Mechanics of Composite Materials

The physical behavior of composite materials is quite different from that of most common engineering materials that are homogeneous and isotropic. Metals will generally have similar composition regardless of where or in what orientation a sample is taken. On the other hand, the makeup and physical properties of composites will vary with location and orientation of the principal axes. These materials are termed anisotropic, which means they exhibit different properties when tested in different directions. Some composite structures are, however, quasi-orthotropic, in their primary plane.

The mechanical behavior of composites is traditionally evaluated on both microscopic and macroscopic scale to take into account inhomogeneity. Micromechanics attempts to quantify the interactions of fiber and matrix (reinforcement and resin) on a microscopic scale on par with the diameter of a single fiber. Macromechanics treats composites as homogeneous materials, with mechanical properties representative of the laminate as a whole. The latter analytical approach is more realistic for the study of marine laminates that are often thick and laden with through-laminate inconsistencies. However, it is instructive to understand the concepts of micromechanics as the basis for macromechanic properties. The designer is again cautioned to verify all analytical work by testing builder's specimens.

Micromechanic Theory

General Fiber/Matrix Relationship

The theory of micromechanics was developed to help explain the complex mechanisms of stress and strain transfer between fiber and matrix within a composite. [3-11] Mathematical relationships have been developed whereby knowledge of constituent material properties can lead to laminate behavior predictions. Theoretical predictions of composite stiffness have traditionally been more accurate than predictions of ultimate strength. Table 3-1 describes the input and output variables associated with micromechanics.

Table 3-1 Micromechanics Concepts
[Chamis, ASM Engineers' Guide to Composite Materials]

Input	Output
Fiber Properties	Uniaxial Strengths
Matrix Properties	Fracture Toughness
Environmental Conditions	Impact Resistance
Fabrication Process Variables	Hygrothermal Effects
Geometric Configuration	

The basic principles of the theory can be illustrated by examining a composite element under a uniaxial force. Figure 3-16 shows the state of stress and transfer mechanisms of fiber and matrix when subjected to pure tension. On a macroscopic scale, the element is in simple tension, while internally a number of stresses can be present. Represented in Figure 3-16 are compressive stresses (vertical arrows pointing inwards) and shear stresses (thinner arrows along the fiber/matrix interface). This combined stress state will determine the failure point of the material. The bottom illustration in Figure 3-16 is representative of a poor fiber/matrix bond or void within the laminate. The resulting imbalance of stresses between the fiber and matrix can lead to local instability, causing the fiber to shift or buckle. A void along 1% of the fiber surface generally reduces interfacial shear strength by 7%. [3-11]

Fiber Orientation

Orientation of reinforcements in a laminate is widely known to dramatically effect the mechanical performance of composites. Figure 3-17 is presented to understand tension failure mechanisms in unidirectional composites on a microscopic scale. Note that at an angle of 0°, the strength of the composite is almost completely dependent on fiber tensile strength. The following equations refer to the three failure mechanisms shown in Figure 3-17:

Fiber tensile failure:

$$\sigma_c = \sigma \qquad (3\text{-}16)$$

Matrix or interfacial shear:

$$\tau = \sigma \sin\Phi \cos\Phi \qquad (3\text{-}17)$$

Composite tensile failure:

$$\sigma_u = \sigma \sin\Phi \qquad (3\text{-}18)$$

where:

σ_c = composite tensile strength

σ = applied stress

Φ = angle between the fibers and tensile axis

τ = shear strength of the matrix or interface

σ_u = tensile strength of the matrix

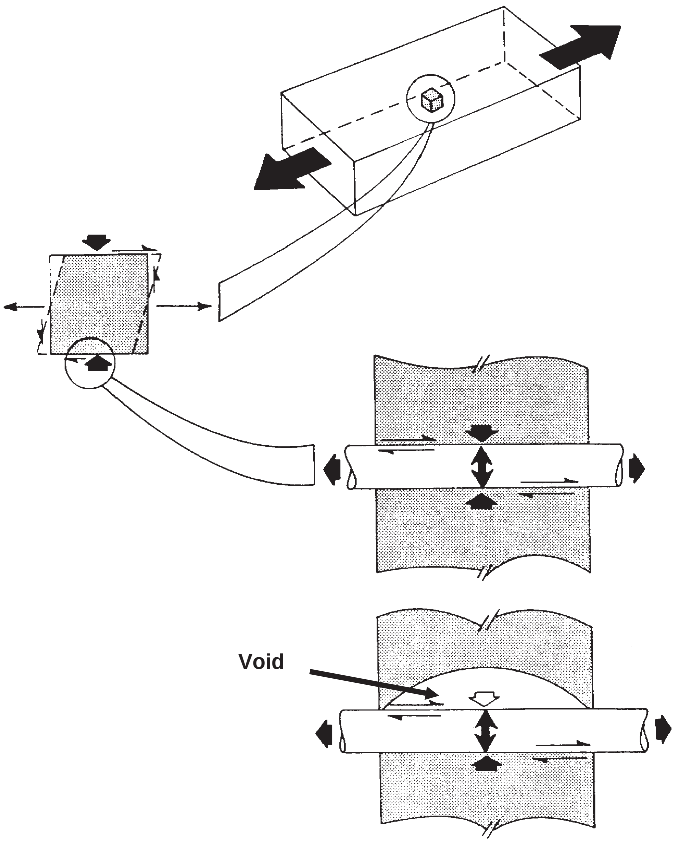


Figure 3-16 State of Stress and Stress Transfer to Reinforcement [*Material Engineering*, May, 1978 p. 29]

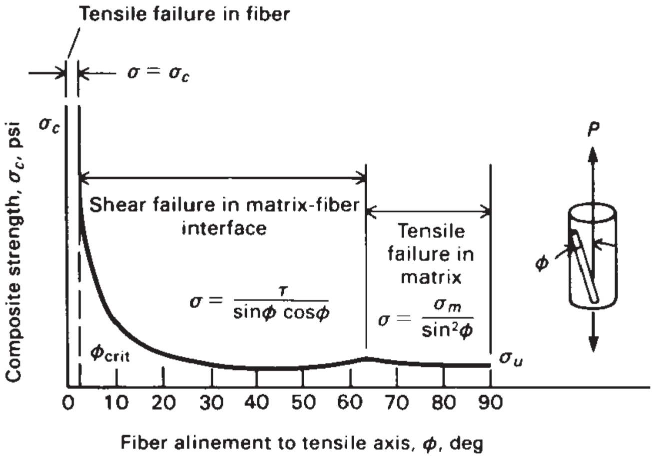


Figure 3-17 Failure Mode as a Function of Fiber Alignment [*ASM Engineers' Guide to Composite Materials*]

Micromechanics Geometry

Figure 3-18 shows the orientation and nomenclature for a typical fiber composite geometry. Properties along the fiber or *x* direction (1-axis) are called longitudinal; transverse or *y* (2-axis) are called transverse; and in-plane shear (1-2 plane) is also called intralaminar shear. The through-thickness properties in the *z* direction (3-axis) are called interlaminar. Ply properties are typically denoted with a letter to describe the property with suitable subscripts to describe the constituent material, plane, direction and sign (with strengths). As an example, S_{m11T} indicates matrix longitudinal tensile strength.

The derivation of micromechanics equations is based on the assumption that: 1) the ply and its constituents behave linearly elastic until fracture (see Figure 3-19), 2) bonding is complete between fiber and matrix and 3) fracture occurs in one of the following modes: a) longitudinal tension, b) fiber compression, c) delamination, d) fiber microbuckling, e) transverse tension, or f) intralaminar shear. [3-2] The following equations describe the basic geometric relationships of composite micromechanics:

Partial volumes:

$$k_f + k_m + k_v = 1 \qquad (3\text{-}19)$$

Ply density:

$$\rho_l = k_f \ \rho_f + k_m \ \rho_m \qquad (3\text{-}20)$$

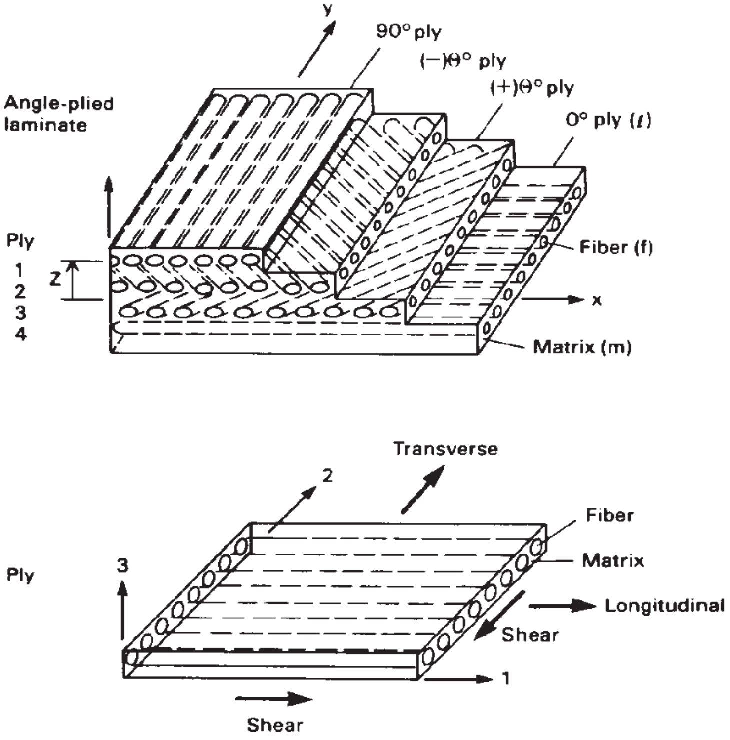


Figure 3-18 Fiber Composite Geometry [Chamis, *ASM Engineers' Guide to Composite Materials*]

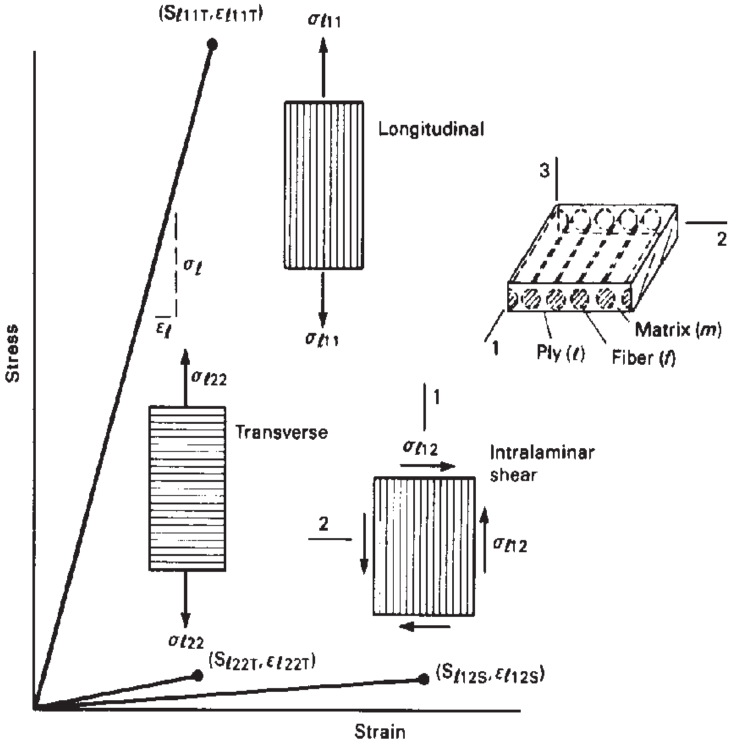


Figure 3-19 Typical Stress-Strain Behavior of Unidirectional Fiber Composites [Chamis, *ASM Engineers' Guide to Composite Materials*]

