
Composite Materials and Processes

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5.1 Introduction

There are two general types of composites, distinguished by the type of materials that are used in construction and by the general market in which they can be found. The more prevalent composites, such as used in printed circuit boards, shower enclosures, and pleasure boats, are generally reinforced with fiberglass fabric, use a type of polyester resin as the matrix, and can be referred to as *commodity* composites. Large overlaps exist for the two types; for instance, there is a significant weight percent of fiberglass-reinforced plastic in most commercial airliners, and carbon/graphite or aramid have been used in reinforcing laminated truss beams for home building. Modern structural composites, frequently referred to as *advanced composites*, can be distinguished from *commodity* composites because of their frequent use of more exotic or expensive matrix materials and higher-priced reinforcements such as carbon/graphite, and they can be found in more structurally demanding locations that have a greater need for weight savings. They are a blend of two or more components. One component is made up of stiff, long fibers, and the other, for polymeric composites, is a resinous binder or *matrix* that holds the fibers in place. The fibers are strong and stiff relative to the matrix and are generally orthotropic (having different properties in two different directions). These properties are most evident when the components are shown in a breakdown view as in Fig. 5.1.

The fiber for advanced structural composites is long, with length-to-diameter ratios >100 . Predominately, for advanced structural compos-

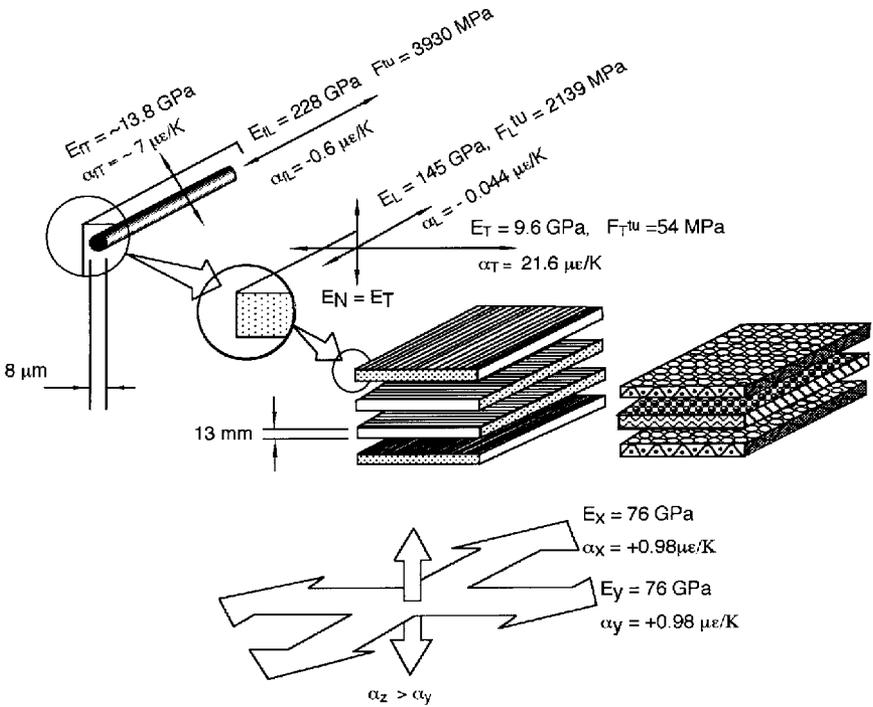


Figure 5.1 The anatomy of a composite laminate.

ites, the fiber has been continuous, but there is an increased awareness that discontinuous fibers allow potentially huge savings in manufacturing costs, so there are now efforts to incorporate them in areas previously reserved for continuous fiber. The fiber's strength and stiffness are much greater—many times more than the matrix material. For instance, the tensile strength quoted for 3502 resin is 4.8 ksi, and the longitudinal elastic modulus (Young's modulus) is 526 ksi. The "B" basis unidirectional tensile strength of the AS-4/3502 lamina is 205 ksi, and the fiber (tow) tensile strength and modulus are 580 ksi and 36 msi, respectively. Thus, for this combination of "typical" advanced composite materials, the fiber is >100 times the strength of the resin and >50 times the modulus.¹⁻³ (These data will change over time due to manufacturing improvements, and more detailed data, including design allowables, will be shown later in this chapter.) When the fiber and matrix are joined to form a composite, they both retain their individual identities, and both directly influence the composite's final properties. The resulting composite is composed of layers (laminates) of the fibers and matrix stacked to achieve the desired properties in one or more directions.

Designers of aircraft structures have been quick to realize that the high strength-to-weight or modulus-to-weight ratios of composites could result in lighter structural components with lower operating costs and better maintenance histories. The first high-performance aircraft to use advanced composites (boron/epoxy horizontal stabilizers, 1500 built) in a production contract was the F-14A. The use of composites has continued and has resulted in a preponderance of the structure being fabricated from composite materials in one aircraft, the Bell-Boeing V-22, of which approximately 60% of the weight of the craft is composite (Fig. 5.2). Some of the advantages in the use of composites are shown in Table 5.1. These advantages translate not only into aircraft production but also into everyday activities. For example, a carbon/graphite-shafted golf club produces longer drives, because more of the mass is concentrated at the club head. Tennis players also experience less fatigue and pain, because a carbon/graphite composite tennis racquet is lighter and has some inherent vibration damping. Generally, the advantages shown in Table 5.1 can be realized for most fiber/composite combinations, and the disadvantages are more obvious



Figure 5.2 The Bell-Boeing V-22. (Courtesy of the Boeing Company)

TABLE 5.1 Reasons for Using Composites

Reason for use	Material selected	Application/driver
Lighter, stiffer, stronger	Boron, all carbon/graphites, some aramid	Military aircraft, better performance; commercial aircraft, operating costs
Controlled or zero thermal expansion	Very high modulus carbon/graphite	Spacecraft with high positional accuracy requirements for optical sensors
Environmental resistance	Fiberglass, vinyl esters, bisphenol-a fumarates, chlorendic resins	Tanks and piping, corrosion resistance to industrial chemicals, crude oil, gasoline at elevated temperatures
Lower inertia, faster startups, less deflection	High-strength carbon/graphite, epoxy	Industrial rolls, for paper, films
Light weight, damage tolerance	High-strength carbon/graphite, fiberglass, (hybrids), epoxy	CNG tanks for “green” cars, trucks and busses to reduce environmental pollution
More reproducible complex surfaces	High-strength or high-modulus carbon graphite/epoxy	High-speed aircraft; metal skins cannot be formed accurately
Less pain and fatigue	Carbon/graphite/epoxy	Tennis, squash and racquetball racquets; metallic racquets no longer available
Reduces logging in “old growth” forests	Aramid, carbon/graphite	Laminated “new” growth wooden support beams with high-modulus fibers incorporated
Reduces need for intermediate support and resists constant 100% humidity atmosphere	High-strength carbon/graphite-epoxy	Cooling tower driveshafts
Tailorability of bending and twisting response	Carbon/graphite-epoxy	Golf club shafts, fishing rods
Transparency to radiation	Carbon/graphite-epoxy	X-ray tables
Crashworthiness	Carbon/graphite-epoxy	Racing cars
Higher natural frequency, lighter	Carbon/graphite-epoxy	Automotive and industrial driveshafts
Water resistance	Fiberglass (woven fabric), polyester, or isopolyester	Commercial boats
Ease of field application	Carbon/graphite, fiberglass- epoxy, tape, and fabric	Freeway support structure repair after earthquake

with some. These advantages have now resulted in composite applications far outside the aircraft industry, with many more reasons for use as shown in Table 5.2. Proper design and material selection can circumvent many of the disadvantages.

5.2 Material Systems

An advanced or commodity composite laminate can be tailored so that the directional dependence of strength and stiffness matches that of the loading environment. To do that, layers of unidirectional material called lamina, or woven fabric with fibers predominately in the expected loading directions, are oriented to satisfy the strength or stiffness requirements. These laminae and fabrics contain both fibers and a matrix. Because of the use of directional laminae, the tensile, flexural, and torsional shear properties of a structure can be disassociated from each other to some extent, and a golf shaft, for example, can be changed in torsional stiffness without changing the flexural or tensile stiffness. This allows for almost infinite variations in the shafts to accommodate individual needs. It also allows for altering the stiffness of a forward-swept aircraft wing to respond to the incoming loads (Fig. 5.3). This is not an option with isotropic metal.

TABLE 5.2 Advantages and Disadvantages of Advanced Composites

Advantages	Disadvantages
Weight reduction	Cost of raw materials and fabrication
High strength- or stiffness-to-weight ratio)	Transverse properties may be weak
Tailorable properties: can tailor strength or stiffness to be in the load direction	Matrix weakness, low toughness
Redundant load paths (fiber to fiber)	Matrix subject to environmental degradation
Longer life (no corrosion)	Difficult to attach
Lower manufacturing costs because of lower part count	Analysis for physical properties and mechanical properties difficult, analysis for damping efficiency has not reached a consensus
Inherent damping	Nondestructive testing tedious
Increased (or decreased) thermal or electrical conductivity	Acceptable methods for evaluation of residual properties have not reached a consensus
Better fatigue life	

5.2.1 Fibers

Fibers can be of the same material within a lamina or several fibers mixed (hybrid). The common commercially available fiber classes are as follows:



Figure 5.3 NASA-Grumman forward-swept wing, X-29 aircraft. (Courtesy of Dryden Flight Research Center)

- Carbon/graphite
- Fiberglass
- Organic
 - Aramid
 - Polyethylene
 - PBO
- Boron
- Silicon carbide
- Silicon nitride, silica, alumina, alumina silica

5.2.1.1 Fiberglass. The most widely used fiber for commodity composites, and the fiber that has had the longest period for development, is fiberglass, which has been marketed in several grades in the United States for more than 40 years. During that time, many different glasses were developed, including, leaded glass, and beryllium high-modulus glass, all of which are no longer produced or are in limited supply. The various types of glass that continue to be useful for composite structures are shown in Table 5.3.⁴

TABLE 5.3 Glass Fibers*

Type	Nominal tensile modulus, GPa (psi $\times 10^6$)	Nominal tensile strength, MPa (psi $\times 10^3$)	Ultimate strain, %	Fiber density, Mg/m ³ (lb/in ³)	Suppliers
E	72.5 (10.5)	3447 (500)	4.8	2600 (0.093)	PPG Manville Co. Owens Corning Fiberglass
R	85.2 (12.5)	2068 (300)	5.1	2491 (0.089)	Vetrotex Certainteed
Te	84.3 (12.2)	4660 (675)	5.5	2491 (0.089)	Nittobo
S-2	86.9 (12.6)	4585 (665)	5.4	2550 (0.092)	Owens Corning
Zentron high silica	94 (13.5)	3970 (575)		2460 (0.089)	Owens Corning

*In order of ascending modulus normalized to 100% fiber volume (vendor data) (see Ref. 4, p. 2-3).

