Structural Composite Materials
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CHAPTER 1

Introduction to Composite Materials

A COMPOSITE MATERIAL can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone. In contrast to metallic alloys, each material retains its separate chemical, physical, and mechanical properties. The two constituents are a reinforcement and a matrix. The main advantages of composite materials are their high strength and stiffness, combined with low density, when compared with bulk materials, allowing for a weight reduction in the finished part.

The reinforcing phase provides the strength and stiffness. In most cases, the reinforcement is harder, stronger, and stiffer than the matrix. The reinforcement is usually a fiber or a particulate. Particulate composites have dimensions that are approximately equal in all directions. They may be spherical, platelets, or any other regular or irregular geometry. Particulate composites tend to be much weaker and less stiff than continuous-fiber composites, but they are usually much less expensive. Particulate reinforced composites usually contain less reinforcement (up to 40 to 50 volume percent) due to processing difficulties and brittleness.

A fiber has a length that is much greater than its diameter. The length-to-diameter (l/d) ratio is known as the *aspect ratio* and can vary greatly. Continuous fibers have long aspect ratios, while discontinuous fibers have short aspect ratios. Continuous-fiber composites normally have a preferred orientation, while discontinuous fibers generally have a random orientation. Examples of continuous reinforcements include unidirectional, woven cloth, and helical winding (Fig. 1.1a), while examples of discontinuous reinforcements are chopped fibers and random mat (Fig. 1.1b). Continuous-fiber composites are often made into laminates by stacking single sheets of continuous fibers in different orientations to obtain the desired strength and stiffness properties with fiber volumes as high as 60 to 70 percent. Fibers produce high-strength composites because of their small diameter; they contain far fewer defects (normally surface defects) compared to the material produced in bulk. As a general rule, the smaller the diameter of the fiber, the higher its strength, but often the cost increases as the diameter becomes smaller. In addition, smaller-diameter high-strength fibers have greater flexibility and are more amenable to fabrication processes such as weaving or forming over radii. Typical fibers include glass, aramid, and carbon, which may be continuous or discontinuous.

The continuous phase is the matrix, which is a polymer, metal, or ceramic. Polymers have low strength and stiffness, metals have intermediate strength and stiffness but high ductility, and ceramics have high strength and stiffness but are brittle. The matrix (continuous phase) performs several critical functions, including maintaining the fibers in the proper orientation and spacing and protecting them from abrasion and the environment. In polymer and metal matrix composites that form a strong bond between the fiber and the matrix, the matrix transmits loads from the matrix to the fibers through shear loading at the interface. In ceramic matrix composites, the objective is often to increase the toughness rather than the strength and stiffness; therefore, a low interfacial strength bond is desirable.

The type and quantity of the reinforcement determine the final properties. Figure 1.2 shows that the highest strength and modulus are obtained with continuous-fiber composites. There is a practical limit of about 70 volume percent reinforcement that can be added to form a composite. At higher percentages, there is too little matrix to support the fibers effectively. The theoretical

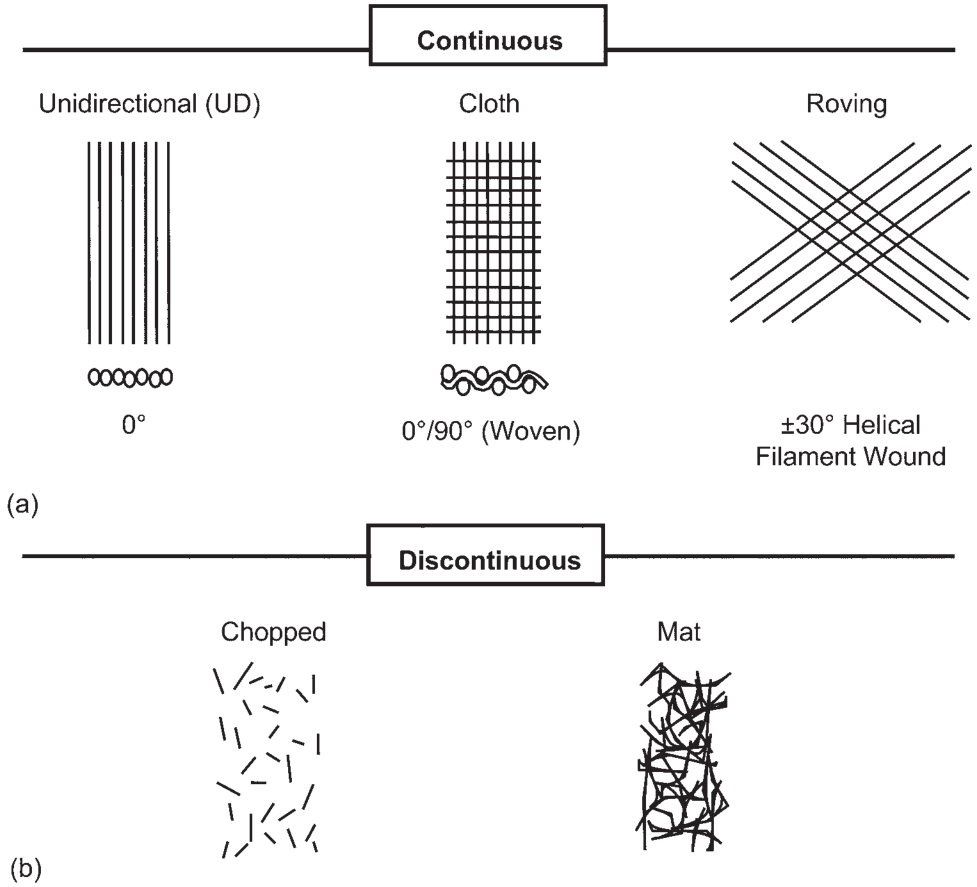


Fig. 1.1 Typical reinforcement types

strength of discontinuous-fiber composites can approach that of continuous-fiber composites if their aspect ratios are great enough and they are aligned, but it is difficult in practice to maintain good alignment with discontinuous fibers. Discontinuous-fiber composites are normally somewhat random in alignment, which dramatically reduces their strength and modulus. However, discontinuous-fiber composites are generally much less costly than continuous-fiber composites. Therefore, continuous-fiber composites are used where higher strength and stiffness are required (but at a higher cost), and discontinuous-fiber composites are used where cost is the main driver and strength and stiffness are less important.

Both the reinforcement type and the matrix affect processing. The major processing routes for polymer matrix composites are shown in Fig. 1.3. Two types of polymer matrices are shown: thermosets and thermoplastics. A thermoset starts as a low-viscosity resin that reacts and cures during processing, forming an intractable solid. A thermoplastic is a high-viscosity resin that is processed by heating it above its melting temperature. Because a thermoset resin sets up and cures during processing, it cannot be reprocessed by reheating. By comparison, a thermoplastic can be reheated above its melting temperature for additional processing. There are processes for both classes of resins that are more amenable to discontinuous fibers and others that are more amenable to continuous fibers. In general, because metal and ceramic matrix composites require very high temperatures and sometimes high pressures for processing, they are normally much more expensive than polymer matrix composites. However, they have much better thermal stability, a requirement in applications where the composite is exposed to high temperatures.

This book will deal with both continuous and discontinuous polymer, metal, and ceramic matrix

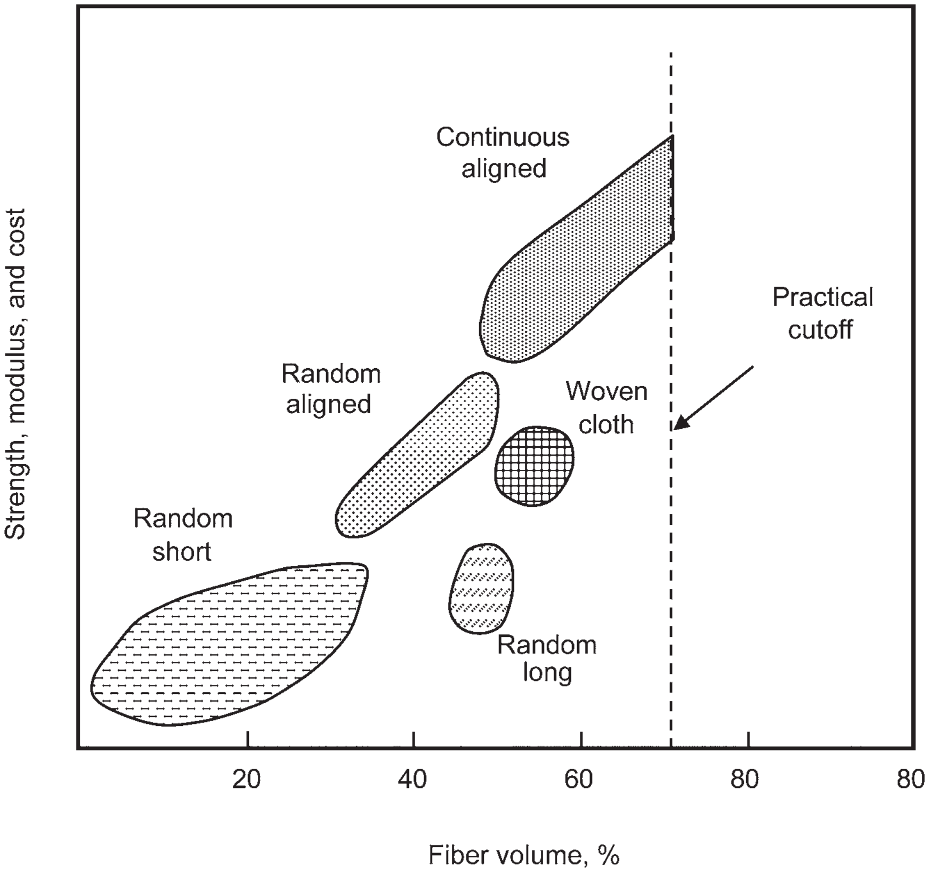


Fig. 1.2 Influence of reinforcement type and quantity on composite performance

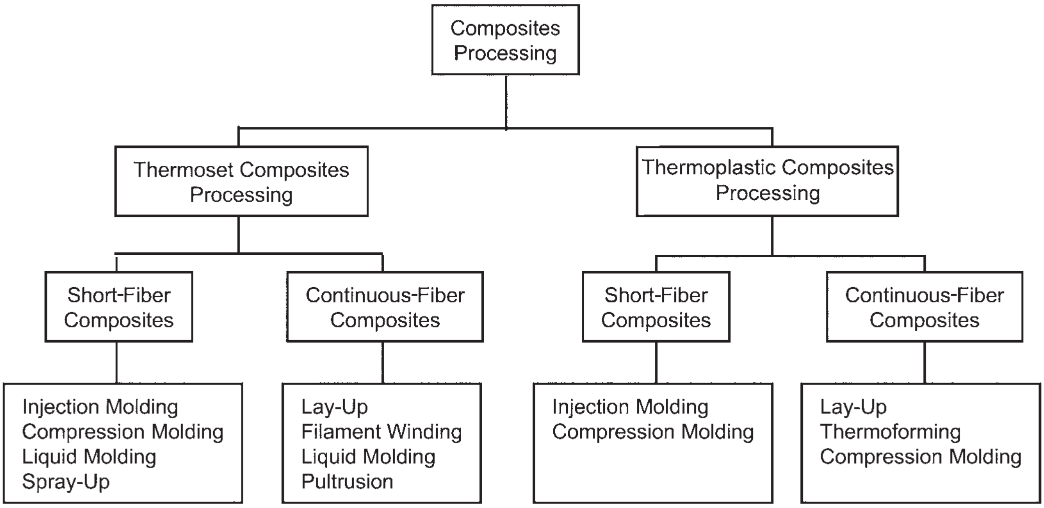


Fig. 1.3 Major polymer matrix composite fabrication processes

composites, with an emphasis on continuous-fiber, high-performance polymer composites.

1.1 Isotropic, Anisotropic, and Orthotropic Materials

Materials can be classified as either isotropic or anisotropic. Isotropic materials have the same material properties in all directions, and normal loads create only normal strains. By comparison, anisotropic materials have different material properties in all directions at a point in the body. There are no material planes of symmetry, and normal loads create both normal strains and shear strains. A material is isotropic if the properties are independent of direction within the material.

For example, consider the element of an isotropic material shown in Fig. 1.4. If the material is loaded along its 0°, 45°, and 90° directions, the modulus of elasticity (E) is the same in each direction ($E_{0°} = E_{45°} = E_{90°}$). However, if the material is anisotropic (for example, the composite ply shown in Fig. 1.5), it has properties that vary with direction within the material. In this example, the moduli are different in each direction ($E_{0°} \neq E_{45°} \neq E_{90°}$). While the modulus of elasticity is used in the example, the same dependence on direction can occur for other material properties, such as ultimate strength, Poisson's ratio, and thermal expansion coefficient.

Bulk materials, such as metals and polymers, are normally treated as isotropic materials, while composites are treated as anisotropic. However, even bulk materials such as metals can become anisotropic—for example, if they are highly cold worked to produce grain alignment in a certain direction.

