Chapter 5
Material Properties

5-1. General

Composite laminate material properties depend upon the properties of the fibers and resins from which they are made. In this chapter, the fiber and resin properties will first be discussed, and then the laminate properties. All of these discussions will concentrate on the three fiber types most likely to be used in civil engineering structures: carbon fibers, glass fibers, and aramid fibers.

5-2. Fiber Properties

a. There are various grades of carbon fiber (or glass fiber or aramid fiber). Table 5-1 lists several types of fibers and typical properties.

b. There are several things that should be noted about the data in Table 5-1. The carbon fibers have the highest modulus, but both the glass and aramid fibers have higher strength. The higher strength of the glass fibers (compared to carbon) does not translate into higher composite strengths because the glass fibers are very sensitive to small defects which can greatly lower their strength. The carbon fibers have very low ductilities. Therefore, they should not be used in applications that will require a significant amount of deformation. Compressive stiffness and strength properties are hard to obtain for pure fibers because they are difficult to test.

c. From Table 5-1 it is not possible to conclude which of the three types of fibers would produce the most efficient structure, because that would depend upon whether modulus or strength was the controlling parameter. The weight would also depend upon the fiber concentration in the composite. For a given number of fibers, the structure's mass will vary with the amount of resin.

5-3. Resin Properties

a. The properties of the resins depend upon their internal structure. Some typical resin properties are shown in Table 5-2. One type of polyester resin that is commonly used is a vinyl ester resin.

Table 5-1
Typical Values of Fiber Properties[1]

Fiber	Axial Tensile Modulus, GPa (10^6 psi)	Axial Tensile Strength, MPa (10^3 psi)	Axial Elongation at Break, percent	Density, g/cm^3 (lb/ft^3)
Carbon—low modulus	170 (24.6)	1380 (200)	0.9	1.90 (119)
Carbon—high modulus	380 (55.1)	1720 (249)	0.4	2.00 (124)
Carbon—very high modulus	760 (110)	2210 (320)	0.3	2.15 (135)
E—glass	81 (11.7)	3450 (500)	4.88	2.60 (162)
S—glass	89 (12.9)	4590 (666)	5.7	2.48 (155)
Aramid—high toughness	83 (12.0)	3620 (525)	4.00	1.44 (90)
Aramid—high modulus	131 (19.0)	3620-4140 (525-600)	2.80	1.44 (90)
Aramid—very high modulus	186 (27.0)	3450 (500)	2.00	1.47 (92)

[1] From *Engineered Materials Handbook (1987)* and *Engineers' Guide to Composite Materials* (1987).

Table 5-2
Typical Resin Properties[1]

Resin	Tensile Strength MPa (10^3 psi)	Tensile Modulus GPa (10^3 psi)	Elongation percent
Epoxy resins	103-172 (14.9-24.9)	4.83-6.21 (700-900)	< 2.0
Polyimide resins	48-83 (6.96-12.0)	2.76-5.52 (400-800)	1.7-3.2
Polyester resins	21-83 (3.05-12.0)	2.76-4.14 (400-600)	1.4-4.0
Thermoplastic resins	76-103 (11.0-14.94)	2.21-4.83 (320-700)	5-10

[1] *From Engineered Materials Handbook (1987)* and *Engineers' Guide to Composite Materials* (1987).

b. As can be seen from comparing Table 5-1 and Table 5-2, many resins contribute very little to the load-carrying capability of the composite material. However, the resins can have a big impact upon the toughness of the composite laminate. The more ductile the resin, the tougher will be the resulting laminate. The resins act to transfer load from one fiber to an adjacent fiber. When one fiber breaks, a ductile resin is more likely to distribute the load to several fibers and not just the adjacent fiber. This will act to resist further fiber failure, thus increasing toughness of the composite.

5-4. Laminate Properties

a. Strength. For a given fiber and resin combination, there are two additional parameters that significantly affect the composite's strength. These parameters are the fiber volume fraction and the fiber orientation. The fiber volume fraction is the percentage of the volume of the composite material that is occupied by the fibers. Tables 5-3 and 5-4 are for composite laminates. Table 5-3 shows properties for a unidirectional laminate. Table 5-4 shows properties for a multidirectional laminate. These are the types of data that should be used in actual designs, rather than combinations of the resin and data shown in Tables 5-1 and 5-2.

