

Objective

To investigate the strength and stiffness characteristics of laminated composite materials as a function of fiber orientation.

Abstract

Composites consist of two or more phases that are usually processed separately and then bonded, resulting in properties that are different from those of either of the component materials. Polymer matrix composites generally combine high-strength, high-stiffness fibers (graphite, kevlar, etc.) with low-density matrix materials (epoxy, polyvinyl, etc.) to produce strong & stiff materials that are lightweight. Laminates are generally built up from multiple layers of lamina; the fibers within each lamina are generally parallel, but laminates usually contain lamina with their fibers oriented in various directions. Each lamina is an anisotropic layer with properties varying as a function of fiber angle. Loading along the fibers (longitudinal) is modeled as Isostrain while loading perpendicular to the fibers (transverse) is modeled as Isostress; these two directions generally represent the extremes in material behavior. Fiber and matrix material property data can be used to predict/approximate the properties of laminated composites using the Rule of Mixtures. In this investigation, the elastic modulus of composites loaded at various angles with respect to the fiber direction will be predicted, tested and discussed. The burn-off method will be applied to determine the fiber volume of the composites being investigated, and ultimate strength and elastic modulus results will be compared with those of metals and polymers.

Background

A Composite Material is a materials system composed of a mixture or combination of two or more micro- or macro-constituents that differ in form and chemical composition and which are essentially insoluble in each other. Composites involve two or more component materials that are generally combined in an attempt to improve material properties such as stiffness, strength, toughness, etc.; the resulting properties are largely dependent on the distribution, relative amounts and geometries of the constituents.

Examples

Modern aircraft combine lightweight, corrosion resistant polymers with relatively strong, stiff graphite, metal and/or glass fibers.

Modern structural ceramics combine heat and wear resistant ceramics with relatively high tensile strength, ductile metals.



Figure 1 – Examples of Modern Composite Applications. [Woldesenbet, 1998]

Generally, Composite Materials consist of a **Dispersed Phase** (commonly **Fibers**) and a **Matrix Phase**.

- The Matrix Phase generally surrounds the Dispersed Phase.
- The Dispersed Phase is generally contained within the Matrix Phase.

The 3 Basic Types of Composites are generally identified as:

- 1.) **Particle-Reinforced** (Aggregates);
- 2.) **Fiber-Reinforced** (Continuous Fiber or Chopped Fiber); and
- 3.) **Natural Composites** (Examples: Wood and Bone).

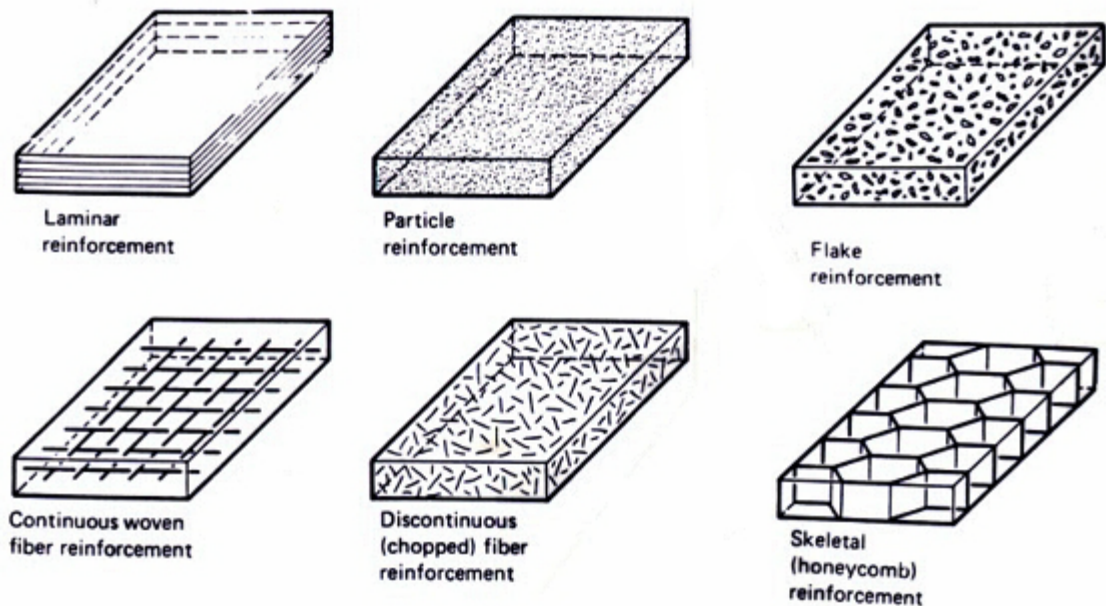


Figure 2 – Schematic Illustrations of Common Composite Reinforcements. [Jones, 1982]

Particle-Reinforced (Aggregate) Composites

Particle-Reinforced Composites include the most used (by weight) construction material in the world - Concrete. Sand (Fine Particles) and Gravel (Coarse Particles) compose from 60% to 75% of standard concrete.