Consider the unidirectional fiber-reinforced composite ply (also known as a *lamina*) shown in Fig. 1.6. The coordinate system used to describe the ply is labeled the *1-2-3 axes*. In this case, the 1-axis is defined to be parallel to the fibers (0°), the 2-axis is defined to lie within the plane of the plate and is perpendicular to the fibers (90°), and the 3-axis is defined to be normal

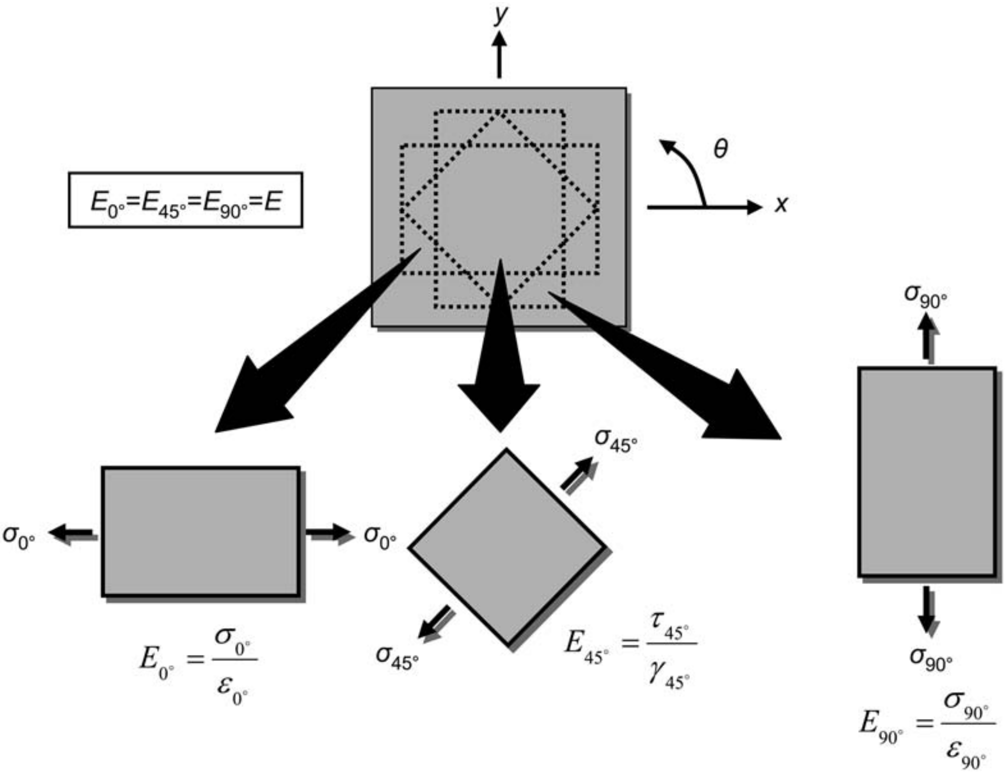


Fig. 1.4 Element of isotropic material under stress

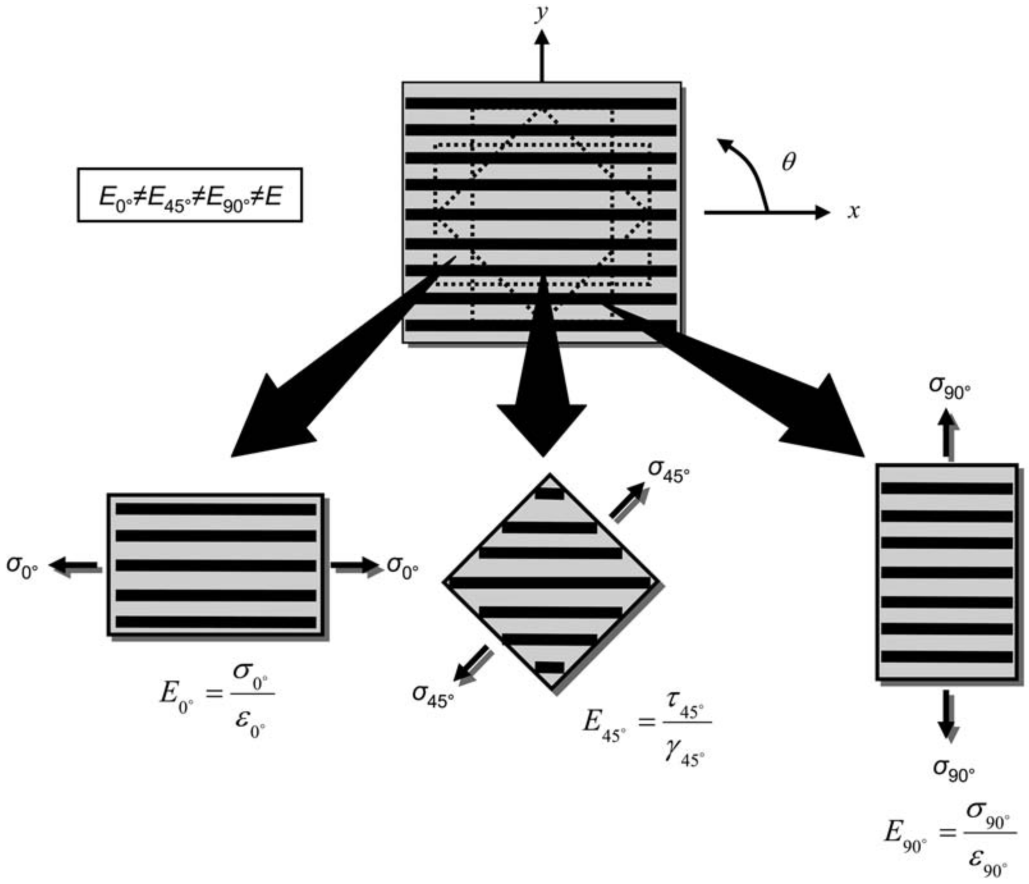
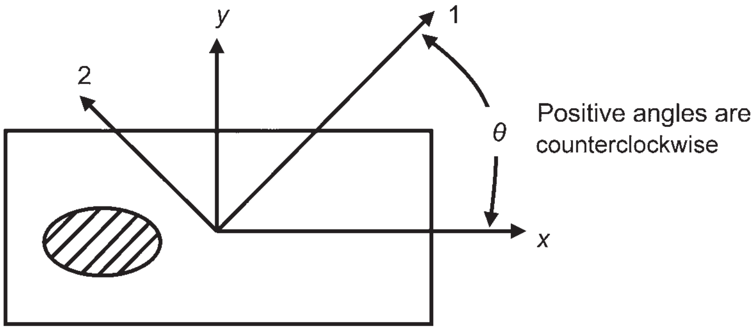


Fig. 1.5 Element of composite ply material under stress



Ply coordinate system:
1-axis is parallel to the fiber direction.
2-axis is perpendicular to the fiber direction.
3-axis is normal to the plane of the ply.

Fig. 1.6 Ply angle definition

to the plane of the plate. The 1-2-3 coordinate system is referred to as the *principal material coordinate system*. If the plate is loaded parallel to the fibers (one- or zero-degree direction), the modulus of elasticity E_{11} approaches that of the fibers. If the plate is loaded perpendicular to the fibers in the two- or 90-degree direction, the modulus E_{22} is much lower, approaching that of the relatively less stiff matrix. Since $E_{11} >> E_{22}$ and the modulus varies with direction within the material, the material is anisotropic.

Composites are a subclass of anisotropic materials that are classified as orthotropic. Orthotropic materials have properties that are different in three mutually perpendicular directions. They have three mutually perpendicular axes of symmetry, and a load applied parallel to these axes produces only normal strains. However, loads that are not applied parallel to these axes produce both normal and shear strains. Therefore, orthotropic mechanical properties are a function of orientation.

Consider the unidirectional composite shown in the upper portion of Fig. 1.7, where the unidirectional fibers are oriented at an angle of 45 degrees with respect to the *x*-axis. In the small, isolated square element from the gage region, because the element is initially square (in this example), the fibers are parallel to diagonal AD of the element. In contrast, fibers are perpendicular to diagonal BC. This implies that the element is stiffer along diagonal AD than along diagonal BC. When a tensile stress is applied, the square element deforms. Because the stiffness is higher along diagonal AD than along diagonal BC, the length of diagonal AD is not increased as much as that of diagonal BC. Therefore, the initially square element deforms into the shape of a parallelogram. Because the element has been distorted into a parallelogram, a shear strain γ_{xy} is induced as a result of coupling between the axial strains ε_{xx} and ε_{yy}.

If the fibers are aligned parallel to the direction of applied stress, as in the lower portion of

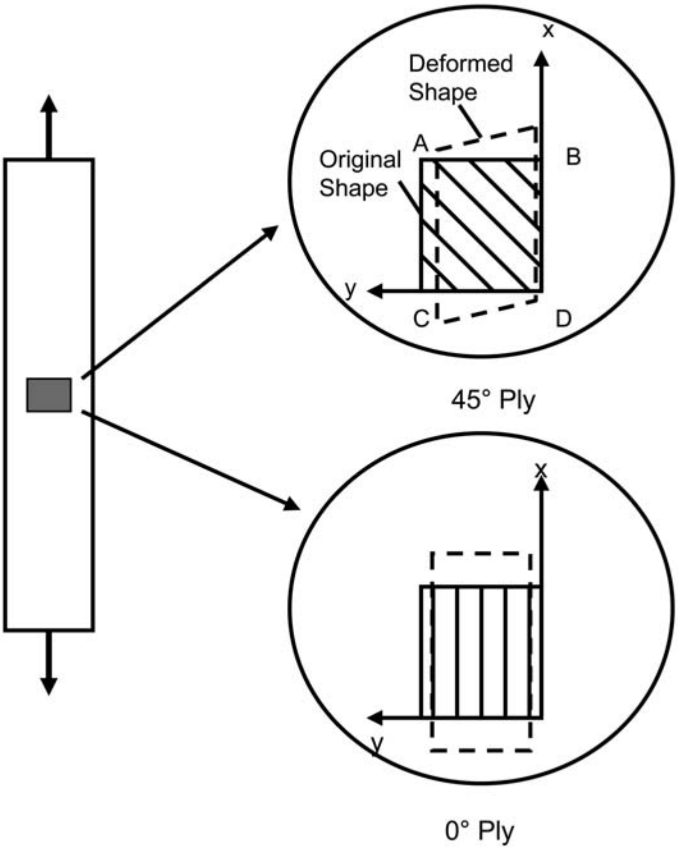


Fig. 1.7 Shear coupling in a 45° ply. Source: Ref 1

Fig. 1.7, the coupling between ε_{xx} and ε_{yy} does not occur. In this case, the application of a tensile stress produces elongation in the *x*-direction and contraction in the *y*-direction, and the distorted element remains rectangular. Therefore, the coupling effects exhibited by composites occur only if stress and strain are referenced to a non–principal material coordinate system. Thus, when the fibers are aligned parallel (0°) or perpendicular (90°) to the direction of applied stress, the lamina is known as a *specially orthotropic lamina* ($\theta = 0°$ or 90°). A lamina that is not aligned parallel or perpendicular to the direction of applied stress is called a *general orthotropic lamina* ($\theta \neq 0°$ or 90°).

1.2 Laminates

When there is a single ply or a lay-up in which all of the layers or plies are stacked in the same orientation, the lay-up is called a *lamina*. When the plies are stacked at various angles, the lay-up is called a *laminate*. Continuous-fiber composites are normally laminated materials (Fig. 1.8) in which the individual layers, plies, or laminae are oriented in directions that will enhance the strength in the primary load direction. Unidirectional (0°) laminae are extremely strong and stiff in the 0° direction. However, they are very weak in the 90° direction because the load must be carried by the much weaker polymeric matrix. While a high-strength fiber can have a tensile strength of 500 ksi (3500 MPa) or more, a typical polymeric matrix normally has a tensile strength of only 5 to 10 ksi (35 to 70 MPa) (Fig. 1.9). The longitudinal tension and compression loads are carried by the fibers, while the matrix distributes the loads between the fibers in tension and stabilizes the fibers and prevents them from buckling in compression. The matrix is also the primary load carrier for interlaminar shear (i.e., shear between the layers) and transverse (90°) tension. The relative roles of the fiber and the matrix in detemining mechanical properties are summarized in Table 1.1.