(1) Tensile strength. In Table 5-3, longitudinal refers to strength in the fiber direction and transverse refers to strength perpendicular to the fiber direction. The longitudinal tensile strengths are about 30 to 40 times greater than the transverse tensile strengths, because in the transverse direction the composite can fail without having to break any fibers. Its strength in this direction is now largely determined by the strength of the resin. The longitudinal tensile strength of a unidirectional composite can frequently be approximated by a simple rule of mixtures formulation:

$$TS_C = TS_f V_f + TS_m V_m \qquad (5\text{-}1)$$

where

TS_C = ultimate tensile strength of the composite

TS_f = ultimate tensile strength of the fibers

V_f = volume fraction of fibers

TS_m = ultimate tensile strength of the resin

V_m = volume fraction of the resin

(2) Compressive strength.

(a) It should be noted that the transverse compressive strength is higher than the transverse tensile strength for a unidirectional system. The resin itself is stronger in compression than in tension. In addition, the fibers can provide resistance to transverse compressive loads, but do not provide significant resistance to transverse tensile loads. Transverse compressive strength is also typically lower than longitudinal compressive strength.

(b) The aramid-based composite has a much lower compressive strength than tensile strength, because what appears to be a fiber in the aramid composite actually has a ropelike structure and is composed of much smaller fibers. This makes it even more likely to buckle on a microscopic level than the carbon or glass fibers, thereby leading to a very poor compressive strength.

Table 5-3
Typical Strength Terms for Unidirectional Laminates (Volume fraction of fibers is approximately 50 percent)[1]

Material	Longitudinal Tensile Strength, MPa (10^3 psi)	Longitudinal Compressive Strength MPa (10^3 psi)	Transverse Tensile Strength, MPa (10^3 psi)	Transverse Compressive Strength MPa (10^3 psi)	Shear Strength MPa (10^3 psi)
Carbon/ epoxy	1448 (210)	600 (30.5)	52 (7.5)	206 (29.9)	93 (13.5)
E-glass/ vinyl ester	610 (88.5)	215 (31.2)	49 (7.1)	49 (7.1)	16.0 (2.3)
Aramid/ epoxy	1400 (203)	235 (34.1)	12 (1.7)	53 (7.7)	34 (4.9)

[1] From Tsai and Hahn (1980) and *Delaware Composites Design Encyclopedia* (1990).

Table 5-4
Effect of Fiber Orientation on the Tensile Strength of a Typical Glass/Polyester Laminate [1]

Lay-up	Typical Strength in Zero-Degree Direction, MPa (10^3 psi)	Typical Strength in Ninety-Degree Direction, MPa (10^3 psi)
$[0_8]$	610 (88.4)	49 (7.1)
$[45_8]$	98.8 (14.3)	98.8 (14.3)
$[45_2/\text{-}45_2]_S$	120 (17.4)	120 (17.4)
$[0_2/90_2]_S$	453 (65.7)	453 (65.7)
$[0/90/45/\text{-}45]_S$	287 (41.6)	287 (41.6)
$[0_4/90_4/45/\text{-}45]_S$	393 (57.0)	393 (57.0)
$[0_6/90_2/45/\text{-}45]_S$	456 (66.1)	123 (17.8)
$[0_8/45/\text{-}45]_S$	539 (78.2)	206 (29.9)

[1] Zero-degree data are from *Engineered Materials Handbook* (1987). The remaining strengths have been calculated using Tsai-Hahn's (1980) quadratic interaction model for strength.

(3) Effect of fiber orientation on strength.

(a) Most composite laminates are not unidirectional but have a variety of fiber orientations. To illustrate what that might do to composites, strengths for a glass/polyester composite with a variety of orientations have been determined. These results are shown in Table 5-4. The lay-up notation format was described in paragraph 4-2*b*(3).

(b) The first lay-up shown in Table 5-4 is a unidirectional one. It will provide the maximum possible strength in one direction but it will have the minimum possible strength in the transverse direction. This could result in premature failure if some off-axis loads are applied to the laminate. Note how much stronger the laminate is that has both plus and minus 45-degree plies compared with the one that has only plus 45-degree plies. This is because the one that has all the plus 45-degree plies can fail along the fiber direction without having to break any fibers. The one that has both plus and minus 45-degree plies will have to break fibers before the laminate can fail.

