3

PLY PROPERTIES

It is of fundamental importance for the designer to understand and to know precisely the geometric and mechanical characteristics of the “fiber + matrix” mixture which is the basic structure of the composite parts. The description of these characteristics is the object of this chapter.

3.1 ISOTROPY AND ANISOTROPY

When one studies the mechanical behavior of elastic bodies under load (elasticity theory), one has to consider the following:

- An **elastic** body subjected to stresses deforms in a **reversible** manner.
- At each point within the body, one can identify the **principal planes** on which there are only **normal stresses**.
- The **normal directions** on these planes are called the **principal stress directions**.
- A small **sphere** of material surrounding a point of the body becomes an **ellipsoid** after loading.

The spatial position of the ellipsoid relative to the principal stress directions enables us to characterize whether the material under study is isotropic or anisotropic. Figure 3.1 illustrates this phenomenon.

Figure 3.2 illustrates the deformation of an isotropic sample and an anisotropic sample. In the latter case, the oblique lines represent the preferred directions along which one would place the fibers of reinforcement. One can consider that a longitudinal loading applied to an isotropic plate would create an extension in the longitudinal direction and a contraction in the transverse direction. The same loading applied to an anisotropic plate creates an angular distortion, in addition to the longitudinal extension and transversal contraction.

In the simple case of plane stress, one can obtain the elastic constants using stress–strain relations.

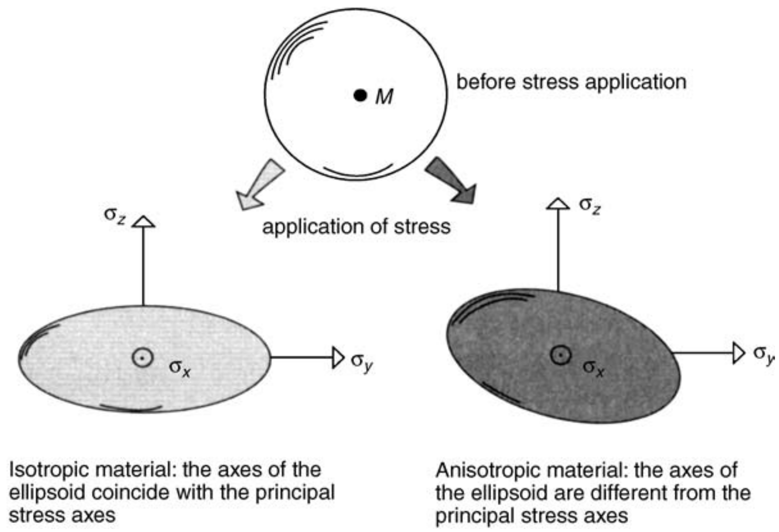


Figure 3.1 Schematic of Deformation

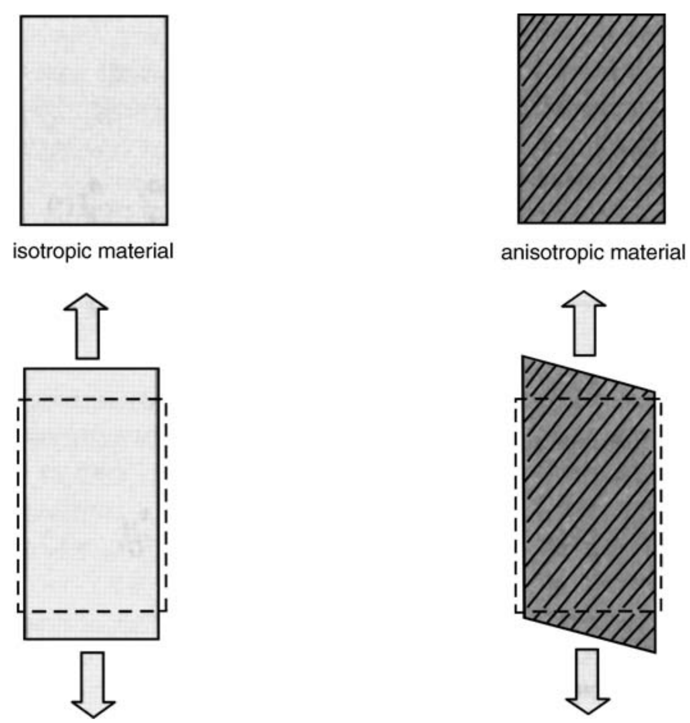


Figure 3.2 Comparison between Deformation of an Isotropic and Anisotropic Plate

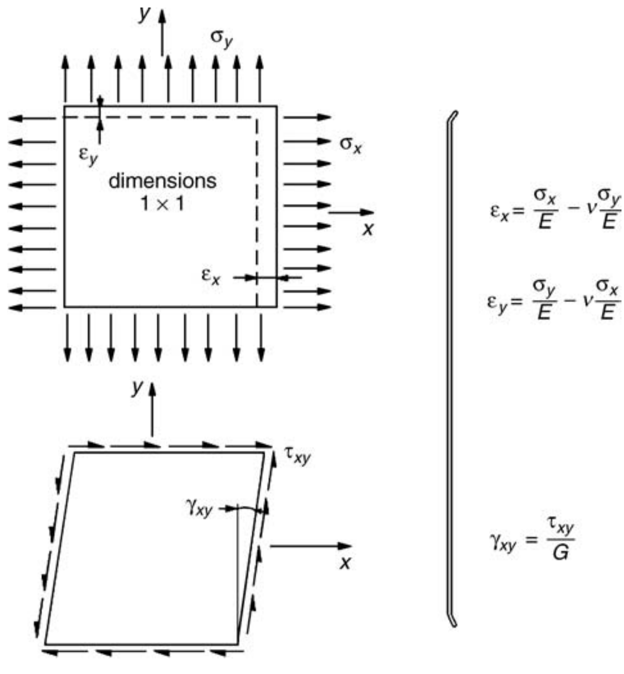
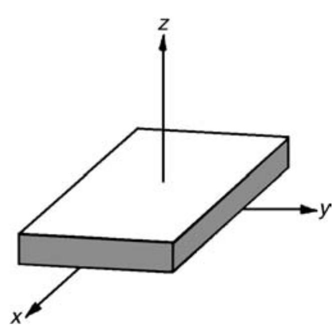


Figure 3.3 Stress–Strain Behavior in an Isotropic Material

3.1.1 Isotropic Materials

The following relations are valid for a material that is elastic and isotropic.



