

CHAPTER 10

Composites

WITH COMPOSITE MATERIALS, combinations of properties can be achieved that could not be achieved with individual materials because of the inclusion of reinforcing material. Some examples of composites are concrete, which is a composite of cement, sand, and gravel; steel-belted tires; plywood with alternating directions of fibers; carbon or glass fiber-reinforced polyester; and epoxy used for furniture, boats, and sporting goods. The reinforcing material of composites may be in the form of fibers, particles, or sheet laminates.

Fiber-Reinforced Composites

In fiber-reinforced composites, the reinforcing material is stronger and stiffer than the matrix material. Different geometric arrangements of the fibers are possible. The fibers may be unidirectionally aligned, aligned at 90° to one another in a woven fabric, or randomly oriented (Fig. 10.1). The fibers may be very long or chopped into short segments for easy fabrication. In thick sections, it is possible to have three-dimensional composites with randomly oriented short fibers. Fiber reinforcement is used to impart

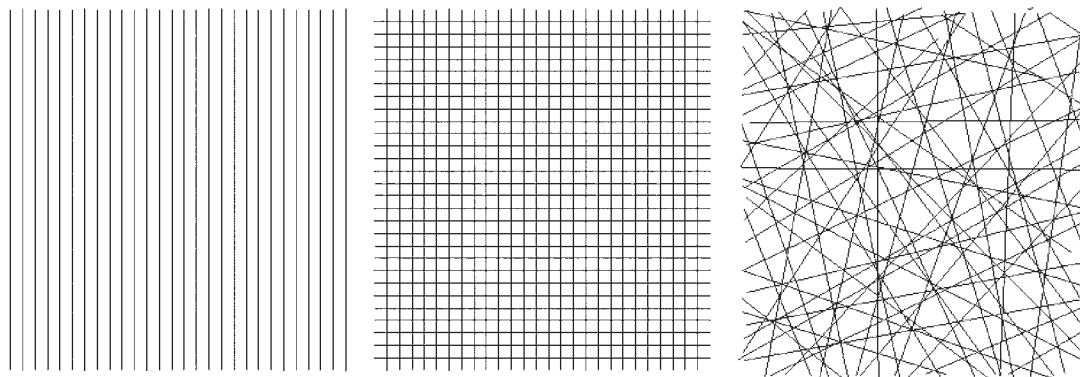


Fig. 10.1 Several geometric arrangements of fiber reinforcements. Source: Ref 10.1

stiffness (increased modulus of elasticity) or strength to the matrix. Fiber reinforcement also increases toughness.

The strains parallel to long parallel fibers must be the same in both the matrix and the fiber, $\epsilon_f = \epsilon_m = \epsilon$. For loading parallel to unidirectionally aligned fibers, the elastic modulus is:

$$E = E_f V_f + E_m V_m$$

where E_f and E_m are the moduli of the fiber material and the matrix, and where V_f and V_m are the volume fractions of fiber and matrix. This often is called the *rule of mixtures*. It is an upper boundary to the elastic modulus of a composite. The modulus is very much lower for loading perpendicular to the fibers. Cross-plyies or randomly oriented fibers give stiffening in other directions. A useful engineering approximation for randomly aligned fibers is:

$$E \approx (3/8)E_{\perp} + (5/8)E_{\parallel}$$

where $E_{\perp}$ and $E_{\parallel}$ are the moduli perpendicular and parallel, respectively, to unidirectional fibers.

The rule of mixtures cannot be used to predict the strengths of composites with uniaxially aligned fibers. The reason can be appreciated by considering the stress-strain behavior of both materials as shown schematically in Fig. 10.2. The strains in the matrix and fibers are equal, thus

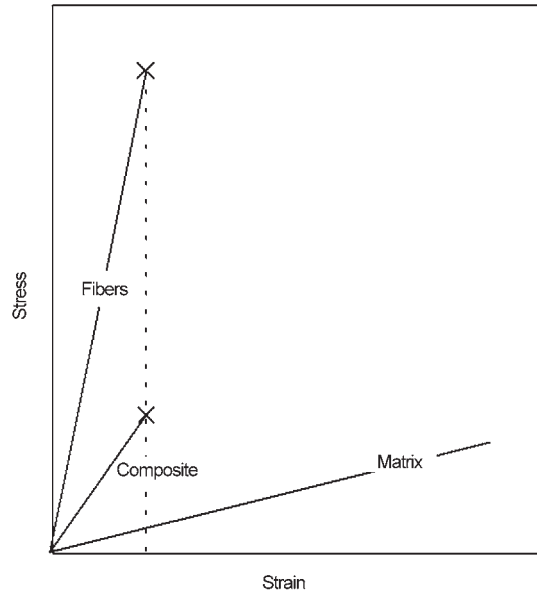


Fig. 10.2 Stress-strain curves for the matrix, the fibers, and the composite. Source: Ref 10.1

the fibers reach their breaking strengths long before the matrix reaches its tensile strength. Thus, the strength of the composite is $UTS < V_m UTS_m + V_f UTS_f$.