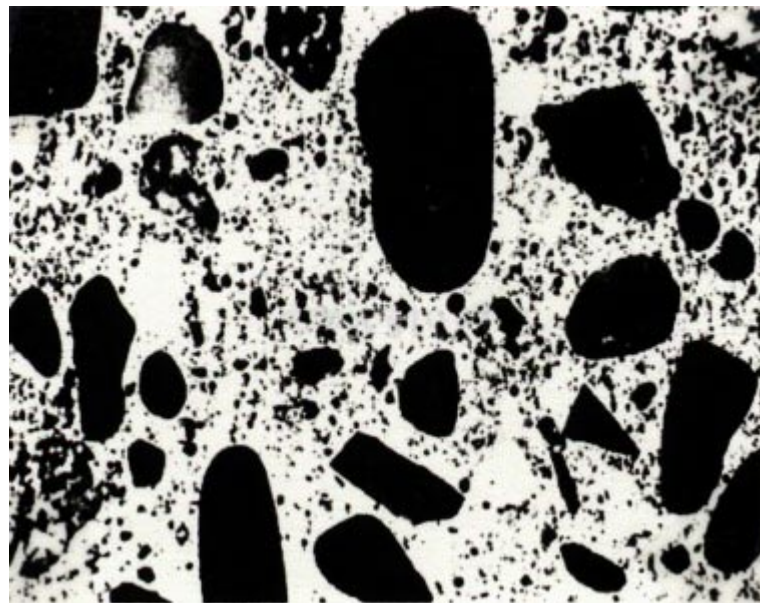


Figure 3 – Photomicrograph of a Typical Concrete Sample. [Smith, 1993]

Note that the Particulates (sand and gravel) are combined with the Matrix (cement) which acts as a bonding agent between the particles. The addition of water to a particle-cement mixture results in a

complex hydration reaction that produces a network of strong ionic/covalent bonds. The Reinforcing Particles are generally stiff and hard and restrain deformation of the cement.

As with polymers, Additives (termed **Admixtures**) are added to concrete to affect its reactions and properties:

- Accelerators speed-up the curing process,
- Retarders slow down the curing process,
- Surface Hardeners produce an abrasion resistant surface, etc.

Prestressed Concrete (Initially stressed in compression) is formed by pouring concrete over elastically elongated steel bars (rebar). After the concrete cures, the bar ends are released; their elastic strain produces prestress in the concrete.

Cermets are Ceramic-Metal composites that contain hard ceramic particles that are embedded in high-strength metals for cutting tool and hardened steel applications.

Fiber-Reinforced Composites

Fiber-Reinforced Composites often aim to improve the strength to weight and stiffness to weight ratios (i.e. desire light-weight structures that are strong and stiff!). Glass or Metal Fibers are generally embedded in polymeric matrices.

Fibers are available in 3 basic forms:

- Continuous** Fibers are long, straight and generally layed-up parallel to each other.
- Chopped** Fibers are short and generally randomly distributed (fiberglass).
- Woven** Fibers come in cloth form and provide multidirectional strength.



Figure 4 – Schematic Illustration of Fiber Types: Unidirectional, Chopped & Woven. [Shackelford, 1996]

Table 1 presents a listing of commonly used fiber materials; commonly utilized fibers include Kevlar (very low density), E-Glass (low-cost) and Carbon (high strength, high modulus). **Whiskers** are small, single crystal fibers that have a nearly perfect crystalline structure.