(c) Actual lay-ups used in laminates would be similar to the last four lay-ups shown in Table 5-4. Traditionally, designers have used lay-ups that had the same number of 0-degree, 45-degree, -45-degree, and 90-degree plies. This produced a laminate that had a strength about one half that of the unidirectional one. These configurations have strengths less than the strength of a unidirectional laminate. Note that the 0-degree strength increases as the proportion of 0-degree plies increases. This increase is not proportional to the increase of 0-degree plies.

(4) Flexural strength.

(a) The flexural strength is related to both the tensile and compressive load-carrying capability of the composite. This is because bending of the composite will put part of it into compression. During flexural loading the tensile stresses are created by bending the member rather than by direct tension loading. Although flexural and tensile strength levels may be about the same, the methods of failure may be very different.

(b) Most composites are very nonisotropic, which can play a significant role if there are bending moments applied to the structure. If the ply orientations with the smallest strength are on the outside of the structure (where the flexural stresses are the largest) then they can fail at relatively low bending loads. If the strongest orientations are placed on the outside of the structure then it would have a greater flexural strength. The flexural strength can be changed by changing the order of the various plies (called the stacking sequence). The issue of stacking sequence of the plies does not play a major role if the loads are axially applied.

(5) Shear strength. As shown in Table 5-3 the shear strength of a unidirectional composite is rather low. This is because the fibers cannot resist deformation in the direction of maximum shear. However, the shear strength can be significantly increased if there are some plies added where the fibers are at ±45 degrees with respect to the applied load. If all fibers are at ±45 degrees then the composite will have its maximum shear strength. However, such a lay-up would have a relatively low tensile strength. If shear resistance is a major issue, then some plies should be placed at ±45 degrees to increase the shear strength.

b. Specific strength. Specific strength is a measure of a given mass of a material's ability to hold a given load. This is in contrast to *strength* which is a measure of a given area of a material's ability to resist a given load. Values of specific strength will vary with fiber content and fiber orientation in the same manner as does strength. If the load-carrying capability of a structure is the controlling parameter, then the composite with the highest specific strength will be the lightest weight. Since specific strength looks at the load-carrying capability of a given mass of material, the lightest weight composite may not be the one with the thinnest cross section.

c. Strain capacity.

(1) The strain capacity of fiber-reinforced polymers is typically not very high. Table 5-1 shows strain capacity for a number of fibers. Strain capacity is the strain to failure as measured by a tensile test. Carbon fibers have a very low ductility, on the order of less than 1 percent. Glass fibers are considerably more ductile, on the order of 4-6 percent. Aramid fibers have a ductility of 2 to 4 percent. As shown in Table 5-2, epoxy resins have low ductility, on the order of less than 1 percent. Thermoplastic resins commonly used in composites can be as large as 10 percent. In contrast to this, ASTM A 36 steel has a minimum ductility of 20 percent. Typical structural steel is therefore much more ductile than either the fibers or resins in these FRP's.

(2) When the fibers and resin are put together, the composite ductility is a weighted average of the fiber and resin ductility. This means that composites frequently have a low ductility (on the order of 1 to 5 percent). Some very ductile polymers can give composite ductility of up to 10 percent. If composites are to be made into complex shapes, then these complex shapes need to be formed during the initial fabrication process. Once a thermoset composite has been cured it cannot be refabricated. This is in contrast to many metals which can be cold-worked into complex shapes.

d. Modulus of elasticity.

(1) Modulus of elasticity is significantly affected by the type of fibers that are involved. Examples of this are shown in Table 5-5.

(2) Carbon/epoxy composites are intrinsically the stiffest. However, glass/epoxy composites have a better resistance to shear. The aramid-based composites are the poorest when loaded transverse to the fibers.

(3) The fiber volume fraction has a significant effect upon the modulus of elasticity. For a unidirectional system, the modulus can usually be represented by a simple rule of mixtures equation.