Usually the load carried by the fibers is greater than the breaking load of the matrix, so the composite will fail when the fibers break. The composite strength is given by:

$$UTS = V_m \sigma_m + V_f (UTS)_f$$

where $\sigma_m = (E_m/E_f)(UTS)_f$ is the stress carried by the matrix when the fiber fractures.

For composites with low-volume-fraction fibers, the fibers may break at a load less than the failure load of the matrix. In this case, after the fibers break, the whole load must be carried by the matrix, thus the predicted strength is $UTS = V_m (UTS)_m$.

Volume Fraction of Fibers

The stiffness and strength of reinforced composites should increase with the volume fraction of fibers, but there are practical limitations on the volume fraction. Fibers must be separated from one another. Fibers often are precoated to ensure this separation, and to control the bonding between fibers and matrix. Variability in fiber spacing (Fig. 10.3) may result during the infiltration of fiber arrangements by liquid resins. Approximately 55 to 60% is the practical upper limit for volume fraction fibers in unidirectional alignments. It is even lower in woven or cross-ply reinforcement.

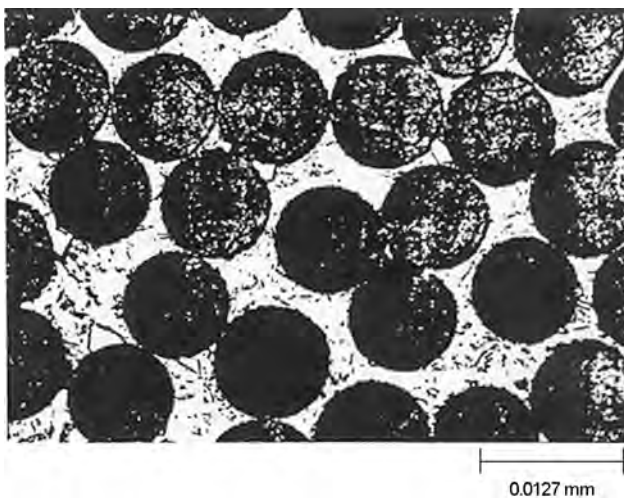


Fig. 10.3 Glass fibers in a polyester matrix. Note the variability in fiber spacing. Source: Ref 10.2

Fiber Length

Fabrication is much simplified if the reinforcement is in the form of chopped fibers. These can be blown onto a surface to form a mat. Shapes can be made with chopped fibers that are impossible with continuous fibers. Examples are extrusions, injection moldings, and transfer moldings. The disadvantage of chopped fibers is that some of the reinforcing effect of the fibers is sacrificed because the average axial stress carried by fibers is less for short ones than long ones. The average axial stress in a fiber depends on its aspect ratio, D/L , where D and L are the diameter and length of the fiber, respectively.

Failure may occur either by the fracture of fibers or by the fibers pulling out of the matrix. Both possibilities are shown in Fig. 10.4. Pullout will occur if the plane of the crack is near the end of the fiber. If it is not near the end, the fiber will fracture. Figure 10.5 is a picture showing the pullout of silicon carbide fibers in a titanium matrix.

More energy is absorbed if fibers pull out than if they break. The energy expended in fiber pullout increases with fiber length up to a critical length and then decreases with further length increase. Often greater toughness can be achieved with shorter fibers and lower fiber-matrix interface strength.

Epoxies and polyesters are common polymer matrices. Most of the polymers used for matrix materials have moduli of 2 to 3 GPa (290 to 435 ksi) and tensile strengths in the range of 35 to 70 MPa (5 to 10 ksi). Fiber rein-

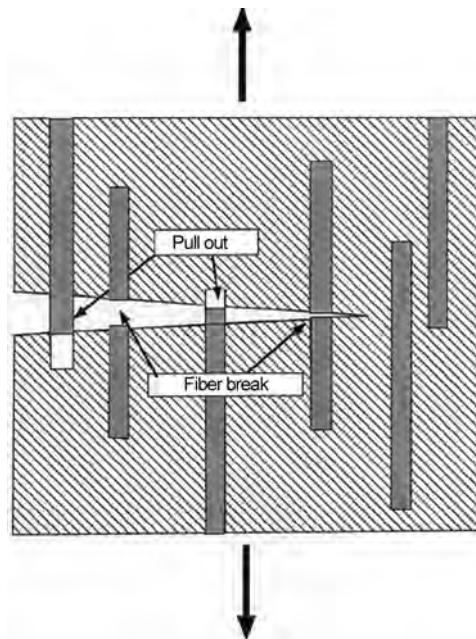


Fig. 10.4 Sketch showing some fibers fracturing at a crack and others pulling out. Source: Ref 10.1

forcements include glass, boron, aramid fiber, and carbon. Properties of some epoxy matrix composite systems are given in Table 10.1. Properties of some commonly used fibers are given in Table 10.2.