Because the fiber orientation directly impacts mechanical properties, it seems logical to orient

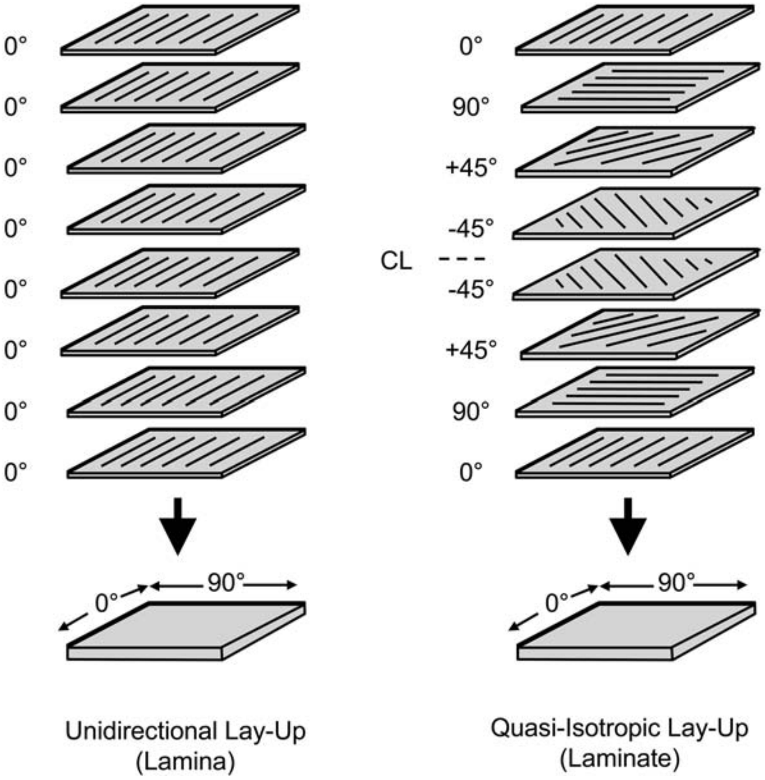


Fig. 1.8 Lamina and laminate lay-ups

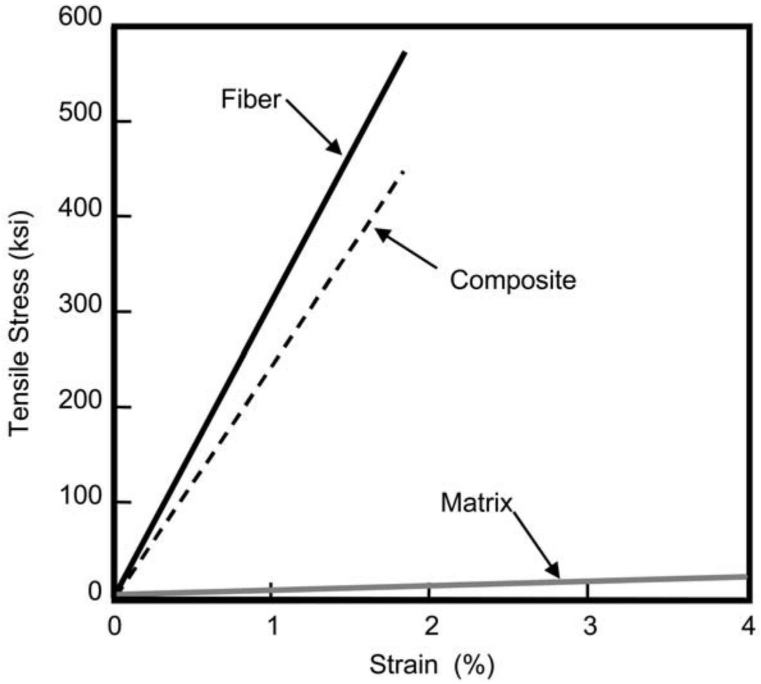


Fig. 1.9 Comparison of tensile properties of fiber, matrix, and composite

Table 1.1 Effect of fiber and matrix on mechanical properties

	Dominating composite constituent	
Mechanical property	Fiber	Matrix
Unidirectional		
0º tension	√	…
0º compression	√	√
Shear	…	√
90º tension	…	√
Laminate		
Tension	√	…
Compression	√	√
In-plane shear	√	√
Interlaminar shear	…	√

as many of the layers as possible in the main load-carrying direction. While this approach may work for some structures, it is usually necessary to balance the load-carrying capability in a number of different directions, such as the 0°, +45°, –45°, and 90° directions. Figure 1.10 shows a photomicrograph of a cross-plied continuous carbon fiber/epoxy laminate. A balanced laminate having equal numbers of plies in the 0°, +45°, –45°, and 90° degrees directions is called a *quasi-isotropic laminate*, because it carries equal loads in all four directions.

1.3 Fundamental Property Relationships

When a unidirectional continuous-fiber lamina or laminate (Fig. 1.11) is loaded in a direction parallel to its fibers (0° or 11-direction), the longitudinal modulus E_{11} can be estimated from its constituent properties by using what is known as the *rule of mixtures*:

$$E_{11} = E_f V_f + E_m V_m \quad \text{(Eq 1.1)}$$

where E_f is the fiber modulus, V_f is the fiber volume percentage, E_m is the matrix modulus, and V_m is the matrix volume percentage.

The longitudinal tensile strength σ_{11} also can be estimated by the rule of mixtures:

$$\sigma_{11} = \sigma V_f + \sigma_m V_m \quad \text{(Eq 1.2)}$$

where σ_f and σ_m are the ultimate fiber and matrix strengths, respectively. Because the properties of the fiber dominate for all practical volume percentages, the values of the matrix can often be ignored; therefore:

$$E_{11} \approx E_f V_f \quad \text{(Eq 1.3)}$$

$$\sigma_{11} \approx \sigma V_f \quad \text{(Eq 1.4)}$$

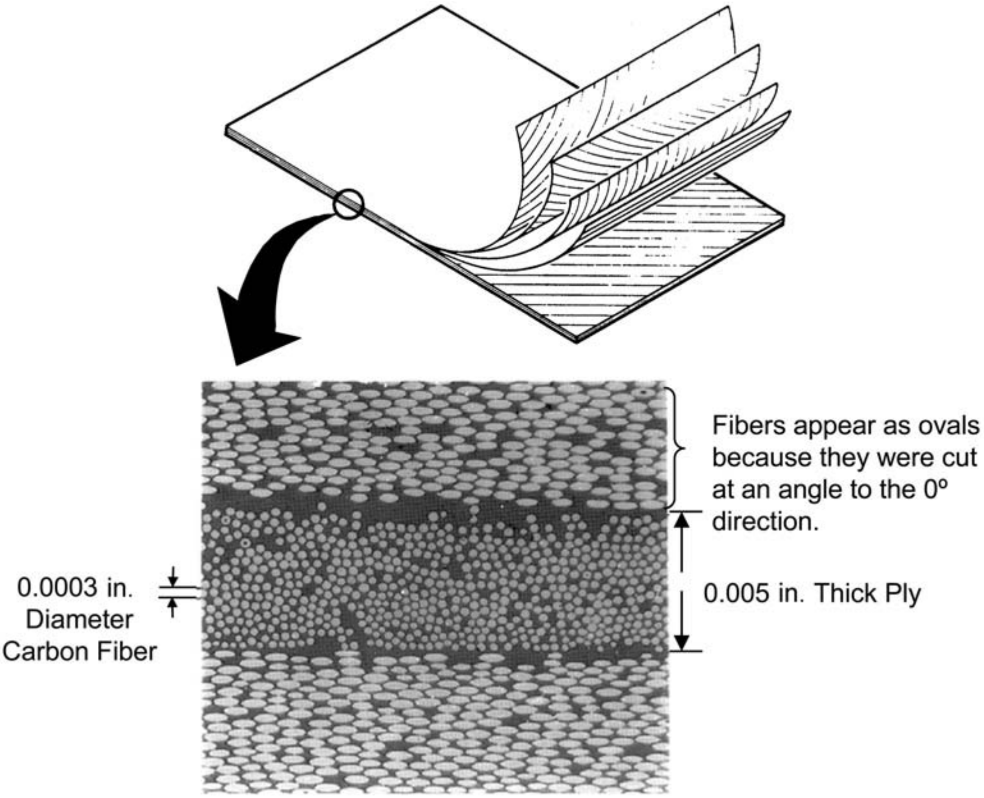


Fig. 1.10 Cross section of a cross-plied carbon/epoxy laminate

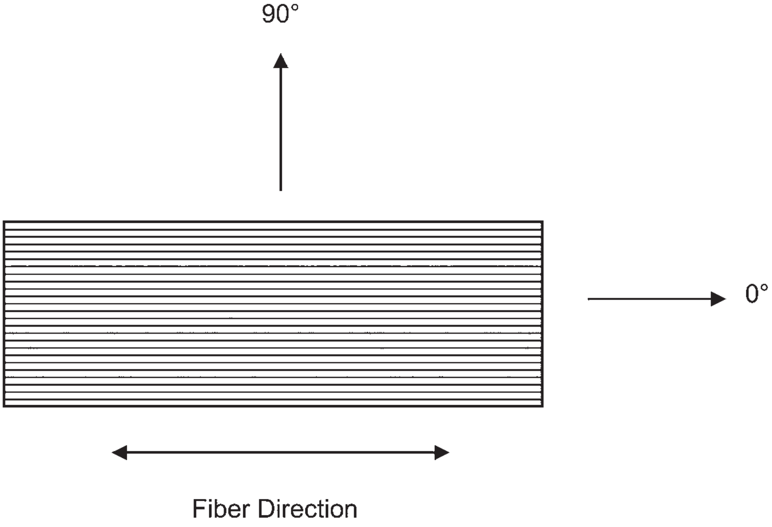


Fig. 1.11 Unidirectional continuous-fiber lamina or laminate

Figure 1.12 shows the dominant role of the fibers in determining strength and stiffness. When loads are parallel to the fibers (0°), the ply is much stronger and stiffer than when loads are transverse (90°) to the fiber direction. There is a dramatic decrease in strength and stiffness resulting from only a few degrees of misalignment off of 0°.

When the lamina shown in Fig. 1.11 is loaded in the transverse (90° or 22-direction), the fibers and the matrix function in series, with both carrying the same load. The transverse modulus of elasticity E_{22} is given as:

$$1/E_{22} = V_f/E_f + V_m/E_m \quad \text{(Eq 1.5)}$$

Figure 1.13 shows the variation of modulus as a function of fiber volume percentage. When the fiber percentage is zero, the modulus is essentially the modulus of the polymer, which increases up to 100 percent (where it is the modulus of the fiber). At all other fiber volumes, the E_{22} or 90° modulus is lower than the E_{11} or zero degrees modulus, because it is dependent on the much weaker matrix.

Other rule of mixture expressions for lamina properties include those for the Poisson's ratio ν_{12} and for the shear modulus G_{12}:

$$\nu_{12} = \nu_f V_f + \nu_m V_m \quad \text{(Eq 1.6)}$$

$$1/G_{12} = V_f/G_f + V_m/G_m \quad \text{(Eq 1.7)}$$

These expressions are somewhat less useful than the previous ones, because the values for Poisson's ratio (ν_f) and the shear modulus (G_f) of the fibers are usually not readily available.

Physical properties, such as density (ρ), can also be expressed using rule of mixture relations:

$$\rho_{12} = \rho_f V_f + \rho_m V_m \quad \text{(Eq 1.8)}$$

While these micromechanics equations are useful for a first estimation of lamina properties when no data are available, they generally do not yield sufficiently accurate values for design purposes. For design purposes, basic lamina and laminate properties should be determined using actual mechanical property testing.

1.4 Composites versus Metallics

As previously discussed, the physical characteristics of composites and metals are significantly different. Table 1.2 compares some properties of composites and metals. Because composites are highly anisotropic, their in-plane strength and

