1 Introduction

1.1 DEFINITION

Fiber-reinforced composite materials consist of fibers of high strength and modulus embedded in or bonded to a matrix with distinct interfaces (boundaries) between them. In this form, both fibers and matrix retain their physical and chemical identities, yet they produce a combination of properties that cannot be achieved with either of the constituents acting alone. In general, fibers are the principal load-carrying members, while the surrounding matrix keeps them in the desired location and orientation, acts as a load transfer medium between them, and protects them from environmental damages due to elevated temperatures and humidity, for example. Thus, even though the fibers provide reinforcement for the matrix, the latter also serves a number of useful functions in a fiber-reinforced composite material.

The principal fibers in commercial use are various types of glass and carbon as well as Kevlar 49. Other fibers, such as boron, silicon carbide, and aluminum oxide, are used in limited quantities. All these fibers can be incorporated into a matrix either in continuous lengths or in discontinuous (short) lengths. The matrix material may be a polymer, a metal, or a ceramic. Various chemical compositions and microstructural arrangements are possible in each matrix category.

The most common form in which fiber-reinforced composites are used in structural applications is called a laminate, which is made by stacking a number of thin layers of fibers and matrix and consolidating them into the desired thickness. Fiber orientation in each layer as well as the stacking sequence of various layers in a composite laminate can be controlled to generate a wide range of physical and mechanical properties for the composite laminate.

In this book, we focus our attention on the mechanics, performance, manufacturing, and design of fiber-reinforced polymers. Most of the data presented in this book are related to continuous fiber-reinforced epoxy laminates, although other polymeric matrices, including thermoplastic matrices, are also considered. Metal and ceramic matrix composites are comparatively new, but significant developments of these composites have also occurred. They are included in a separate chapter in this book. Injection-molded or reaction injection-molded (RIM) discontinuous fiber-reinforced polymers are not discussed; however, some of the mechanics and design principles included in this book are applicable to these composites as well. Another material of great commercial interest is classified as particulate composites. The major constituents in these composites are particles of mica, silica, glass spheres, calcium carbonate, and others. In general, these particles do not contribute to the load-carrying capacity of the material and act more like a filler than a reinforcement for the matrix. Particulate composites, by themselves, deserve a special attention and are not addressed in this book.

Another type of composites that have the potential of becoming an important material in the future is the nanocomposites. Even though nanocomposites are in the early stages of development, they are now receiving a high degree of attention from academia as well as a large number of industries, including aerospace, automotive, and biomedical industries. The reinforcement in nanocomposites is either nanoparticles, nanofibers, or carbon nanotubes. The effective diameter of these reinforcements is of the order of 10^{-9} m, whereas the effective diameter of the reinforcements used in traditional fiber-reinforced composites is of the order of 10^{-6} m. The nanocomposites are introduced in Chapter 8.

1.2 GENERAL CHARACTERISTICS

Many fiber-reinforced polymers offer a combination of strength and modulus that are either comparable to or better than many traditional metallic materials. Because of their low density, the strength–weight ratios and modulus–weight ratios of these composite materials are markedly superior to those of metallic materials (Table 1.1). In addition, fatigue strength as well as fatigue damage tolerance of many composite laminates are excellent. For these reasons, fiber-reinforced polymers have emerged as a major class of structural materials and are either used or being considered for use as substitution for metals in many weight-critical components in aerospace, automotive, and other industries.

Traditional structural metals, such as steel and aluminum alloys, are considered isotropic, since they exhibit equal or nearly equal properties irrespective of the direction of measurement. In general, the properties of a fiber-reinforced composite depend strongly on the direction of measurement, and therefore, they are not isotropic materials. For example, the tensile strength and modulus of a unidirectionally oriented fiber-reinforced polymer are maximum when these properties are measured in the longitudinal direction of fibers. At any other angle of measurement, these properties are lower. The minimum value is observed when they are measured in the transverse direction of fibers, that is, at 90° to the longitudinal direction. Similar angular dependence is observed for other mechanical and thermal properties, such as impact strength, coefficient of thermal expansion (CTE), and thermal conductivity. Bi- or multidirectional reinforcement yields a more balanced set of properties. Although these properties are lower than the longitudinal properties of a unidirectional composite, they still represent a considerable advantage over common structural metals on a unit weight basis.

The design of a fiber-reinforced composite structure is considerably more difficult than that of a metal structure, principally due to the difference in its

TABLE 1.1
Tensile Properties of Some Metallic and Structural Composite Materials

Material[a]	Density, g/cm^3	Modulus, GPa (Msi)	Tensile Strength, MPa (ksi)	Yield Strength, MPa (ksi)	Ratio of Modulus to Weight,[b] 10^6 m	Ratio of Tensile Strength to Weight,[b] 10^3 m
SAE 1010 steel (cold-worked)	7.87	207 (30)	365 (53)	303 (44)	2.68	4.72
AISI 4340 steel (quenched and tempered)	7.87	207 (30)	1722 (250)	1515 (220)	2.68	22.3
6061-T6 aluminum alloy	2.70	68.9 (10)	310 (45)	275 (40)	2.60	11.7
7178-T6 aluminum alloy	2.70	68.9 (10)	606 (88)	537 (78)	2.60	22.9
Ti-6A1-4V titanium alloy (aged)	4.43	110 (16)	1171 (170)	1068 (155)	2.53	26.9
17-7 PH stainless steel (aged)	7.87	196 (28.5)	1619 (235)	1515 (220)	2.54	21.0
INCO 718 nickel alloy (aged)	8.2	207 (30)	1399 (203)	1247 (181)	2.57	17.4
High-strength carbon fiber–epoxy matrix (unidirectional)[a]	1.55	137.8 (20)	1550 (225)	—	9.06	101.9
High-modulus carbon fiber–epoxy matrix (unidirectional)	1.63	215 (31.2)	1240 (180)	—	13.44	77.5
E-glass fiber–epoxy matrix (unidirectional)	1.85	39.3 (5.7)	965 (140)	—	2.16	53.2
Kevlar 49 fiber–epoxy matrix (unidirectional)	1.38	75.8 (11)	1378 (200)	—	5.60	101.8
Boron fiber-6061 A1 alloy matrix (annealed)	2.35	220 (32)	1109 (161)	—	9.54	48.1
Carbon fiber–epoxy matrix (quasi-isotropic)	1.55	45.5 (6.6)	579 (84)	—	2.99	38
Sheet-molding compound (SMC) composite (isotropic)	1.87	15.8 (2.3)	164 (23.8)		0.86	8.9

[a] For unidirectional composites, the fibers are unidirectional and the reported modulus and tensile strength values are measured in the direction of fibers, that is, the longitudinal direction of the composite.
[b] The modulus–weight ratio and the strength–weight ratios are obtained by dividing the absolute values with the specific weight of the respective material. Specific weight is defined as weight per unit volume. It is obtained by multiplying density with the acceleration due to gravity.

properties in different directions. However, the nonisotropic nature of a fiber-reinforced composite material creates a unique opportunity of tailoring its properties according to the design requirements. This design flexibility can be used to selectively reinforce a structure in the directions of major stresses, increase its stiffness in a preferred direction, fabricate curved panels without any secondary forming operation, or produce structures with zero coefficients of thermal expansion.

The use of fiber-reinforced polymer as the skin material and a lightweight core, such as aluminum honeycomb, plastic foam, metal foam, and balsa wood, to build a sandwich beam, plate, or shell provides another degree of design flexibility that is not easily achievable with metals. Such sandwich construction can produce high stiffness with very little, if any, increase in weight. Another sandwich construction in which the skin material is an aluminum alloy and the core material is a fiber-reinforced polymer has found widespread use in aircrafts and other applications, primarily due to their higher fatigue performance and damage tolerance than aluminum alloys.