One can write the stress–strain relation (see Figure 3.3) in matrix form as[1]

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E} & -\frac{\nu}{E} & 0 \\ -\frac{\nu}{E} & \frac{1}{E} & 0 \\ 0 & 0 & \frac{1}{G} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}$$

[1] In these equations, $\varepsilon_x, \varepsilon_y, \gamma_{xy}$ are also the small strains that are obtained in a classical manner from the displacements u_x and u_y as: $\varepsilon_x = \partial u_x / \partial x$; $\varepsilon_y = \partial u_y / \partial y$; $\gamma_{xy} = \partial u_x / \partial y + \partial u_y / \partial x$.

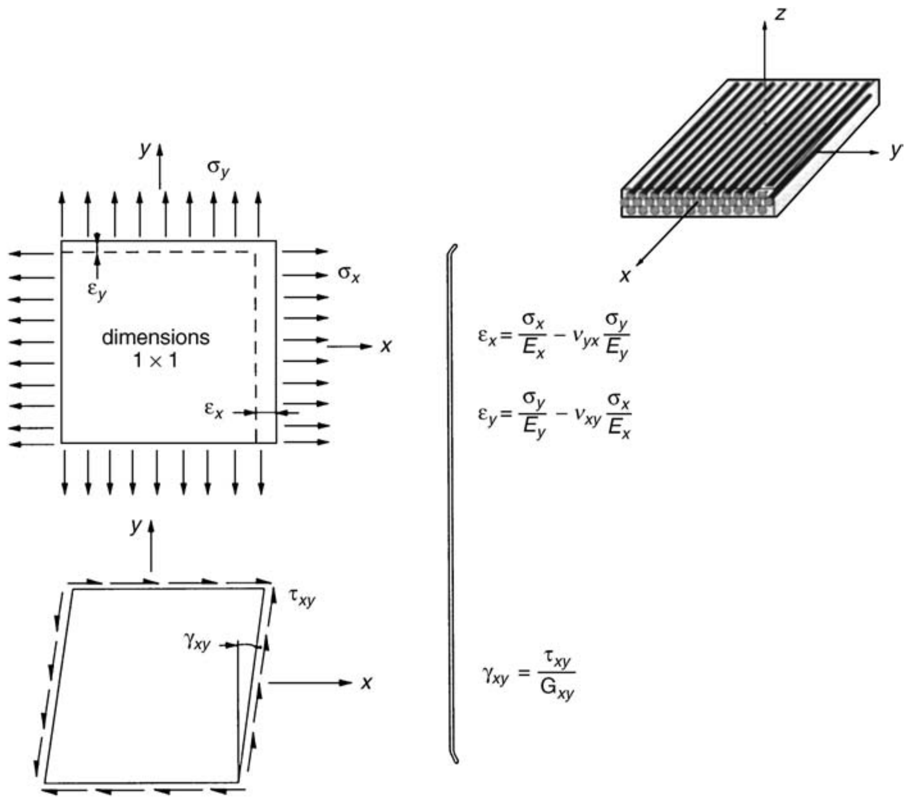


Figure 3.4 Deformation in an Anisotropic Material

There are three elastic constants: $E, \nu,\ G$. There exists a relation among them as:

$$G = \frac{E}{2(1+\nu)}$$

The above relation shows that a material that is isotropic and elastic can be characterized by two independent elastic constants: E and ν.

3.1.2 Anisotropic Material

The matrix equation for anisotropic material (see Figure 3.4) is

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \dfrac{1}{E_x} & -\dfrac{\nu_{yx}}{E_y} & 0 \\ -\dfrac{\nu_{xy}}{E_x} & \dfrac{1}{E_y} & 0 \\ 0 & 0 & \dfrac{1}{G_{xy}} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}$$

Note that the stress–strain matrix above is symmetric.[2] The number of distinct elastic constants is five:

- Two moduli of elasticity: E_x and E_y,
- Two Poisson coefficients: ν_{yx} and ν_{xy}, and
- One shear modulus: G_{xy}.

In fact there are only four independent elastic constants:[3] E_x, E_y, G_{xy}, and ν_{yx} (or ν_{xy}). The fifth elastic constant can be obtained from the others using the symmetry relation:

$$\nu_{xy} = \nu_{yx}\frac{E_x}{E_y}$$

3.2 CHARACTERISTICS OF THE REINFORCEMENT–MATRIX MIXTURE

We denote as **ply** the semi-product "reinforcement + resin" in a quasi-bidimensional form.[4] This can be

- A tape of unidirectional fiber + matrix,
- A fabric + matrix, or
- A mat + matrix.

These are examined more below.

3.2.1 Fiber Mass Fraction

Fiber mass fraction is defined as

$$M_f = \frac{\text{Mass of fibers}}{\text{Total mass}}$$

In consequence, the mass of matrix is

$$M_m = \frac{\text{Mass of matrix}}{\text{Total mass}}$$

with

$$M_m = 1 - M_f$$

[2] To know more about the development on this point, refer to Section 9.2 and Exercise 18.1.2.
[3] Refer to Section 13.2.
[4] Such condition exists in the commercial products. These are called *preimpregnated* or *SMC* (sheet molding compound). One can also find non-preformed mixtures of short fibers and resin. These are called *premix* or *BMC* (bulk molding compound).

Table 3.1 Common Fiber Volume Fractions in Different Processes

Molding Process	*Fiber Volume Fraction*
Contact Molding	30%
Compression Molding	40%
Filament Winding	60%–85%
Vacuum Molding	50%–80%

3.2.2 Fiber Volume Fraction

Fiber volume fraction is defined as

$$V_f = \frac{\text{Volume of fiber}}{\text{Total volume}}$$

As a result, the volume of matrix is given as

$$V_m = \frac{\text{Volume of matrix}}{\text{Total volume}}$$

with[5]

$$V_m = 1 - V_f$$

Note that one can convert from mass fraction to volume fraction and vice versa. If ρ_f and ρ_m are the specific mass of the fiber and matrix, respectively, we have

$$V_f = \frac{\dfrac{M_f}{\rho_f}}{\dfrac{M_f}{\rho_f} + \dfrac{M_m}{\rho_m}} \qquad M_f = \frac{V_f \rho_f}{V_f \rho_f + V_m \rho_m}$$

Depending on the method of fabrication, the common fiber volume fractions are as shown in Table 3.1.

3.2.3 Mass Density of a Ply

The mass density of a ply can be calculated as

$$\rho = \frac{\text{total mass}}{\text{total volume}}$$

[5] In reality, the mixture of fiber/matrix also includes a small volume of voids, characterized by the *porosity* of the composite. One has then $V_m + V_f + V_p = 1$, in which V_p denotes the percentage of "volume of void/total volume." V_p is usually much less than 1 (See Exercise 18.1.11).