Table 1 – Properties of Selected Fiber-Reinforcing Materials. [Shackelford, 1992]

Group	Dispersed Phase	E [MPa (ksi)]	T.S. [MPa (ksi)]	Compressive Strength [MPa (ksi)]	Percent Elongation at Failure
	C-glass	$69 \times 10^3 (10 \times 10^5)$		—	4.5
	E-glass	$72.4 \times 10^3 (10.5 \times 10^5)$		—	4.8
	S-glass	$85.5 \times 10^3 (12.4 \times 10^5)$		—	5.6
Ceramic fiber ^a	C (graphite)	$340\text{--}380 \times 10^3 (49\text{--}55 \times 10^5)$		—	—
	SiC	$430 \times 10^3 (62 \times 10^5)$		—	—
Ceramic whisker ^b	Al ₂ O ₃	$430 \times 10^3 (62 \times 10^5)$		—	—
Polymer fiber ^c	Kevlar ^d	$131 \times 10^3 (19 \times 10^5)$		—	2.8
Metal filament ^e	Boron	$410 \times 10^3 (60 \times 10^5)$		—	—
Concrete aggregate ^f	Crushed stone and sand	$34\text{--}69 \times 10^3 (5\text{--}10 \times 10^5)$		69–340 (10–50)	—

Matrix materials bind the fibers and transmit loads to the fibers through chemical or mechanical bonds; they also generally have low strength and modulus values as compared to the fibers that they bind. Table 2 presents a listing of polymers often used as matrix materials; these include the polyesters (very low cost), polyvinyls (low cost, good strength) and epoxies (high strength). Other matrix materials such as thermoplastics of considerable toughness and heat resistant ceramics are being developed for composite applications.

Class	Example	E [MPa (ksi)]	T.S. [MPa (ksi)]	Flexural Strength [MPa (ksi)]	Compressive Strength (After 28 days) [MPa (ksi)]	Percent Elongation at Failure	K_{Ic} (MPa \sqrt{m})
Polymer ^a	Epoxy	6900 (1000)	69 (10)	—	—	0	0.3–0.5
	Polyester	6900 (1000)	28 (4)	—	—	0	—
Metal ^b	Al	69×10^3 (10×10^3)	76 (11)	—	—	—	—
	Cu	115×10^3 (17×10^3)	170 (25)	—	—	—	—
Ceramic ^c	Al ₂ O ₃	—	—	550 (80)	—	—	4–5
	SiC	—	—	500 (73)	—	—	4.0
	Si ₃ N ₄ (reaction bonded)	—	—	260 (38)	—	—	2–3
Portland cements ^d	Type I	—	2.4 (0.35)	—	24 (3.5)	—	—
	Type II	—	2.3 (0.33)	—	24 (3.5)	—	—
	Type III	—	2.6 (0.38)	—	21 (3.0)	—	—
	Type IV	—	2.1 (0.30)	—	14 (2.0)	—	—
	Type V	—	2.3 (0.33)	—	21 (3.0)	—	—

Table 2 – Properties of Selected Matrix Materials. [Shackelford, 1992]

When component fiber and matrix materials are combined to form a Composite Material, the properties of the result differs from most engineering materials in that the mechanical properties of composites are highly dependent on the direction in which the loads are applied. Composite strength and stiffness are generally **Anisotropic** -> the material properties are a function of loading direction.

Note: Strength and stiffness are generally much higher along the fiber direction (isostrain) than perpendicular to the fiber direction (isostress) (see Figure 5).

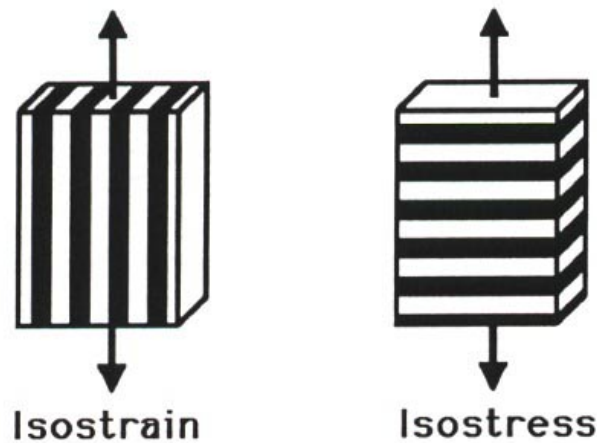


Figure 5 – Geometry of Idealized Unidirectional Composite Materials:
Loading Parallel to Fiber Direction (Isostrain).
Loading Perpendicular to Fiber Direction (Isostress).

Composite **Laminates** are formed by combining individual layers (lamina) into a multi-layered structure. Continuous fiber composites combine Unidirectional Lamina (fibers aligned) into a layered structure with different layers in a laminate generally having the fibers oriented in different directions as depicted in Figure 6.