The table shows the common description for the glass and the nominal tensile strength and tensile modulus of strands and composite. The composite data are average values generated from a series of tests by the manufacturer of the fiber, and they reflect the "ideal" or maximum strength and stiffness of a single fiber or tow or thin unidirectional laminated composite. A tensile test by the user will generally not reflect these values for strength. The maximum number of fibers per strand is usually important information for applications (e.g., filament winding or pultrusion) that use dry fibers mixed with the matrix resin at the point of fiber laydown, since it influences handling ease and per ply thickness. The fiber density is included so that the rule of mixtures equations involving fiber volume and resin volume can be used to evaluate void volume and theoretical mechanical properties. Compressive strength of glass-reinforced composites is relatively high and has led to their selection for use in underwater deep diving applications. The electrical properties of glass-reinforced composites have allowed their use as radomes and printed circuit boards, and in many other areas that require high dielectric strength.

Fiberglass is a product of silica sand, limestone, boric acid, and other ingredients that are dry-mixed, melted (at approximately 1260°C), and then drawn into fibers. Fiberglass, for structural use, is marketed in the form of fiber strand, unidirectional fabric, woven and knitted fabrics, and as preform shapes. It is by far the most widely used fiber, primarily because of its low cost, but its mechanical proper-

ties and specific mechanical properties (i.e., its strength or modulus to weight ratio) are not comparable with other structural fibers. Fiber properties for any of the materials, by themselves, are of little use to most designers, given that they prefer to work with laminate or lamina data. However, with the equations shown later, the designer can use these fiber values to compute the preliminary laminate properties, without the benefit of a computer program or extensive laminate data, which may not be available for newer fibers.

Glass fibers, like all other continuous composite reinforcements, are coated with a thin coating, somewhat like a paint and called a *finish* or *sizing*, that forms a bond between the fiber and the matrix material, improves the handling characteristics, and protects the fiber in the composite from some environmental effects. Each fiber type has a series of unique finishes that are formulated specifically for that type of fiber. Finishes are of little interest to the composite manufacturer, but they are somewhat critical to some processes that use dry strands or tow. For instance, if the fiber finish on the strand or tow for wet filament winding is changed, the spread of the fiber will be changed. If there are no other changes in the process, the resulting width of the applied band will be wider or narrower, and there will be overlaps or gaps in the laminae. Usually, the operator of the machine will adjust to remove laps and gaps (they are usually covered in a specification). Thus, the final laminate thickness will be less than specified and could result in a problem such as premature burst of a pressure vessel.

5.2.1.2 Carbon/graphite. Carbon/graphite fibers have demonstrated the widest variety of strengths and moduli and have the greatest number of suppliers (Table 5.4).⁴ The carbon/graphite fiber manufacturers, as a result of the turmoil in the composite industry induced by the severe decline in the U.S. defense demand for advanced composites, have gone through drastic price declines, inducing the departure of several manufacturers during the past 10 years. The fibers begin as an organic fiber, such as rayon, polyacrylonitrile (PAN), or pitch (a derivative of crude oil) that is called the *precursor*. The precursor is then stretched, oxidized, carbonized, and graphitized. There are many ways to produce these fibers,⁵ but the relative amount of exposure at temperatures from 2500–3000°C results in greater or less graphitization of the fiber. The degree of graphitization in most high-strength or intermediate fibers is low (less than 10%), so the appellation *graphite* fiber is a misnomer and has been promulgated as a marketing tool for sporting goods. Higher degrees of graphitization usually result in a stiffer fiber (higher modulus) with greater electrical and thermal conductivities. Pitch fibers above 689 GPa (100 msi) tensile modulus have thermal conductiv-

TABLE 5.4a Carbon/Graphite Fibers (Pan) (from Ref. 4, p. 2-7)

Class of fiber	Nominal tensile modulus, GPa (psi × 10 ⁶)	Nominal tensile strength, MPa (psi × 10 ³)	Ultimate strain, %	Fiber density, Mg/m ³ (lb/in ³)	Suppliers/typical products
High tensile strength	227 (33)	3996 (580)	1.60	1.750 (0.063)	Amoco T-300 Hexcel AS-4
High strain	234 (34)	4500 (650)	1.9	1.800 (0.064)	Mitsubishi Grafil 34-700 Amoco T-650-35
	248 (36)	4550 (660)	1.7	1.77	
Intermediate modulus	275 (40)	5133 (745)	1.75	1740 (0.062)	Hexcel IM-6 Amoco T-40
	290	5650	1.8	1.81	
Very high strength	289 (42.7)	6370 (924)	2.1	1800 (0.06)	Toray T-1000G
High modulus	390 (57)	2900 (420)	0.70	1810 (0.065)	Amoco T-50 Toray M-46J
	436	4.210	1.0	1.84	
Very high modulus	540	3920	0.7	1.750	Toray M55-J

ity greater than copper and have been used in spacecraft for thermal control as well as for structural applications. Figures 5.4 and 5.5^{5,6} show the effect of processing temperature on tensile strength, tensile modulus, and thermal and electrical conductivity.

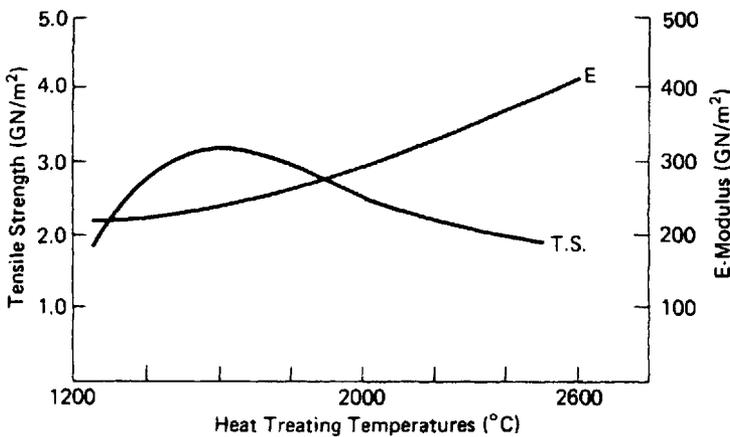


Figure 5.4 Graphitization temperature vs. modulus and tensile strength for carbon graphite fibers.⁶

TABLE 5.4b Carbon/Graphite Fibers (Pitch) (from Ref. 4, p. 2–7)

Class of fiber	Nominal tensile modulus, GPa (psi × 10 ⁶)	Nominal tensile strength, MPa (psi × 10 ³)	Ultimate strain, %	Fiber density, Mg/m ³ (lb/in ³)	Thermal conductivity, ^{*,†} K W/m-K (Btu/h/°F)	CTE, [†] ppm/K (10 ⁻⁶ /°F)	Suppliers/typical products
High modulus (55–65 msi)	379 (55)	2068 (300)	0.50	2000 (0.072)	120	-1.3	Amoco P-55 Nippon Granoc XN-40
	441		0.76	2080	n/a [‡]	n/a	Mitsubishi-Kasei Dialead K-1334U
Very high modulus (75–85 msi)	517 (75)	2068 (300)	0.40	2000 (0.072)	185	-1.4	Mitsubishi K-9354U Amoco P-75
Ultra high modulus (90–100 msi)	689 (100)	2240 (325)	0.31	2150 (0.077)	520	-1.6	Granoc XN-70 Mitsubishi K1374U Amoco P-100
Extreme high modulus (>100 msi)	895–999 (130–145)	2411–3789 (350–550)	n/a	2150–2250 (0.077–0.081)	1000	-1.6	Amoco Thornel K-1100X
	780	3530	0.5	n/a	n/a		Granoc XN 80
	826	2239	0.3	2180	640	-1.45	Amoco P-120K
	900 (130)	3800 (550)	0.42	2200	620	-1.2	Mitsubishi Dialead K13C2U

^{*}K and CTE for copper are 400 and 17, respectively.

[†]Unidirectional composite property, not fiber.

[‡]Not available.

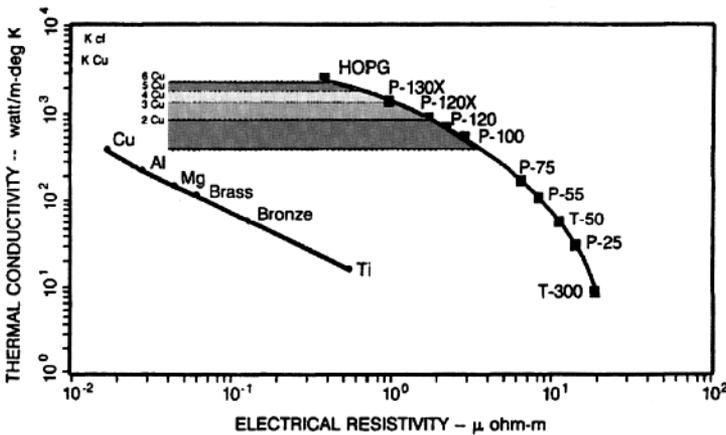


Figure 5.5 Electrical and thermal conductivity of carbon fibers and metals.⁷

5.2.1.3 Aramid fibers. Table 5.5⁴ shows the properties of several organic reinforcing fibers. Aramid fibers were introduced by DuPont in 1972. Kevlar 49, one aramid, essentially revolutionized pressure vessel technology because of its great tensile strength and consistency coupled with low density, resulting in much more weight-effective designs for rocket motors. The specific tensile strength of Kevlar was, at its introduction, the highest of any fiber. Carbon/graphite fibers, because of advances in processing, have the highest values now. (Specific strength and modulus based on fiber values are simply tensile strength or tensile modulus/density and are a good measure of structural efficiency of a fiber for airborne applications.) The values for tensile moduli may be near to those developed in a composite structure, but the tensile strength values for fibers may be quite different because of factors such as translation efficiency, possibility of flaws, processing damage, or incorrect fiber orientations. Aramid composites are still widely used for pressure vessels but have been largely supplanted by the very high-strength carbon/graphite fibers. Aramids have outstanding toughness and creep resistance, and their failure mode in compression, shear, or flexure is not in a brittle manner and requires a relatively great deal of work. Aramid composites have relatively poor shear and compression properties; careful design is required for their use in structural applications that involve bending.