In addition to the directional dependence of properties, there are a number of other differences between structural metals and fiber-reinforced composites. For example, metals in general exhibit yielding and plastic deformation. Most fiber-reinforced composites are elastic in their tensile stress–strain characteristics. However, the heterogeneous nature of these materials provides mechanisms for energy absorption on a microscopic scale, which is comparable to the yielding process. Depending on the type and severity of external loads, a composite laminate may exhibit gradual deterioration in properties but usually would not fail in a catastrophic manner. Mechanisms of damage development and growth in metal and composite structures are also quite different and must be carefully considered during the design process when the metal is substituted with a fiber-reinforced polymer.

Coefficient of thermal expansion (CTE) for many fiber-reinforced composites is much lower than that for metals (Table 1.2). As a result, composite structures may exhibit a better dimensional stability over a wide temperature range. However, the differences in thermal expansion between metals and composite materials may create undue thermal stresses when they are used in conjunction, for example, near an attachment. In some applications, such as electronic packaging, where quick and effective heat dissipation is needed to prevent component failure or malfunctioning due to overheating and undesirable temperature rise, thermal conductivity is an important material property to consider. In these applications, some fiber-reinforced composites may excel over metals because of the combination of their high thermal conductivity–weight ratio (Table 1.2) and low CTE. On the other hand, electrical conductivity of fiber-reinforced polymers is, in general, lower than that of metals. The electric charge build up within the material because of low electrical conductivity can lead to problems such as radio frequency interference (RFI) and damage due to lightning strike.

TABLE 1.2
Thermal Properties of a Few Selected Metals and Composite Materials

Material	Density (g/cm^3)	Coefficient of Thermal Expansion ($10^{-6}/°C$)	Thermal Conductivity (W/m°K)	Ratio of Thermal Conductivity to Weight (10^{-3} m^4/s^3 °K)
Plain carbon steels	7.87	11.7	52	6.6
Copper	8.9	17	388	43.6
Aluminum alloys	2.7	23.5	130–220	48.1–81.5
Ti-6Al-4V titanium alloy	4.43	8.6	6.7	1.51
Invar	8.05	1.6	10	1.24
K1100 carbon fiber–epoxy matrix	1.8	−1.1	300	166.7
Glass fiber–epoxy matrix	2.1	11–20	0.16–0.26	0.08–0.12
SiC particle-reinforced aluminum	3	6.2–7.3	170–220	56.7–73.3

Another unique characteristic of many fiber-reinforced composites is their high internal damping. This leads to better vibrational energy absorption within the material and results in reduced transmission of noise and vibrations to neighboring structures. High damping capacity of composite materials can be beneficial in many automotive applications in which noise, vibration, and harshness (NVH) are critical issues for passenger comfort. High damping capacity is also useful in many sporting goods applications.

An advantage attributed to fiber-reinforced polymers is their noncorroding behavior. However, many fiber-reinforced polymers are capable of absorbing moisture or chemicals from the surrounding environment, which may create dimensional changes or adverse internal stresses in the material. If such behavior is undesirable in an application, the composite surface must be protected from moisture or chemicals by an appropriate paint or coating. Among other environmental factors that may cause degradation in the mechanical properties of some polymer matrix composites are elevated temperatures, corrosive fluids, and ultraviolet rays. In metal matrix composites, oxidation of the matrix as well as adverse chemical reaction between fibers and the matrix are of great concern in high-temperature applications.

The manufacturing processes used with fiber-reinforced polymers are different from the traditional manufacturing processes used for metals, such as casting, forging, and so on. In general, they require significantly less energy and lower pressure or force than the manufacturing processes used for metals. Parts integration and net-shape or near net-shape manufacturing processes are also great advantages of using fiber-reinforced polymers. Parts integration reduces the number of parts, the number of manufacturing operations, and also, the number of assembly operations. Net-shape or near net-shape manufacturing processes, such as filament winding and pultrusion, used for making many fiber-reinforced polymer parts, either reduce or eliminate the finishing operations such as machining and grinding, which are commonly required as finishing operations for cast or forged metallic parts.

1.3 APPLICATIONS

Commercial and industrial applications of fiber-reinforced polymer composites are so varied that it is impossible to list them all. In this section, we highlight only the major structural application areas, which include aircraft, space, automotive, sporting goods, marine, and infrastructure. Fiber-reinforced polymer composites are also used in electronics (e.g., printed circuit boards), building construction (e.g., floor beams), furniture (e.g., chair springs), power industry (e.g., transformer housing), oil industry (e.g., offshore oil platforms and oil sucker rods used in lifting underground oil), medical industry (e.g., bone plates for fracture fixation, implants, and prosthetics), and in many industrial products, such as step ladders, oxygen tanks, and power transmission shafts. Potential use of fiber-reinforced composites exists in many engineering fields. Putting them to actual use requires careful design practice and appropriate process development based on the understanding of their unique mechanical, physical, and thermal characteristics.

1.3.1 Aircraft and Military Applications

The major structural applications for fiber-reinforced composites are in the field of military and commercial aircrafts, for which weight reduction is critical for higher speeds and increased payloads. Ever since the production application of boron fiber-reinforced epoxy skins for F-14 horizontal stabilizers in 1969, the use of fiber-reinforced polymers has experienced a steady growth in the aircraft industry. With the introduction of carbon fibers in the 1970s, carbon fiber-reinforced epoxy has become the primary material in many wing, fuselage, and empennage components (Table 1.3). The structural integrity and durability of these early components have built up confidence in their performance and prompted developments of other structural aircraft components, resulting in an increasing amount of composites being used in military aircrafts. For example, the airframe of AV-8B, a vertical and short take-off and landing (VSTOL) aircraft introduced in 1982, contains nearly 25% by weight of carbon fiber-reinforced epoxy. The F-22 fighter aircraft also contains ~25% by weight of carbon fiber-reinforced polymers; the other major materials are titanium (39%) and aluminum (16%). The outer skin of B-2 (Figure 1.1) and other stealth aircrafts is almost all made of carbon fiber-reinforced polymers. The stealth characteristics of these aircrafts are due to the use of carbon fibers, special coatings, and other design features that reduce radar reflection and heat radiation.

TABLE 1.3
Early Applications of Fiber-Reinforced Polymers in Military Aircrafts

Aircraft	Component	Material	Overall Weight Saving Over Metal Component (%)
F-14 (1969)	Skin on the horizontal stabilizer box	Boron fiber–epoxy	19
F-11	Under the wing fairings	Carbon fiber–epoxy	
F-15 (1975)	Fin, rudder, and stabilizer skins	Boron fiber–epoxy	25
F-16 (1977)	Skins on vertical fin box, fin leading edge	Carbon fiber–epoxy	23
F/A-18 (1978)	Wing skins, horizontal and vertical tail boxes; wing and tail control surfaces, etc.	Carbon fiber–epoxy	35
AV-8B (1982)	Wing skins and substructures; forward fuselage; horizontal stabilizer; flaps; ailerons	Carbon fiber–epoxy	25

Source: Adapted from Riggs, J.P., *Mater. Soc.*, 8, 351, 1984.

The composite applications on commercial aircrafts began with a few selective secondary structural components, all of which were made of a high-strength carbon fiber-reinforced epoxy (Table 1.4). They were designed and produced under the NASA Aircraft Energy Efficiency (ACEE) program and were installed in various airplanes during 1972–1986 [1]. By 1987, 350 composite components were placed in service in various commercial aircrafts, and over the next few years, they accumulated millions of flight hours. Periodic inspection and evaluation of these components showed some damages caused by ground handling accidents, foreign object impacts, and lightning strikes.