Other fiber composites include ceramics reinforced with metal or ceramic fibers. Metals such as aluminum-base alloys may be reinforced with ceramic fibers to increase their stiffness. In some eutectic systems,

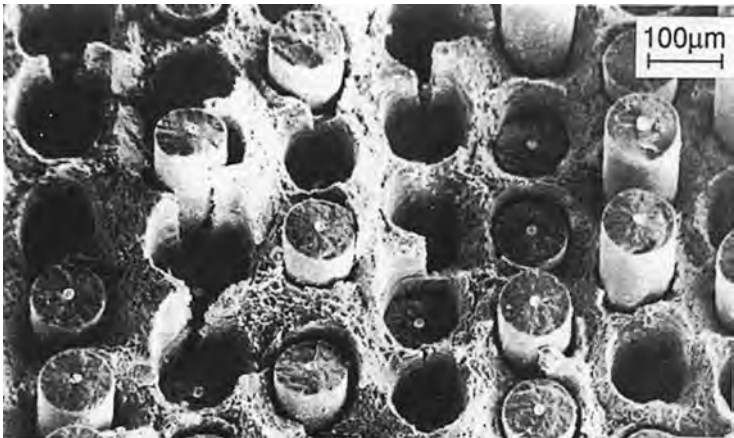


Fig. 10.5 Photograph of SiC fibers pulling out of a titanium matrix. Source: Ref 10.3

Table 10.1 Properties of epoxy matrix composites

Fiber	Fiber, vol%	Young's modulus, GPa (ksi)		Tensile strength, MPa (ksi)	
		Longitudinal	Transverse	Longitudinal	Transverse
E-glass (unidirectional)	60	40 (5,801)	10 (1,450)	780 (113)	28 (4)
E-glass (bidirectional)	35	16.5 (2,393)	16.5 (2,393)	280 (40)	280 (40)
E-glass (chopped matte)	20	7 (1,015)	7 (1,015)	100 (14)	100 (14)
Boron (unidirectional)	60	215 (31,183)	24 (3,480)	1400 (203)	65 (9)
Kevlar29 (unidirectional)	60	50 (7,251)	5 (725)	1350 (195)	...
Kevlar49 (unidirectional)	60	76 (11,022)	6 (870)	1350 (195)	30 (4)
Carbon	62	145 (21,030)	...	1850 (268)	...

Kevlar is a registered tradename of E.I. du Pont de Nemours and Company.

Table 10.2 Typical fiber properties

Fiber	Young's modulus, GPa (ksi)	Tensile strength, MPa (ksi)	Elongation, %
Carbon (PAN* HS)	250 (36,259)	2.7 (0.39)	1.0
Carbon (PAN* HM)	390 (56,564)	2.2 (0.32)	0.5
SiC	70 (10,152)	...	...
Steel	210 (30,457)	2.5 (0.36)	...
E-glass	70 (10,152)	1.75 (0.25)	...
Boron	390 (56,564)	2.0–6.0 (0.29–0.87)	...
Kevlar29	65 (9,427)	2.8 (0.41)	4.0
Kevlar49	125 (18,129)	2.8 (0.41)	2.3
Al ₂ O ₃	379 (54,969)	1.4 (0.20)	...
β-SiC	430 (62,366)	3.5 (0.51)	...

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NOTES OF INTEREST

The use of composites dates back to biblical times. Exodus chapter 5 describes how the Pharaoh forced the Israelites to use straw in making bricks.

The first use of reinforced concrete usually is attributed to Joseph-Louis Lambot in 1448. In 1868 Joseph Monier, a French gardener, patented a design for reinforced garden tubs and later patented reinforced concrete beams and posts for railway and road guardrails.

directional solidification can lead to rods of one phase reinforcing the matrix.

Particulate Composites

Composites reinforced by particles rather than long fibers are called particulate composites and include such diverse materials as concrete (cement matrix with sand and gravel particles) and “carbide tools” with a cobalt-base matrix alloy hardened by tungsten carbide particles.

Lamellar Composites

Two or more sheets of materials bonded together can be considered lamellar composites. Examples of lamellar composites include safety glass, plywood, plated metals, and glazed ceramics. The properties of plywood, such as stiffness and water expansion, are much less *anisotropic* (dependent on direction) than those of the wood itself.

Exercise

1. Fractured Surface of Fiberglass

Break a piece of fiberglass and note the appearance of the fractured surface.

Some glass fibers that have pulled out of the other surface should be visible, like those in Fig. 10.4.

REFERENCES

- 10.1 W.F. Hosford, *Mechanical Behavior of Materials*, Cambridge, 2005
- 10.2 *Composites*, Vol 1, *Engineered Materials Handbook*, ASM International, 1987
- 10.3 T.W. Clyne and P.J. Withers, *An Introduction to Metal Matrix Composites*, Cambridge University Press, 1993