5.2.1.4 PBO fibers. A new fiber, poly(p-phenylene-2,6-benzobisoxazole) (PBO) was introduced in the 1990s. It was developed by Dow Chemical

TABLE 5.5 Organic Fibers (from Ref. 4, p. 2-5)

Type	Nominal tensile modulus, GPa (psi $\times 10^6$)	Nominal tensile strength, MPa (psi $\times 10^3$)	Ultimate strain, %	Fiber density, Mg/m ³ (lb/in ³)	Suppliers/products
Aramid (medium modulus)	62 (9.0)	3617 (525)	4.0	1440 (0.052)	DuPont Kevlar 29
	80 (11.6)	3150 (457)	3.3	1440	Enka Twaron
	70 (10.1)	3000 (440)	4.4	1390	Teijin Technora
Oriented polyethylene	117 (17)	2585 (375)	3.5	968 (0.035)	Allied Fibers Spectra 900
Aramid (intermediate modulus)	121 (18)	3792 (550)	2.9	1440 (0.052)	DuPont Kevlar 49
	121(18)	3150 (457)	2.0	1450	Enka Twaron HM
Oriented polyethylene	172 (25)	3274 (471)	2.7	968 (0.035)	Allied Fibers Spectra 1000
Aramid (high modulus)	186(27)	3445 (500)	1.8	1440 (0.052)	DuPont Kevlar 149
PBO	180 (26)	5800 (840)	2.5	1540 (0.056)	Toyobo Zylon AS*

*High-modulus grade also available.

Co. under U.S. Air Force funding and was tested in pressure vessels by Lincoln Composites. It has shown great promise due to its high strength (5.5 GPa, 798 ksi) and low density (1560 kg/m³, 0.056 lb/in³). Pressure vessels (Fig. 5.6) fabricated with the fiber and a proprietary Brunswick Composites resin system, LRF-0092, demonstrated a performance factor 30% better than test vessels fabricated with the highest-performing carbon/graphite fibers.⁷ There are two grades of the fiber, with tensile strengths and moduli almost double those of p-aramid fibers, along with attractive strain to failure and low moisture regain, making them competitive with carbon high-strength fibers for pressure vessels. The performance factor of the fiber, using strength and density values quoted by the vendor, shows that the PBO fiber is 3% less efficient than T-1000 carbon/graphite fiber. Pressure vessel testing may result in a higher efficiency factor because of the higher strain-to-failure and other considerations. Development ended in the U.S., and now the fiber is manufactured in Japan and marketed by Toyobo under the trade name *Zylon*.

5.2.1.5 Polyethylene fibers. The polyethylene fibers have the same shear and compression property drawbacks as the aramids, but they

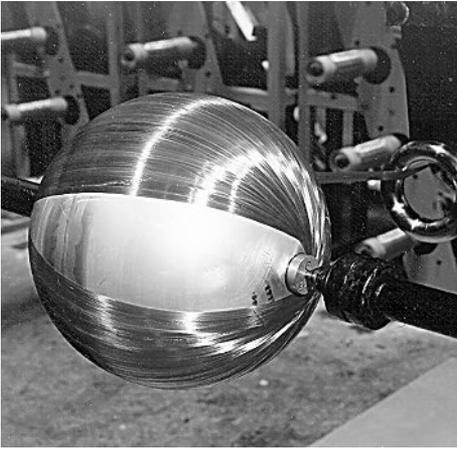


Figure 5.6 Completed PBO spherical test vessel. (Courtesy of Lincoln Composites)

also suffer from a low melting temperature that limits their use to composites that cure or operate below 149°C (300°F) and a susceptibility to degradation by ultraviolet light exposure. Both the aramids and the polyethylene fibers have wide use in personal protective armor, and the polyethylene fibers have found wide use as ropes and lines for boating and sailing due to their high strength and low density. They float on water and have a pleasant feel or *hand* as a rope or line. In spite of the drawbacks, both of these fibers are enjoying strong worldwide growth.

5.2.1.6 Boron fibers. Boron fibers, the first fibers to be used on production aircraft (rudders for USAF F-14A fighter, and horizontal stabilizers for the F-111 in approximately 1964–1970), are produced as individual monofilaments on a tungsten or carbon substrate by pyrolytic reduction of boron trichloride (BCl_3) in a sealed glass chamber. (Fig. 5.7). Because the fiber is made as a single filament rather than as a group or tow, the manufacturing process is slower, and the prices are, and will continue to be, higher than for most carbon/graphite fibers. The relatively large-cross-section fiber is used today primarily in polymeric composites that undergo significant compressive stresses (combat aircraft control surfaces) or in composites that are processed at temperatures that would attack carbon/graphite fibers (i.e., metal matrix composites). The carbon/graphite core is protected by the unreactive boron (Table 5.6).⁴

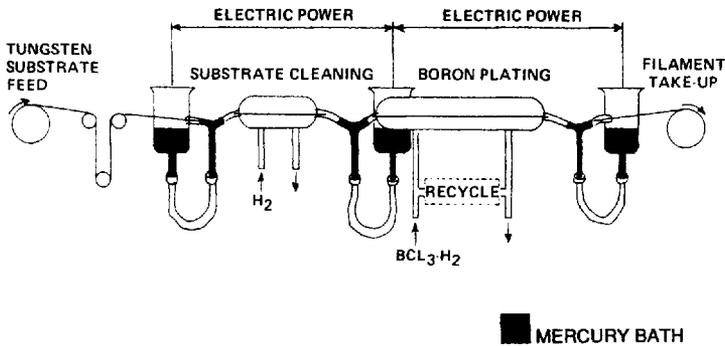


Figure 5.7 Production of boron fiber (from Ref. 8).

5.2.1.7 Ceramic fibers. The other fibers shown in Table 5.6⁴ have varying uses, and several are still in development. Silicon carbide continuous fiber is produced in a chemical vapor deposition (CVD) process similar to that for boron, and it has many mechanical properties identical to those of boron. The other fibers show promise in metal matrix composites, as high-temperature polymeric ablative reinforcements, in ceramic-ceramic composites, and in microwave transparent structures (radomes or microwave printed wiring boards).

5.2.2 Matrix Materials

If parallel and continuous fibers are combined with a suitable matrix and cured properly, unidirectional composite properties such as those shown in Table 5.7 are the result. The functions for and requirements of the matrix are to:

- Help to distribute or transfer loads
- Protect the filaments, both in the structure and before and during structure fabrication
- Control the electrical and chemical properties of the composite
- Carry interlaminar shear

The requirements of and for the matrix, which will vary somewhat with the purpose of the structure, are as follows. It must:

- Minimize moisture absorption
- Have low shrinkage
- Wet and bond to fiber

TABLE 5.6 Boron and Ceramic Fibers (from Ref. 4, p. 2-4)

Class of fiber	Nominal tensile modulus, GPa (psi $\times 10^6$)	Nominal tensile strength, MPa (psi $\times 10^3$)	Ultimate strain, %	Fiber density, Mg/m ³ (lb/in ³)	Thermal conductivity,* K W/m-K (Btu/h/°F)	CTE, ppm/K (10 ⁻⁶ /°F)	Suppliers/typical products
Alumina	206 (30)	1760 (255)	n/a	3200	1.32	n/a	Sumitomo Altex
	150 (22)	1700 (250)	1.2	2700	0.06	3	3M Nextel 312
SiC	167 (24.3)	2962 (430)	1.4–1.5	2300–2400	n/a	3.1	UBE Tyranno
	186 (27)	2962 (430)	1.6	2360	n/a	n/a	Nippon (DC) HVR Nicolon
SiO ₂	69 (10)	3600 (530)	n/a	2200	n/a	n/a	J.P. Stevens Astroquartz II
	72 (10)	3600 (530)	n/a	2200	n/a	n/a	Quartz Products Quartzel

*Unidirectional composite property, not. fiber.

TABLE 5.7 Properties of Typical Unidirectional Graphite/Epoxy Composites (Fiber Volume Fraction, $V_f = 0.60$) (from Ref. 10)

	High strength	High modulus
<i>Elastic constants, GPa ($\text{psi} \times 10^6$)</i>		
Longitudinal modulus, E_L	145 (21)	220 (32)
Transverse modulus, E_T	10 (1.5)	6.9 (1.0)
Shear modulus, G_{LT}	4.8 (0.7)	4.8 (0.7)
Poisson's ratio (dimensionless) ν_{LT}	0.25	0.25
<i>Strength properties, MPa (10^3 psi)</i>		
Longitudinal tension, F_L^{tu}	1240 (180)	760 (110)
Transverse tension, F_T^{tu}	41 (6)	28 (4)
Longitudinal compression, F_L^{cu}	1240 (180)	690 (100)
Transverse compression, F_T^{cu}	170 (25)	170 (25)
In-plane shear, F_{LT}^{su}	80 (12)	70 (10)
Interlaminar shear, F^{Lsu}	90 (13)	70 (10)
<i>Ultimate strains, %</i>		
Longitudinal tension, ϵ_L^{tu}	0.9	0.3
Transverse tension, ϵ_T^{tu}	0.4	0.4
Longitudinal compression, ϵ_L^{cu}	0.9	0.3
Transverse compression, ϵ_T^{cu}	1.6	2.8
In-plane shear	2.0	—
<i>Physical properties</i>		
Specific gravity	1.6	1.7
Density (lb/in^3)	0.056	0.058
Longitudinal CTE, $10^{-6} \text{ in/in/}^\circ\text{F}$ ($10^{-6} \text{ m/m/}^\circ\text{C}$)	-0.2	-0.3
Transverse CTE, $10^{-6} \text{ m/m/}^\circ\text{C}$ ($10^{-6} \text{ in/in/}^\circ\text{F}$)	32 (18)	32 (18)

- Have a low coefficient of thermal expansion
- Flow to penetrate the fiber bundles completely and eliminate voids during the compacting/curing process

- Have reasonable strength, modulus, and elongation (elongation should be greater than fiber)
- Be elastic to transfer load to fibers
- Have strength at elevated temperature (depending on application)
- Have low-temperature capability (depending on application)
- Have excellent chemical resistance (depending on application)
- Be easily processable into the final composite shape
- Have dimensional stability (maintain its shape)

There are two alternates in matrix selection, thermoplastic and thermoset, and there are many matrix choices available within the two main divisions. The basic difference between the two is that thermoplastic materials can be repeatedly softened by heat, and thermosetting resins cannot be changed after the chemical reaction to cause their cure has been completed. The two alternatives differ profoundly in terms of manufacture, processing, physical and mechanical properties of the final product, and the environmental resistance of the resultant composite.