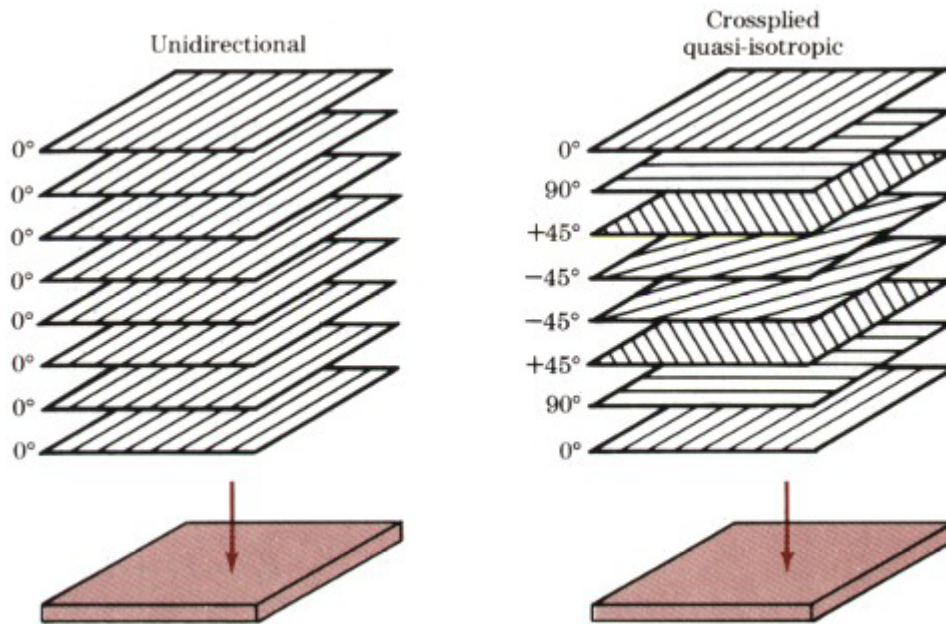


Figure 6 – Schematic Illustration of Lamina being combined to form a Laminate. [Smith, 1993]

Property Averaging

As mentioned previously, the mechanical behavior of fiber reinforced composite materials is highly dependent on the direction of loading. For instance, considering a unidirectional laminate, the elastic modulus Parallel to the fiber direction, E_L , (Isostrain – referred to as the Longitudinal direction) is significantly different from the elastic modulus Perpendicular to the fiber direction, E_T , (Isostress – referred to as the Transverse direction). First order approximations of these moduli can be calculated from the elastic constants of the constituent materials by considering the Isostrain and Isostress models as depicted in Figure 5.

Isostrain (Loading Parallel to the Fibers)

When a Unidirectional Composite is loaded parallel the fiber direction, then the composite strain (ϵ_c) = matrix strain (ϵ_m)= fiber strain (ϵ_f), (see Figure 5a) thus

$$\epsilon_c = \frac{\sigma_c}{E_c} = \epsilon_m = \frac{\sigma_m}{E_m} = \epsilon_f = \frac{\sigma_f}{E_f} \quad (1)$$

where c -> Composite Property,
 m -> Matrix Property, and
 f -> Fiber Property.

In the Isostrain case, the Load carried by the Composite (P_c) is approximately equal to the sum of the Matrix Load (P_m) and the Fiber Load (P_f), thus

$$P_c = P_m + P_f \rightarrow \sigma_c A_c = \sigma_m A_m + \sigma_f A_f \quad (2)$$

Combining (1) and (2) and recognizing that the matrix and fiber area fractions (A_m and A_f) are proportional to the volume fractions (V_m and V_f),

$$E_c = V_m E_m + V_f E_f = E_L \quad (3)$$

where $V_m = v_m/v_c$ and $V_f = v_f/v_c$. Note the $V_m = 1 - V_f$. Equation (3) is known as the “**Rule of Mixtures**” and implies that the contribution of a constituent is directly proportional to its volume fraction. The expression for determination of Composite Density has the same form.

Isostress (Loading Parallel to the Fibers)

When a Unidirectional Composite is loaded Perpendicular to the fiber direction, then the Stress in the Composite is approximately equal to the Matrix Stress which equals the Fiber Stress (see Figure 5b); i.e.

$$\sigma_c = \sigma_m = \sigma \quad (4)$$

In this case, the Composite Elongation (ΔL_c) in the direction of loading is equal to the sum of the Matrix Elongation (ΔL_m) and the Fiber Elongation (ΔL_f) thus

$$\Delta L_c = \Delta L_m + \Delta L_f \quad (5)$$

Since elongation is the product of strain and thickness, and layer thickness is proportional volume fraction,

$$\epsilon_c = V_m \epsilon_m + V_f \epsilon_f \quad (6)$$

Writing the strains in terms of stresses (assuming elastic behavior) and noting equation (4), we find

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_f}{E_f} = \frac{1}{E_T} \quad (7)$$

Equation (7) is known as the “**Inverse Rule of Mixtures**” and implies that the fibers are much less effective in raising the composite modulus under conditions of Isostress.