Table 5-5
Typical Modulus Terms for Unidirectional Composite Laminates [1]

Material	Longitudinal Modulus GPa (10^6 psi)	Transverse Modulus GPa (10^6 psi)	Shear Modulus GPa (10^6 psi)	Major Poisson's Ratio
Carbon/ epoxy	181 (26.2)	10.3 (1.49)	7.17 (1.04)	0.30
E-glass/ polyester	54.10 (7.84)	14.05 (2.04)	5.44 (0.789)	0.25
Aramid/ epoxy	75.86 (11.0)	5.45 (.79)	2.28 (0.331)	0.34

[1] Aramid and carbon data are from Tsai and Hahn (1980); glass data are from *Delaware Composites Design Encyclopedia* (1990).

$$E_L = E_f V_f + E_m V_m \qquad (5\text{-}2)$$

$$\frac{1}{E_T} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \qquad (5\text{-}3)$$

where

E_L = longitudinal modulus of the composite (in fiber direction)

E_f = modulus of fiber phase

V_f = volume fraction of fiber phase

E_m = modulus of matrix phase

V_m = volume fraction of matrix phase

E_T = transverse modulus of the composite (perpendicular to fiber direction)

(4) An engineer should not design using Equations 5-2 and 5-3. They are only first approximations, because the modulus also depends upon prior processing of the composite part.

(3) Fiber orientation also plays a big role in the composite stiffness. Figure 5-1 shows how the longitudinal and transverse moduli vary with orientation. As might be expected, the composite is stiffest when loaded in the fiber direction and least stiff when loaded perpendicular to the fibers. As Figure 5-1 shows, the relationship between modulus and orientation is not a simple one. Likewise, shear modulus is also a significant function of fiber orientation. Shear modulus reaches a maximum at 45 degrees and is a minimum at either 0 or 90 degrees. A graph of shear modulus as a function of fiber orientation is shown in Figure 5-2. Many applications have minimum requirements for both tensile and shear moduli, and some combination of 0- and 45-degree plies is frequently required.

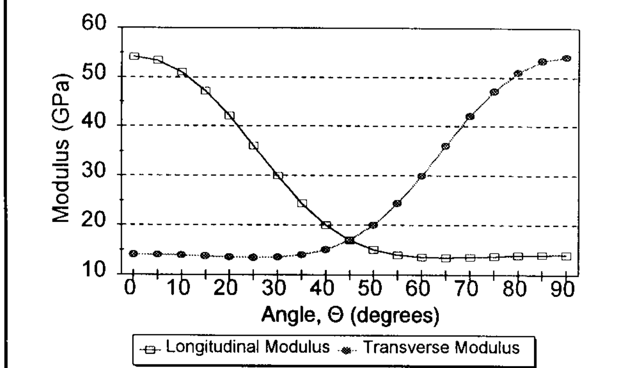

Figure 5-1. Modulus as a function of fiber orientation for a typical glass/polyester composite. Lay-up is of the form [Θ(1)/–Θ(2)/Θ(1)], where Θ is the angle in degrees

e. Specific modulus of elasticity. Specific modulus is a measure of a given mass of a material's ability to resist deformation. This is in contrast to modulus, which is a measure of a given area of a material's ability to resist deformation. The specific modulus of a material is its modulus divided by its density (or specific gravity). Values of specific modulus will vary with fiber content and fiber orientation in the same manner as does modulus. If the stiffness (or modulus) of a structure is the controlling parameter, then the composite with the highest specific modulus will be the lightest weight.

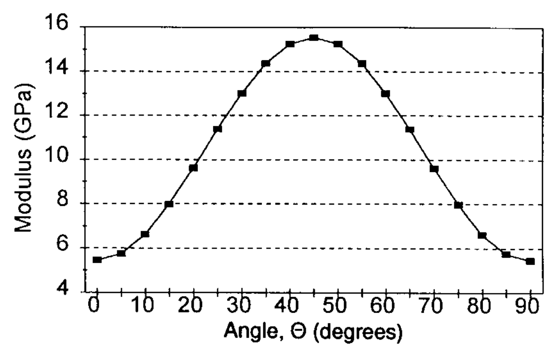

Figure 5-2. Shear modulus as a function of fiber orientation for a typical glass/polyester composite. Lay-up is of the form [Θ(1)/–Θ(2)/Θ(1)], where Θ is the angle in degrees

f. Density. Density values for various types of fibers were given in Table 5-1. They varied from about 1.4 to 2.5 g/cm^3 (88 to 156 lb/ft^3). Resin densities vary from about 1.3 to 1.8 g/cm^3 (81 to 112 lb/ft^3). Density of the composite can be calculated from a simple rule of mixtures equation.