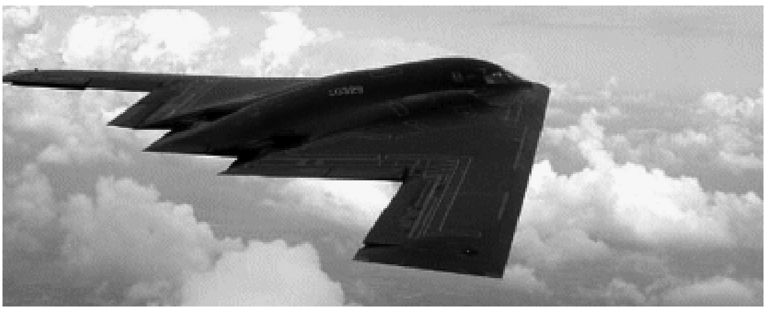

FIGURE 1.1 Stealth aircraft (note that the carbon fibers in the construction of the aircraft contributes to its stealth characteristics).

TABLE 1.4
Early Applications of Fiber-Reinforced Polymers in Commercial Aircrafts

Aircraft	Component	Weight (lb)	Weight Reduction (%)	Comments
Boeing				
727	Elevator face sheets	98	25	10 units installed in 1980
737	Horizontal stabilizer	204	22	
737	Wing spoilers	—	37	Installed in 1973
756	Ailerons, rudders, elevators, fairings, etc.	3340 (total)	31	
McDonnell-Douglas				
DC-10	Upper rudder	67	26	13 units installed in 1976
DC-10	Vertical stabilizer	834	17	
Lockheed				
L-1011	Aileron	107	23	10 units installed in 1981
L-1011	Vertical stabilizer	622	25	

Apart from these damages, there was no degradation of residual strengths due to either fatigue or environmental exposure. A good correlation was found between the on-ground environmental test program and the performance of the composite components after flight exposure.

Airbus was the first commercial aircraft manufacturer to make extensive use of composites in their A310 aircraft, which was introduced in 1987. The composite components weighed about 10% of the aircraft's weight and included such components as the lower access panels and top panels of the wing leading edge, outer deflector doors, nose wheel doors, main wheel leg fairing doors, engine cowling panels, elevators and fin box, leading and trailing edges of fins, flap track fairings, flap access doors, rear and forward wing–body fairings, pylon fairings, nose radome, cooling air inlet fairings, tail leading edges, upper surface skin panels above the main wheel bay, glide slope antenna cover, and rudder. The composite vertical stabilizer, which is 8.3 m high by 7.8 m wide at the base, is about 400 kg lighter than the aluminum vertical stabilizer previously used [2]. The Airbus A320, introduced in 1988, was the first commercial aircraft to use an all-composite tail, which includes the tail cone, vertical stabilizer, and horizontal stabilizer. Figure 1.2 schematically shows the composite usage in Airbus A380 introduced in 2006. About 25% of its weight is made of composites. Among the major composite components in A380 are the central torsion box (which links the left and right wings under the fuselage), rear-pressure bulkhead (a dome-shaped partition that separates the passenger cabin from the rear part of the plane that is not pressurized), the tail, and the flight control surfaces, such as the flaps, spoilers, and ailerons.

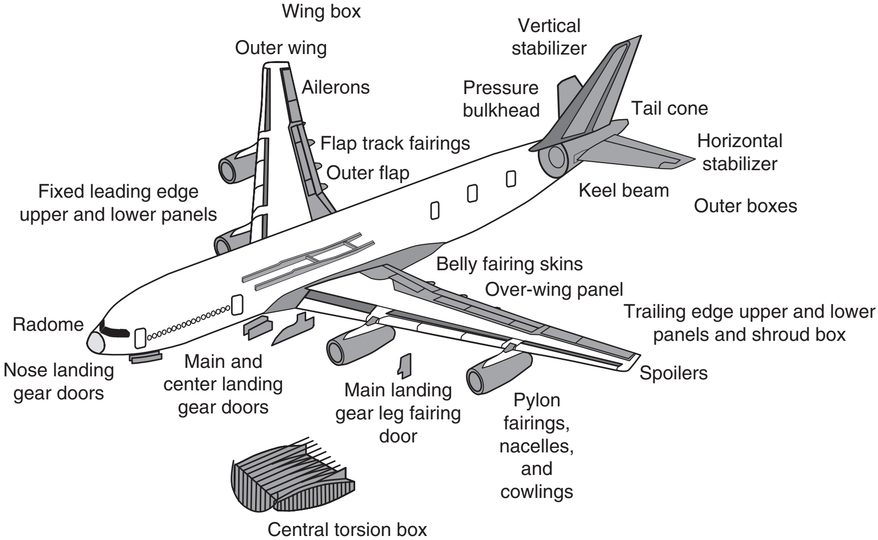

FIGURE 1.2 Use of fiber-reinforced polymer composites in Airbus 380.

Starting with Boeing 777, which was first introduced in 1995, Boeing has started making use of composites in the empennage (which include horizontal stabilizer, vertical stabilizer, elevator, and rudder), most of the control surfaces, engine cowlings, and fuselage floor beams (Figure 1.3). About 10% of Boeing 777's structural weight is made of carbon fiber-reinforced epoxy and about 50% is made of aluminum alloys. About 50% of the structural weight of Boeing's

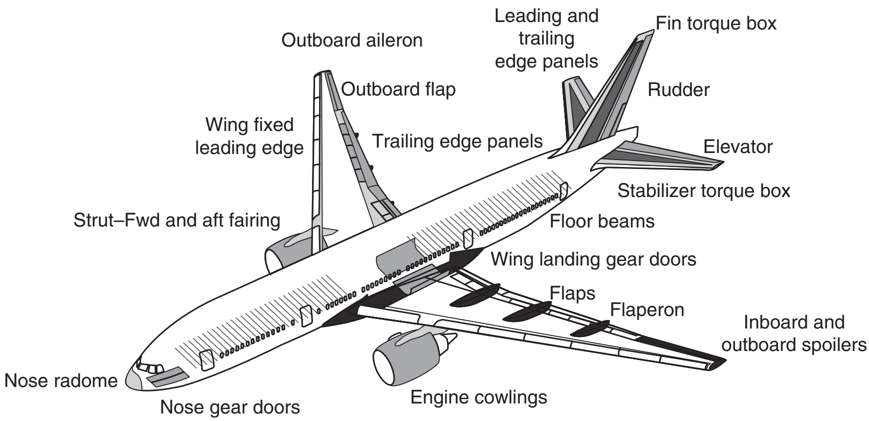

FIGURE 1.3 Use of fiber-reinforced polymer composites in Boeing 777.

next line of airplanes, called the Boeing 787 Dreamliner, will be made of carbon fiber-reinforced polymers. The other major materials in Boeing 787 will be aluminum alloys (20%), titanium alloys (15%), and steel (10%). Two of the major composite components in 787 will be the fuselage and the forward section, both of which will use carbon fiber-reinforced epoxy as the major material of construction.

There are several pioneering examples of using larger quantities of composite materials in smaller aircrafts. One of these examples is the Lear Fan 2100, a business aircraft built in 1983, in which carbon fiber–epoxy and Kevlar 49 fiber–epoxy accounted for ~70% of the aircraft's airframe weight. The composite components in this aircraft included wing skins, main spar, fuselage, empennage, and various control surfaces [3]. Another example is the Rutan Voyager (Figure 1.4), which was an all-composite airplane and made the first-ever nonstop flight around the world in 1986. To travel 25,000 miles without refueling, the Voyager airplane had to be extremely light and contain as much fuel as needed.

