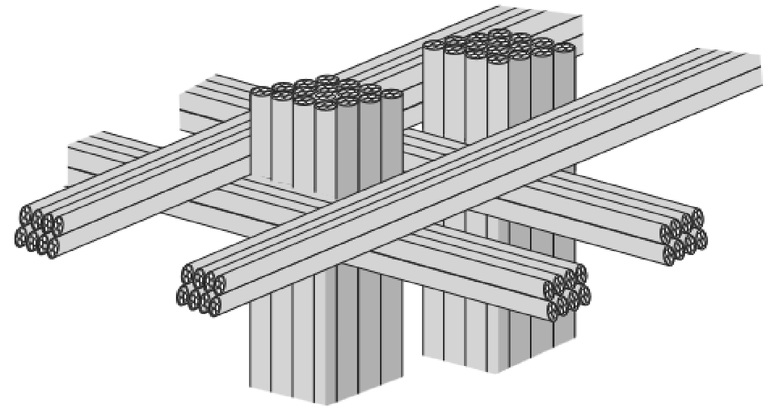


Figure 17-13
A three-dimensional weave for fiber-reinforced composites.

Fiber Properties In most fiber-reinforced composites, the fibers are strong, stiff, and lightweight. If the composite is to be used at elevated temperatures, the fiber should also have a high melting temperature. Thus the **specific strength** and **specific modulus** of the fiber are important characteristics:

$$\text{Specific strength} = \frac{TS}{\rho} \tag{17-11}$$

$$\text{Specific modulus} = \frac{E}{\rho} \tag{17-12}$$

where TS is the tensile strength, ρ is the density, and E is the modulus of elasticity.

Properties of typical fibers are shown in Table 17-2 and Figure 17-14. Note in Table 17-2, the density is in g/cm^3. Also, note that $1\frac{\text{gm}}{\text{cm}^3} = 0.0361\frac{\text{lb}}{\text{in.}^3}$. The highest specific modulus is usually found in materials having a low atomic number and covalent bonding, such as carbon and boron. These two elements also have a high strength and melting temperature.

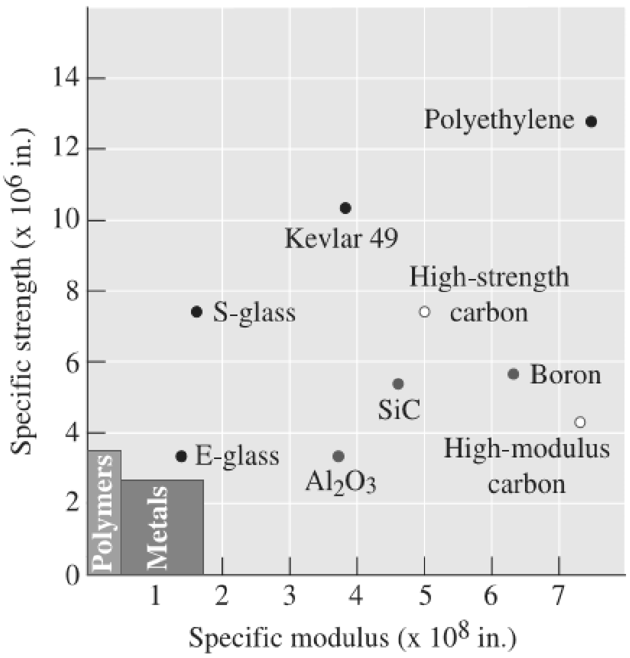


Figure 17-14
Comparison of the specific strength and specific modulus of fibers versus metals and polymers.

TABLE 17-2 ■ ***Properties of selected reinforcing materials****

Material	Density (g/cm^3)	Tensile Strength (ksi)	Modulus of Elasticity (×10^6 psi)	Melting Temperature (°C)	Specific Modulus (×10^7 in.)	Specific Strength (×10^6 in.)
Polymers:						
Kevlar™	1.44	650	18.0	500	34.7	12.5
Nylon	1.14	12	0.5	249	1.0	2.9
Polyethylene	0.97	3–7	0.04–0.1	147	7.1	13.7
Metals:						
Be composites	1.83	40–50	44.0	1277	77.5	2.8
Boron	2.36	500	55.0	2030	64.7	4.7
W	19.40	580	59.0	3410	8.5	0.8
Glass:						
E-glass	2.55	500	10.5	<1725	11.4	5.6
S-glass	2.50	650	12.6	<1725	14.0	7.2
Carbon:						
HS (high strength)	1.75	820	40.0	3700	63.5	13.0
HM (high modulus)	1.90	270	77.0	3700	112.0	3.9
Ceramics:						
Al_2O_3	3.95	300	55.0	2015	38.8	2.1
B_4C	2.36	330	70.0	2450	82.4	3.9
SiC	3.00	570	70.0	2700	47.3	5.3
ZrO_2	4.84	300	50.0	2677	28.6	1.7
Whiskers:						
Al_2O_3	3.96	3000	62.0	1982	43.4	21.0
Cr	7.20	1290	35.0	1890	13.4	4.9
Graphite	1.66	3000	102.0	3700	170.0	50.2
SiC	3.18	3000	70.0	2700	60.8	26.2
Si_3N_4	3.18	2000	55.0		47.8	17.5

$^*1\frac{\text{gm}}{\text{cm}^3} = 0.0361\frac{\text{lb}}{\text{in.}^3}$

Aramid fibers, of which Kevlar™ is the best known example, are aromatic polyamide polymers strengthened by a backbone containing benzene rings (Figure 17-15) and are examples of liquid-crystalline polymers in that the polymer chains are rod-like and very stiff. Specially prepared polyethylene fibers are also available. Both the aramid and polyethylene fibers have excellent strength and stiffness but are limited to low-temperature use. Because of their lower density, polyethylene fibers have superior specific strength and specific modulus.

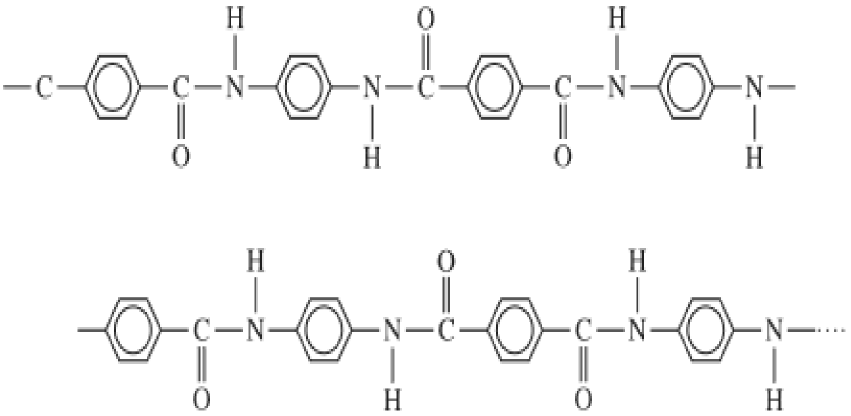


Figure 17-15
The structure of Kevlar™. The fibers are joined by secondary bonds between oxygen and hydrogen atoms on adjoining chains.

Ceramic fibers and whiskers, including alumina, glass, and silicon carbide, are strong and sti¤. Glass fibers, which are the most commonly used, include pure silica, S-glass (25% Al2O3, 100% MgO, balance SiO2), and E-glass (18% CaO, 15% Al2O3, balance SiO2). Although they are considerably denser than the polymer fibers, the ceramics can be used at much higher temperatures. Beryllium and tungsten, although metallically bonded, have a high modulus that makes them attractive fiber materials for certain applications. The following example discusses issues related to designing with composites.