Isostrain and Isostress represent the extreme conditions for a composite material as depicted in Figure 7 which illustrates that the transverse modulus is not appreciably increased beyond the modulus of the less stiff constituent, the matrix, at the fiber volumes usually encountered in engineering composites ($V_f = 0.5 - 0.6$). Particulate Composites generally exhibit behavior between the Isostrain and Isostress conditions.

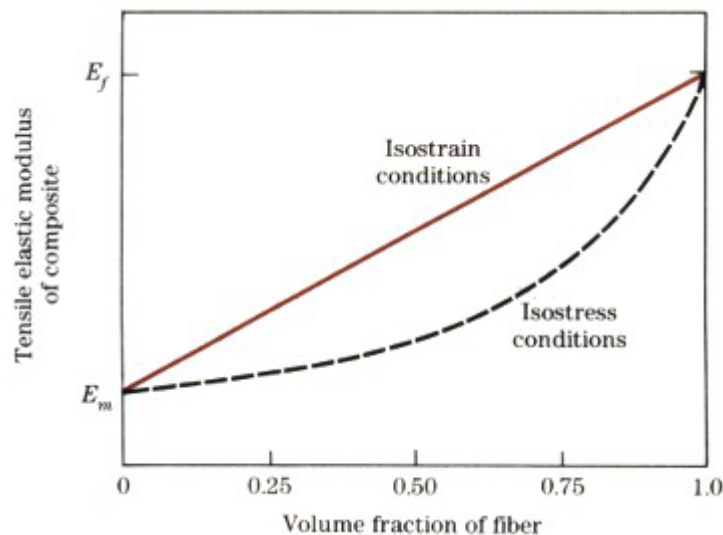


Figure 7 – Elastic Modulus versus Fiber Volume Fraction for the Isostrain (E_L) and Isostress (E_T) Models.[Smith, 1993]

The L and T directions are generally referred to as the “Material Axis” and, if the composite is loaded in either of these directions, the corresponding strains can be calculated (see Figure 8a). However, if a stress is applied at an acute angle, θ , to the fiber direction (see Figure 8b), the elastic response along the “Loading Axis” (1 and 2 Directions) can be calculated from the properties measured along the “Material Axis” (L and T) where

$$E_1 = E_L \left[\cos^4 \theta + \frac{E_L}{E_T} \sin^4 \theta + \frac{1}{4} \left(\frac{E_L}{G_{LT}} - 2\nu_{LT} \right) \sin^2 2\theta \right]^{-1} \quad (8)$$

$$\text{and } E_2 = E_L \left[\sin^4 \theta + \frac{E_L}{E_T} \cos^4 \theta + \frac{1}{4} \left(\frac{E_L}{G_{LT}} - 2\nu_{LT} \right) \sin^2 2\theta \right]^{-1} \quad (9)$$

Notice that in Equations (8) and (9), the material parameters needed include Transformation Angle (θ), In-Plane Shear Modulus (G_{LT}), In-Plane Poisson’s Ratio (ν_{LT}) and the Longitudinal and Transverse Elastic Moduli (E_L and E_T).