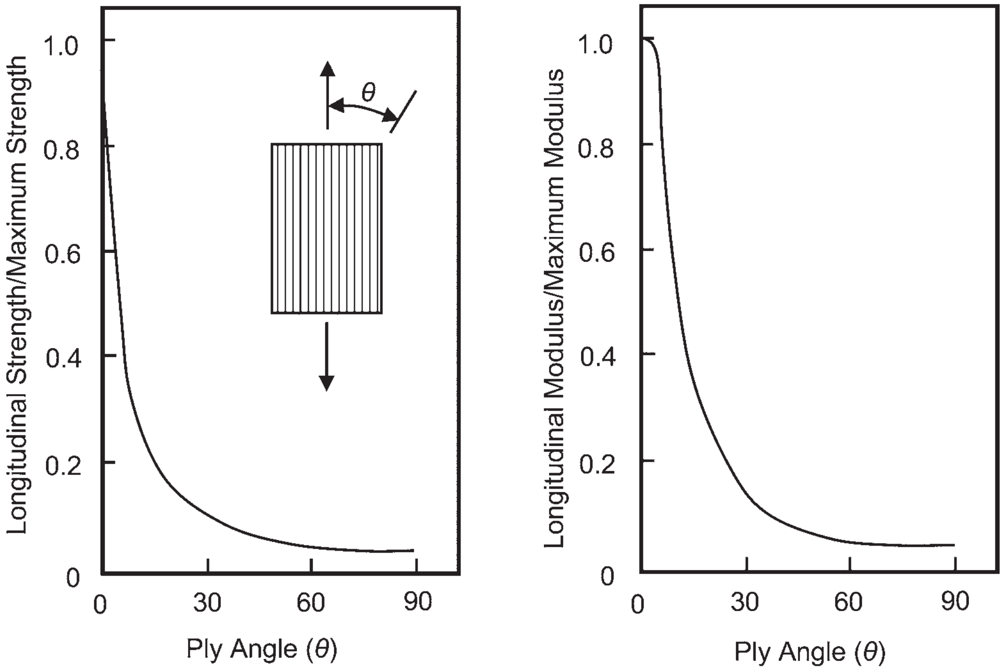


Fig. 1.12 Influence of ply angle on strength and modulus

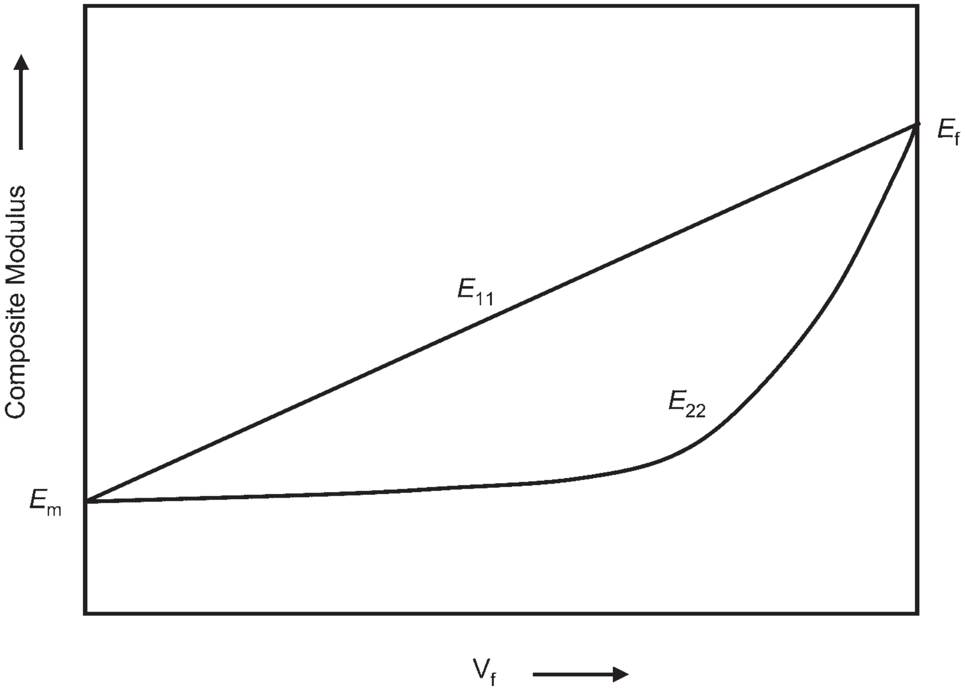


Fig. 1.13 Variation of composite modulus of a unidirectional 0° lamina as a function of fiber volume fraction

Table 1.2 Composites versus metals comparison

Condition	Comparative behavior relative to metals
Load-strain relationship	More linear strain to failure
Notch sensitivity	
Static	Greater sensitivity
Fatigue	Less sensitivity
Transverse properties	Weaker
Mechanical property variability	Higher
Fatigue strength	Higher
Sensitivity to hydrothermal environment	Greater
Sensitivity to corrosion	Much less
Damage growth mechanism	In-plane delamination instead of through thickness cracks

Source: Ref 2

stiffness are usually high and directionally variable, depending on the orientation of the reinforcing fibers. Properties that do not benefit from this reinforcement (at least for polymer matrix composites) are comparatively low in strength and stiffness—for example, the through-the-thickness tensile strength where the relatively weak matrix is loaded rather than the high-strength fibers. Figure 1.14 shows the low through-the-thickness strength of a typical composite laminate compared with aluminum.

Metals typically have reasonable ductility, continuing to elongate or compress considerably when they reach a certain load (through yielding) without picking up more load and without failure. Two important benefits of this ductile yielding are that (1) it provides for local load relief by distributing excess load to an adjacent material or structure; therefore, ductile metals have a great capacity to provide relief from stress concentrations when statically loaded; and (2) it provides great energy-absorbing capability (indicated by the area under a stress-strain curve). As a result, when impacted, a metal structure typically deforms but does not actually fracture. In contrast, composites are relatively brittle. Figure 1.15 shows a comparison of typical tensile stress-strain curves for two materials. The brittleness of the composite is reflected in its poor ability to tolerate stress concentrations, as shown in Fig. 1.16. The characteristically brittle composite material has poor ability to resist impact damage without extensive internal matrix fracturing.

The response of damaged composites to cyclic loading is also significantly different from that of metals. The ability of composites to withstand cyclic loading is far superior to that of metals, in contrast to the poor composite static strength when it has damage or defects. Figure 1.17

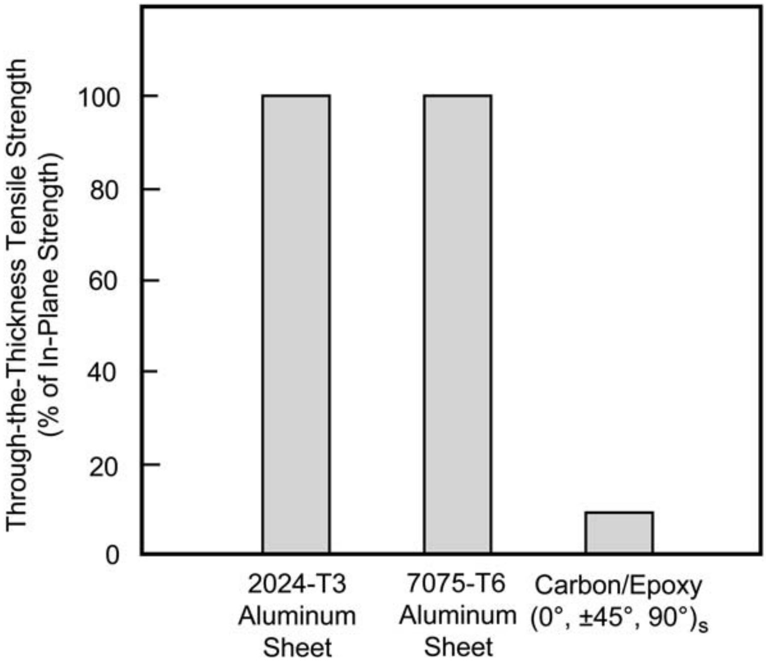


Fig. 1.14 Comparison of through-the-thickness tensile strength of a composite laminate with aluminum alloy sheet. Source: Ref 3

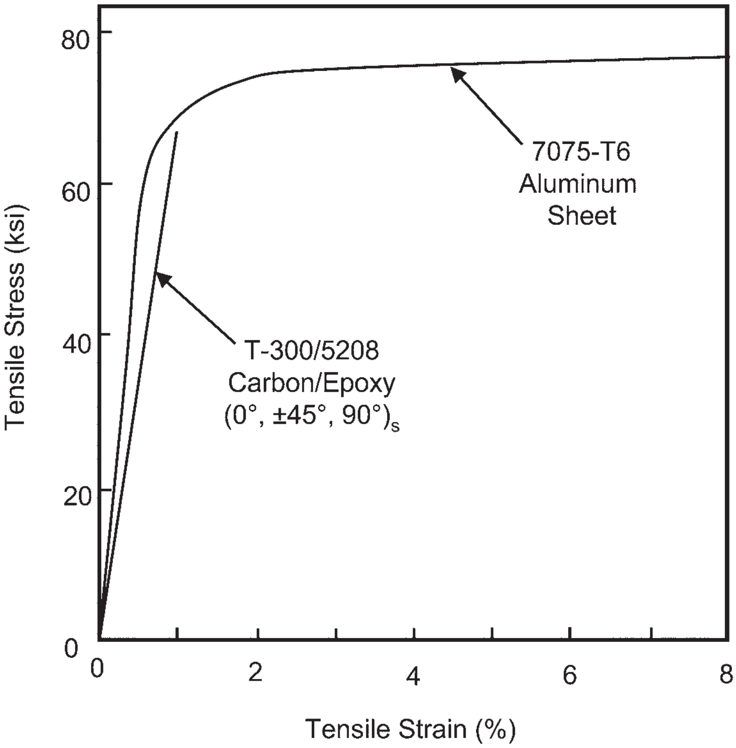


Fig. 1.15 Comparison of typical stress-strain curves for a composite laminate and aluminum alloy sheet. Source: Ref 3

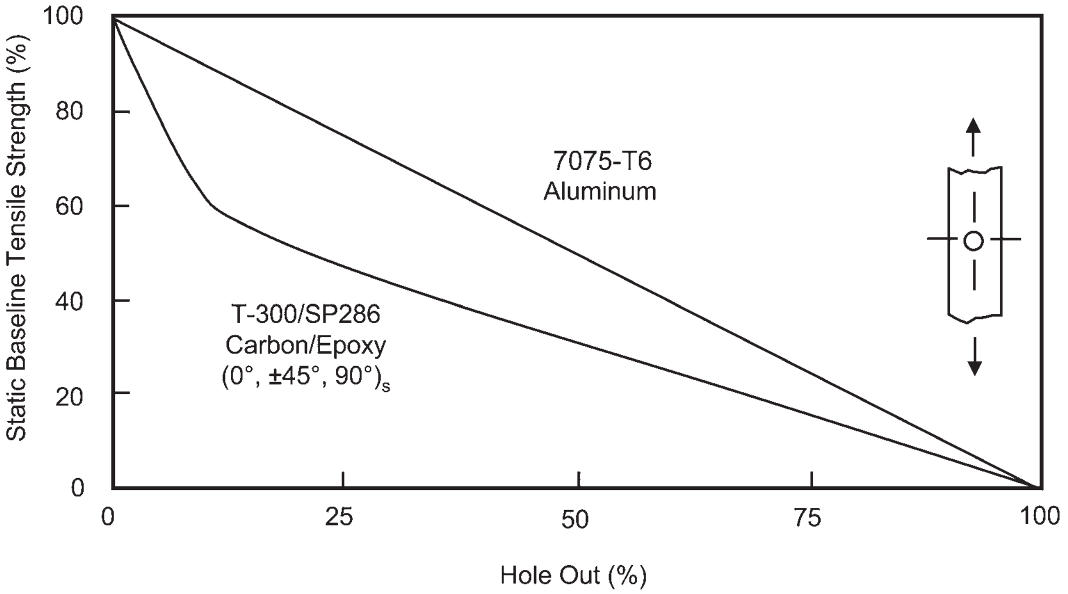


Fig. 1.16 Compared with aluminum alloy sheet, a composite laminate has poor tolerance of stress concentration because of its brittle nature. Source: Ref 3

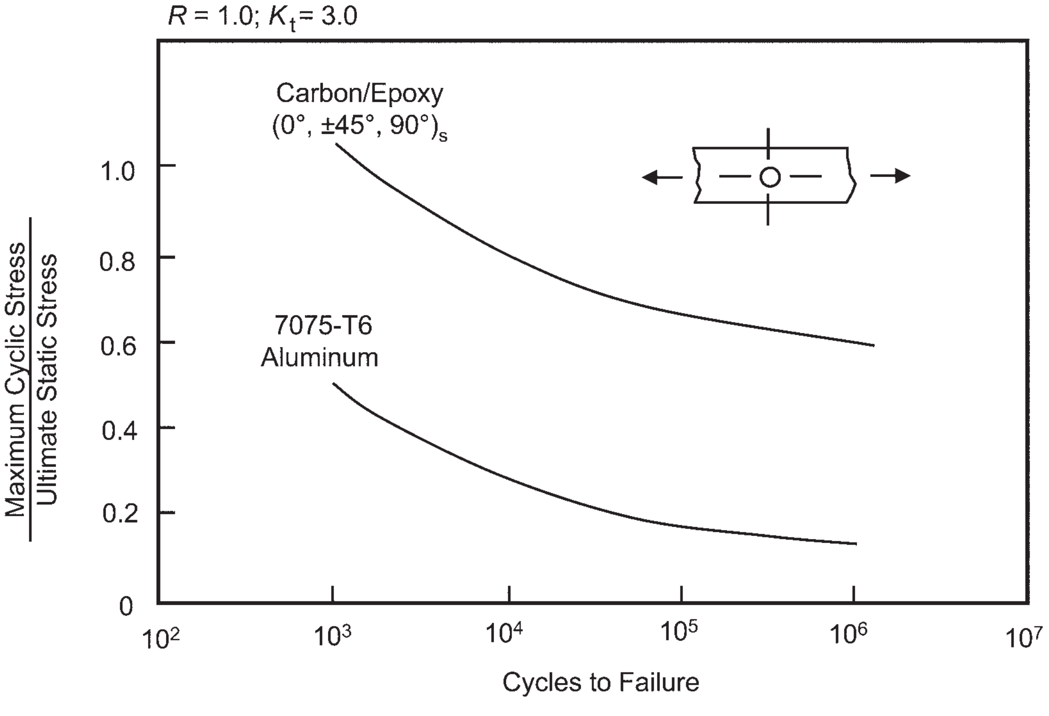


Fig. 1.17 Comparative notched fatigue strength of composite laminate and aluminum alloy sheet. Source: Ref 3

shows a comparison of the normalized notched specimen fatigue response of a common 7075-T6 aluminum aircraft metal and a carbon/epoxy laminate. The fatigue strength of the composite is much higher relative to its static or residual strength. The static or residual strength requirement for structures is typically much higher than the fatigue requirement. Therefore, because the fatigue threshold of composites is a high percentage of their static or damaged residual strength, they are usually not fatigue critical. In metal structures, fatigue is typically a critical design consideration.