5.2.2.1 Thermoplastic matrices. Several thermoplastic matrices were developed to increase hot-wet use temperature and the fracture toughness of aerospace, continuous-fiber composites. There are also many thermoplastic matrices, such as polyethylene, ABS, and nylon, that are common to the *commodity* plastics arena. Although continuous-fiber, high-performance “aerospace” thermoplastic composites are still not in general usage, their properties are well documented because of sponsorship of development programs by the U.S. Air Force. Table 5.8 shows the relative advantages and disadvantages of both thermoplastics and thermoset matrices. Thermoplastic matrix choices range from nylon and polypropylene in the commodity arena to those matrices selected for extreme resistance to high temperature and aggressive solvents encountered in the commercial aircraft daily environment, such as the polyether-ether-ketone (PEEK) resins. There is a decided difference in the costs of the commodity resins and the resins that would be used for aerospace use—in a similar order as the differences in fiber prices, for instance, (~U.S.\$1.00/lb for polypropylene to >U.S.\$100.00/lb for PEEK). Some manufacturers have elected to propose the use of a commodity approach to manufacturing aerospace structures such as small aircraft with polypropylene/glass.⁸ The aerospace, high-performance thermoplastic composites have a relatively high potential advantage, because their large-scale use is still in the future. Some special considerations must be made for thermoplastics, as follows:

TABLE 5.8 Composite Matrix Trade-Offs

Property	Thermoset	Thermoplastic	Notes
Resin cost	Low to medium-high, based on resin requirements	Low to high premium thermoplastic prepreps are more than thermoset prepreps	Will decrease for thermoplastics as volume increases
Formulation	Complex	Simple	
Melt viscosity	Very low	High	High melt viscosity interferes with fiber impregnation
Fiber impregnation	Easy	Difficult	
Prepreg tack/drape	Good	None	Simplified by co-mingled fibers
Prepreg stability	Poor	Good	
Composite voids	Good (low)	Good to excellent	
Processing cycles	Long	Short to long (long processing degrades polymer)	
Fabrication costs	High for aerospace, low for pipes and tanks with glass fibers	Low (potentially); some shapes still cannot be processed economically	
Composite mechanical properties	Fair to good	Good	
Interlaminar fracture toughness	Low	High	
Resistance to fluids/solvents	Good	Poor to excellent; choose matrix well	Thermoplastics stress craze
Damage tolerance	Poor to excellent	Fair to good	
Resistance to creep	Good	Not known	
Data base	Very large	Small	
Crystallinity problems	None	Possible	Crystallinity affects solvent resistance
Other		Thermoplastics can be reformed to make an interference joint	

- Because high temperatures (up to 300°C) are required for processing the higher-performance matrices, special autoclaves, processes, ovens, and bagging materials may be needed.
- The fiber finishes used for thermosetting resins may not be compatible with thermoplastic matrices, requiring alternative treatment.
- Thermoplastic composites can have greater or much less solvent resistance than a thermoset material. If the stressed matrix of the composite is not resistant to the solvent, the attack and destruction of the composite may be nearly instantaneous. (This is due to *stress corrosion cracking*, a common concern for commodity thermoplastics. Thermoplastic liquid detergent bottle materials must undergo rigorous testing to verify their resistance to stress cracking with the contained material, and the addition of fibers into the matrix aggravates the propensity to crack).

5.2.2.2 Thermoset matrices. Thermoset matrices do not necessarily have the same stress corrosion problems but have a completely different and just as extensive set of environmental and physical-mechanical concerns. To provide solutions for these potential problems, a great number of matrices have been under development for over 50 years.

The common thermoset matrices for composites include the following:

- Polyester and vinylesters
- Epoxy
- Bismaleimide
- Polyimide
- Cyanate ester and phenolic triazine

Each of the resin systems has some drawbacks that must be accounted for in design and manufacturing plans. Polyester matrices have been in use for the longest period, and they are used in the widest variety and greatest number of structures. These structures have included storage tanks with fiberglass and many types of watercraft, ranging from small fishing or speed boats to large minesweepers. The usable polymers can contain up to 50% by weight of unsaturated monomers and solvents such as styrene. These can cause a significant shrinkage on matrix cure. Polyesters cure via a catalyst (usually a peroxide), which results in an exothermic reaction. This reaction can be initiated at room temperature. Because of the large shrinkage with the polyester-type matrices, they are generally not used with the high-modulus fibers.

The most widely used matrices for advanced composites have been the epoxy resins. These resins cost more than polyesters and do not have the high-temperature capability of the bisimides or polyimides; but, because of the advantages shown in Table 5.9, they are widely used.

TABLE 5.9 Epoxy Resin Selection Factors

Advantages	Disadvantages
Adhesion to fibers and resin	Resins and curatives somewhat toxic in uncured form
No by-products formed during cure	Moisture absorption:
Low shrinkage during cure	Heat distortion point lowered by moisture absorption
Solvent and chemical resistance	Change in dimensions and physical properties due to moisture absorption
High or low strength and flexibility	Limited to about 200°C upper temperature use (dry)
Resistance to creep and fatigue	Difficult to combine toughness and high temperature resistance
Good electrical properties	High thermal coefficient of expansion
Solid or liquid resins in uncured state	High degree of smoke liberation in a fire
Wide range of curative options	May be sensitive to UV light degradation
	Slow curing

There are two resin systems in common use for higher temperatures, bismaleimides and polyimides. New designs for aircraft demand a 177°C (350°F) operating temperature that is not met by the other common structural resin systems. The primary bismaleimide (BMI) in use is based on the reaction product from methylene dianiline (MDA) and maleic anhydride: bis (4 maleimidophenyl) methane (MDA BMI).

Two newer resin systems have been developed and have found applications in widely diverse areas. The cyanate ester resins, marketed by Ciba-Geigy, have shown superior dielectric properties and much lower moisture absorption than any other structural resin for composites. The dielectric properties have enabled their use as adhesives in multilayer microwave printed circuit boards and the low moisture absorbance have caused them to be the resin of universal choice for structurally stable spacecraft components.

The PT resins also have superior elevated temperature properties, along with excellent properties at cryogenic temperatures. Their resistance to proton radiation under cryogenic conditions was a prime cause for their choice for use in the superconducting supercollider, subsequently canceled by the U.S. Congress. They are still available from the Lonza Company.

Polyimides are the highest-temperature polymer in general advanced composite use, with a long-term upper temperature limit of

232°C (450°F) or 316°C (600°F). Two general types are *condensation* polyimides, which release water during the curing reaction, and *addition* type polyimides, with somewhat easier process requirements.

Several problems consistently arise with thermoset matrices and prepregs that do not apply to thermoplastic composite starting materials. Because of the problems shown below, if raw material and processing costs were comparable for the two matrices, the choice would probably always be thermoplastic composites, without regard to the other advantages resulting in the composite. These problems lead to a great increase in quality control efforts that may result in the bulk of final composite structure costs. They are as follows:

Problems Associated with Thermoset Matrices

1. Frequent variations from batch to batch
 - Effects of small amounts of impurities
 - Effects of small changes in chemistry
 - Change in matrix component vendor or manufacturing location
2. Void generation, caused by
 - Premature gelation
 - Premature pressure application
 - Effects on interlaminar shear and flexural modulus because of water absorption
3. Change in processing characteristics
 - Absorbed water in prepreg
 - Length of time under refrigeration
 - Length of time out before cure
 - Loss of solvent in wet systems

Some other resins that are in general commercial and aerospace use are not treated here, because they are not in wide use with the modern fibers.

The following general notes are more or less applicable to all thermoset matrices:

- The higher the service temperature limitation the less strain to failure.
- The greater the service temperature, the more difficult the processing that may be due to:
 1. Volatiles in matrix

2. Higher melt viscosity
 3. Longer heating curing cycles
- The greater the service temperature or the greater the curing temperature, the greater the chance for development of color in the matrix.
 - Higher service temperatures and higher curing temperatures may sometimes result in better flame resistance (although this is not evident for epoxies with curing temperatures between 250°F and 350°F).

5.2.3 Fiber Matrix Systems

The end-user sees a composite structure. Someone else, probably a prepregger, combined the fiber and the resin system, and someone else caused the cure and compaction to result in a laminated structure. A schematic of the steps is shown in Fig. 5.8. In many cases, the end-user of the structure has fabricated the composite from prepreg. The three types of continuous fibers, roving or tow, tape, and woven fabric available as prepregs give the end user many options in terms of design and manufacture of a composite structure. Although the use of dry fibers and impregnation at the work (i.e., filament winding pultrusion or hand layup) is very advantageous in terms of raw material costs, there are many advantages to the use of prepregs, as shown in Table 5.10, particularly for the manufacture of modern composites. In general, fabricators skilled in manufacturing from prepreg will not care to use wet processes.

TABLE 5.10 Advantages of Prepregs over Wet Impregnation

Prepregs reduce the handling damage to dry fibers.
They improve laminate properties via better dispersion of short fibers.
Prepregs allow the use of hard-to-mix or proprietary resin systems.
They allow more consistency, because there is a chance for inspection before use.
Heat curing provides more time for the proper laydown of fibers and for the resin to move and degas before cure.
Increasing curing pressure reduces voids and improves fiber wetting.
Most prepregs have been optimized as individual systems to improve processing.