Table 3.2 Ply Thicknesses of Some Common Composites

	M_f	H
E glass	34%	0.125 mm
R glass	68%	0.175 mm
Kevlar	65%	0.13 mm
H.R. Carbon	68%	0.13 mm

The above equation can also be expanded as

$$\rho = \frac{\text{mass of fiber}}{\text{total volume}} + \frac{\text{mass of matrix}}{\text{total volume}}$$
$$= \frac{\text{volume of fiber}}{\text{total volume}}\rho_f + \frac{\text{volume of matrix}}{\text{total volume}}\rho_m$$

or

$$\rho = \rho_f V_f + \rho_m V_m$$

3.2.4 Ply Thickness

The ply thickness is defined as the number of **grams** of mass of fiber m_{of} per m^2 of area. The ply thickness, denoted as h, is such that:

$$h \times 1(m^2) = \text{total volume} = \text{total volume} \times \frac{m_{of}}{\text{fiber volume} \times \rho_f}$$

or

$$h = \frac{m_{of}}{V_f \rho_f}$$

One can also express the thickness in terms of mass fraction of fibers rather than in terms of volume fraction.

$$h = m_{of}\left[\frac{1}{\rho_f} + \frac{1}{\rho_m}\left(\frac{1-M_f}{M_f}\right)\right]$$

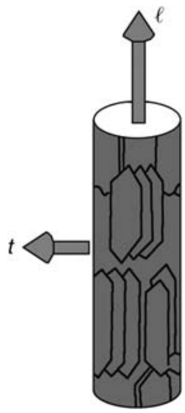
Table 3.2 shows a few examples of ply thicknesses.

3.3 UNIDIRECTIONAL PLY

3.3.1 Elastic Modulus

The mechanical characteristics of the fiber/matrix mixture can be obtained based on the characteristics of each of the constituents. In the literature, there are theoretical as well as semi-empirical relations. As such, the results from these relations may not always agree with experimental values. One of the reasons is

Table 3.3 Fiber Elastic Modulus



	Glass E	Kevlar	Carbon H.R.	Carbon H.M.
fiber longitudinal modulus in ℓ direction Ef_ℓ (MPa)	74,000	130,000	230,000	390,000
fiber transverse modulus in t direction Ef_t (MPa)	74,000	5400	15,000	6000
fiber shear modulus $Gf_{\ell t}$ (Mpa)	30,000	12,000	50,000	20,000
fiber Poisson ratio $vf_{\ell t}$	0.25	0.4	0.3	0.35
	Isotropic	*Anisotropic*		

because the fibers themselves exhibit some degree of anisotropy. In Table 3.3, one can see small values of the elastic modulus in the transverse direction for Kevlar and carbon fibers, whereas glass fiber is isotropic.[6]

With the definitions in the previous paragraph, one can use the following relations to characterize the unidirectional ply:

- **Modulus of elasticity along the direction of the fiber E_l** is given by[7]

$$E_\ell = E_f V_f + E_m V_m$$

or

$$E_\ell = E_f V_f + E_m (1 - V_f)$$

In practice, this modulus depends essentially on the longitudinal modulus of the fiber, E_f, because $E_m << E_f$ (as $E_{m\ \mathrm{resin}}/E_{f\ \mathrm{glass}}$ # 6%).

- **Modulus of elasticity in the transverse direction to the fiber axis, E_t:** In the following equation, E_{ft} represents the modulus of elasticity of the

[6] This is due to the drawing of the carbon and Kevlar fibers during fabrication. This orients the chain of the molecules.

[7] Chapter 10 gives details for the approximate calculation of the moduli E_ℓ, E_t, $G_{\ell t}$ and $\upsilon_{\ell t}$ which lead to these expressions.

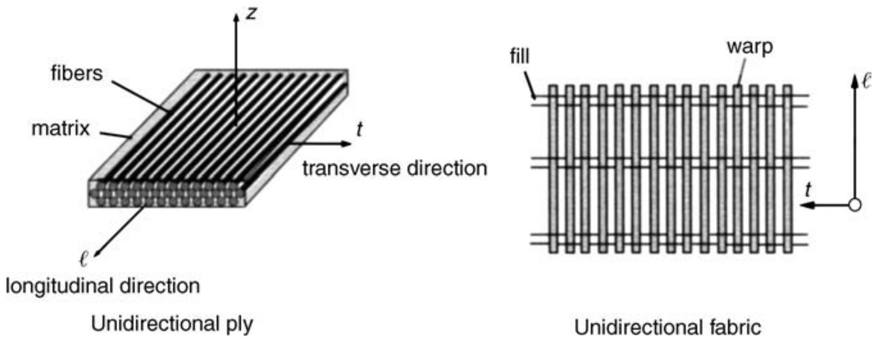


Figure 3.5 Orientations in Composite Layers

fiber in the direction that is transverse to the fiber axis as indicated in Table 3.3.

$$E_t = E_m\left[\frac{1}{(1-V_f)+\frac{E_m}{E_{ft}}V_f}\right]$$

- **Shear modulus $G_{\ell t}$:** An order of magnitude of this modulus is given in the following expression, in which $G_{f\ell t}$ represents the shear modulus of the fiber (as shown in Table 3.3).

$$G_{\ell t} = G_m\left[\frac{1}{(1-V_f)+\frac{G_m}{G_{f\ell t}}V_f}\right]$$

- **Poisson coefficient $\nu_{\ell t}$:** The Poisson coefficient represents the contraction in the transverse direction t when a ply is subjected to tensile loading in the longitudinal direction ℓ (see Figure 3.5).

$$\nu_{\ell t} = \nu_f V_f + \nu_m V_m$$

- **Modulus along any direction:** The modulus along a certain direction in plane ℓt, other than along the fiber and transverse to the fiber,[8] is given in the expression below, where $c = \cos\theta$ and $s = \sin\theta$. Note that this modulus decreases rapidly as one is moving away from the fiber direction (see Figure 3.6).

$$E_x = \frac{1}{\frac{c^4}{E_\ell}+\frac{s^4}{E_t}+2c^2s^2\left(\frac{1}{2G_{\ell t}}-\frac{\nu_{\ell t}}{E_t}\right)}$$

[8] The calculation of these moduli is shown in details in Chapter 11.