1.5 Advantages and Disadvantages of Composite Materials

The advantages of composites are many, including lighter weight, the ability to tailor the layup for optimum strength and stiffness, improved fatigue life, corrosion resistance, and, with good design practice, reduced assembly costs due to fewer detail parts and fasteners.

The specific strength (strength/density) and specific modulus (modulus/density) of high-strength fibers (especially carbon) are higher than those of other comparable aerospace metallic alloys (Fig. 1.18). This translates into greater weight savings resulting in improved performance, greater payloads, longer range, and fuel savings. Figure 1.19 compares the overall structural efficiency of carbon/epoxy, Ti-6Al-4V, and 7075-T6 aluminum.

The chief engineer of aircraft structures for the U.S. Navy once told the author that he liked composites because “they don’t rot [corrode] and they don’t get tired [fatigue].” Corrosion of aluminum alloys is a major cost and a constant maintenance problem for both commercial and military aircraft. The corrosion resistance of composites can result in major savings in supportability costs. Carbon fiber composites cause galvanic corrosion of aluminum if the fibers are placed in direct contact with the metal surface, but bonding a glass fabric electrical insulation layer on all interfaces that contact aluminum eliminates this problem. The fatigue

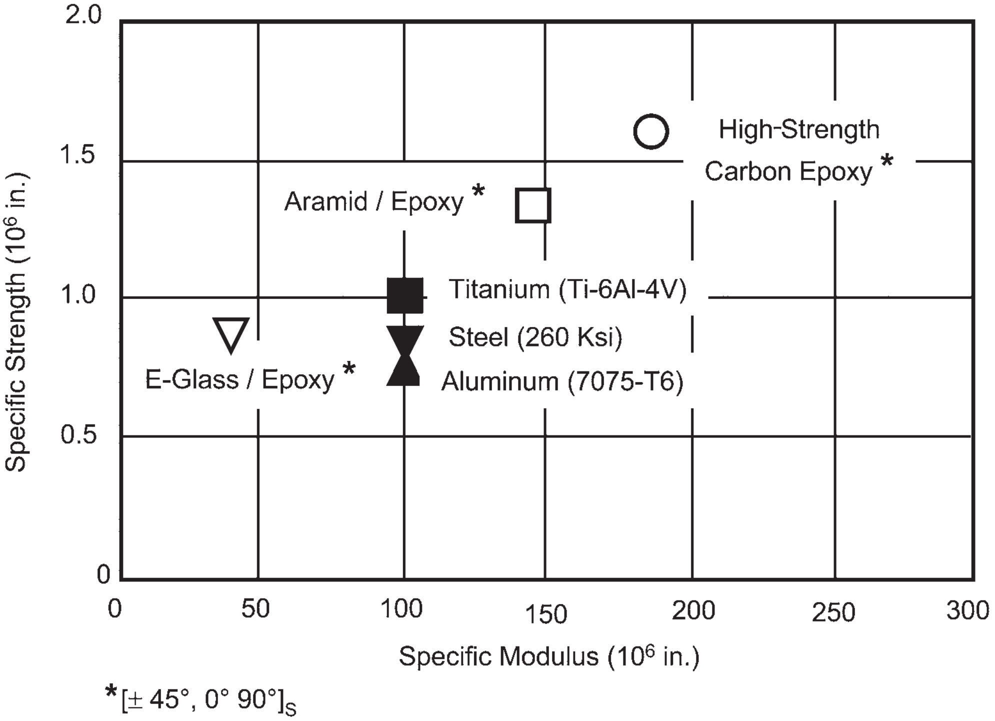


Fig. 1.18 Comparison of specific strength and modulus of high-strength composites and some aerospace alloys

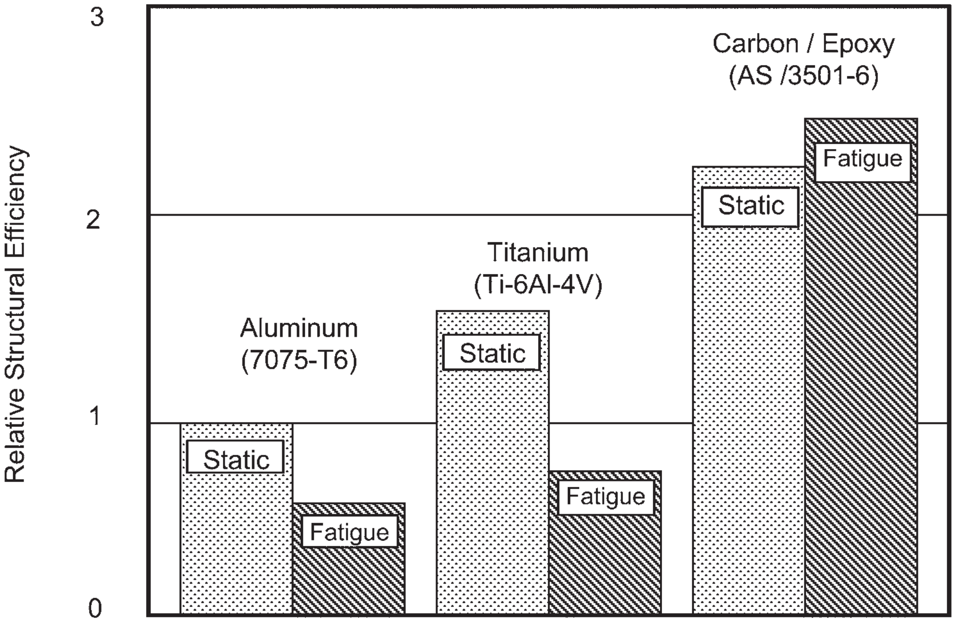


Fig. 1.19 Relative structural efficiency of aerospace materials

resistance of composites compared to high-strength metals is shown in Fig. 1.20. As long as reasonable strain levels are used during design, fatigue of carbon fiber composites should not be a problem.

Assembly costs can account for as much as 50 percent of the cost of an airframe. Composites offer the opportunity to significantly reduce the amount of assembly labor and the number of required fasteners. Detail parts can be combined into a single cured assembly either during initial cure or by secondary adhesive bonding.

Disadvantages of composites include high raw material costs and usually high fabrication and assembly costs; adverse effects of both temperature and moisture; poor strength in the out-of-plane direction where the matrix carries the primary load (they should not be used where load paths are complex, such as with lugs and fittings); susceptibility to impact damage and delaminations or ply separations; and greater difficulty in repairing them compared to metallic structures.

The major cost driver in fabrication for a composite part using conventional hand lay-up is the cost of laying up or collating the plies. This cost is generally 40 to 60 percent of the fabrication cost, depending on part complexity (Fig. 1.21). Assembly cost is another major cost driver, accounting for about 50 percent of the total part cost. As previously stated, one of the potential advantages of composites is the ability to cure or bond a number of detail parts together to reduce assembly costs and the number of required fasteners.

Temperature has an effect on composite mechanical properties. Typically, matrix-dominated mechanical properties decrease with increasing temperature. Fiber-dominated properties are somewhat affected by cold temperatures, but the effects are not as severe as those of elevated temperature on the matrix-dominated properties. Design parameters for carbon/epoxy are cold-dry tension and hot-wet compression (Fig. 1.22). An important design factor in the selection of a matrix resin for elevated-temperature applications is the cured glass transition temperature. The cured glass transition temperature (T_g) of a polymeric material is the temperature at which it changes from a rigid, glassy solid into a softer, semiflexible material. At this point, the polymer structure is still intact but the crosslinks are no longer locked in position. Therefore, the T_g determines the upper use temperature for a composite or an adhesive and is the temperature above which the material will exhibit significantly

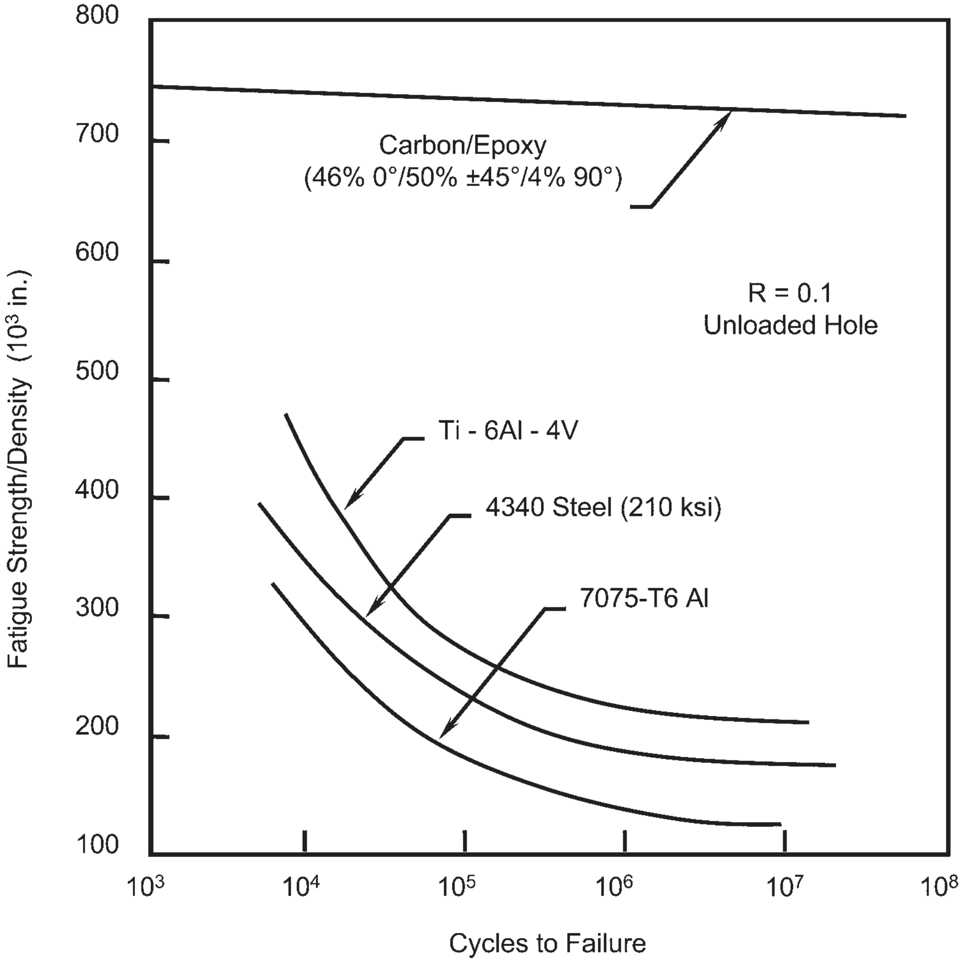


Fig. 1.20 Fatigue properties of aerospace materials

reduced mechanical properties. Since most thermoset polymers will absorb moisture that severely depresses the T_g, the actual use temperature should be about 50 °F (30 °C) lower than the wet or saturated T_g.

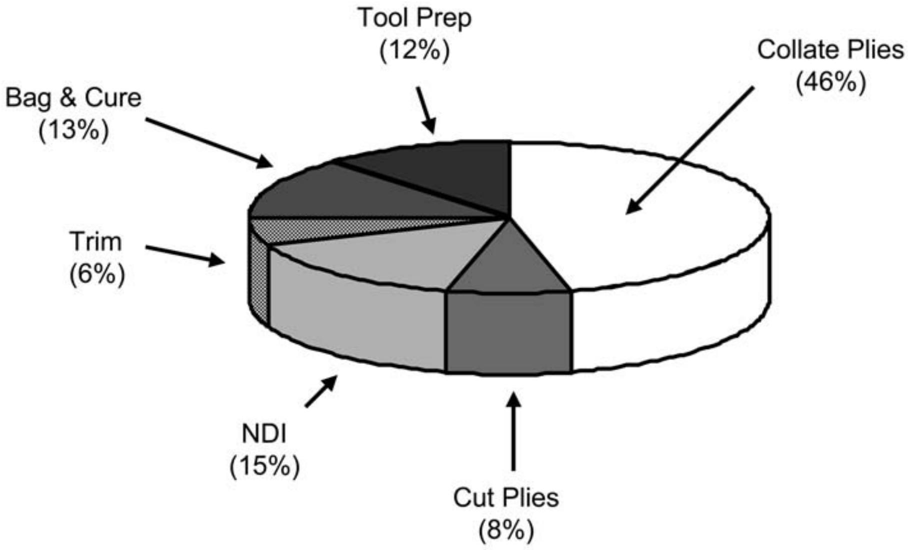
$$\text{Upper Use Temperature} = \text{Wet } T_g - 50\ ^\circ\text{F} \qquad \text{(Eq 1.9)}$$

In general, thermoset resins absorb more moisture than comparable thermoplastic resins.