The prepreg process for thermoset matrices is accomplished by feeding the fiber continuous tape, woven fabric, strands, or roving through a resin-rich solvent solution and then removing the solvent by hot tower drying. The excess resin is removed via a doctor blade or metering rolls, and then the product is staged to the cold-stable prepreg form (B stage). The newer technique, the hot-melt procedure for prepregs, has substantially replaced the solvent method because of en-

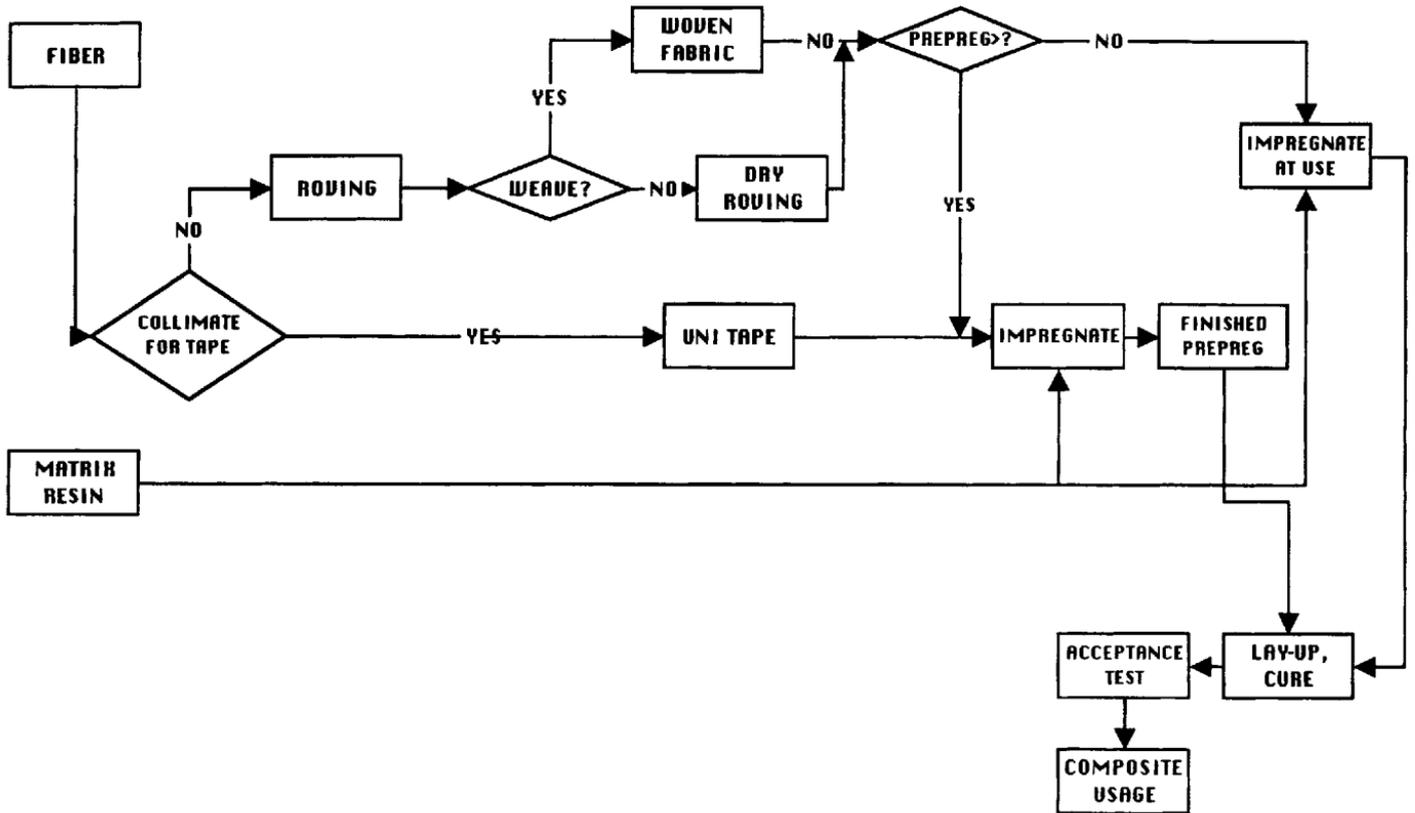


Figure 5.8 The manufacturing steps in composite structure fabrication.

environmental concerns and the need to exert better control over the amount of resin on the fiber. A film of resin that has been cast hot onto release paper is fed, along with the reinforcement, through a series of heaters and rollers to force the resin into the reinforcement. Two layers of resin are commonly used so that a resin film is on both sides of the reinforcement; one of the release papers is removed, and the prepreg is then trimmed, rolled, and frozen. The two types of prepregging techniques, solvent and film are shown in Figs. 5.9 and 5.10.⁹

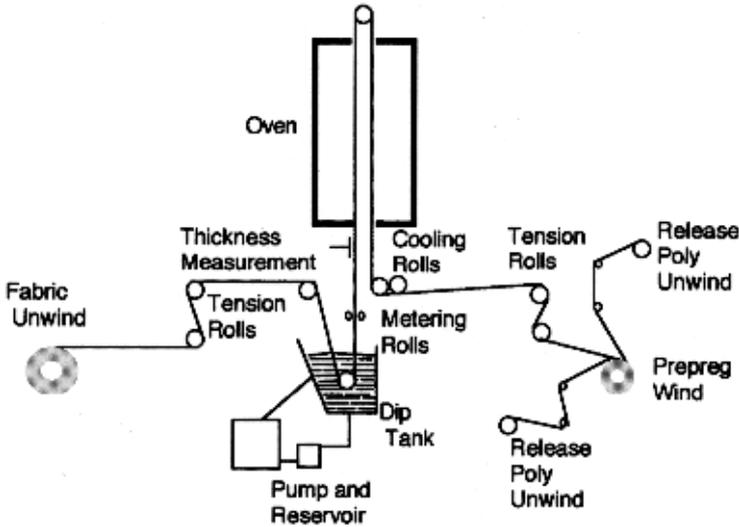


Figure 5.9 Schematic of the typical solution prepregging process.

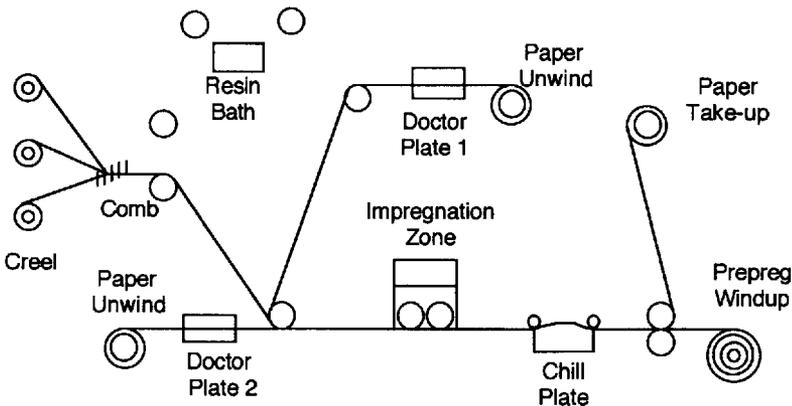


Figure 5.10 Schematic of the typical film prepregging process.

5.2.4 Unidirectional Ply Properties

The manufacturer of the prepreg reports an areal weight for the prepreg and a resin percentage, by weight. Since fiber volume is used to relate the properties of the manufactured composites, the following equations can be used to convert between weight fraction and fiber volume.

$$W_f = \frac{w_f}{w_c} = \frac{\rho_f V_f}{\rho_c V_f} = \frac{\rho_f}{\rho_c} V_f \quad (5.1)$$

$$V_f = \frac{\rho_c}{\rho_f} W_f = 1 - V_m \quad (5.2)$$

where W_f = weight fraction of fiber

w_f = weight of fiber

w_c = weight of composite

ρ_f = density of fiber

ρ_c = density of composite

V_f = volume fraction of fiber

V_m = volume fraction of matrix

ρ_m = density of matrix

A percentage fiber that is easily achievable and repeatable in a composite and convenient for reporting mechanical and physical properties for several fibers is 60%. The properties of unidirectional fiber laminates are shown in Tables 5.7, 5.11, 5.12, and 5.13.¹⁰ These values are for individual lamina or for a unidirectional composite, and they represent the theoretical maximum (for that fiber volume) for longitudinal in-plane properties. Transverse, shear, and compression properties will show maximums at different fiber volumes and for different fibers, depending on how the matrix and fiber interact. These properties are not reflected in strand data. These values may also be used to calculate the properties of a laminate that has fibers oriented in several directions. Using the techniques shown in Sec. 5.5.1, the methods of description for ply orientation must be introduced.

5.3 Ply Orientations, Symmetry, and Balance

5.3.1 Ply Orientations

One of the advantages of using a modern composite is the potential to orient the fibers to respond to the load requirements. This means that the composite designer must show the material, the fiber orientations

TABLE 5.11 Properties of Typical Unidirectional Glass/Epoxy Composites (Fiber Volume Fraction, $V_f = 0.60$); Elastic Constants, Strengths, Strains, and Physical Properties (from Ref. 10)

	E-glass	S-glass
<i>Elastic constants, GPa (psi $\times 10^6$)</i>		
Longitudinal modulus, E_L	45 (6.5)	55 (8.0)
Transverse modulus, E_T	12 (1.8)	16 (2.3)
Shear modulus, G_{LT}	5.5 (0.8)	7.6 (1.1)
Poisson's ratio (dimensionless) ν_{LT}	0.19	0.28
<i>Strength properties, MPa (10^3 psi)</i>		
Longitudinal tension, F_L^{tu}	1020 (150)	1620 (230)
Transverse tension, F_T^{tu}	40 (7)	40 (7)
Longitudinal compression, F_L^{cu}	620 (90)	690 (100)
Transverse compression, F_T^{cu}	140 (20)	140 (20)
In-plane shear, F_{LT}^{su}	60 (9)	60 (9)
Interlaminar shear, F^{lsu}	60 (9)	80 (12)
<i>Ultimate strains, %</i>		
Longitudinal tension, ϵ_L^{tu}	2.30.9	2.9
Transverse tension, ϵ_T^{tu}	0.4	0.3
Longitudinal compression, ϵ_L^{cu}	1.4	1.3
Transverse compression, ϵ_T^{cu}	1.1	1.9
In-plane shear	—	3.2
<i>Physical properties</i>		
Specific gravity	2.1	2.0
Density (lb/in ³)	0.075	0.72
Longitudinal CTE, 10^{-6} in/in/ $^{\circ}$ F (10^{-6} m/m/ $^{\circ}$ C)	3.7 (6.6)	3.5 (6.3)
Transverse CTE, 10^{-6} m/m/ $^{\circ}$ C (10^{-6} in/in/ $^{\circ}$ F)	30 (17)	32 (18)

in each ply, and how the plies are arranged (ply stackup). A shorthand “code” (Fig. 5.11b) for ply fiber orientations has been adapted for use in layouts and studies.

Each ply (lamina) is shown by a number representing the direction of the fibers in degrees, with respect to a reference (x) axis. 0° fibers of both tape and fabric are normally aligned with the largest axial load (axis) (Fig. 5.11a).