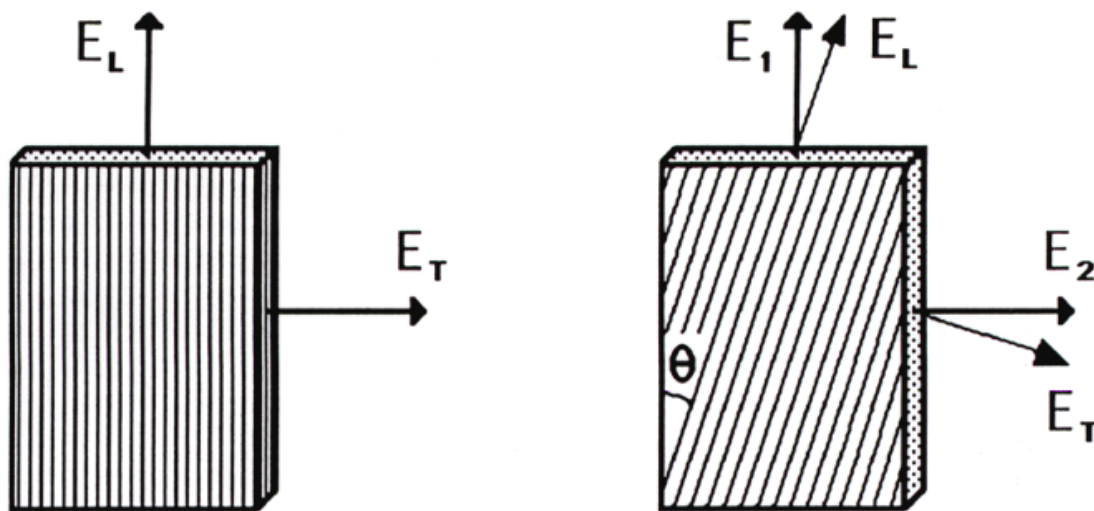


Figure 8 – Illustration of Shear Strain Produced by Tensile Loading of a Fiber Composite. Recall that for isotropic materials

Recall that for isotropic materials

$$G = \frac{E}{2(1 - \nu)} \quad (10)$$

For Unidirectional Composites, In-Plane Shear Modulus follows the Inverse Rule of Mixtures and can be determined from the constituent matrix and fiber properties G_m and G_f . Thus the In-Plane Shear Modulus (G_{LT}) for a Unidirectional Composite can be approximated as

$$\frac{1}{G_{LT}} = \frac{V_m}{G_m} + \frac{V_f}{G_f} \quad (11)$$

The major Poisson’s Ratio, ν_{LT} (a Longitudinal Stress causing Transverse Strain), can be determined by applying the Rule of Mixtures where

$$\nu_{LT} = V_m \nu_m + V_f \nu_f \quad (12)$$

What about ν_{TL} (a Transverse Stress causing Longitudinal Strain); should it be equal to ν_{LT} ? ν_{TL} is generally NOT equal to ν_{LT} , but can be easily determined as follows:

$$\nu_{TL} = \frac{E_T}{E_L} \nu_{LT} \quad (13)$$

The transformation of ν_{LT} (along the material axes) into ν_{12} (along the loading axes) is given by (see Figure 8):

$$\nu_{12} = \frac{E_L}{E_T} \left[\nu_{LT} - \frac{1}{4} \left(1 + 2\nu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{G_{LT}} \right) \sin^2 2\theta \right] \quad (14)$$

One of the most important phenomena that occurs during off-axis loading of a unidirectional composite is the production of a shear strain from a purely tensile stress state. As illustrated in Figure 9, if a 90° reference angle is inscribed on the sample prior to loading, this angle will change as the sample is loaded uniaxially indicating the existence of a shear strain. This clearly should not occur in isotropic materials or in a uniaxial composite loaded along one of the material axes ($\theta = 0^\circ$ or $\theta = 90^\circ$). The amount of change in the 90° angle (measured in radians) that occurs upon stressing of the uniaxial composite is the shear strain, γ_{12} . The Shear Coupling Coefficient, β , relates the applied normal stress, σ_1 , to the resulting shear strain where