$$\rho_c = \rho_m V_m + \rho_f V_f \qquad (5\text{-}4)$$

where

ρ_c = density of the composite

ρ_m = density of the matrix

V_m = volume fraction of the matrix

ρ_f = density of the fibers

V_f = volume fraction of the fibers

Most of these composites will have densities somewhere between 1.5 and 2.5 g/cm^3 (93 to 156 lb/ft^3). This is in contrast to the density of iron, which is 7.87 g/cm^3 (490 lb/ft^3). The FRPs' low density (when compared to metals) is what gives them such high values of specific modulus and specific strength.

g. Poisson's ratio. Poisson's ratio for a given composite can vary significantly with respect to fiber orientation. When fibers are in the 0-degree direction with respect to the applied load, Poisson's ratio is frequently similar to that of most metals, being in the 0.25 to 0.35 range. However, at other fiber orientations, Poisson's ratio can vary a great deal. When the fibers are all in the 90-degree direction, Poisson's ratio can be very small, on the order of 0.02 to 0.05. This is because the very stiff fibers are resisting the resin contraction. On the other hand, with fiber orientations between 30 and 40 degrees, Poisson's ratio is often large. For some materials, Poisson's ratio can be larger than one, because the fibers are trying to align themselves with the applied load. As the fiber angles decrease slightly, they act to bring the resin in alignment with the load, which gives a very high value for Poisson's ratio. An example of this is shown in Figure 5-3.

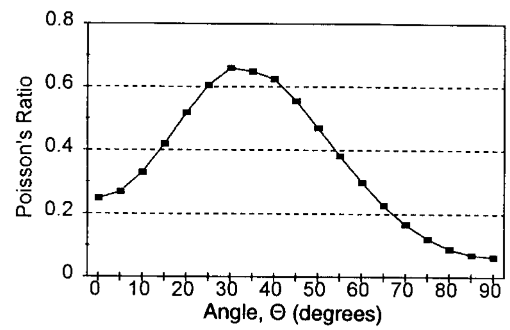

Figure 5-3. Poisson's ratio as a function of fiber orientation for a typical glass/polyester composite. Lay-up is of the form [Θ(1)/–Θ(2)/Θ(1)], where Θ is the angel in degrees

h. Coefficient of thermal expansion.

(1) Like all the other properties discussed so far, the thermal expansion coefficients are significantly affected by fiber orientation. Properties for some unidirectional composites are shown in Table 5-6. Also shown are values for steel and aluminum. Unidirectional composites are interesting in that many of them have a negative value for thermal expansion in the fiber direction. This is because the fibers resist thermal expansion of the resin in the fiber direction. Perpendicular to the fibers, the resin can expand a great deal because the fibers do not resist the expansion.

(2) It should be noted that these composites have a thermal expansion coefficient (perpendicular to the fibers)

Table 5-6
Typical Thermal Expansion Coefficients for Different Materials[1]

Material	Coefficient of Thermal Expansion Parallel to Fibers, (m/m)/°C ((in./in.)/°F)	Coefficient of Thermal Expansion Perpendicular to Fibers, (m/m)/°C ((in./in.)/°F)
Fiber-reinforced composites		
Carbon/epoxy (unidirectional lay-up)	-0.3×10^{-6} (-0.17×10^{-6})	28.1×10^{-6} (15.6×10^{-6})
E-glass/epoxy (unidirectional lay-up)	8.6×10^{-6} (4.8×10^{-6})	22.1×10^{-6} (12.3×10^{-6})
Kevlar 49/epoxy (unidirectional lay-up)	-4.0×10^{-6} (-2.2×10^{-6})	79.0×10^{-6} (43.9×10^{-6})
Isotropic (noncomposite) materials	Coefficient of Thermal Expansion (m/m)/°C ((in./in.)/°F)	
Pure epoxy resin	54×10^{-6} (30.0×10^{-6})	
Steel	11.8 x 10-^{6} (6.6×10^{-6})	
Aluminum	23.6×10^{-6} (13.1×10^{-6})	

[1] Data from Tsai and Hahn (1980) and *Engineered Materials Handbook* (1987).

that is considerably greater than that of steel. However, it is possible to design carbon or aramid composites with very low values of the thermal expansion coefficient because these composites have negative values of the thermal expansion coefficient in one direction and positive values in another. If a proper choice of ply lay-ups is made it is possible to obtain a thermal expansion coefficient for the structure to be essentially zero. This will allow for very thermally stable structures to be designed. However, the stacking sequence that produces a zero value for thermal expansion will probably not be the one with the highest value of strength. Therefore, the designer may have to use materials with nonzero thermal expansion coefficients.