TABLE 5.12 Properties of Unidirectional Aramid/Epoxy Composites (Fiber Volume Fraction, $V_f = 0.60$) (from Ref. 10)

	Kevlar 49
<i>Elastic constants, GPa ($\text{psi} \times 10^6$)</i>	
Longitudinal modulus, E_L	76 (11)
Transverse modulus, E_T	5.5 (0.8)
Shear modulus, G_{LT}	2.1 (0.3)
Poisson's ratio (dimensionless) ν_{LT}	0.34
<i>Strength properties, MPa (10^3 psi)</i>	
Longitudinal tension, F^{tu}_L	1380 (200)
Transverse tension, F^{tu}_T	30 (4.3)
Longitudinal compression, F^{cu}_L	280 (40)
Transverse compression, F^{cu}_T	140 (20)
In-plane shear, F^{su}_{LT}	60 (9)
Interlaminar shear, F^{Lsu}	60 (9)
<i>Ultimate strains, %</i>	
Longitudinal tension, ϵ^{tu}_L	1.8
Transverse tension, ϵ^{tu}_T	0.5
Longitudinal compression, ϵ^{cu}_L	2.0
Transverse compression, ϵ^{cu}_T	2.5
In-plane shear	—
<i>Physical properties</i>	
Specific gravity	1.4
Density (lb/in^3)	0.050
Longitudinal CTE, $10^{-6} \text{ in/in/}^\circ\text{F}$ ($10^{-6} \text{ m/m/}^\circ\text{C}$)	-4 (-2.2)
Transverse CTE, $10^{-6} \text{ m/m/}^\circ\text{C}$ ($10^{-6} \text{ in/in/}^\circ\text{F}$)	70 (40)

Individual adjacent plies are separated by a slash in the code if their angles are different (Fig. 5.11b).

The plies are listed in sequence, from one laminate face to the other, starting with the ply first on the tool and indicated by the code arrow with brackets indicating the beginning and end of the code. Adjacent plies of the same angle of orientation are shown by a numerical subscript (Fig. 5.11c).

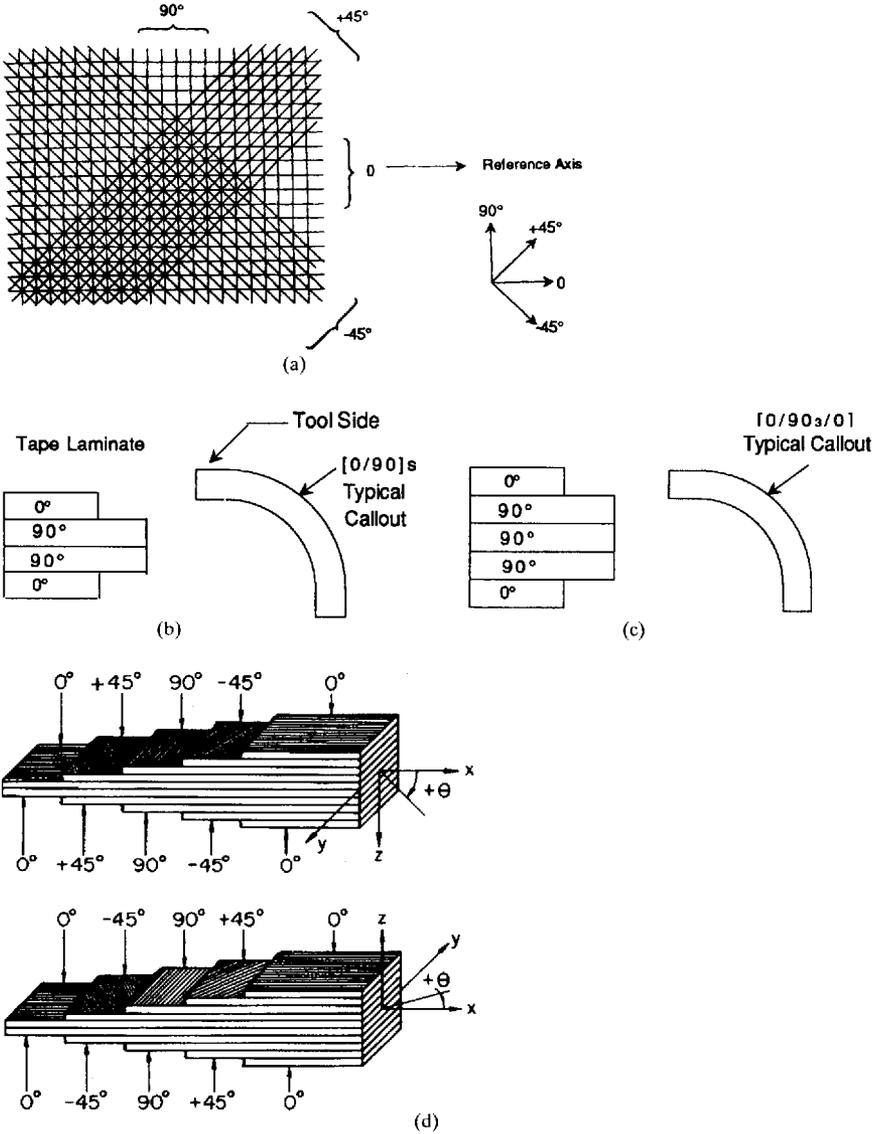


Figure 5.11 Ply orientations, symmetry, and balance.

When tape plies are oriented at angles equal in magnitude but opposite in sign, (+) and (-) are used. Each (+) or (-) sign represents one ply. A numerical subscript is used only when there are repeating angles of the same sign. Positive and negative angles should be consistent with the coordinate system chosen. An orientation shown as

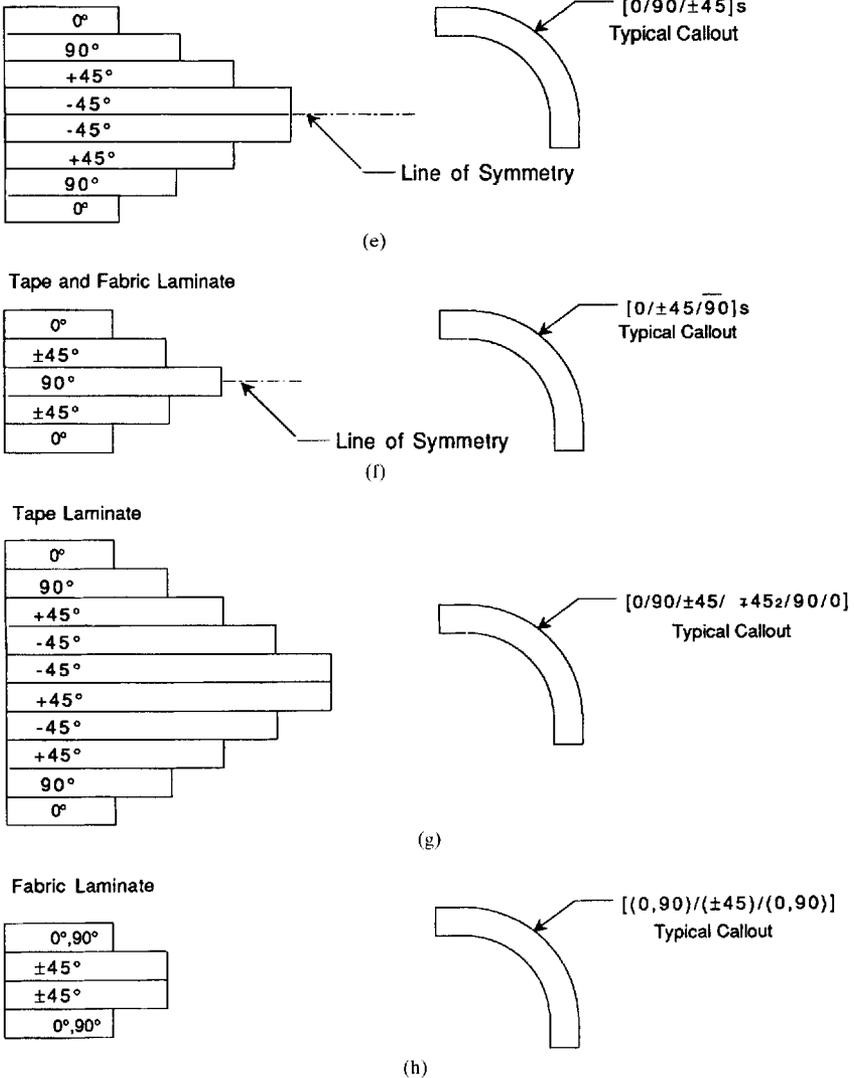


Figure 5.11 Ply orientations, symmetry, and balance (continued).

positive in one right-handed coordinate system may be negative in another. If the Y and Z axis directions are reversed, the ±45 plies are reversed (Fig. 5.11d).

Symmetric laminates with an even number of plies are listed in sequence, starting at one face and stopping at the midpoint. A subscript “S” following the bracket indicates only one half of the code is shown (Fig. 5.11e).

TABLE 5.13 Properties of Typical Unidirectional Boron/Epoxy Composites (from Ref. 10)

	Boron
<i>Elastic constants, GPa (psi $\times 10^6$)</i>	
Longitudinal modulus, E_L	207 (30)
Transverse modulus, E_T	19 (2.7)
Shear modulus, G_{LT}	4.8 (0.7)
Poisson's ratio (dimensionless) ν_{LT}	0.21
<i>Strength properties, MPa (10^3 psi)</i>	
Longitudinal tension, F_L^{tu}	1320 (192)
Transverse tension, F_T^{tu}	72 (10.4)
Longitudinal compression, F_L^{cu}	2430 (350)
Transverse compression, F_T^{cu}	276 (40)
In-plane shear, F_{LT}^{su}	105 (15)
Interlaminar shear, F^{Lsu}	90 (13)
<i>Ultimate strains, %</i>	
Longitudinal tension, ϵ_L^{tu}	0.6
Transverse tension, ϵ_T^{tu}	0.4
Longitudinal compression, ϵ_L^{cu}	—
Transverse compression, ϵ_T^{cu}	—
In-plane shear	—
<i>Physical properties</i>	
Specific gravity	2.0
Density (lb/in ³)	0.072
Longitudinal CTE, 10^{-6} in/in/ $^{\circ}$ F (10^{-6} m/m/ $^{\circ}$ C)	4.1 (2.3)
Transverse CTE, 10^{-6} m/m/ $^{\circ}$ C (10^{-6} in/in/ $^{\circ}$ F)	19 (11)

Symmetric laminates with an odd number of plies are coded as a symmetric laminate except that the center ply, listed last, is overlined to indicate that half of it lies on either side of the plane of symmetry (Fig. 5.11f–h).