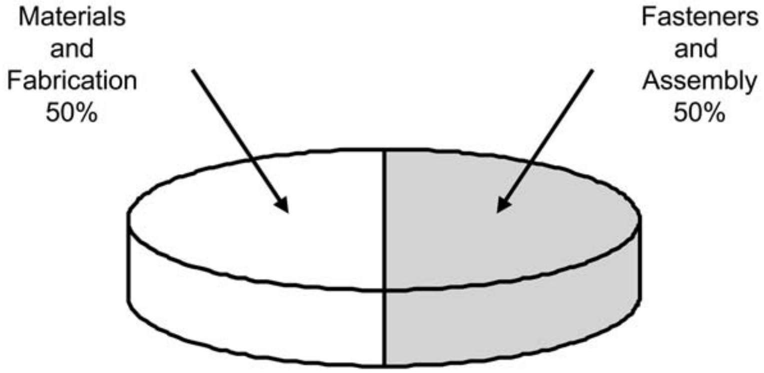
The cured glass transition temperature (T_g) can be determined by several methods that are outlined in Chapter 3, "Matrix Resin Systems."

The amount of absorbed moisture (Fig. 1.23) depends on the matrix material and the relative humidity. Elevated temperatures increase the rate of moisture absorption. Absorbed moisture reduces the matrix-dominated mechanical properties and causes the matrix to swell, which relieves locked-in thermal strains from elevated-temperature curing. These strains can be large, and large panels fixed at their edges can buckle due to strains caused by swelling. During freeze-thaw cycles, absorbed moisture expands during freezing, which can crack the matrix, and it can turn into steam during thermal spikes. When the internal steam pressure exceeds the flatwise tensile (through-the-thickness) strength of the composite, the laminate will delaminate.

Composites are susceptible to delaminations (ply separations) during fabrication, during assembly,



Fabrication Cost



Total Cost

Fig. 1.21 Cost drivers for composite hand lay-up. NDI, nondestructive inspection

and in service. During fabrication, foreign materials such as prepreg backing paper can be inadvertently left in the lay-up. During assembly, improper part handling or incorrectly installed fasteners can cause delaminations. In service, low-velocity impact damage from dropped tools or forklifts running into aircraft can cause damage. The damage may appear as only a small indentation on the surface but it can propagate through the laminates, forming a complex network of delaminations and matrix cracks, as shown in Fig. 1.24. Depending on the size of the delamination, it can reduce the static and fatigue strength and the compression buckling strength. If it is large enough, it can grow under fatigue loading.

Typically, damage tolerance is a resin-dominated property. The selection of a toughened

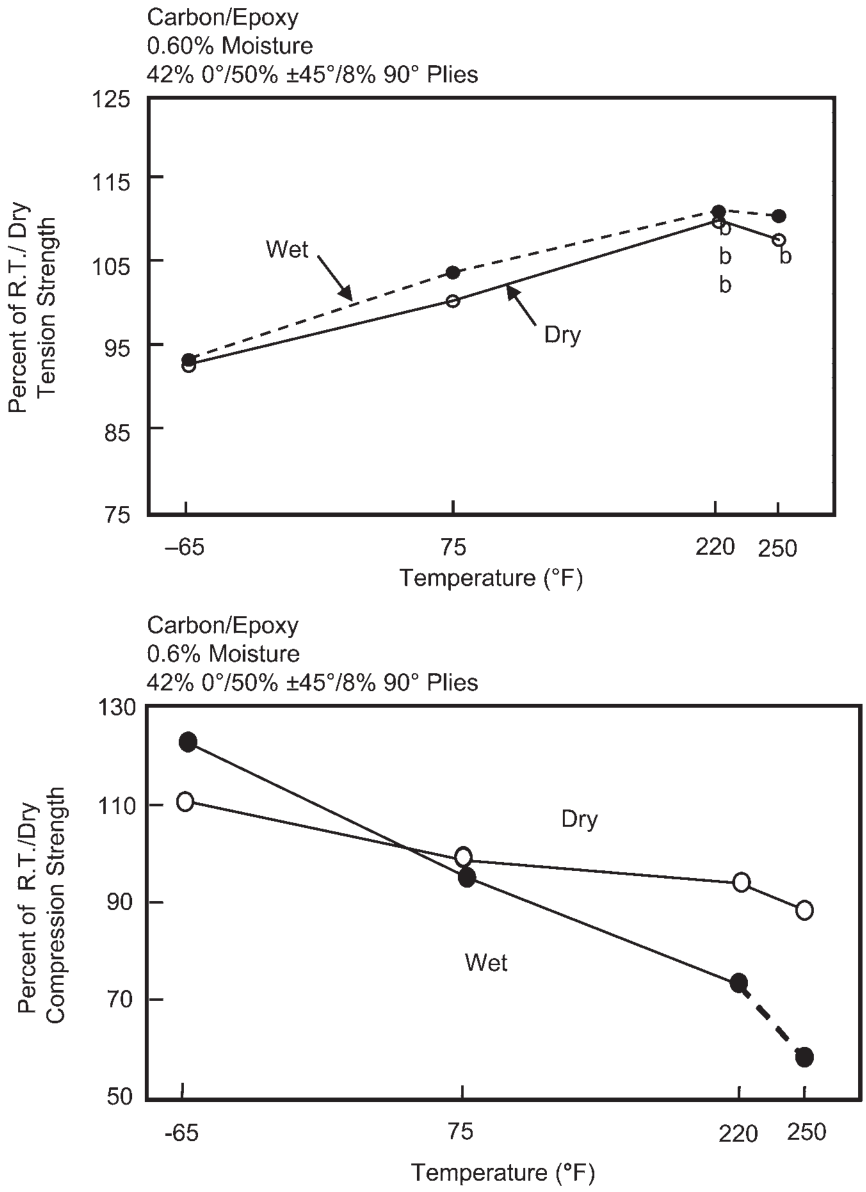


Fig. 1.22 Effects of temperature and moisture on strength of carbon/epoxy. R.T., room temperature

resin can significantly improve the resistance to impact damage. In addition, S-2 glass and aramid fibers are extremely tough and damage tolerant. During the design phase, it is important to recognize the potential for delaminations and use sufficiently conservative design strains so that a damaged structure can be repaired.

1.6 Applications

Applications include aerospace, transportation, construction, marine goods, sporting goods, and more recently infrastructure, with construction and transportation being the largest. In general, high-performance but more costly continuous-carbon-fiber composites are used

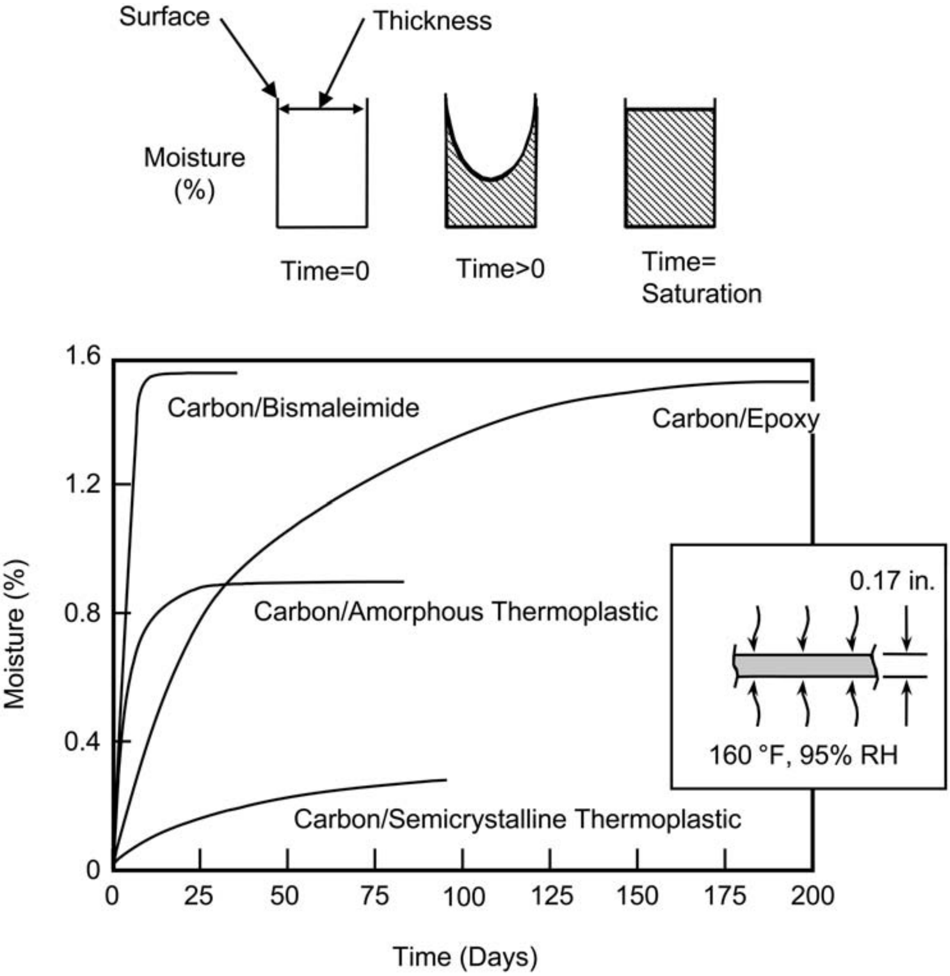


Fig. 1.23 Absorption of moisture for polymer matrix composites. RH, relative humidity

where high strength and stiffness along with light weight are required, and much lower-cost fiberglass composites are used in less demanding applications where weight is not as critical.

In military aircraft, low weight is "king" for performance and payload reasons, and composites often approach 20 to 40 percent of the airframe weight (Fig. 1.25). For decades, helicopters have incorporated glass fiber–reinforced rotor blades for improved fatigue resistance, and in recent years helicopter airframes have been built largely of carbon-fiber composites. Military aircraft applications, the first to use high-performance continuous-carbon-fiber composites, drove the development of much of the technology now being used by other industries. Both small and large commercial aircraft rely on composites to decrease weight and increase fuel performance, the most striking example being the 50 percent composite airframe for the new Boeing 787 (Fig. 1.26). All future Airbus and Boeing aircraft will use large amounts of high-performance composites. Composites are also used extensively in both weight-critical reusable and expendable launch vehicles and satellite structures (Fig. 1.27). Weight savings due to the use of composite materials in aerospace applications generally range from 15 to 25 percent.

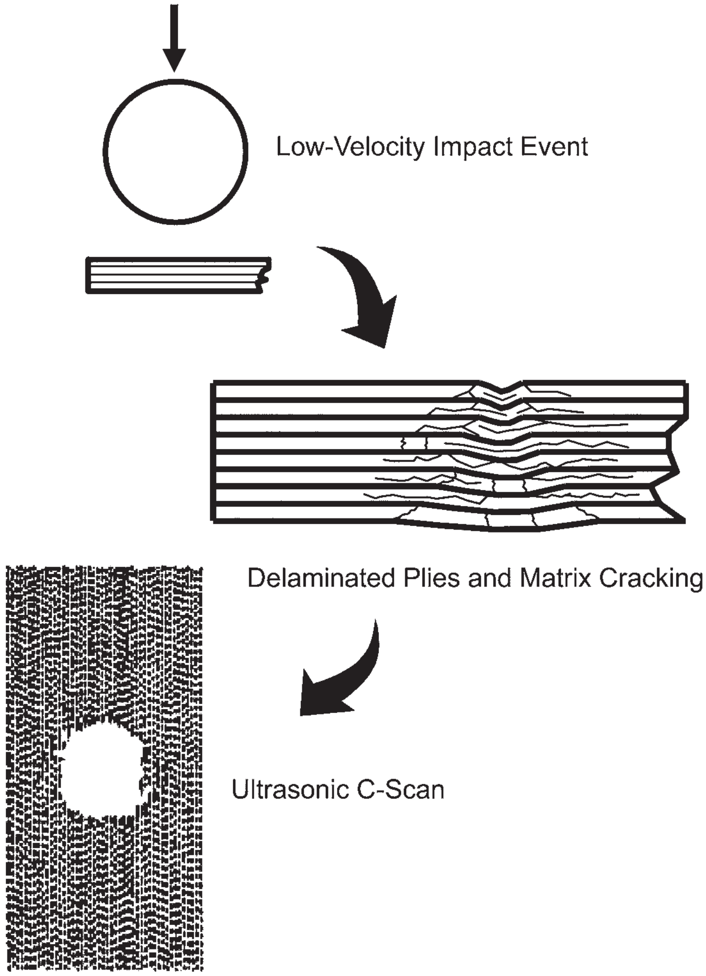
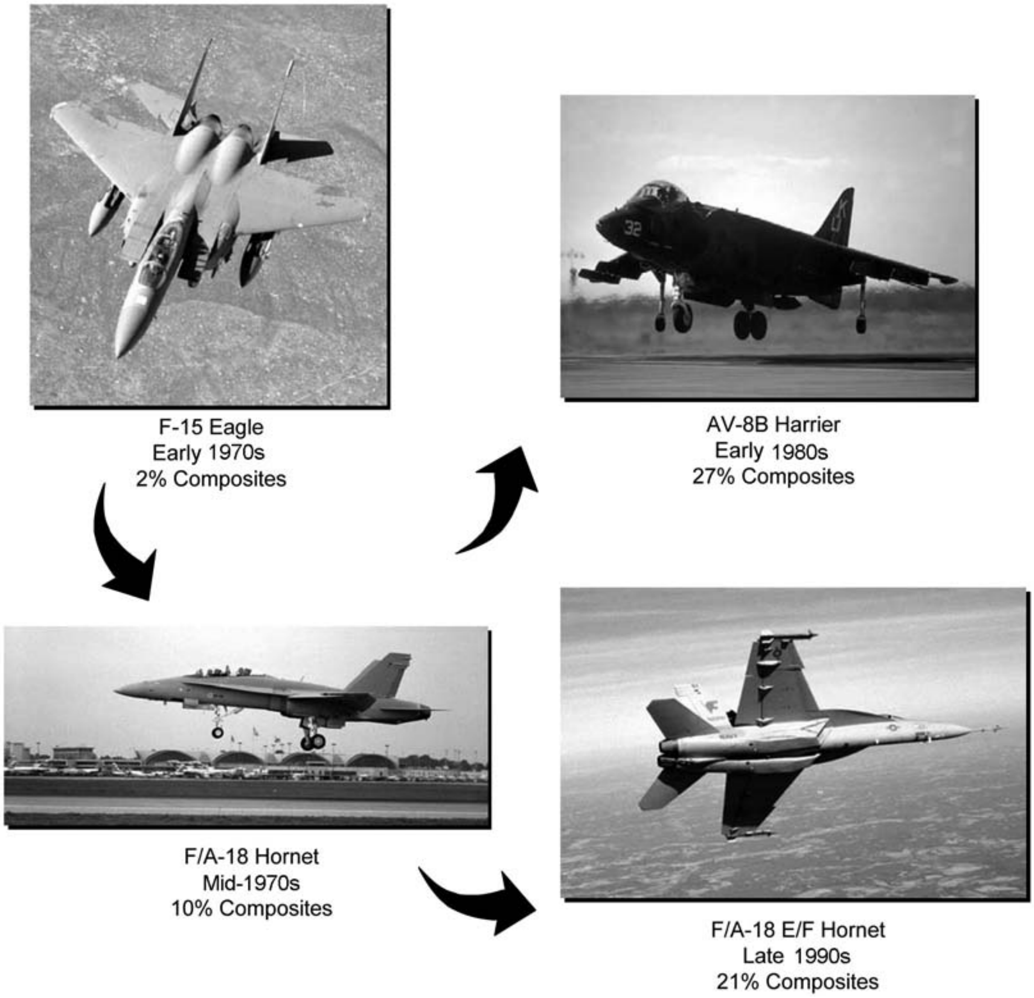