Fiber-reinforced polymers are used in many military and commercial helicopters for making baggage doors, fairings, vertical fins, tail rotor spars, and so on. One key helicopter application of composite materials is the rotor blades. Carbon or glass fiber-reinforced epoxy is used in this application. In addition to significant weight reduction over aluminum, they provide a better control over the vibration characteristics of the blades. With aluminum, the critical flopping

FIGURE 1.4 Rutan Voyager all-composite plane.

and twisting frequencies are controlled principally by the classical method of mass distribution [4]. With fiber-reinforced polymers, they can also be controlled by varying the type, concentration, distribution, as well as orientation of fibers along the blade's chord length. Another advantage of using fiber-reinforced polymers in blade applications is the manufacturing flexibility of these materials. The composite blades can be filament-wound or molded into complex airfoil shapes with little or no additional manufacturing costs, but conventional metal blades are limited to shapes that can only be extruded, machined, or rolled.

The principal reason for using fiber-reinforced polymers in aircraft and helicopter applications is weight saving, which can lead to significant fuel saving and increase in payload. There are several other advantages of using them over aluminum and titanium alloys.

1. Reduction in the number of components and fasteners, which results in a reduction of fabrication and assembly costs. For example, the vertical fin assembly of the Lockheed L-1011 has 72% fewer components and 83% fewer fasteners when it is made of carbon fiber-reinforced epoxy than when it is made of aluminum. The total weight saving is 25.2%.
2. Higher fatigue resistance and corrosion resistance, which result in a reduction of maintenance and repair costs. For example, metal fins used in helicopters flying near ocean coasts use an 18 month repair cycle for patching corrosion pits. After a few years in service, the patches can add enough weight to the fins to cause a shift in the center of gravity of the helicopter, and therefore the fin must then be rebuilt or replaced. The carbon fiber-reinforced epoxy fins do not require any repair for corrosion, and therefore, the rebuilding or replacement cost is eliminated.
3. The laminated construction used with fiber-reinforced polymers allows the possibility of aeroelastically tailoring the stiffness of the airframe structure. For example, the airfoil shape of an aircraft wing can be controlled by appropriately adjusting the fiber orientation angle in each lamina and the stacking sequence to resist the varying lift and drag loads along its span. This produces a more favorable airfoil shape and enhances the aerodynamic characteristics critical to the aircraft's maneuverability.

The key limiting factors in using carbon fiber-reinforced epoxy in aircraft structures are their high cost, relatively low impact damage tolerance (from bird strikes, tool drop, etc.), and susceptibility to lightning damage. When they are used in contact with aluminum or titanium, they can induce galvanic corrosion in the metal components. The protection of the metal components from corrosion can be achieved by coating the contacting surfaces with a corrosion-inhibiting paint, but it is an additional cost.

1.3.2 Space Applications

Weight reduction is the primary reason for using fiber-reinforced composites in many space vehicles [5]. Among the various applications in the structure of space shuttles are the mid-fuselage truss structure (boron fiber-reinforced aluminum tubes), payload bay door (sandwich laminate of carbon fiber-reinforced epoxy face sheets and aluminum honeycomb core), remote manipulator arm (ultrahigh-modulus carbon fiber-reinforced epoxy tube), and pressure vessels (Kevlar 49 fiber-reinforced epoxy).

In addition to the large structural components, fiber-reinforced polymers are used for support structures for many smaller components, such as solar arrays, antennas, optical platforms, and so on [6]. A major factor in selecting them for these applications is their dimensional stability over a wide temperature range. Many carbon fiber-reinforced epoxy laminates can be ‘‘designed’’ to produce a CTE close to zero. Many aerospace alloys (e.g., Invar) also have a comparable CTE. However, carbon fiber composites have a much lower density, higher strength, as well as a higher stiffness–weight ratio. Such a unique combination of mechanical properties and CTE has led to a number of applications for carbon fiber-reinforced epoxies in artificial satellites. One such application is found in the support structure for mirrors and lenses in the space telescope [7]. Since the temperature in space may vary between $-100°C$ and $100°C$, it is critically important that the support structure be dimensionally stable; otherwise, large changes in the relative positions of mirrors or lenses due to either thermal expansion or distortion may cause problems in focusing the telescope.

Carbon fiber-reinforced epoxy tubes are used in building truss structures for low earth orbit (LEO) satellites and interplanetary satellites. These truss structures support optical benches, solar array panels, antenna reflectors, and other modules. Carbon fiber-reinforced epoxies are preferred over metals or metal matrix composites because of their lower weight as well as very low CTE. However, one of the major concerns with epoxy-based composites in LEO satellites is that they are susceptible to degradation due to atomic oxygen (AO) absorption from the earth's rarefied atmosphere. This problem is overcome by protecting the tubes from AO exposure, for example, by wrapping them with thin aluminum foils.

Other concerns for using fiber-reinforced polymers in the space environment are the outgassing of the polymer matrix when they are exposed to vacuum in space and embrittlement due to particle radiation. Outgassing can cause dimensional changes and embrittlement may lead to microcrack formation. If the outgassed species are deposited on the satellite components, such as sensors or solar cells, their function may be seriously degraded [8].

1.3.3 Automotive Applications

Applications of fiber-reinforced composites in the automotive industry can be classified into three groups: body components, chassis components, and engine components. Exterior body components, such as the hood or door panels, require high stiffness and damage tolerance (dent resistance) as well as a ''Class A'' surface finish for appearance. The composite material used for these components is E-glass fiber-reinforced sheet molding compound (SMC) composites, in which discontinuous glass fibers (typically 25 mm in length) are randomly dispersed in a polyester or a vinyl ester resin. E-glass fiber is used instead of carbon fiber because of its significantly lower cost. The manufacturing process used for making SMC parts is called compression molding. One of the design requirements for many exterior body panels is the ''Class A'' surface finish, which is not easily achieved with compression-molded SMC. This problem is usually overcome by in-mold coating of the exterior molded surface with a flexible resin. However, there are many underbody and under-the-hood components in which the external appearance is not critical. Examples of such components in which SMC is used include radiator supports, bumper beams, roof frames, door frames, engine valve covers, timing chain covers, oil pans, and so on. Two of these applications are shown in Figures 1.5 and 1.6.

SMC has seen a large growth in the automotive industry over the last 25 years as it is used for manufacturing both small and large components, such as hoods, pickup boxes, deck lids, doors, fenders, spoilers, and others, in automobiles, light trucks, and heavy trucks. The major advantages of using SMC instead of steel in these components include not only the weight reduction, but also lower tooling cost and parts integration. The tooling cost for compression molding SMC parts can be 40%–60% lower than that for stamping steel parts. An example of parts integration can be found in radiator supports in which SMC is used as a substitution for low carbon steel. The composite

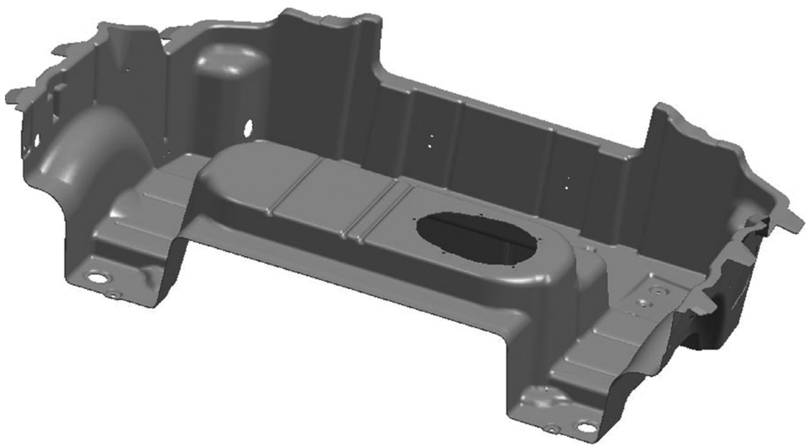

FIGURE 1.5 Compression-molded SMC trunk of Cadillac Solstice. (Courtesy of Molded Fiber Glass and American Composites Alliance. With permission.)