$$\beta = \frac{\gamma_{12}}{\sigma_1} \quad (15)$$

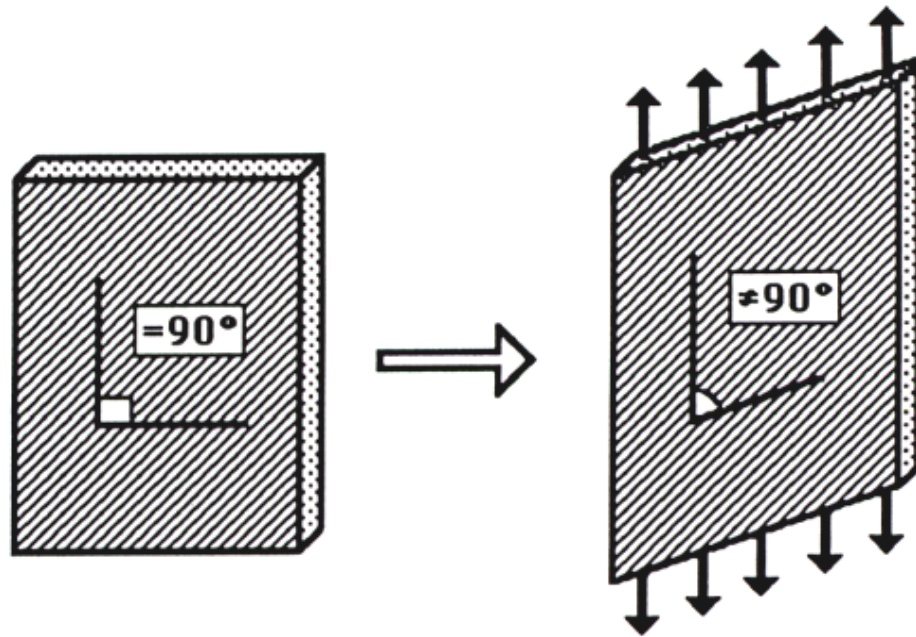


Figure 9 – Illustration of the Shear Strain Produced by Tensile Loading of a Unidirectional Composite.

Table 3 – Properties of Selected Composite Materials. [Shackelford, 1992]

Class	E [MPa (ksi)]	T.S. [MPa (ksi)]	Flexural Strength [MPa (ksi)]	Compressive Strength [MPa (ksi)]	Percent Elongation at Failure	K_{Ic} ^a (MPa √m)
Polymer-matrix						
E-glass (73.3 vol %) in epoxy (parallel loading of continuous fibers) ^f	56 × 10 ³ (8.1 × 10 ³)	1640 (238)	—	—	2.9	42-60
Al ₂ O ₃ whiskers (14 vol %) in epoxy ^b	41 × 10 ³ (6 × 10 ³)	779 (113)	—	—	—	—
C (67 vol %) in epoxy (parallel loading) ^f	221 × 10 ³ (32 × 10 ³)	1206 (175)	—	—	—	—
Kevlar ^a (82 vol %) in epoxy (parallel loading) ^f	86 × 10 ³ (12 × 10 ³)	1517 (220)	—	—	—	—
B (70 vol %) in epoxy (parallel loading of continuous filaments) ^f	210-280 × 10 ³ (30-40 × 10 ³) ^f	1400-2100 (200-300) ^f	—	—	—	46
Metal-matrix						
Al ₂ O ₃ (10 vol %) dispersion-strengthened aluminum ^b	—	330 (48)	—	—	—	—
W (50 vol %) in copper (parallel loading of continuous filaments) ^b	260 × 10 ³ (38 × 10 ³)	1100 (160)	—	—	—	—
W particles (50 vol %) in copper ^b	190 × 10 ³ (27 × 10 ³)	380 (55)	—	—	—	—
Ceramic-matrix						
SiC whiskers in Al ₂ O ₃ ^a	—	—	800 (116)	—	—	8.7
SiC fibers in SiC ^a	—	—	750 (109)	—	—	25.0
SiC whiskers in reaction-bonded Si ₃ N ₄ ^a	—	—	900 (131)	—	—	20.0
Wood						
Douglas fir, kiln-dried at 12% moisture (loaded parallel to grain) ^f	13.4 × 10 ³ (1.95 × 10 ³) ^f	85.5 (12.4) ^f	—	49.9 (7.24)	—	11-13
Douglas fir, kiln-dried at 12% moisture (loaded perpendicular to grain) ^f	—	—	—	5.5 (0.80)	—	0.5-1
Concrete						
Standard concrete, water/cement ratio of 4 (after 28 days) ^b	—	—	—	41 (6.0)	—	0.2
Standard concrete, water/cement ratio of 4 (after 28 days) with air entrainer ^b	—	—	—	33 (4.8)	—	—

To determine the fiber content of the composite (fiber volume fraction, V_f), conduct a burn-off test.

An Epoxy composite's fiber content can be determined by:

1. Weighing a representative small sample in a crucible
2. Placing the Crucible/Sample in a preheated oven (600°C) for 40 minutes.
3. Remove the Crucible/Sample and reweigh

$$\rho_c = \frac{1}{\left(\frac{W_f}{\rho_f}\right) + \left(\frac{W_m}{\rho_m}\right)}$$

$$V_m = \frac{\rho_c}{\rho_m} W_m$$

$$V_f = \frac{\rho_c}{\rho_f} W_f$$

A set of seven tensile tests will be conducted on pre-fabricated IM7/8551 graphite/epoxy specimens. All of the specimens are machined from a seven-layer unidirectional laminate and are oriented as follows with respect to the fiber direction:

$\theta = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, \text{ and } 90^\circ$; the orientation of each specimen should be clearly labeled.

The gauge length of the extensometer is 1.00" and the gauge length for the specimen in terms of stroke is 3.0".