Fig. 1.24 Delaminations and matrix cracking in polymer matrix composite due to impact damage

The major automakers (Fig. 1.28) are increasingly turning to composites to help them meet performance and weight requirements, thus improving fuel efficiency. Cost is a major driver for commercial transportation, and composites offer lower weight and lower maintenance costs. Typical materials are fiberglass/ polyurethane made by liquid or compression molding and fiberglass/ polyester made by compression molding. Recreational vehicles have long used glass fibers, mostly for their durability and weight savings over metal. The product form is typically fiberglass sheet molding compound made by compression molding. For high-performance Formula 1 racing cars, where cost is not an impediment, most of the chassis, including the monocoque, suspension, wings, and engine cover, is made from carbon fiber composites.

Corrosion is a major headache and expense for the marine industry. Composites help minimize these problems, primarily because they do not corrode like metals or rot like wood. Hulls of boats ranging from small fishing boats to large racing yachts (Fig. 1.29) are routinely made of glass fibers and polyester or vinyl ester resins. Masts are frequently fabricated from carbon fiber composites. Fiberglass filament-wound SCUBA



F-15 Eagle
Early 1970s
2% Composites

AV-8B Harrier
Early 1980s
27% Composites

F/A-18 Hornet
Mid-1970s
10% Composites

F/A-18 E/F Hornet
Late 1990s
21% Composites

Fig. 1.25 Typical fighter aircraft applications. Source: The Boeing Company

tanks are another example of composites improving the marine industry. Lighter tanks can hold more air yet require less maintenance than their metallic counterparts. Jet skis and boat trailers often contain glass composites to help minimize weight and reduce corrosion. More recently, the topside structures of many naval ships have been fabricated from composites.

Using composites to improve the infrastructure (Fig. 1.30) of our roads and bridges is a relatively new, exciting application. Many of the world's roads and bridges are badly corroded and in need of continual maintenance or replacement. In the United States alone, it is estimated that more than 250,000 structures, such as bridges and parking garages, need repair, retrofit, or replacement. Composites offer much longer life with less maintenance due to their corrosion resistance. Typical processes/materials include wet lay-up repairs and corrosion-resistant fiberglass pultruded products.

In construction (Fig. 1.31), pultruded fiberglass rebar is used to strengthen concrete, and glass fibers are used in some shingling materials. With the number of mature tall trees dwindling, the use of composites for electrical towers and

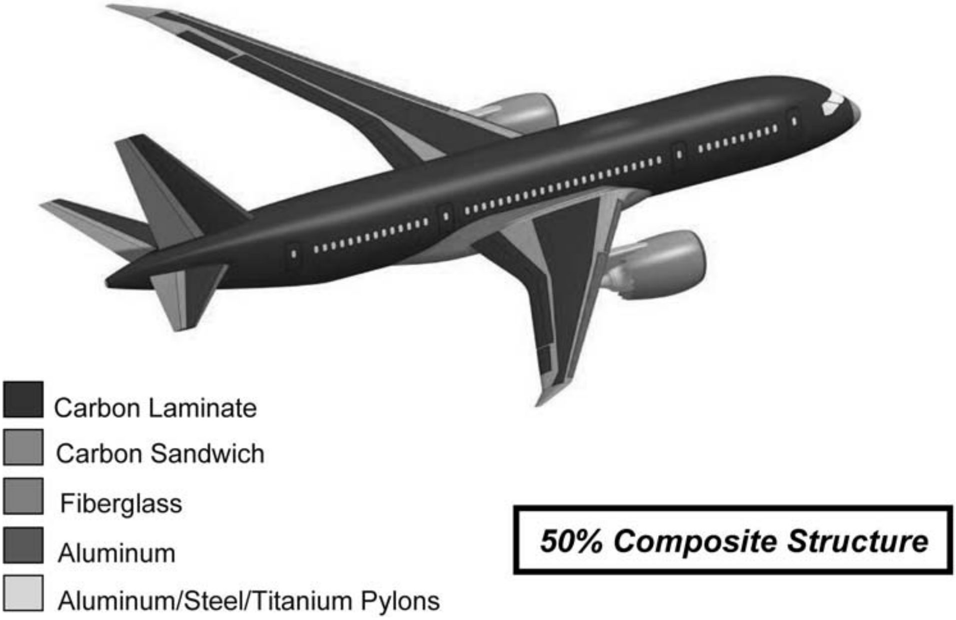


Fig. 1.26 Boeing 787 Dreamliner commercial airplane. Source: The Boeing Company

Fig. 1.27 Launch and spacecraft structures

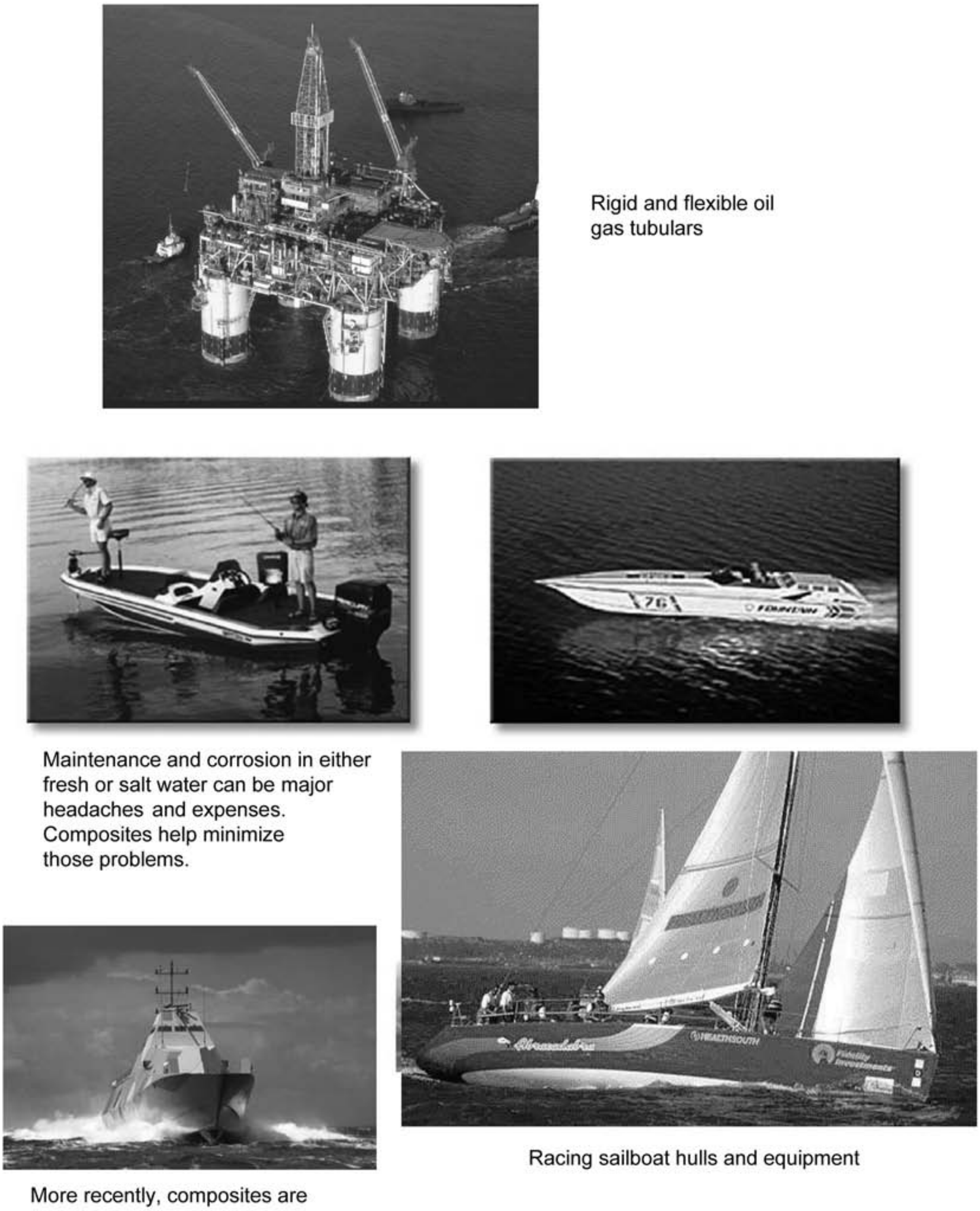
Composites are used in both trucks and cars to reduce weight and Increase fuel efficiency.

Recreational vehicles have long used fiberglass composites, mostly for its durability and weight savings over metal.

Fig. 1.28 Transportation applications

light poles is greatly increasing. Typically, these are pultruded or filament-wound glass.

Wind power is the world's fastest-growing energy source. The blades for large wind turbines (Fig. 1.32) are normally made of composites to improve electrical energy generation efficiency. These blades can be as long as 120 ft (37 m) and weigh up to 11,500 lb (5200 kg). In 2007, nearly 50,000 blades for 17,000 turbines were delivered, representing roughly 400 million pounds



Rigid and flexible oil gas tubulars

Maintenance and corrosion in either fresh or salt water can be major headaches and expenses. Composites help minimize those problems.