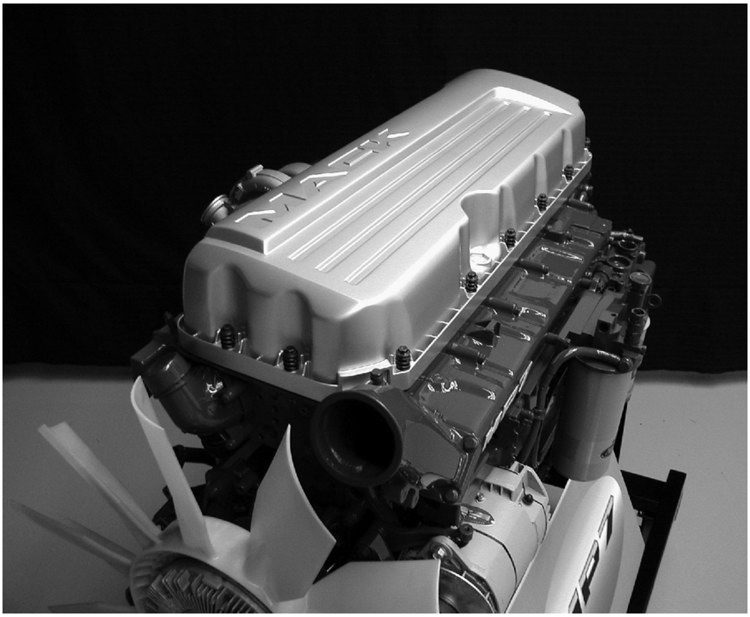

FIGURE 1.6 Compression-molded SMC valve cover for a truck engine. (Courtesy of Ashland Chemicals and American Composites Alliance. With permission.)

radiator support is typically made of two SMC parts bonded together by an adhesive instead of 20 or more steel parts assembled together by large number of screws. The material in the composite radiator support is randomly oriented discontinuous E-glass fiber-reinforced vinyl ester. Another example of parts integration can be found in the station wagon tailgate assembly [9], which has significant load-bearing requirements in the open position. The composite tailgate consists of two pieces, an outer SMC shell and an inner reinforcing SMC piece. They are bonded together using a urethane adhesive. The composite tailgate replaces a seven-piece steel tailgate assembly, at about one-third its weight. The material for both the outer shell and the inner reinforcement is a randomly oriented discontinuous E-glass fiber-reinforced polyester.

Another manufacturing process for making composite body panels in the automotive industry is called the structural reaction injection molding (SRIM). The fibers in these parts are usually randomly oriented discontinuous E-glass fibers and the matrix is a polyurethane or polyurea. Figure 1.7 shows the photograph of a one-piece 2 m long cargo box that is molded using this process. The wall thickness of the SRIM cargo box is 3 mm and its one-piece construction replaces four steel panels that are joined together using spot welds.

Among the chassis components, the first major structural application of fiber-reinforced composites is the Corvette rear leaf spring, introduced first in

FIGURE 1.7 One-piece cargo box for a pickup truck made by the SRIM process.

1981 [10]. Unileaf E-glass fiber-reinforced epoxy springs have been used to replace multileaf steel springs with as much as 80% weight reduction. Other structural chassis components, such as drive shafts and road wheels, have been successfully tested in laboratories and proving grounds. They have also been used in limited quantities in production vehicles. They offer opportunities for substantial weight savings, but so far they have not proven to be cost-effective over their steel counterparts.

The application of fiber-reinforced composites in engine components has not been as successful as the body and chassis components. Fatigue loads at very high temperatures pose the greatest challenge in these applications. Development of high-temperature polymers as well as metal matrix or ceramic matrix composites would greatly enhance the potential for composite usage in this area.

Manufacturing and design of fiber-reinforced composite materials for automotive applications are significantly different from those for aircraft applications. One obvious difference is in the volume of production, which may range from 100 to 200 pieces per hour for automotive components compared with a few hundred pieces per year for aircraft components. Although the labor-intensive hand layup followed by autoclave molding has worked well for fabricating aircraft components, high-speed methods of fabrication, such as compression molding and SRIM, have emerged as the principal manufacturing process for automotive composites. Epoxy resin is the major polymer matrix used in aerospace composites; however, the curing time for epoxy resin is very long, which means the production time for epoxy matrix composites is also very long. For this reason, epoxy is not considered the primary matrix material in automotive composites. The polymer matrix used in automotive applications is either a polyester, a vinyl ester, or polyurethane, all of which require significantly lower curing time than epoxy. The high cost of carbon fibers has prevented their use in the cost-conscious automotive industry. Instead of carbon fibers, E-glass fibers are used in automotive composites because of their significantly lower cost. Even with E-glass fiber-reinforced composites, the cost-effectiveness issue has remained particularly critical, since the basic material of construction in present-day automobiles is low-carbon steel, which is much less expensive than most fiber-reinforced composites on a unit weight basis.

Although glass fiber-reinforced polymers are the primary composite materials used in today's automobiles, it is well recognized that significant vehicle weight reduction needed for improved fuel efficiency can be achieved only with carbon fiber-reinforced polymers, since they have much higher strength–weight and modulus–weight ratios. The problem is that the current carbon fiber price, at $16/kg or higher, is not considered cost-effective for automotive applications. Nevertheless, many attempts have been made in the past to manufacture structural automotive parts using carbon fiber-reinforced polymers; unfortunately most of them did not go beyond the stages of prototyping and structural testing. Recently, several high-priced vehicles have started using carbon fiber-reinforced polymers in a few selected components. One recent example of this is seen in the BMW M6 roof panel (Figure 1.8), which was produced by a process called resin transfer molding (RTM). This panel is twice as thick as a comparable steel panel, but 5.5 kg lighter. One added benefit of reducing the weight of the roof panel is that it slightly lowers the center of gravity of the vehicle, which is important for sports coupe.

Fiber-reinforced composites have become the material of choice in motor sports where lightweight structure is used for gaining competitive advantage of higher speed [11] and cost is not a major material selection decision factor. The first major application of composites in race cars was in the 1950s when glass fiber-reinforced polyester was introduced as replacement for aluminum body panels. Today, the composite material used in race cars is mostly carbon fiber-reinforced epoxy. All major body, chassis, interior, and suspension components in today's Formula 1 race cars use carbon fiber-reinforced epoxy. Figure 1.9 shows an example of carbon fiber-reinforced composite used in the gear box and rear suspension of a Formula 1 race car. One major application of carbon fiber-reinforced epoxy in Formula 1 cars is the survival cell, which protects the driver in the event of a crash. The nose cone located in front of the survival cell is also made of carbon fiber-reinforced epoxy. Its controlled crush behavior is also critical to the survival of the driver.

FIGURE 1.8 Carbon fiber-reinforced epoxy roof panel in BMW M6 vehicle. (Photograph provided by BMW. With permission.)

FIGURE 1.9 Carbon fiber-reinforced epoxy suspension and gear box in a Formula 1 race car. (Courtesy of Bar 1 Formula 1 Racing Team. With permission.)

1.3.4 Sporting Goods Applications

Fiber-reinforced polymers are extensively used in sporting goods ranging from tennis rackets to athletic shoes (Table 1.5) and are selected over such traditional materials as wood, metals, and leather in many of these applications [12]. The advantages of using fiber-reinforced polymers are weight reduction, vibration damping, and design flexibility. Weight reduction achieved by substituting carbon fiber-reinforced epoxies for metals leads to higher speeds and quick maneuvering in competitive sports, such as bicycle races and canoe races. In some applications, such as tennis rackets or snow skis, sandwich constructions of carbon or boron fiber-reinforced epoxies as the skin material and a soft, lighter weight urethane foam as the core material produces a higher weight reduction without sacrificing stiffness. Faster damping of vibrations provided by fiber-reinforced polymers reduces the shock transmitted to the player's arm in tennis or racket ball games and provides a better "feel" for the ball. In archery bows and pole-vault poles, the high stiffness–weight ratio of fiber-reinforced composites is used to store high elastic energy per unit weight, which helps in propelling the arrow over a longer distance or the pole-vaulter to jump a greater height. Some of these applications are described later.