5.3.2 Symmetry

The geometric midplane is the reference surface for determining if a laminate is symmetrical. In general, to reduce out-of-plane strains, coupled bending and stretching of the laminate, and complexity of analysis, symmetric laminates should be used. However, some composite structures (e.g., filament wound pressure vessels) are geometrically symmetric, so symmetry through a single laminate wall is not necessary if it constrains manufacture. To construct a midplane symmetric laminate, for each layer above the midplane there must exist an identical layer (same thickness, material properties, and angular orientation) below the midplane (Fig. 5.11e).

5.3.3 Balance

All laminates should be balanced to achieve in-plane orthotropic behavior. To achieve balance, for every layer centered at some positive angle $+\theta$, there must exist an identical layer oriented at $-\theta$ with the same thickness and material properties. If the laminate contains only 0° and/or 90° layers, it satisfies the requirements for balance. Laminates may be midplane symmetric but not balanced, and vice versa. Figure 5.11e is symmetric and balanced, whereas Fig. 5.11g is balanced but unsymmetric.

5.4 Quasi-isotropic Laminate. The goal of composite design is to achieve the lightest, most efficient structure by aligning most of the fibers in the direction of the load. Many times, there is a need, however, to produce a composite that has some isotropic properties, similar to metal, because of multiple or undefined load paths or for a more conservative design. A *quasi-isotropic* laminate layup accomplishes this for the x and y planes only; the z, or through-the-laminate thickness plane, is quite different and lower. Most laminates produced for aircraft applications have been, with few exceptions, quasi-isotropic. One exception was the X-29 (Fig. 5.3). As designers become more confident and have access to a greater database with fiber-based structures, more applications will evolve. For a quasi-isotropic (QI) laminate, the following are requirements:

- It must have three layers or more.
- Individual layers must have identical stiffness matrices and thicknesses
- The layers must be oriented at equal angles. For example, if the total number of layers is n , the angle between two adjacent layers should be $360^\circ/n$. If a laminate is constructed from identical sets of three or more layers each, the condition on orientation must be satisfied by the layers in each set, for example: $[0^\circ/\pm 60^\circ]_S$ or $[0^\circ/\pm 45^\circ/90^\circ]_S$ [Ref. 11, p. 199].

Table 5.14¹² shows mechanical values for several composite laminates with the high-strength fiber of Table 5.4 and a typical resin system. The first and second entries are for simple 0/90 laminates and show the effect of changing the position of the plies. The effect of increasing the number of 0° plies is shown next, and the final two laminates demonstrate the effect of $\pm 45^\circ$ plies on mechanical properties, particularly the shear modulus. The last entry is a quasi-isotropic laminate. These laminates are then compared to a typical aluminum alloy. This effectively shows that there is a strength and modulus penalty that goes with the conservatism of the use a QI laminate.

TABLE 5.14 High-Strength Carbon Graphite Laminate Properties

Laminate	Longitudinal modulus, E_{11} , GPa	Bending modulus, E_B , GPa	Shear modulus, G_{xy} , GPa
[0/90 ₂ /0]	76.5	126.8	5.24
[90/0 ₂ /90]	76.5	26.3	5.24
[0 ₂ /90 ₂ /0]	98.5	137.8	5.24
[0 ₂ /±45 ₂ /0]	81.5	127.5	21.0
[0/±45/90] _s	55.0	89.6	21.0
Aluminum	41.34	41.34	27.56

When employing the data extracted from tables, there are some cautions that should be observed by the reader. The values seen in many tables of data may not always be consistent for the same materials or the same group of materials from several sources for the following reasons:

1. Manufacturers have been refining their production processes so that newer fibers may have greater strength or stiffness. These new data may not be reflected in the compiled data.
2. The manufacturer may not be able to change the value quoted for the fiber because of government or commercial restrictions imposed by the specification process of his customers.
3. Many different high-strength fibers are commercially available. Each manufacturer has optimized its process to maximize the mechanical properties, and each of the processes may be different from that of the competitor, so all vendor values in a generic class may differ widely.
4. Most tables of values are presented as “typical values.” Those values and the values that are part of the menu of many computer analysis programs should be used with care. Each user must find the most appropriate set of values for design, develop useful design allowables, and apply appropriate “knock down” factors, based on the operating environments expected in service.

5.5 Analysis

5.5.1 Micromechanical Analysis

A number of methods are in common use for the analysis of composite laminates. The use of micromechanics, i.e., the application of the properties of the constituents to arrive at the properties of the composite ply, can be used to:

1. Arrive at “back of the envelope” values to determine if a composite is feasible
2. Arrive at values for insertion into computer programs for laminate analysis or finite element analysis
3. Check on the results of computer analysis

The rule of mixtures holds for composites. The micromechanics formula to arrive at the Young’s modulus for a given composite is

$$E_C = V_f E_f + V_m E_m$$

and $V_f + V_m = 1$

$$E_c = V_f E_f + E_m (1 - V_f) \quad (5.3)$$

where E_c = composite or ply Young’s modulus in tension for fibers oriented in direction of applied load

V = volume fraction of fiber (f) or matrix (m)

E = Young’s modulus of fiber (f) or matrix (m)

But, since the fiber has much higher Young’s modulus than the matrix, (Table 5.7 vs. the value for the 3502 matrix on p. 5.1), the second part of the equation can be ignored.

$$E_f \gg E_m$$

$$E_c = E_f V_f \quad (5.4)$$

This is the basic rule of mixture and represents the highest Young’s modulus composite, where all fibers are aligned in the direction of load. The minimum Young’s modulus for a reasonable design (other than a preponderance of fibers being orientated transverse to the load direction) is the quasi-isotropic composite and can be approximated by

$$E_c \cong \frac{3}{8} E_f V_f \quad (5.5)$$

Note: the quasi-isotropic modulus, E , of a composite laminate is

$$\frac{3}{8} E_{11} + \frac{5}{8} E_{22} \quad (\text{see Ref. 13})$$

where E_{11} is the modulus of the lamina in the fiber direction and E_{22} is the transverse modulus of the lamina. The transverse modulus for polymeric-based composites is a small fraction of the longitudinal modulus (see E_t in Table 5.7) and can be ignored for preliminary estimates, resulting in a slightly lower-than-theoretical value for E_c for a quasi-isotropic laminate. This approximate value for quasi-isotropic modulus represents the lower bound of composite modulus. It is useful for comparisons of composite properties to those of metals and to establish if a composite is appropriate for a particular application.

The following formulas also can be used to obtain important data for unidirectional composites:

$$\text{Density,} \quad \rho_c = V_f \rho_f + V_m \rho_m \quad (5.6)$$

$$\text{Poisson's ratio,} \quad \nu_{12} = \nu_f V_f + \nu_m V_m \quad (5.7)$$

$$\text{Transverse Young's modulus,} \quad E_2 = \frac{E_{2m}(1 + \xi \eta_2 V_f)}{1 - \eta_2 V_f} \quad (5.8)$$

and values for η_2 and ξ can be seen in Ref. 14 and Ref. 11, pp. 76–78. The matrix is isotropic.

5.5.2 Carpet Plots

The analysis of a multilayered composite, if attempted by hand calculations, is not trivial. Fortunately, there are a significant number of computer programs to perform the matrix multiplications and the transformations.^{14–16} However, the use of carpet plots is still in practice in U.S. industry, and these plots are useful for preliminary analysis. The carpet plot shows graphically the range of properties available with a specific laminate configuration. For example, if the design options include $[\pm 0/90]_S$ laminates, a separate carpet plot for each value of θ would show properties attainable by varying percentage of $\pm \theta$ plies versus 90° plies. A sequence of these charts would display attainable properties over a range of θ values. The computer programs described above can be programmed to produce such charts for arbitrary laminates.

Figure 5.12 shows a sample carpet plot¹⁷ of extensional modulus of elasticity E_x for Kevlar 49/epoxy with $[0/\pm 45/90]_S$ construction. As expected, the chart shows $E_x = 76$ GPa (11×10^6 psi) with all 0° plies, and $E_x = 5.5$ GPa (0.8×10^6 psi) with all 90s. With all 45s, an axial modulus is only slightly higher, 8 GPa (1.1×10^6 psi), than the all 90s value predicted for this material. A quasi-isotropic laminate (Sec.

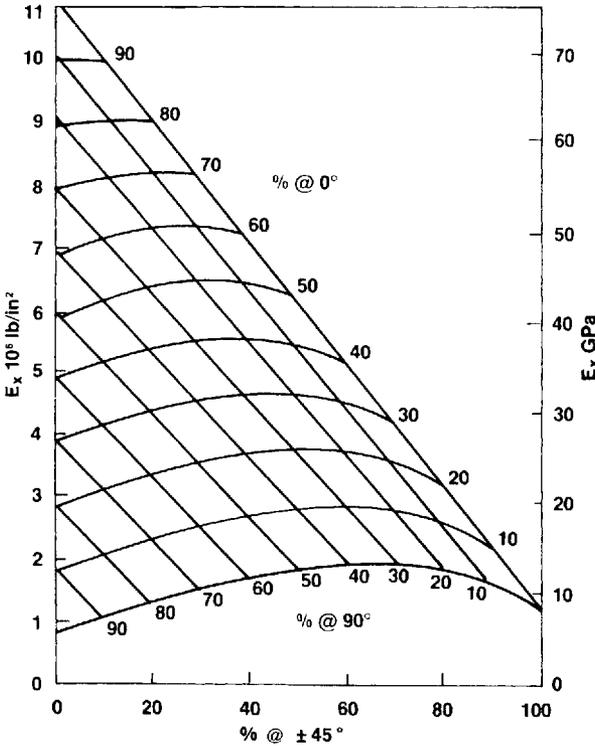


Figure 5.12 Predicted axial moduli for $[0/\pm 45/90]$ kevlar epoxy laminates.

5.5.2) with 25% 0s, 50% ± 45 s, and 25% 90s, produces an intermediate value of $E_x = 29 \text{ GPa}$ ($4.2 \times 10^6 \text{ psi}$).