Resin volume ratio:

$$k_m = \frac{(1 - k_v)}{\left[1 + \left(\frac{\rho_m}{\rho_f}\right)\left(\frac{1}{\lambda_m} - 1\right)\right]} \tag{3-21}$$

Fiber volume ratio:

$$k_f = \frac{(1 - k_v)}{\left[1 + \left(\frac{\rho_f}{\rho_m}\right)\left(\frac{1}{\lambda_f} - 1\right)\right]} \tag{3-22}$$

Weight ratio:

$$\lambda_f + \lambda_m = 1 \tag{3-23}$$

where:

f = fiber
m = matrix
v = void
l = ply
λ = weight percent

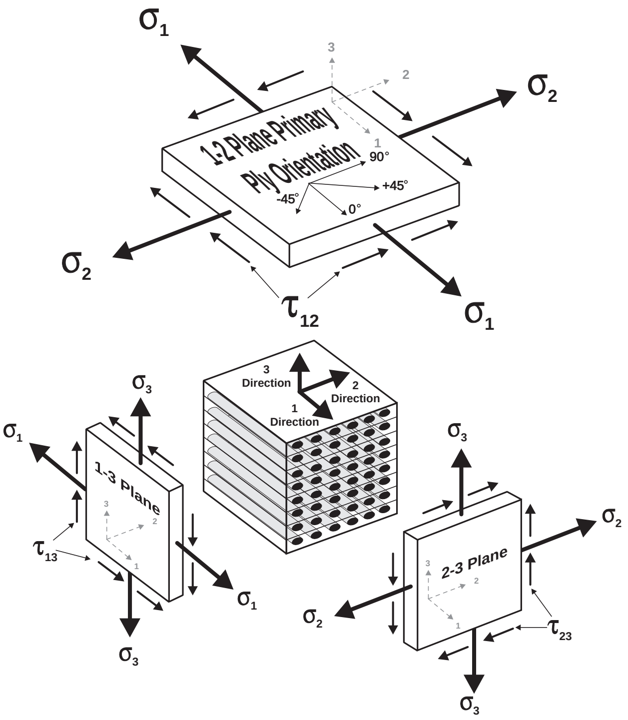


Figure 3-20 Notation Typically Used to Describe Ply Properties

Elastic Constants

The equations for relating elastic moduli and Poisson's ratios are given below. Properties in the 3-axis direction are the same as the 2-axis direction because the ply is assumed transversely isotropic in the 2-3 plane (see bottom illustration of Figure 3-18).

Longitudinal modulus:

$$E_{l\,11} = k_f\,E_{f\,11} + k_m E_m \tag{3-24}$$

Transverse modulus:

$$E_{l\,22} = \frac{E_m}{1 - \sqrt{k_f}\left(1 - \frac{E_m}{E_{f\,22}}\right)} = E_{l\,33} \tag{3-25}$$

Shear modulus:

$$G_{l\,12} = \frac{G_m}{1 - \sqrt{k_f}\left(1 - \frac{G_m}{G_{f\,12}}\right)} = G_{l\,13} \tag{3-26}$$

$$G_{l\,23} = \frac{G_m}{1 - \sqrt{k_f}\left(1 - \frac{G_m}{G_{f\,23}}\right)} = G_{l\,13} \tag{3-27}$$

Poisson's ratio:

$$\nu_{l\,12} = k_f\;\nu_{l\,12} + k_m\,\nu_m = \nu_{l\,13} \tag{3-28}$$

In-Plane Uniaxial Strengths

The equations for approximating composite strength properties are based on the fracture mechanisms outlined above under micromechanics geometry. Three of the fracture modes fall under the heading of longitudinal compression. It should be emphasized that prediction of material strength properties is currently beyond the scope of simplified mathematical theory. The following approximations are presented to give insight into which physical properties dominate particular failure modes.