Bicycle frames for racing bikes today are mostly made of carbon fiber-reinforced epoxy tubes, fitted together by titanium fittings and inserts. An example is shown in Figure 1.10. The primary purpose of using carbon fibers is

TABLE 1.5
Applications of Fiber-Reinforced Polymers in Sporting Goods

Tennis rackets
Racket ball rackets
Golf club shafts
Fishing rods
Bicycle frames
Snow and water skis
Ski poles, pole vault poles
Hockey sticks
Baseball bats
Sail boats and kayaks
Oars, paddles
Canoe hulls
Surfboards, snow boards
Arrows
Archery bows
Javelins
Helmets
Exercise equipment
Athletic shoe soles and heels

FIGURE 1.10 Carbon fiber-reinforced epoxy bicycle frame. (Photograph provided by Trek Bicycle Corporation. With permission.)

weight saving (the average racing bicycle weight has decreased from about 9 kg in the 1980s to 1.1 kg in 1990s); however, to reduce material cost, carbon fibers are sometimes combined with glass or Kevlar 49 fibers. Fiber-reinforced polymer wrapped around thin-walled metal tube is not also uncommon. The ancillary components, such as handlebars, forks, seat post, and others, also use carbon fiber-reinforced polymers.

Golf clubs made of carbon fiber-reinforced epoxy are becoming increasingly popular among professional golfers. The primary reason for the composite golf shaft's popularity is its low weight compared with steel golf shafts. The average weight of a composite golf shaft is 65–70 g compared with 115–125 g for steel shafts. Weight reduction in the golf club shaft allows the placement of additional weight in the club head, which results in faster swing and longer drive.

Glass fiber-reinforced epoxy is preferred over wood and aluminum in pole-vault poles because of its high strain energy storage capacity. A good pole must have a reasonably high stiffness (to keep it from flapping excessively during running before jumping) and high elastic limit stress so that the strain energy of the bent pole can be recovered to propel the athlete above the horizontal bar. As the pole is bent to store the energy, it should not show any plastic deformation and should not fracture. The elastic limit of glass fiber-reinforced epoxy is much higher than that of either wood or high-strength aluminum alloys. With glass fiber-reinforced epoxy poles, the stored energy is high enough to clear 6 m or greater height in pole vaulting. Carbon fiber-reinforced epoxy is not used, since it is prone to fracture at high bending strains.

Glass and carbon fiber-reinforced epoxy fishing rods are very common today, even though traditional materials, such as bamboo, are still used. For fly-fishing rods, carbon fiber-reinforced epoxy is preferred, since it produces a smaller tip deflection (because of its higher modulus) and "wobble-free" action during casting. It also dampens the vibrations more rapidly and reduces the transmission of vibration waves along the fly line. Thus, the casting can be longer, quieter, and more accurate, and the angler has a better "feel" for the catch. Furthermore, carbon fiber-reinforced epoxy rods recover their original shape much faster than the other rods. A typical carbon fiber-reinforced epoxy rod of No. 6 or No. 7 line weighs only 37 g. The lightness of these rods is also a desirable feature to the anglers.

1.3.5 Marine Applications

Glass fiber-reinforced polyesters have been used in different types of boats (e.g., sail boats, fishing boats, dinghies, life boats, and yachts) ever since their introduction as a commercial material in the 1940s [13]. Today, nearly 90% of all recreational boats are constructed of either glass fiber-reinforced polyester or glass fiber-reinforced vinyl ester resin. Among the applications are hulls, decks, and various interior components. The manufacturing process used for making a majority of these components is called contact molding. Even though it is a labor-intensive process, the equipment cost is low, and therefore it is affordable to many of the small companies that build these boats. In recent years, Kevlar 49 fiber is replacing glass fibers in some of these applications because of its higher tensile strength–weight and modulus–weight ratios than those of glass fibers. Among the application areas are boat hulls, decks, bulkheads, frames, masts, and spars. The principal advantage is weight reduction, which translates into higher cruising speed, acceleration, maneuverability, and fuel efficiency.

Carbon fiber-reinforced epoxy is used in racing boats in which weight reduction is extremely important for competitive advantage. In these boats, the complete hull, deck, mast, keel, boom, and many other structural components are constructed using carbon fiber-reinforced epoxy laminates and sandwich laminates of carbon fiber-reinforced epoxy skins with either honeycomb core or plastic foam core. Carbon fibers are sometimes hybridized with other lower density and higher strain-to-failure fibers, such as high-modulus polyethylene fibers, to improve impact resistance and reduce the boat's weight.

The use of composites in naval ships started in the 1950s and has grown steadily since then [14]. They are used in hulls, decks, bulkheads, masts, propulsion shafts, rudders, and others of mine hunters, frigates, destroyers, and aircraft carriers. Extensive use of fiber-reinforced polymers can be seen in Royal Swedish Navy's 72 m long, 10.4 m wide Visby-class corvette, which is the largest composite ship in the world today. Recently, the US navy has commissioned a 24 m long combat ship, called Stiletto, in which carbon fiber-reinforced epoxy will be the primary material of construction. The selection of carbon fiber-reinforced epoxy is based on the design requirements of lightweight and high strength needed for high speed, maneuverability, range, and payload capacity of these ships. Their stealth characteristics are also important in minimizing radar reflection.

1.3.6 Infrastructure

Fiber-reinforced polymers have a great potential for replacing reinforced concrete and steel in bridges, buildings, and other civil infrastructures [15]. The principal reason for selecting these composites is their corrosion resistance, which leads to longer life and lower maintenance and repair costs. Reinforced concrete bridges tend to deteriorate after several years of use because of corrosion of steel-reinforcing bars (rebars) used in their construction. The corrosion problem is exacerbated because of deicing salt spread on the bridge road surface in winter months in many parts of the world. The deterioration can become so severe that the concrete surrounding the steel rebars can start to crack (due to the expansion of corroding steel bars) and ultimately fall off, thus weakening the structure's load-carrying capacity. The corrosion problem does not exist with fiber-reinforced polymers. Another advantage of using fiber-reinforced polymers for large bridge structures is their lightweight, which means lower dead weight for the bridge, easier transportation from the production factory (where the composite structure can be prefabricated) to the bridge location, easier hauling and installation, and less injuries to people in case of an earthquake. With lightweight construction, it is also possible to design bridges with longer span between the supports.

One of the early demonstrations of a composite traffic bridge was made in 1995 by Lockheed Martin Research Laboratories in Palo Alto, California. The bridge deck was a 9 m long $\times$ 5.4 m wide quarter-scale section and the material selected was E-glass fiber-reinforced polyester. The composite deck was a sandwich laminate of 15 mm thick E-glass fiber-reinforced polyester face sheets and a series of E-glass fiber-reinforced polyester tubes bonded together to form the core. The deck was supported on three U-shaped beams made of E-glass fabric-reinforced polyester. The design was modular and the components were stackable, which simplified both their transportation and assembly.