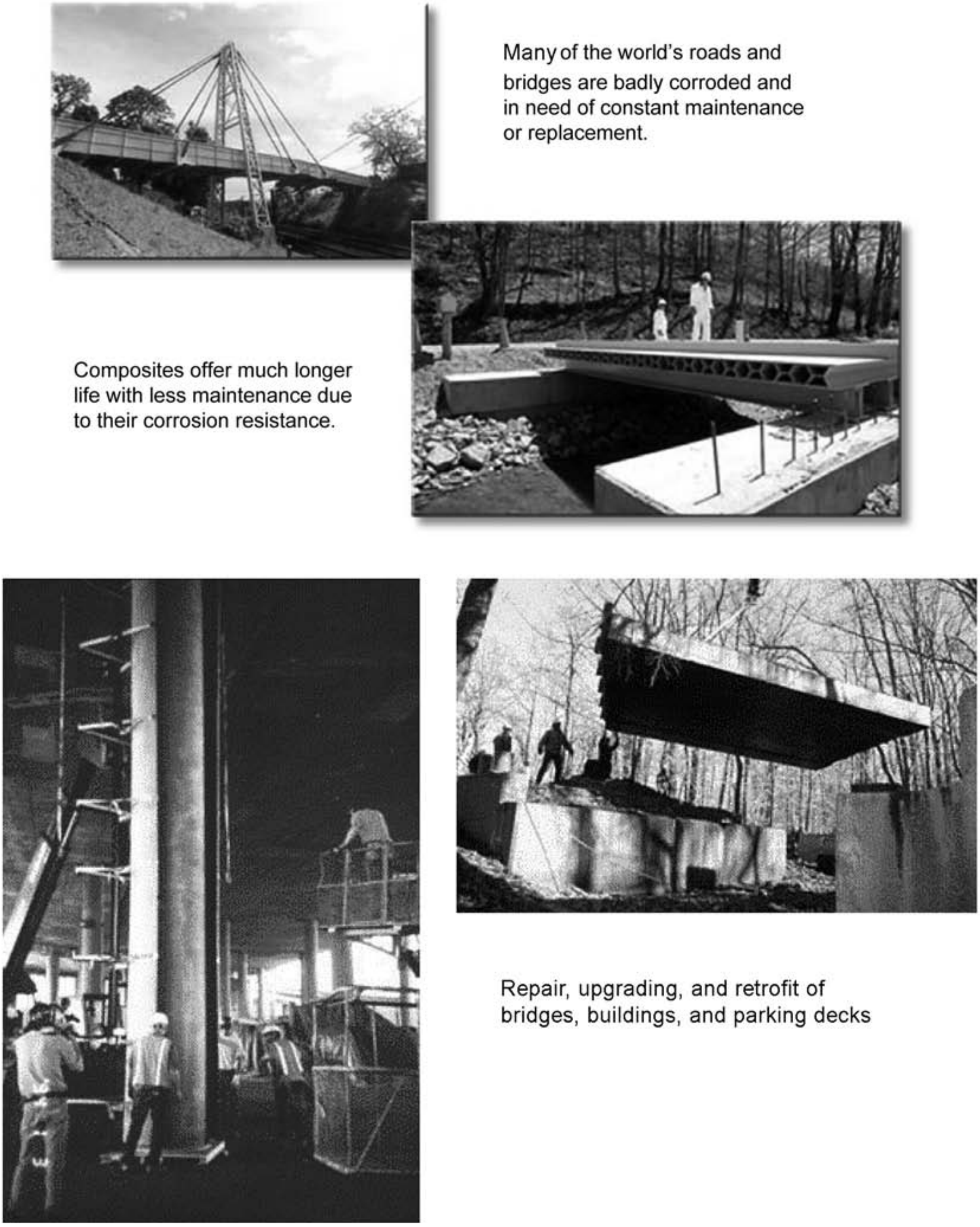
Racing sailboat hulls and equipment

More recently, composites are being used for major components In naval ships.

Fig. 1.29 Marine applications

(approximately 180 million kg) of composites. The predominant material is continuous glass fibers manufactured by either lay-up or resin infusion.

Tennis racquets (Fig. 1.33) have been made of glass for years, and many golf club shafts are made of carbon. Processes include compression molding for tennis racquets and tape wrapping or



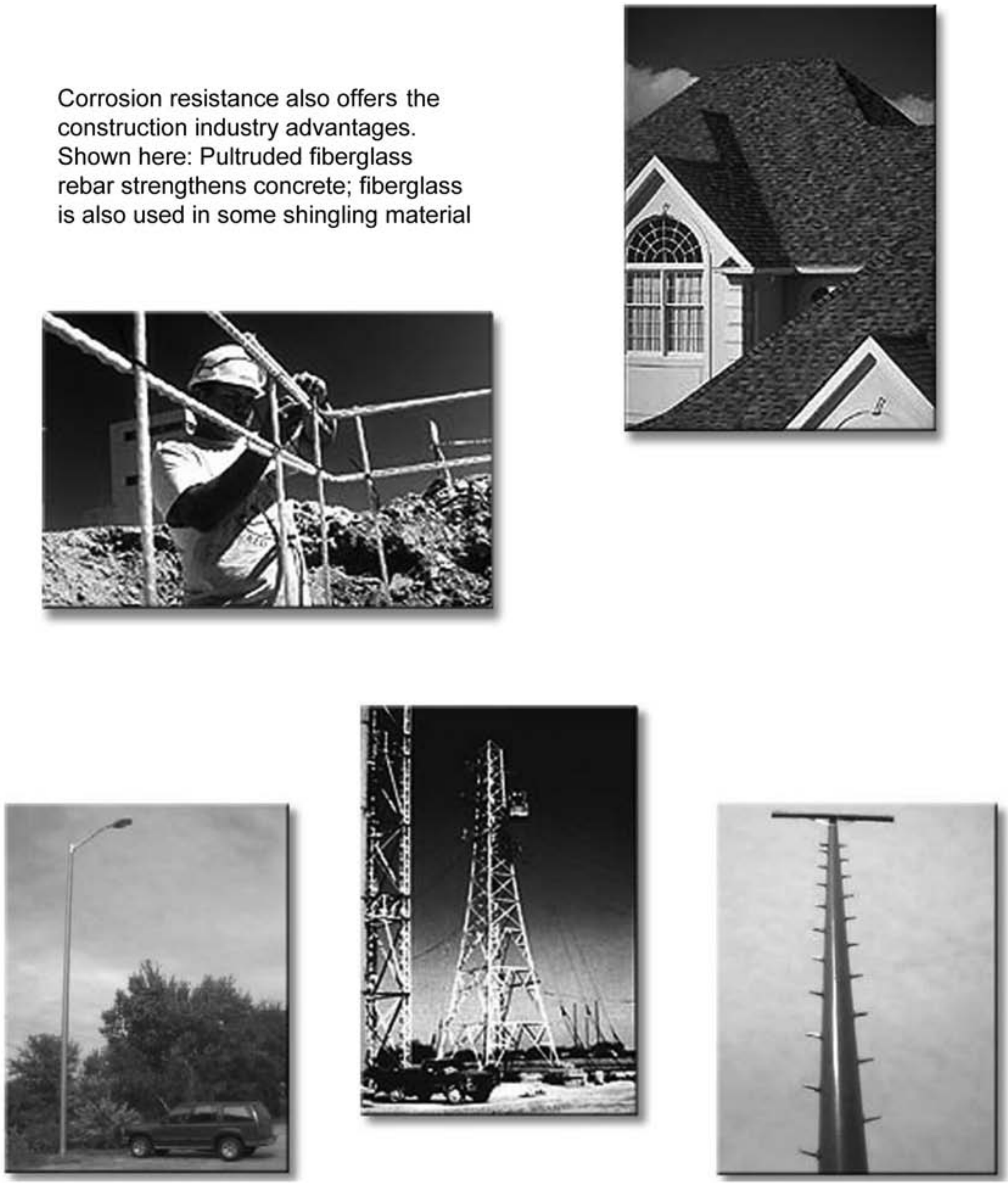
Many of the world's roads and bridges are badly corroded and in need of constant maintenance or replacement.

Composites offer much longer life with less maintenance due to their corrosion resistance.

Repair, upgrading, and retrofit of bridges, buildings, and parking decks

Fig. 1.30 Infrastructure applications

filament winding for golf shafts. Lighter, stronger skis and surfboards also are possible using composites. Another example of a composite application that takes a beating yet keeps on performing is a snowboard, which typically involves the use of a sandwich construction (composite skins with a honeycomb core) for maximum specific stiffness.



Corrosion resistance also offers the construction industry advantages. Shown here: Pultruded fiberglass rebar strengthens concrete; fiberglass is also used in some shingling material

With the number of mature tall trees dwindling, the use of composites for electrical towers and light poles is greatly increasing.

Fig. 1.31 Construction applications

Although metal and ceramic matrix composites are normally very expensive, they have found uses in specialized applications such as those shown in Fig. 1.34. Frequently, they are used where high temperatures are involved. However, the much higher temperatures and pressures required for the fabrication of metal and ceramic matrix composites lead

Composites are being used for wind turbine blades to improve energy generation efficiency and reduce corrosion problems.

Fig. 1.32 Composite clean energy generation

to very high costs, which severely limits their application.

Composites are not always the best solution. An example is the avionics rack for an advanced fighter aircraft shown in Fig. 1.35. This part was machined from a single block of aluminum in about 8.5 hours and assembled into the final component in five hours. Such a part made of composites would probably not be cost competitive.

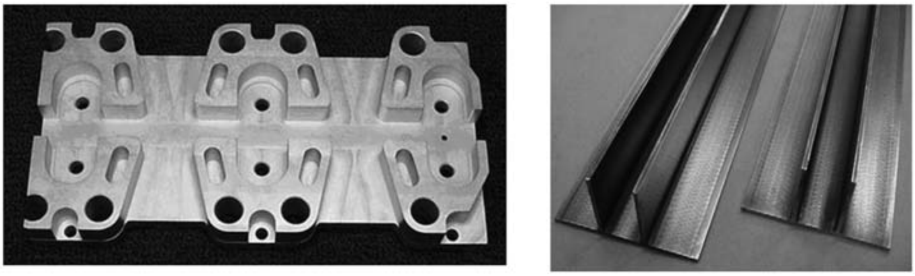
Advanced composites are a diversified and growing industry due to their distinct advantages over competing metallics, including lighter weight, higher performance, and corrosion resistance. They are used in aerospace, automotive, marine, sporting goods, and, more recently, infrastructure applications. *The major disadvantage of composites is their high cost*. However, the proper selection of materials (fiber and matrix), product forms, and processes can have a major impact on the cost of the finished part.

REFERENCES

1. M.E. Tuttle, *Structural Analysis of Polymeric Composite Materials*, Marcel Dekker, Inc., 2004

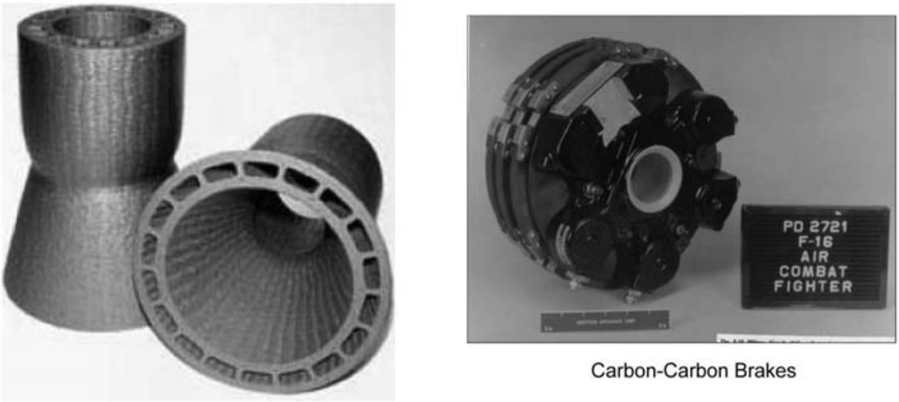
Composites improve the performance
of sports equipment.

Fig. 1.33 Sporting goods applications



Metal Matrix Composite
Electronic Components

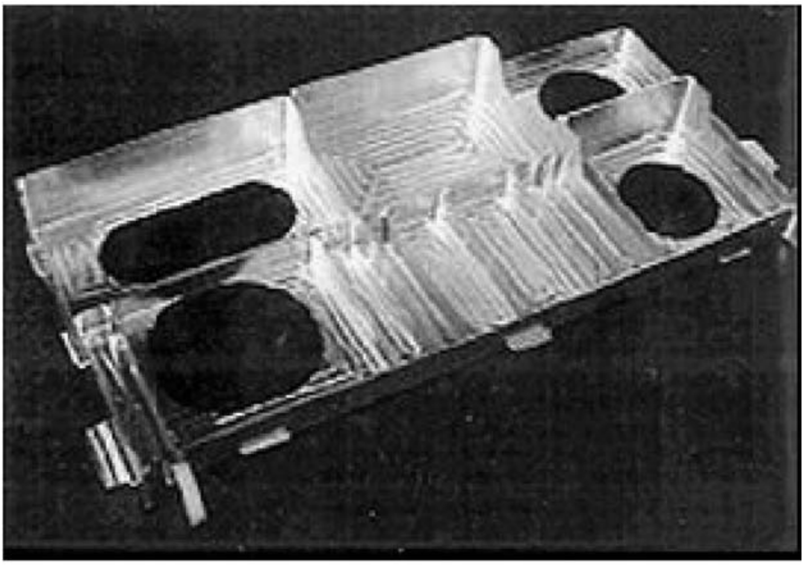
Metal Matrix Composite
Structural Components



Ceramic Matrix Ceramic
Exhaust Nozzles

Carbon-Carbon Brakes

Fig. 1.34 Metal and ceramic matrix composite applications



Number of Pieces	6
Number of Tools	5
Design and Fabrication hr (Tools)	30
Fabrication hr	8.6
Assembly Man-hours	5.3
Weight (lb)	8.56

Fig. 1.35 Composites are not always the best choice. This avionics rack machined from an aluminum alloy block would not be cost-competitive if made of composites. Source: The Boeing Company

2. M.C.Y. Niu, *Composite Airframe Structures*, 2nd ed., Hong Kong Conmilit Press Limited, 2000
3. R.E. Horton and J.E. McCarty, Damage Tolerance of Composites, *Engineered Materials Handbook*, Vol 1, *Composites*, ASM International, 1987

SELECTED REFERENCES

- *High-Performance Composites Sourcebook 2009*, Gardner Publications Inc
- S.K. Mazumdar, *Composites Manufacturing: Materials, Product, and Process Engineering*, CRC Press, 2002