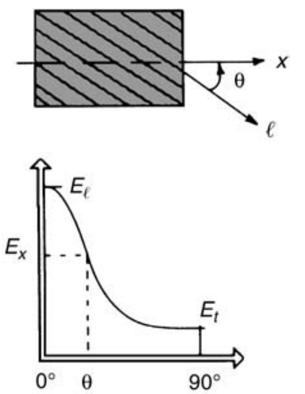


Figure 3.6 Off-axis Modulus

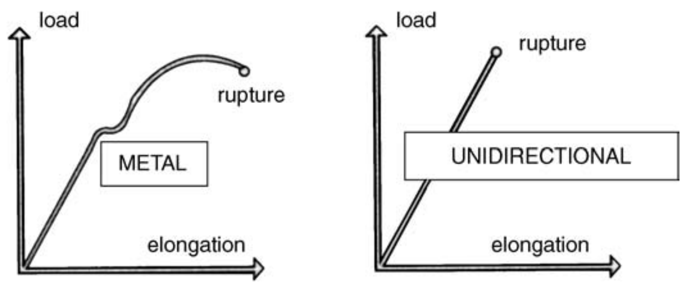


Figure 3.7 Loading Curves of Metal and Unidirectional Composite

3.3.2 Ultimate Strength of a Ply

The curves in Figure 3.7 show the important difference in the behavior between classical metallic materials and the unidirectional plies. These differences can be summarized in a few points as

- There is lack of plastic deformation in the unidirectional ply. (This is a disadvantage.)
- Ultimate strength of the unidirectional ply is higher. (This is an advantage.)
- There is important elastic deformation for the unidirectional ply. (This can be an advantage or a disadvantage, depending on the application; for example, this is an advantage for springs, arcs, or poles.)

When the fibers break before the matrix during loading along the fiber direction, one can obtain the following for the composite:

$$\underset{rupture}{\sigma_\ell} = \underset{rupture}{\sigma_f}\left[V_f + (1 - V_f)\frac{E_m}{E_f}\right]$$

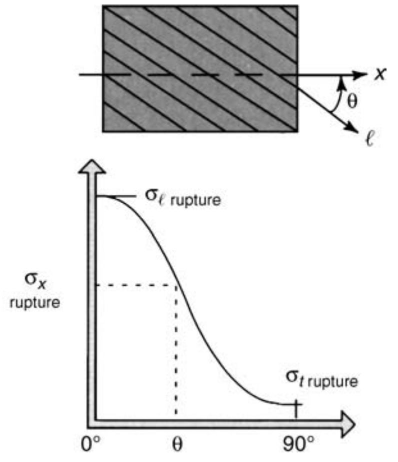


Figure 3.8 Off-axis Rupture Strength

or, approximately

$$\underset{rupture}{\sigma_\ell} \approx \underset{rupture}{\sigma_f} \times V_f$$

The **ultimate strength along any direction**[9] is given by the following relation (see Figure 3.8), where

$\sigma_{l,rupture}$ = Fracture strength in the direction of the fibers,
$\sigma_{t,rupture}$ = Fracture strength transverse to the direction of the fibers,
$\tau_{\ell t,rupture}$ = Shear strength in the plane (ℓ,t) of the ply

$$c = \cos\theta$$

$$s = \sin\theta$$

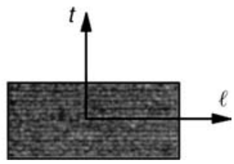
$$\boxed{\underset{rupture}{\sigma_x} = \frac{1}{\sqrt{\dfrac{c^4}{\underset{rupture}{\sigma_\ell^2}} + \dfrac{s^4}{\underset{rupture}{\sigma_t^2}} + \left(\dfrac{1}{\underset{rupture}{\tau_{\ell t}^2}} - \dfrac{1}{\underset{rupture}{\sigma_l^2}}\right)c^2 s^2}}}$$

3.3.3 Examples

Table 3.4 gives the properties of the fibers/epoxy unidirectional ply at 60% fiber volume fraction.[10]

[9] Detailed calculation is shown in Section 14.3.
[10] The values assigned in this table can vary depending on the fabrication procedure.

Table 3.4 Properties of Fiber/Epoxy Plies



$V_f = 0.6$	*Glass*	*Kevlar*	*Carbon*
Specific mass (kg/m^3)	2080	1350	1530
Longitudinal tensile fracture strength (MPa)	1250	1410	1270
Longitudinal compressive fracture strength (MPa)	600	280	1130
Transverse tensile fracture strength (MPa)	35	28	42
Transverse compressive fracture strength (MPa)	141	141	141
In plane shear strength (MPa)	63	45	63
Interlaminar shear strength (MPa)	80	60	90
Longitudinal elastic modulus E_ℓ (MPa)	45,000	85,000	134,000
Transverse elastic modulus E_t (MPa)	12,000	5600	7000
Shear modulus $G_{\ell t}$ (MPa)	4500	2100	4200
Poisson ratio $\upsilon_{\ell t}$	0.3	0.34	0.25
Longitudinal coefficient of thermal expansion at 20°C α_ℓ (°C^{-1})	0.4 to 0.7 $\times 10^{-5}$	-0.4×10^{-5}	-0.12×10^{-5}
Transverse coefficient of thermal expansion at 20°C α_t(°C^{-1})	1.6 to 2 $\times 10^{-5}$	5.8×10^{-5}	3.4×10^{-5}

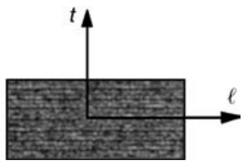
The compression strength along the longitudinal direction is smaller than the tensile strength along the same direction due to the **micro buckling** phenomenon of the fibers in the matrix.

3.3.4 Examples of "High Performance" Unidirectional Plies

The unidirectionals in Table 3.5 have V_f = 50% boron fibers. The boron/aluminum composite mentioned above belongs to the group of metal matrix composites (see Section 3.7), among these one can find the following:

- For fibers, these can be
  - Glass
  - Silicon carbide
  - Aluminum
  - Other ceramics
- For matrices, these can be
  - Magnesium and its alloys

Table 3.5 Properties of Unidirectional Plies Made of Boron Fibers

$V_f = 0.5$ 	*Boron/Epoxy*	*Boron/ Aluminum*
Specific mass (kg/m^3)	1950	2650
Longitudinal tensile strength (MPa)	1400	1400
Longitudinal compressive strength (MPa)	2600	3000
Transverse tensile strength (MPa)	80	120
Longitudinal elastic modulus E_ℓ (MPa)	210,000	220,000
Transverse elastic modulus E_t (MPa)	12,000	140,000
Shear modulus $G_{\ell t}$ (MPa)		7500
Longitudinal coefficient of thermal expansion at 20°C, α_ℓ (°C^{-1})	0.5×10^{-5}	0.65×10^{-5}

- Aluminum
- Ceramics

3.4 WOVEN FABRICS

3.4.1 Forms of Woven Fabric

The fabrics are made of fibers oriented along two perpendicular directions: one is called the **warp** and the other is called the **fill** (or weft) direction. The fibers are woven together, which means the fill yarns pass over and under the warp yarns, following a fixed pattern. Figure 3.9a shows a **plain weave** where each fill goes over a warp yarn then under a warp yarn and so on. In Figure 3.9b, each fill yarn goes over 4 warp yarns before going under the fifth one. For this reason, it is called a "5-harness satin." Figure 3.9c shows a twill weave.