5.6 Composite Failure and Design Allowables

5.6.1 Failure¹⁸⁻²⁰

Composite failure modes are different from those of isotropic materials such as metals. Because of the fibers, they do not tend to fail in only one area, they do not have the strain-bearing capacity of most metals, and they are prone to premature failure if stressed in a direction that was not anticipated in the design. Useful structures nearly always have been constructed from ductile materials such as steel or aluminum, with fairly well defined strengths. This allows designers to accurately comprehend and specify safety factors that provide some assurance that the structures will not fail in service.

It has become necessary, in the practical design of structures for demanding environments, to use brittle materials such as glass and ceramics to take advantage of special properties such as high-temperature strength. When brittle materials are employed in practical structures, the designer still has the need to ensure that the structure will not fail prematurely.

The data that provide the background for the design confidence can be obtained from various sources. They can be derived from previous designs that have proven reliable and resulted in data being published in a reference work such as *Mil-Handbook-5 for Aerospace Metals* (Ref. 21) or industry journals. Or the data can be obtained through testing conducted by the designer's own organization. Typically, on the basis of laboratory experiments on a statistically determined number of small specimens tested in simple tension or bending, the probability of failure can be calculated for structural members of other sizes and shapes, often under completely different loading conditions. The tool for accomplishing this is *statistical fracture theory*.

To predict strength of the ply with the laminate, it is usually assumed that knowledge of failure of a ply by itself under simple tension, compression, or shear will allow prediction of failure of that ply under combined loading in the laminate.

The matrix plays a special role in the failure of the composite. The matrix is extremely weak compared to the fibers (particularly if they are the *advanced composite* fibers) and cannot carry primary loads, but it efficiently allows the transfer of the loads in the composite. This is demonstrated by the experimental observation that the strength of matrix-impregnated fiber bundles can be on the order of a factor of 2 higher than the measured tensile strength of dry fiber bundles without matrix impregnation. The key to this apparently contradictory evidence lies in a synergistic effect between fiber and matrix. The first and primary design rule for composites of this type is that the fibers must be oriented to carry the primary loads. A comparison of the tensile strengths illustrates this point. High-strength carbon fibers have tensile strengths that approach 1×10^6 psi (6900 MPa), while the tensile strength of typical polymer matrices may be on the order of 3×10^4 psi (200 MPa) or less. Clearly, the tensile strength of the matrix is insignificant in comparison.

A number of investigators have provided an explanation for the above observation. It can be explained by noting that the strength of individual brittle fibers varies widely because of a statistical distribution of flaws. The fibers can be considered to be brittle and sensitive to surface imperfections randomly distributed over the fiber length. The strength of individual fibers varies widely and will decrease with increasing length. These are characteristics that are typical of brittle

materials failing at random defects, and they are changed dramatically through the addition of the matrix. The matrix acts to almost double the apparent strength of a fiber bundle, and it significantly reduces the variability.

In a dry fiber bundle, when a fiber breaks, it loses all of its load-carrying ability over its entire length, and the load is shifted to the remaining fibers. When enough of the weaker fibers fail, the strength of the remaining fibers is exceeded, and the bundle fails. In matrix-impregnated fiber bundles, the matrix acts to bridge around individual fiber breaks so that adjacent fibers quickly pick up the load. Thus, the adjacent fibers have to carry an increased load over only a small axial distance. Statistical distribution of fiber defects makes it unlikely that each fiber would be weakest at the same axial location, so failure will occur at a higher load value after enough fibers have failed in adjacent locations. Because of the small diameter of individual fibers (5.7 mm for some typical carbon fibers), there are many millions of fibers in a structure. This makes statistical effects important.

5.6.2 Failure Theories

For over three decades, there has been a continuous effort to develop a more universal failure criterion for unidirectional fiber composites and their laminates. A recent FAA publication lists 21 of these theories.²² The simplest choices for failure criteria are maximum stress or maximum strain. With the maximum stress theory, the ply stresses, in-plane tensile, out-of-plane tensile, and shear are calculated for each individual ply using lamination theory and compared with the allowables. When one of these stresses equals the allowable stress, the ply is considered to have failed. Other theories use more complicated (e.g., quadratic) parameters, which allow for interaction of these stresses in the failure process.

Although long-fiber composites typically fail at low tensile strains, they are generally not considered to be brittle, i.e., in the realm of glass or ceramics. The fibers do have strain to failure, and the failures can be predicted. A bundle of fibers bound together by a matrix does not usually fail when the first fiber ruptures. Instead, the final failure is preceded by a period of progressive damage.

The basic assumption of statistical fracture theory is that the reason for the variations in strength of nominally identical specimens is their varying content of randomly distributed (and generally invisible) flaws. The strength of a specimen thus becomes the strength of its weakest flaw, just as the strength of a chain is that of its weakest link.

Since it is not possible to obtain strengths in all possible lamina orientations or for all combinations of lamina, a means must be estab-

lished by which these characteristics can be determined from basic layer data. Theories of failure are hypotheses concerning the limit of load-carrying ability under different load combinations. Using expressions derived from these theories, it is possible to construct failure envelopes or, if in three dimensions, failure surfaces that represent the limit of usefulness of the material as a load-bearing component, i.e., if a given loading condition is within the envelope, the material will not fail. The suitability of any proposed criterion is determined by a number of factors, the most important of which has to do with the nature of the failure mode. As a result, it is important that proposed failure criteria be accompanied by a definition of material behavior.

5.6.3 Design Allowables

The design of composites involves knowledge of a significantly greater number of material properties than those needed for conventional isotropic metals. As mentioned previously, these data are not always conveniently available from a single source of data such as a handbook. The data at the maximum, for the design of aerospace structures, takes the form of those shown in Table 5.15.²³

Data for design use requires statistical significance with a known confidence level. The old MIL-Hdbk-17B²⁴ provides a guide concerning the number and type of tests sufficient to establish statistically based material properties along with some limited data that is now somewhat out of date. The (new) Composites Materials Handbook, Mil-17,²⁵ in preparation, has somewhat enhanced statistical treatment approaches. Three classes of allowables, pertinent to current usage of composites for many applications, are:

- *A-Basis Allowable.* The value above which 99% of the population of values is expected to fall, with a confidence of 95%.
- *B-Basis Allowable.* The value above which 90% of the population of values is expected to fall, with a confidence of 95%.
- *S-Basis Allowable.* The value that is usually the specified minimum value of the appropriate government specification.

For most flightworthy composites, material properties are usually required to be either A-Basis or B-Basis allowables.

The effort is still in progress to provide a new family of design allowables including the most advanced fiber composites and the background guidance for their use. This is a reprise of the Mil-Hdbk-17 effort initiated in 1972, which had property values primarily for fiberglass fibers. The new Mil-Hdbk-17 committee has published the first interim report on the effort. The original Mil-Hdbk-17 treated

TABLE 5.15 Lamina Properties and Equations Used To Calculate Material Properties²³

Lamina material properties	Definition	Equation used to calculate material property
<i>Elastic</i>		
E_1	Elastic modulus in the fiber direction	Property based on test data
E_2	Elastic modulus transverse to the fiber direction	Property based on test data
E_3	Elastic modulus through-the-thickness	Transverse isotropy: $E_3 = E_2$
G_{12}	Shear modulus in the 1-2 plane	Property based on test data
G_{23}	Shear modulus in the 2-3 plane	$G_{23} = \frac{E_3}{2(1 + \nu_{23})}$
G_{13}	Shear modulus in the 1-3 plane	Transverse isotropy: $G_{13} = G_{12}$
ν_{12}	Poisson's ratio in 1-3 plane	Property based on test data
ν_{23}	Poisson's ratio in 2-3 plane	$\nu_{23} = \nu_f V_f + \nu_m (1 - V_f) \left[\frac{1 + \nu_m - \nu_{12} \frac{E_m}{E_1}}{1 - \nu_m^2 + \nu_m \nu_{12} \frac{E_m}{E_1}} \right]$
ν_{13}	Poisson's ratio in 1-3 plane	Transverse isotropy: $\nu_{13} = \nu_{12}$
<i>Strength</i>		
σ_1	Tensile strength in the fiber direction	Property based on test data
$-\sigma_1$	Compressive strength in the fiber direction	Property based on test data
σ_2	Tensile strength transverse to the fiber	Property based on test data
$-\sigma_2$	Compressive strength transverse to the fiber	Property based on test data
σ_3	Tensile strength through-the-thickness	$\sigma_3 = \sigma_2$
$-\sigma_3$	Compressive strength through-the-thickness	$-\sigma_3 = -\sigma_2$
τ_{12}	Shear strength in 1-2 plane (in-plane)	Property based on test data
τ_{13}	Shear strength in the 1-3 plane (interlaminar)	Property based on test data
τ_{23}	Shear strength in the 2-3 plane (interlaminar)	$\tau_{23} = \tau_{13}$

unidirectional and woven fabric laminates, and two typical entries are shown in Tables 5.16 and 5.17. The first table shows the properties of 3M XP 2515 fiberglass epoxy with 100% unidirectional fibers. Although the resin portion of this laminate is no longer produced, and the data has not been upgraded, this is one of the few areas in which one can see statistically significant data for unidirectional fiberglass that is of a quality suitable for inclusion in computer analysis programs for laminate analysis. The second table is for materials that still exist in the marketplace and was continued in the 1999 edition of the handbook. This table shows the data for a woven fabric with a heat-curing epoxy resin. The 7781 fabric is a reasonably balanced fabric with good drape qualities in wide use. Tables 5.18 and 5.19, presented for carbon/graphite/epoxy materials, are extracted from the new MIL-Hdbk. They show the “B” basis allowables for strength and modulus of a unidirectional and a woven fabric laminate for three temperatures of interest. If the values of the fiber and the resin as shown by the vendor are used for contrast, a full picture of the laminate materials emerges and further simplifies analysis of laminates made with these materials or similar materials for extrapolation

5.7 Composite Fabrication Techniques

5.7.1 Choosing the Manufacturing Method

There is a history of choosing the composite manufacturing technique for the wrong reasons. Sometimes the choice is good regardless of the method, but often the end product or the schedule suffers and, in turn, the customer is unhappy. The rationales for choice have historically been as outlined below.

Design needs. This is the best reason for choosing a manufacturing method. The key to attaining a good composite design with a manufacturing process that can operate with minimum dysfunction is the choice of the method based on the design of the composite component. Thus, the manufacturing process must be kept in mind during the component design phase and must also be a consideration in laminate design.

Part configuration. This must have a great influence on manufacturing technique. In no other manufacturing endeavor does the finished configuration of the structure play such an important role. Some component configurations, such as pressure vessels, drive the process deci-