i. Creep. Creep can occur at room temperature for many composite materials. The portion of the composite that actually creeps is usually the resin. Carbon and glass fibers do not creep a significant amount at room temperature. Creep is a function of the applied stress, fiber orientation, fiber volume fraction, and ductility of the resin. Fiber orientation is important because the more fibers that are aligned in the load direction, the lower will be the stress (and amount of creep) in the resin portion. The higher the concentration of fibers (at any orientation), the lower will be the creep rate. This is because there is less of the resin available to deform. A more ductile resin will creep more than will a more brittle one. Creep and relaxation are not usually a problem with epoxy and other thermoset resins, but can be a problem when the more ductile thermoplastics are used.

j. Relaxation. For a material to relax, it must first have deformed. The amount of relaxation that is possible is related to the initial applied stress, the fiber orientation, fiber volume fraction, and the ductility of the resin. Higher initial stress will allow for more relaxation to occur later. More fibers oriented in the load direction will decrease the amount of creep, and the amount of potential relaxation. A more ductile resin will have deformed more and will, therefore, be able to relax more than will a more brittle one.

k. Toughness. The toughness of the material is dependent upon the type of fibers, the type of resin, and the volume fraction of fibers. The stacking sequence of the plies does not appear to significantly affect the toughness of the laminate.

(1) Impact toughness (resistance).

(a) Impact tests in the traditional sense (like Charpy tests) are rarely done on composite materials. The epoxy-based composites have very low impact toughness. Thermoplastic-based composites have a somewhat higher impact toughness. The *Engineered Materials Handbook* (1987) reports impact toughness for a unidirectional glass/polyester composite of about 972 J/m (18 ft-lbf/in.)

which is contrasted to a typical aluminum of 215-647 J/m (4-12 ft-lbf/in.) and a typical stainless steel of 458-593 J/m (8.5-11 ft-lbf/in.).

(b) A more common impact test is to apply a smaller impact load to the structure that damages it but does not break it. The internal damage caused by the impact load will change the strength and stiffness of the composite. The compressive strength of the structure is measured after impact. This type of test will evaluate whether or not the structure can still be used after it has been hit with an impact load. This test has not yet been standardized.

(2) Delamination toughness.

(a) Delamination failure is a common failure for these fiber-reinforced polymers. Delamination is the separating of a composite into its original layers (or plies). This can occur because of the relatively weak bonding that occurs between the layers. Therefore the designer needs to specify a toughness sufficient for this application.

(b) Delamination toughness is largely a function of the type of resin and amount of resin (volume fraction resin). The stacking sequence of the plies does not appear to significantly affect the delamination toughness. The more ductile the resin, the higher will be the toughness. However, it is not a linear relationship. A doubling of the resin toughness will not double the composite toughness because the toughness of the composite is also affected by the resin/fiber interface. The presence of the fibers may also act to decrease the size of the resin's plastic zone. This would also decrease the toughness of the composite.

(c) Volume fraction of resin is only important for resins of medium toughness or higher (with a G_{IC} about 250 J/m^2 or 1.4 in.-lb/in^2.). For these resins, as the amount of resin increases, the plastic zone can also increase (since there are now fewer fibers to interfere with its expansion), thus increasing the toughness. For a more brittle resin, the plastic zone within the resin does not extend beyond the resin-rich region between plies. Making this region bigger will not help the plastic zone to grow at all, and the overall toughness will not increase.

(d) Another important parameter is the strength of the fiber resin interface. A poor interfacial strength will result in a lower than expected toughness. Typical resin toughness (G_{IC}) can range from 200 to 8,000 J/m^2 (1.1-46 in.-lb/in^2.). Composite delamination toughness (G_{IC}) can range from 200 to 2,500 J/m^2 (1.1-14 in.-lb/in^2.). This is in contrast to A36 steel which has a value of G_{IC} of about 13,000 J/m^2 (74 in.-lb/in^2.).

(e) One problem with laminates concerns the joining of the individual plies of the composite material. The separation of individual plies is called delamination. A number of techniques have been developed to prevent delamination. One method is to use a tougher resin matrix material. Another method is to have some occasional fiber reinforcement through the thickness. One way that has been done is by using what looks like a giant sewing machine to "sew together" the layers before they have been cured.