For an approximation (about 15%) of the elastic properties of the fabrics, one can consider these to consist of two plies of unidirectionals crossing at 90° angles with each other. One can use the following notation:

e = total layer thickness
n_1 = number of warp yarns per meter
n_2 = number of fill yarns per meter
$k = \dfrac{n_1}{n_1 + n_2}$
V_f = volume fraction of fibers

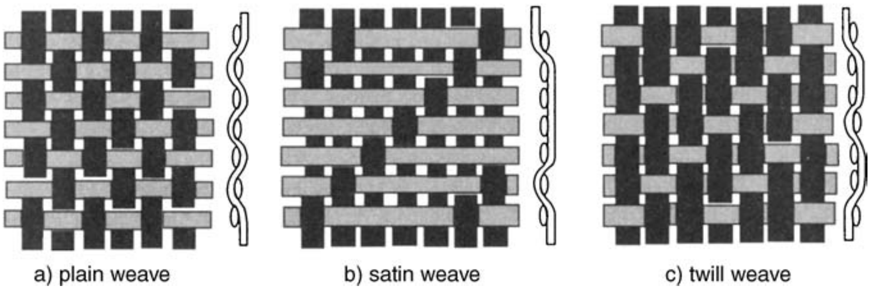


Figure 3.9 Forms of Woven Fabrics

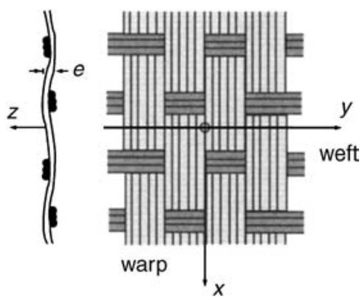


Figure 3.10 Notation for a Fabric Layer

One can deduce the thickness of the equivalent unidirectional plies (see Figure 3.10) as

$$e_{warp} = e \times \frac{n_1}{n_1 + n_2} = k \times e$$

$$e_{fill} = e \times \frac{n_2}{n_1 + n_2} = (1 - k) \times e$$

3.4.2 Elastic Modulus of Fabric Layer

For approximate values, the two plies of reinforcement can be considered separately or together.

- **Separately**, the fabric layer is replaced by two unidirectional plies crossed at 90° with each other, with the following thicknesses:

$$e_{warp} = k \times e \qquad e_{fill} = (1 - k) \times e$$

The average fiber volume fraction V_f is already known, and the mechanical properties E_ℓ, E_t, $G_{\ell t}$, $\nu_{\ell t}$ of these plies can be determined according Section 3.3.1.

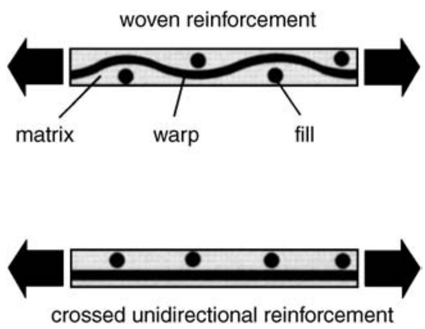


Figure 3.11 Cross Section of a Layer with Fibers Crossed at 90°

- **Together**, the fabric layer is replaced by one single anisotropic layer with thickness e, x being along the warp direction and y along the fill direction (see Figure 3.9). One can therefore obtain[11]

$$E_x \approx k \times E_\ell + (1-k) \times E_t$$
$$E_y \approx (1-k) \times E_\ell + k \times E_t$$
$$G_{xy} = G_{\ell t}$$
$$\nu_{xy} \approx \nu_{\ell t} \bigg/ \left(k + (1-k)\frac{E_\ell}{E_t}\right)$$

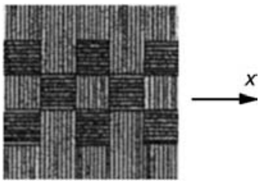
  Notes: The stiffness obtained with a woven fabric is less than what is observed if one were to superpose two cross plies of unidirectionals. This is due to the curvature of the fibers during the weaving operation (see Figure 3.11). This curvature makes the woven fabric more deformable than the two cross plies when subjected to the same loading. (There exist fabrics that are of "high modulus" where the unidirectional layers are not connected with each other by weaving. The unidirectional plies are held together by stitching fine threads of glass or polymer.)
- There is also a stronger tensile strength of a woven fabric and a lower compressive strength, as compared with the strengths obtained by superposing two cross plies.[12]

3.4.3 Examples of Balanced Fabrics/Epoxy

A fabric is said to be **balanced** when the number of yarns along the warp and fill directions are the same. The material is therefore identical along the two directions.

[11] For the corresponding calculations, cf. Section 12.1.2 and also Chapter 18, Application 18.2.12.
[12] For example, compare the strengths in tension and in compression in Table 3.6, and in Tables 5.1, 5.6, and 5.11 of Section 5.4 for proportions of 50% for 0° and 50% for 90° (taking into account the difference in fiber volume fraction).

Table 3.6 Properties of Balanced Fabric/Epoxy Composites



	E Glass	*Kevlar*	*Carbon*
Fiber volume fraction V_f (%)	50	50	45
Specific mass (kg/m^3)	1900	1330	1450
Tensile fracture strength along x or y (MPa)	400	500	420
Compressive fracture strength along x or y (MPa)	390	170	360
In plane shear strength (MPa)		150	55
Elastic modulus E_x (= E_y) (MPa)	20,000	22,000	54,000
Shear modulus G_{xy} (MPa)	2850		4000
Poisson coefficient υ_{xy}	0.13		0.045
Coefficient of thermal expansion $\alpha_x = \alpha_y$(°C^{-1})		-0.2×10^{-5}	0.05×10^{-5}
Maximum elongation (%)		2.1	1.0
Price (relative)	1	4.2	7.3

The warp and fill directions play equal roles affecting the thermomechanical properties. The material in Table 3.6 is of epoxy matrix.

3.5 MATS AND REINFORCED MATRICES

3.5.1 Mats

Mats are made of cut fibers (fiber lengths between 5 and 10 cm) or of continuous fibers making a bidimensional layer. Mats are isotropic within their plane (x, y). Therefore they can be characterized by only two elastic constants, as identified in Section 3.1.