In recent years, a number of composite bridge decks have been constructed and commissioned for service in the United States and Canada. The Wickwire Run Bridge located in West Virginia, United States is an example of one such construction. It consists of full-depth hexagonal and half-depth trapezoidal profiles made of glass fabric-reinforced polyester matrix. The profiles are supported on steel beams. The road surface is a polymer-modified concrete. Another example of a composite bridge structure is shown in Figure 1.11, which replaced a 73 year old concrete bridge with steel rebars. The replacement was necessary because of the severe deterioration of the concrete deck, which reduced its load rating from 10 to only 4.3 t and was posing safety concerns. In

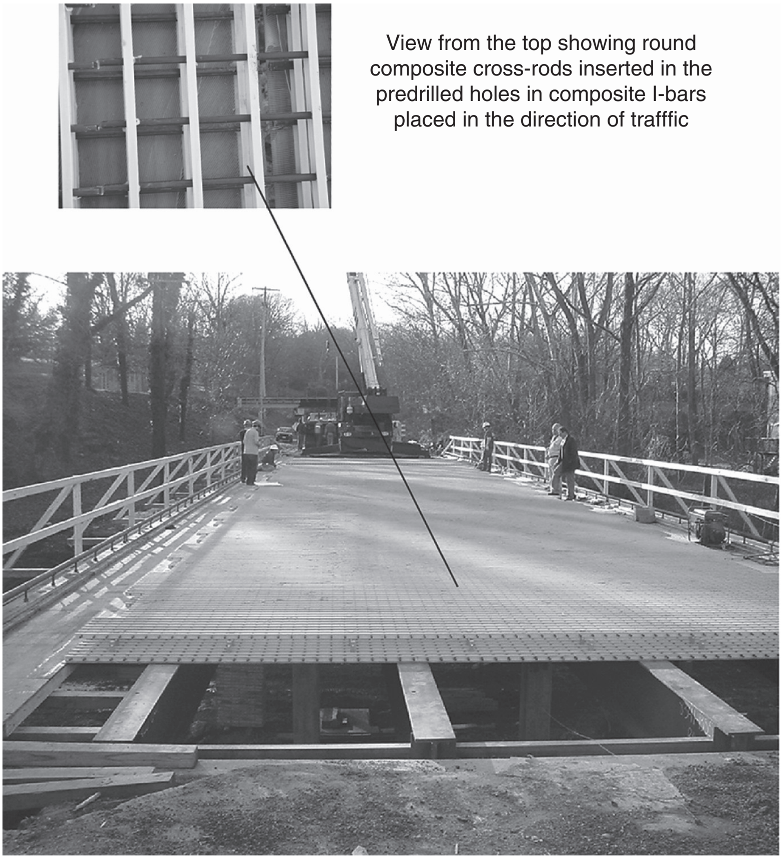

FIGURE 1.11 Glass fiber-reinforced vinyl ester pultruded sections in the construction of a bridge deck system. (Photograph provided by Strongwell Corporation. With permission.)

the composite bridge, the internal reinforcement for the concrete deck is a two-layer construction and consists primarily of pultruded I-section bars (I-bars) in the width direction (perpendicular to the direction of traffic) and pultruded round rods in the length directions. The material for the pultruded sections is glass fiber-reinforced vinyl ester. The internal reinforcement is assembled by inserting the round rods through the predrilled holes in I-bar webs and keeping them in place by vertical connectors.

Besides new bridge construction or complete replacement of reinforced concrete bridge sections, fiber-reinforced polymer is also used for upgrading, retrofitting, and strengthening damaged, deteriorating, or substandard concrete or steel structures [16]. For upgrading, composite strips and plates are attached in the cracked or damaged areas of the concrete structure using adhesive, wet layup, or resin infusion. Retrofitting of steel girders is accomplished by attaching composite plates to their flanges, which improves the flange stiffness and strength. The strengthening of reinforced concrete columns in earthquake prone areas is accomplished by wrapping them with fiber-reinforced composite jackets in which the fibers are primarily in the hoop direction. They are found to be better than steel jackets, since, unlike steel jackets, they do not increase the longitudinal stiffness of the columns. They are also much easier to install and they do not corrode like steel.

1.4 MATERIAL SELECTION PROCESS

Material selection is one of the most important and critical steps in the structural or mechanical design process. If the material selection is not done properly, the design may show poor performance; may require frequent maintenance, repair, or replacement; and in the extreme, may fail, causing damage, injuries, or fatalities. The material selection process requires the knowledge of the performance requirements of the structure or component under consideration. It also requires the knowledge of

1. Types of loading, for example, axial, bending, torsion, or combination thereof
2. Mode of loading, for example, static, fatigue, impact, shock, and so on
3. Service life
4. Operating or service environment, for example, temperature, humidity conditions, presence of chemicals, and so on
5. Other structures or components with which the particular design under consideration is required to interact
6. Manufacturing processes that can be used to produce the structure or the component
7. Cost, which includes not only the material cost, but also the cost of transforming the selected material to the final product, that is, the manufacturing cost, assembly cost, and so on

The material properties to consider in the material selection process depend on the performance requirements (mechanical, thermal, etc.) and the possible mode or modes of failure (e.g., yielding, brittle fracture, ductile failure, buckling, excessive deflection, fatigue, creep, corrosion, thermal failure due to overheating, etc.). Two basic material properties often used in the preliminary selection of materials for a structural or mechanical design are the modulus and strength. For a given design, the modulus is used for calculating the deformation, and the strength is used for calculating the maximum load-carrying capacity. Which property or properties should be considered in making a preliminary material selection depends on the application and the possible failure modes. For example, yield strength is considered if the design of a structure requires that no permanent deformation occurs because of the application of the load. If, on the other hand, there is a possibility of brittle failure because of the influence of the operating environmental conditions, fracture toughness is the material property to consider.

In many designs the performance requirement may include stiffness, which is defined as load per unit deformation. Stiffness should not be confused with modulus, since stiffness depends not only on the modulus of the material (which is a material property), but also on the design. For example, the stiffness of a straight beam with solid circular cross section depends not only on the modulus of the material, but also on its length, diameter, and how it is supported (i.e., boundary conditions). For a given beam length and support conditions, the stiffness of the beam with solid circular cross section is proportional to Ed^4, where E is the modulus of the beam material and d is its diameter. Therefore, the stiffness of this beam can be increased by either selecting a higher modulus material, or increasing the diameter, or doing both. Increasing the diameter is more effective in increasing the stiffness, but it also increases the weight and cost of the beam. In some designs, it may be possible to increase the beam stiffness by incorporating other design features, such as ribs, or by using a sandwich construction.

In designing structures with minimum mass or minimum cost, material properties must be combined with mass density (ρ), cost per unit mass (\$/kg), and so on. For example, if the design objective for a tension linkage or a tie bar is to meet the stiffness performance criterion with minimum mass, the material selection criterion involves not just the tensile modulus of the material (E), but also the modulus–density ratio (E/ρ). The modulus–density ratio is a material index, and the material that produces the highest value of this material index should be selected for minimum mass design of the tension link. The material index depends on the application and the design objective. Table 1.6 lists the material indices for minimum mass design of a few simple structures.

As an example of the use of the material index in preliminary material selection, consider the carbon fiber–epoxy quasi-isotropic laminate in Table 1.1. Thin laminates of this type are considered well-suited for many aerospace applications [1], since they exhibit equal elastic properties (e.g., modulus) in all directions in the plane of load application. The quasi-isotropic laminate in Table 1.1 has an elastic modulus of 45.5 GPa, which is 34% lower than that of the 7178-T6 aluminum alloy and 59% lower than that of the Ti-6 Al-4V titanium alloy. The aluminum and the titanium alloys are the primary metallic alloys used in the construction of civilian and military aircrafts. Even though the quasi-isotropic carbon fiber–epoxy composite laminate has a lower modulus, it is a good candidate for substituting the metallic alloys in stiffness-critical aircraft structures. This is because the carbon fiber–epoxy quasi-isotropic laminate has a superior material index in minimum mass design of stiffness-critical structures. This can be easily verified by comparing the values of the material index $\frac{E^{1/3}}{\rho}$ of all three materials, assuming that the structure can be modeled as a thin plate under bending load.