Prior to Conducting the Tensile Tests, measure and record the specimen thickness and width for each specimen (Identify Specimens by Fiber Orientation - θ). Beginning with 90° specimen, conduct a tensile test following the procedures presented as "Tensile Testing Instron Operation" and "Tensile Testing Data Acquisition."

After each test, note the characteristics of the failure.

Lab Requirements

IM7 Fibers: $E = 45.0 \times 10^6$ psi, $\nu = 0.20$, $\rho = 0.065$ lb/in³

8551 Epoxy Resin: $E = 0.67 \times 10^6$ psi, $\nu = 0.36$, $\rho = 0.050$ lb/in³

Steel: $E = 29.0 \times 10^6$ psi, $\nu = 0.32$, $\rho = 0.284$ lb/in³, $S_U = 250$ ksi

Aluminum: $E = 10.0 \times 10^6$ psi, $\nu = 0.33$, $\rho = 0.097$ lb/in³, $S_U = 70$ ksi

1. Based on the results of the Burn-Off test, compute the Fiber Volume Fraction (V_f) and Matrix Volume Fraction (V_m) for the IM7/8551 specimens tested.
2. Calculate the Longitudinal and Transverse Moduli (E_L and E_T respectively) based on the fiber and matrix property data for IM7/8551.
3. Calculate the Major In-Plane Shear Modulus (G_{LT}) and the Major Poisson's Ratio (ν_{LT}) for the IM7/8551 unidirectional composite being investigated.
4. Follow the PROCEDURE section to obtain load versus displacement data for the set of IM7/8551 graphite/epoxy specimens. All of the specimens are machined from a seven-layer unidirectional laminate and are oriented as follows with respect to the fiber direction (fiber direction is the Longitudinal direction where $\theta = 0^\circ$):

Fiber Angle, $\theta = 0^\circ, 30^\circ, 60^\circ,$ and 90° .

5. Convert the Load-Displacement data to Stress-Strain data and plot out the Stress versus Strain curve for each specimen.
6. From the Stress-Strain curves, determine the Elastic Modulus (E_1) and Ultimate Strength (S_{U1}) for each sample tested.
7. Compare the theoretically determined Longitudinal and Transverse Moduli (E_L and E_T) obtained in step 2 with the experimentally determined Longitudinal and Transverse Moduli (E_L and E_T) in step 6. Comment on any differences.
8. Calculate the Elastic Modulus along the loading axis, E_1 , and the In-Plane Poisson's Ratio along the loading axis, ν_{12} , for each orientation tested based on the experimentally obtained values of Longitudinal and Transverse Moduli and the calculated values of the In-Plane Shear Modulus and the Major Poisson's Ratio.
9. On a single graph, plot Elastic Modulus, E_1 , as a function of Fiber Angle:
 - a.) based on the Calculated values of the Elastic Modulus, and
 - b.) based on the Measured values of the Elastic Modulus.**Comment on the results.**
10. Determine the Specific Stiffness and Specific Strength for IM7/8551, with respect to aluminum and steel, for loading along the Longitudinal axis.

Specific Stiffness = $(E/\rho)_{IM7/8551}$ divided by $(E/\rho)_{Al}$ or Steel

Specific Strength = $(S_U/\rho)_{IM7/8551}$ divided by $(S_U/\rho)_{Al}$ or Steel

Comment on the results.

11. Compare the stiffness and strength results of the polymers tested with the results of the graphite/epoxy composite.

Homework

1. What is a Composite Material?
2. What are the primary advantages of polymer matrix composites?
3. Most composites are Pseudo-Isotropic, Orthotropic or Anisotropic; what do these three terms mean?
4. What is the primary function of the matrix in a composite material?
5. Whiskers are sometimes used as fibers in composite materials because of their very high strength; why are whiskers so strong?
6. What's the difference between a Lamina and a Laminate?
7. List at least three items made of Composites; identify the Matrix and Reinforcement materials for each.
8. Suppose the elastic moduli of the component materials of a unidirectional graphite/epoxy composite are known to be as follows:

$$E_{\text{graphite}} = 75.0 \times 10^6 \text{ psi}$$

$$E_{\text{epoxy}} = 0.35 \times 10^6 \text{ psi}$$

If the composite material has a fiber volume fraction of 0.65, approximate the following using the Rule of Mixtures:

- a) The Composite's Elastic Modulus when it's loaded Parallel to the fibers.
- b) The Composite's Elastic Modulus when it's loaded Perpendicular to the fibers.