If E_ℓ and E_t are the elastic moduli (along the longitudinal and transverse directions) of an unidirectional ply with the same volume fraction of V_f, one has

$$E_{mat} \approx \frac{3}{8}E_\ell + \frac{5}{8}E_t$$

$$G_{mat} \approx \frac{E_{mat}}{2(1 + \nu_{mat})}$$

$$\nu_{mat} \approx 0.3$$

For example, mats with cut fibers made of glass/epoxy have the following characteristics:

Fiber volume fraction	28%
Specific mass (kg/m^3)	1800
Elastic modulus (MPa)	14,000
Tensile fracture strength (MPa)	140
Heat capacity (J/g × °C)	1.15
Coefficient of heat conduction (W/m × °C)	0.25
Linear coefficient of thermal expansion (°C^{-1})	2.2×10^{-5}

3.5.2 Summary Example of Glass/Epoxy Layers

Figures 3.12 and 3.13 give a summary of the principal characteristics of different types of layers (unidirectionals, fabrics, and mats) with the variation of the fiber volume fraction V_f.

3.5.3 Spherical Fillers

Spherical fillers are reinforcements associated with polymer matrices (see Figure 3.14). They are in the form of **microballs**, either solid or hollow, with diameters between 10 and 150 μm. They are made of glass, carbon, or polystyrene.

- The filler volume fraction V_f can reach up to 50%.
- The filler properties are such that $E_f >> E_m$.

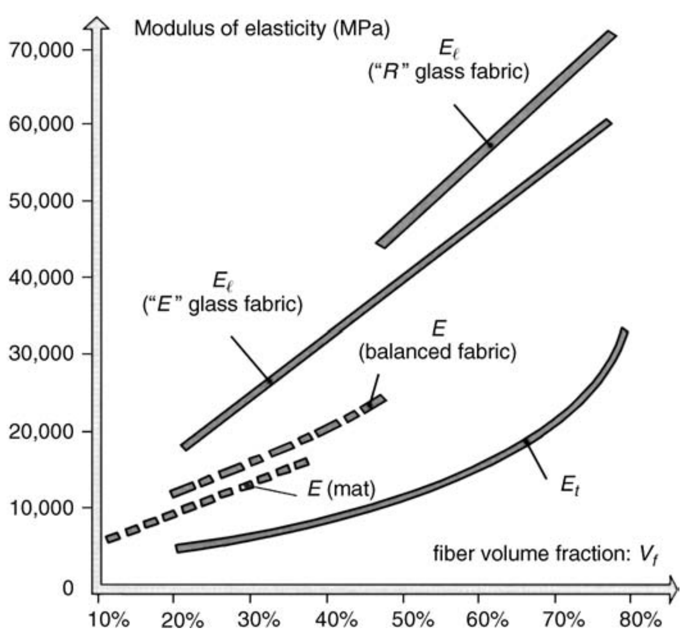


Figure 3.12 Elastic Modulus of Glass/Epoxy Layers

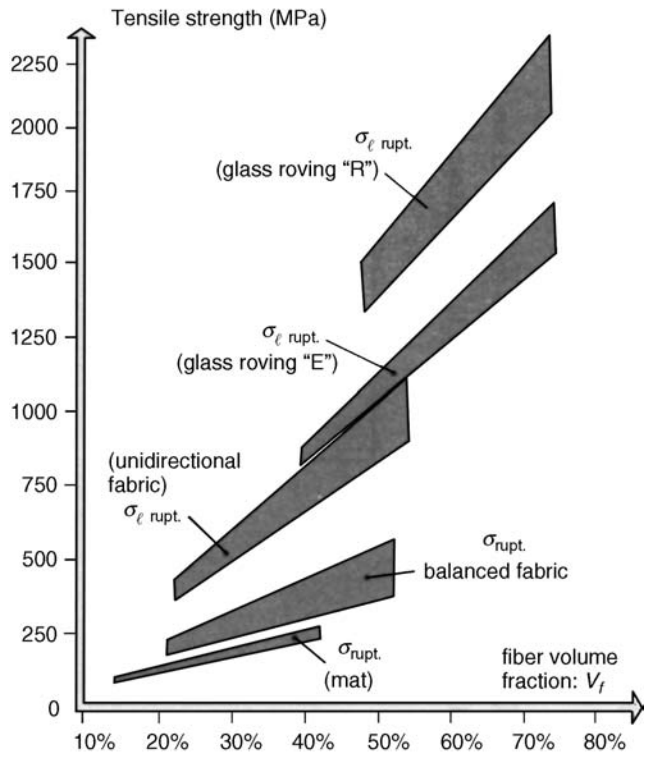


Figure 3.13 Tensile Strength of Glass/epoxy Layers

The composite (matrix + filler) is isotropic, with elastic properties E, G, ν given by the following relations:

$$\text{Defining:} \quad K = \frac{E_m}{3(1-2\nu_m)}\left[1 + 3\left(\frac{1-\nu_m}{1+\nu_m}\right)\frac{V_f}{(1-V_f)}\right]$$

$$E \approx \frac{9KG}{3K+G}$$

$$G \approx \frac{E_m}{2(1+\nu_m)}\left[1 + \frac{15}{2}\left(\frac{1-\nu_m}{4-5\nu_m}\right)\frac{V_f}{(1-V_f)}\right]$$

$$\nu \approx \frac{1}{2}\left(\frac{3K-2G}{3K+G}\right)$$

3.5.4 Other Reinforcements

One may also use reinforcements in the form of crushed fibers, flakes (see Figure 3.15), or powders made of the following:

- Glass
- Graphite
- Metals

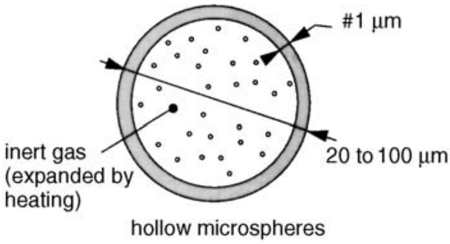


Figure 3.14 Spherical Fillers

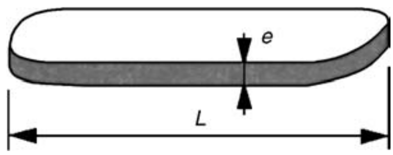


Figure 3.15 Form of Flakes

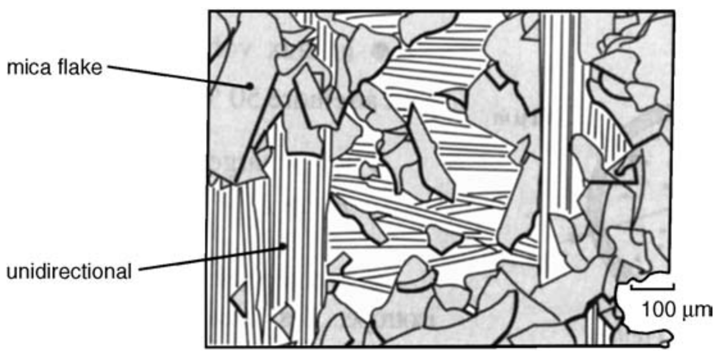


Figure 3.16 Mica Flakes Arrangement

- Aluminum
- Mica ($L \approx 100$ µm)
- Talc ($L \approx 10$ µm)