TABLE 1.6
Material Index for Stiffness and Strength-Critical Designs at Minimum Mass

Structure	Constraints	Design Variable	Material Index: Stiffness-Critical Design	Material Index: Strength-Critical Design
Round tie bar loaded in axial tension	Length fixed	Diameter	$\frac{E}{\rho}$	$\frac{S_f}{\rho}$
Rectangular beam loaded in bending	Length and width fixed	Height	$\frac{E^{1/3}}{\rho}$	$\frac{S_f^{1/2}}{\rho}$
Round bar or shaft loaded in torsion	Length fixed	Diameter	$\frac{G^{1/2}}{\rho}$	$\frac{S_f^{2/3}}{\rho}$
Flat plate loaded in bending	Length and width fixed	Thickness	$\frac{E^{1/3}}{\rho}$	$\frac{S_f^{1/2}}{\rho}$
Round column loaded in compression	Length	Diameter	$\frac{E^{1/2}}{\rho}$	$\frac{S_f}{\rho}$

Source: Adapted from Ashby, M.F., *Material Selection in Mechanical Design*, 3rd Ed., Elsevier, Oxford, UK, 2005.

Note: ρ = mass density, E = Young's modulus, G = shear modulus, and S_f = strength.

Weight reduction is often the principal consideration for selecting fiber-reinforced polymers over metals, and for many applications, they provide a higher material index than metals, and therefore, suitable for minimum mass design. Depending on the application, there are other advantages of using fiber-reinforced composites, such as higher damping, no corrosion, parts integration, control of thermal expansion, and so on, that should be considered as well, and some of these advantages add value to the product that cannot be obtained with metals. One great advantage is the tailoring of properties according to the design requirements, which is demonstrated in the example of load-bearing orthopedic implants [17]. One such application is the bone plate used for bone fracture fixation. In this application, the bone plate is attached to the bone fracture site with screws to hold the fractured pieces in position, reduce the mobility at the fracture interface, and provide the required stress-shielding of the bone for proper healing. Among the biocompatible materials used for orthopedic implants, stainless steel and titanium are the two most common materials used for bone plates. However, the significantly higher modulus of both of these materials than that of bone creates excessive stress-shielding, that is, they share the higher proportion of the compressive stresses during healing than the bone. The advantage of using fiber-reinforced polymers is that they can be designed to match the modulus of bone, and indeed, this is the reason for selecting carbon fiber-reinforced epoxy or polyether ether ketone (PEEK) for such an application [18,19].

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PROBLEMS*

P1.1. The modulus and tensile strength of a SMC composite are reported as 15 GPa and 230 MPa, respectively. Assuming that the density of the SMC is 1.85 g/cm^3, calculate the strength–weight ratio and modulus–weight ratio for the composite.

P1.2. The material of a tension member is changed from AISI 4340 steel to a unidirectional high-modulus (HM) carbon fiber-reinforced epoxy.

1. Calculate the ratio of the cross-sectional areas, axial stiffnesses, and weights of these two members for equal load-carrying capacities
2. Calculate the ratio of the cross-sectional areas, load-carrying capacities, and weights of these two members for equal axial stiffness (*Hint*: Load = strength $\times$ cross-sectional area, and axial stiffness = modulus $\times$ cross-sectional area)

P1.3. Compare the heights and weights of three rectangular beams made of aluminum alloy 6061-T6, titanium alloy Ti-6Al-4V, and a unidirectional high-strength (HS) carbon fiber-reinforced epoxy designed to posses (a) equal bending stiffness and (b) equal bending moment carrying capacity. Assume that all three beams have the same length and width. (*Hint*: The bending stiffness is proportional to Eh^3 and the bending moment is proportional to Sh^2, where E, S, and h are the modulus, strength, and height, respectively.)

P1.4. Calculate the flexural (bending) stiffness ratio of two cantilever beams of equal weight, one made of AISI 4340 steel and the other made of a unidirectional high-modulus carbon fiber–epoxy composite. Assume that both beams have the same length and width, but different heights. If the beams were simply supported instead of fixed at one end like a cantilever beam, how will the ratio change?

P1.5. In a certain application, a steel beam of round cross section (diameter = 10 mm) is to be replaced by a unidirectional fiber-reinforced epoxy beam of equal length. The composite beam is designed to have a natural frequency of vibration 25% higher than that of the steel beam. Among the fibers to be considered are high-strength carbon fiber, high-modulus carbon fiber, and Kevlar 49 (see Table 1.1). Select one of these fibers on the basis of minimum weight for the beam.

Note that the natural frequency of vibration of a beam is given by the following equation:

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* Use Table 1.1 for material properties if needed.

$$w_n = C\left(\frac{EI}{mL^4}\right)^{1/2},$$

where

w_n = fundamental natural frequency
C = a constant that depends on the beam support conditions
E = modulus of the beam material
I = moment of inertia of the beam cross section
m = mass per unit length of the beam
L = beam length

P1.6. The material of a thin flat panel is changed from SAE 1010 steel panel (thickness = 1.5 mm) an E-glass fiber-reinforced polyester SMC panel with equal flexural stiffness. Calculate the percentage weight and cost differences between the two panels. Note that the panel stiffness is $\frac{Eh^3}{12(1-\nu^2)}$, where E is the modulus of the panel material, ν is the Poisson's ratio of the panel material, and h is the panel thickness. The following is known for the two materials:

	Steel	**SMC**
Modulus (GPa)	207	16
Poisson's ratio	0.30	0.30
Density (g/cm^3)	7.87	1.85
Cost ($/kg)	0.80	1.90

Suggest an alternative design approach by which the wall thickness of the flat SMC panel can be reduced without lowering its flexural stiffness.

P1.7. To reduce the material cost, an engineer decides to use a hybrid beam instead of an all-carbon fiber beam. Both beams have the same overall dimensions. The hybrid beam contains carbon fibers in the outer layers and either E-glass or Kevlar 49 fibers in the core. The matrix used is an epoxy. Costs of these materials are as follows:

Carbon fiber–epoxy matrix: $25.00/lb
E-glass fiber–epoxy matrix: $1.20/lb
Kevlar 49 fiber–epoxy matrix: $8.00/lb

The total carbon fiber–epoxy thickness in the hybrid beam is equal to the core thickness. Compare the percentage weight penalty and cost savings for each hybrid beam over an all-carbon fiber beam. Do you expect both all-carbon and hybrid beams to have the same bending stiffness? If the answer is "no," what can be done to make the two stiffnesses equal?

P1.8. The shear modulus (G) of steel and a quasi-isotropic carbon fiber–epoxy is 78 and 17 GPa, respectively. The mean diameter (D) of a thin-walled steel torque tube is 25 mm and its wall thickness (t) is 3 mm. Knowing that the torsional stiffness of a thin-walled tube is proportional to D^3tG, calculate:

1. Mean diameter of a composite tube that has the same torsional stiffness and wall thickness as the steel tube
2. Wall thickness of a composite tube that has the same torsional stiffness and mean diameter as the steel tube
3. Difference in weight (in percentage) between the steel tube and the composite tube in each of the previous cases, assuming equal length for both tubes

P1.9. Using the information in Problem P1.8, design a composite torque tube that is 30% lighter than the steel tube but has the same torsional stiffness. Will the axial stiffnesses of these two tubes be the same?

P1.10. Write the design and material selection considerations for each of the following applications and discuss why fiber-reinforced polymers can be a good candidate material for each application.

1. Utility poles
2. Aircraft floor panels
3. Aircraft landing gear doors
4. Household step ladders
5. Wind turbine blades
6. Suspension arms of an automobile
7. Drive shaft of an automobile
8. Underground gasoline storage tanks
9. Hydrogen storage tanks for fuel cell vehicles
10. Leg prosthetic
11. Flywheel for energy storage