Immersed in a resin with stratified fibers, mica flakes have the arrangement as shown in the Figure 3.16. One can observe that the modulus of the resin is increased as[13]

$$E = \left[1 - \frac{Ln(1+u)}{u}\right] \times E_{mica} V_{mica} + E_m V_m; \qquad u = \frac{L}{e}\sqrt{\frac{G_m}{E_{mica}} \times \frac{V_{mica}}{V_m}}$$

[13] For more details, see "Interaction Effects in Fiber Composites," which is listed in the Bibliography at the end of the book.

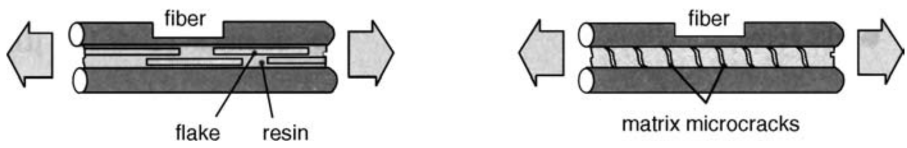


Figure 3.17 Cross Section with and without Mica

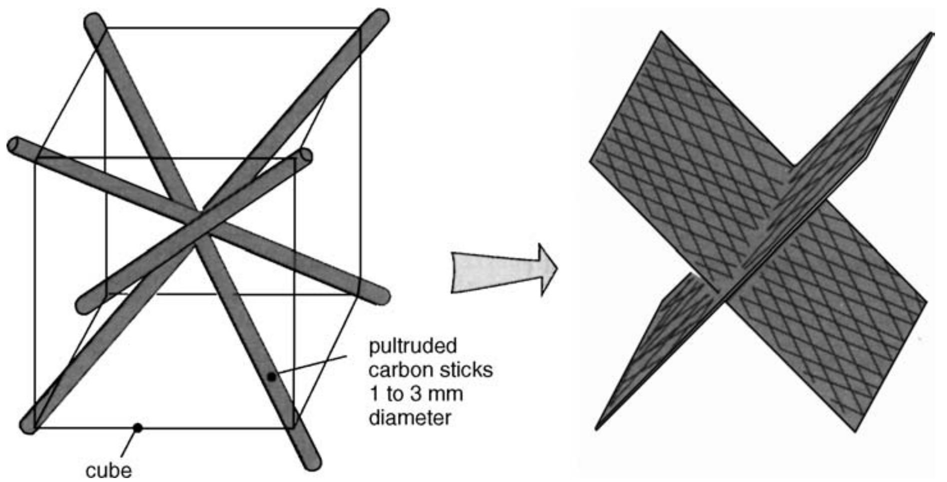


Figure 3.18 4D Architecture

The average properties of mica are

$$E_{\text{mica}} = 170{,}000 \text{ MPa} \quad \text{and} \quad \rho_{\text{mica}} = 2{,}800 \text{ kg/m}^3.$$

Figure 3.17 shows the increase resistance against the microfracture of the resin.

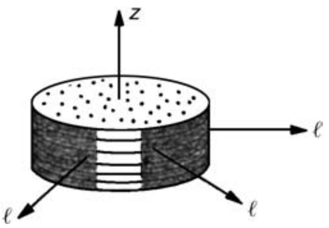
3.6 MULTIDIMENSIONAL FABRICS

An example of "4D" architecture of carbon reinforcement from the European society of propulsion (FRA) has the reinforcement assembled according to pre-established directions (see Figure 3.18). The fiber volume fraction is on the order of 30%. The matrix comes to fill the voids between the fibers.[14] The principal advantages of these types of composites are

- The supplementary connection (as compared with the bidimensional plies) makes the composites safe from delamination.
- The mechanical resistance is conserved—and even improved—at high temperatures (up to 3,000°C for carbon/carbon).
- The coefficient of expansion remains small.
- They are resistant against thermal shock.

[14] See Section 2.2.4.

Table 3.7 Properties of Three-Dimensional Carbon/Carbon

	*Aerolor 41*[16]	*Septcarb 4*[17]
Specific mass (kg/m^3)	1700 to 2000	1500 to 2000
Longitudinal tensile fracture strength (MPa)	40 to 100	95 and increasing, up to 2000°C
Longitudinal compressive fracture strength (MPa)	80 to 200	65
Tensile strength in z direction (MPa)	>10	3
Compressive strength in z direction (MPa)	80 to 200	120
Shear strength in ℓz plane (MPa)	20 to 40	10
Longitudinal elastic modulus E_ℓ (MPa)	30,000	16,000
Elastic modulus E_z (MPa)		5000
Shear modulus $G_{\ell z}$ (MPa)		2200
Shear modulus $G_{\ell\ell}$ (MPa)		5700
Poisson ratio $\upsilon_{z\ell}$		0.17
Poisson ratio $\upsilon_{\ell\ell}$		0.035
Thermal expansion coefficient α_ℓ(°C^{-1}) at 1000°C at 2,500°C	0.7×10^{-6}; 3×10^{-6}	3×10^{-6}; 4×10^{-6}
Thermal expansion coefficient α_z(°C^{-1}) at 1000°C at 2,500°C	6×10^{-6}; 6×10^{-6}	7×10^{-6}; 9×10^{-6}
Coefficient of thermal conductivity (W/m × °C)	300	

- There is a high coefficient of thermal conductivity.
- They have small density.
- The silicon/silicon is transparent to radio-electric waves.

Table 3.7 gives the characteristics of two composites made of tridimensional carbon/carbon. The mechanical properties are the same along all directions noted by ℓ in the following figure. The composite is **transversely isotropic**.[15]

[15] This notion is shown in detail in Section 13.2.
[16] Product of the Aerolor company (FRA).
[17] Product of European company in propulsion (FRA).

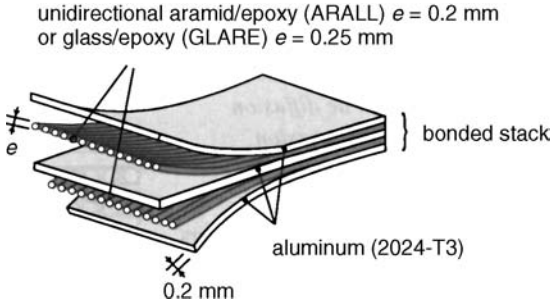


Figure 3.19 Layers of ARALL and GLARE

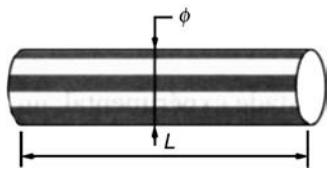


Figure 3.20 Sic Whisker

3.7 METAL MATRIX COMPOSITES

There are a number of products in development or in experimental stage including:

- Matrices: aluminum, magnesium, titanium (see also Section 7.4) and
- Reinforcements (fibers): aramid, carbon, boron, silicon carbide (SiC)

Example: ARALL (Aluminum Reinforced Aramid) and **GLARE** (Aluminum Reinforced Glass).[18] The essential advantage is better impact damage tolerance because of better resistance to failure due to thin metallic layers and resistance against the crack propagation from one layer to the other (see Figure 3.19).

Example: Short silicon carbide fibers (whiskers)/aluminum. This is a so-called "incompatible" composite because the big difference between the thermo-mechanical properties of the constituents leads to high stress concentrations and debonding between the fibers and the matrix (see Figure 3.20). This has good applications at high temperatures. The diameter of the whisker is about 20 μm. Slenderness ratio L/∅ ≈ 5 and fiber volume fraction $V_f \approx 0.3$.

Example: Boron/aluminum. This is used in aerospace applications (see Section 7.5.4). The technique to obtain these materials is shown schematically in Figure 3.21. This composite can be used continuously at temperatures on the order of 300°C, while maintaining notable mechanical properties (see Section 1.6 for the properties of boron).

[18] AKZO Fibers/DELFT University (Holland). ®Structural Laminates Company/New Kensington (USA).

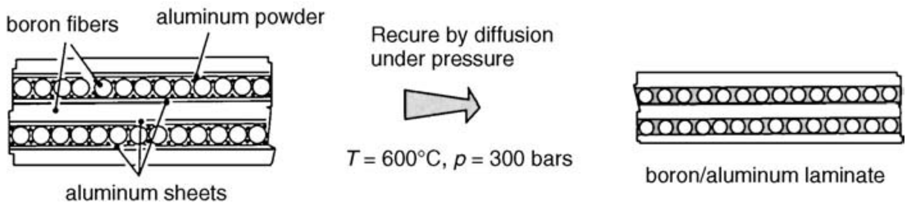


Figure 3.21 Boron/Aluminum Composite

Some characteristics of unidirectional plies made of aluminum matrix (6061) include:

	HR Carbon	*Aluminum*	*Silicon Carbide*
Fiber volume fraction V_f (%)	50	50	50
Specific mass (kg/m^3)	2300	3100	2700
Longitudinal tensile strength (MPa)	800	550	1400
Longitudinal compressive strength (MPa)	600	3100	3000
Longitudinal elastic modulus (MPa)	200,000	190,000	140,000

3.8 TESTS

The relations cited on the previous pages for the calculation of the modulus and Poisson coefficients of the composites only allow obtaining an order of magnitude for the mechanical properties. Some of these relations are not quite accurate, particularly for the shear modulus. Also, these properties are very sensitive to the fabrication conditions. It is necessary for the design engineer to have the results provided by the suppliers of the reinforcement and the matrix materials or to better the results obtained by tests in the labs. Some of these tests have been standardized, for example, tensile tests, flexure tests, and impact tests.

A tensile test (NF T 51–034, ASTM D 3039) on the specimen in Figure 3.22, instrumented with electrical strain gage, allows the measurement of the strength and the elongation to fracture. A delamination test (NF T 57–104) on a specimen which has a small span for bending (see Figure 3.23). It fails by delamination under the effect of interlaminar shear stress. One can obtain the interlaminar shear strength.[19]

There are other tests, not yet standardized, that are very useful for the fabrication of high performance composites, for example, for control of the fiber volume fraction. In fact, during the phase of polymerization under pressure of a polymer matrix composite, the resin gets absorbed into an absorbing fabric, in variable quantity depending on the cycle of pressure and temperature. In consequence,

[19] This is a simplified way that little reflects the complexity of the state of real stress due to the presence of very close concentrated loads.

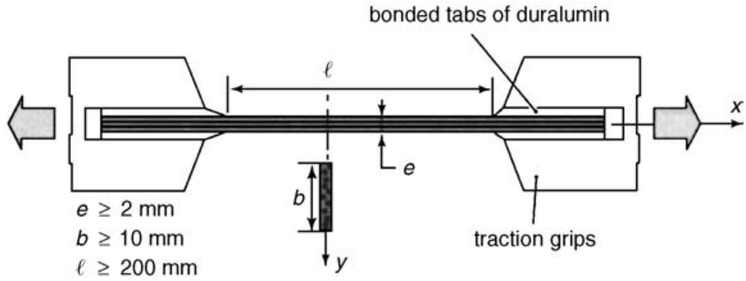


Figure 3.22 Tensile Test

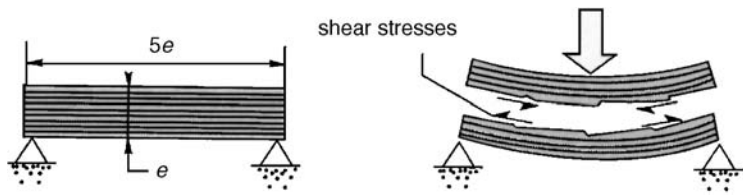


Figure 3.23 Short Beam Shear Test

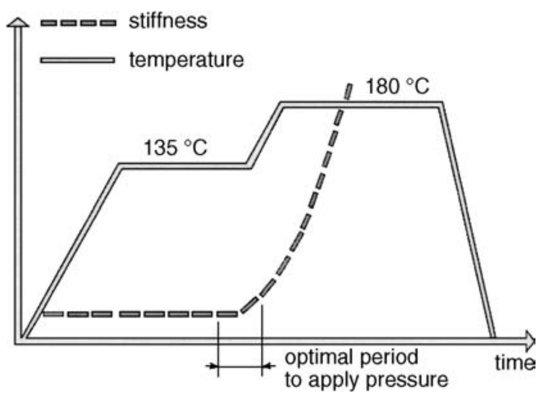


Figure 3.24 Variation In Stiffness During Curing

the fiber volume fraction V_f varies, and as a result, the dimensional characteristics of the piece (thickness) also vary. To deal with this problem, one may want to evaluate by test the optimal moment for the application of pressure, by the measurement of the flexural rigidity of a specimen as a function of time of fabrication (see Figure 3.24).