Approximate longitudinal tension:

$$S_{l\,11T} \approx k_f\, S_{fT} \tag{3-29}$$

Approximate fiber compression:

$$S_{l\,11C} \approx k_f\, S_{fC} \tag{3-30}$$

Approximate delamination/shear:

$$S_{l\,11C} \approx 10\, S_{l\,12S} + 2.5 S_{mT} \tag{3-31}$$

Approximate microbuckling:

$$S_{l\,11C} \approx \frac{G_m}{1 - k_f\left(1 - \dfrac{G_m}{G_{f\,12}}\right)} \tag{3-32}$$

Approximate transverse tension:

$$S_{l\,22T} \approx \left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{E_m}{E_{f\,22}}\right)\right] S_{mT} \tag{3-33}$$

Approximate transverse compression:

$$S_{l\,22C} \approx \left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{E_m}{E_{f\,22}}\right)\right] S_{mC} \tag{3-34}$$

Approximate intralaminar shear:

$$S_{l\,12S} \approx \left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{G_m}{G_{f\,12}}\right)\right] S_{mS} \tag{3-35}$$

Approximate void influence on matrix:

$$S_m \approx \left\{1 - \left[\frac{4k_v}{(1 - k_f)\,\pi}\right]^{1/2}\right\} S_m \tag{3-36}$$

Through-Thickness Uniaxial Strengths

Estimates for properties in the 3-axis direction are given by the equations below. Note that the interlaminar shear equation is the same as that for in-plane. The short beam shear depends heavily on the resin shear strength and is about 1½ times the interlaminar value. Also, the longitudinal flexural strength is fiber dominated while the transverse flexural strength is more sensitive to matrix strength.

Approximate interlaminar shear:

$$S_{l\,13S} \approx \left[1 - \left(\sqrt{k_f} - 1\right)\left(1 - \frac{G_m}{G_{f\,12}}\right)\right] S_{mS} \qquad (3\text{-}37)$$

$$S_{l\,23S} \approx \left[\frac{1 - \sqrt{k_f}\left(1 - \frac{G_m}{G_{f\,23}}\right)}{1 - k_f\left(1 - \frac{G_m}{G_{f\,23}}\right)}\right] S_{mS} \qquad (3\text{-}38)$$

Approximate flexural strength:

$$S_{l\,11F} \approx \frac{3\,k_f\,S_{f\,T}}{1 + \frac{S_{f\,T}}{S_{f\,C}}} \qquad (3\text{-}39)$$

$$S_{l\,22F} \approx \frac{3\left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{E_m}{E_{f\,22}}\right)\right] S_{m\,T}}{1 + \frac{S_{m\,T}}{S_{m\,C}}} \qquad (3\text{-}40)$$

Approximate short-beam shear:

$$S_{l\,13SB} \approx 1.5\,S_{l\,13S} \qquad (3\text{-}41)$$

$$S_{l\,23SB} \approx 1.5\,S_{l\,23S} \qquad (3\text{-}42)$$

Uniaxial Fracture Toughness

Fracture toughness is an indication of a composite material's ability to resist defects or discontinuities such as holes and notches. The fracture modes of general interest include: opening mode, in-plane shear and out-of-plane shear. The equations to predict longitudinal, transverse and intralaminar shear fracture toughness are beyond the scope of this text and can be found in the cited reference. [3-2]

In-Plane Uniaxial Impact Resistance

The impact resistance of unidirectional composites is defined as the in-plane uniaxial impact energy density. The five densities are: longitudinal tension and compression; transverse tension and compression; and intralaminar shear. The reader is again directed to reference [3-2] for further elaboration.

Through-Thickness Uniaxial Impact Resistance

The through-thickness impact resistance is associated with impacts normal to the surface of the composite, which is generally of particular interest. The energy densities are divided as follows: longitudinal interlaminar shear, transverse interlaminar shear, longitudinal flexure, and transverse flexure. The derivation of equations and relationships for this and the remaining micromechanics phenomena can be found in reference [3-2].

Thermal

The following thermal behavior characteristics for a composite are derived from constituent material properties: heat capacity, longitudinal conductivity, and longitudinal and transverse thermal coefficients of expansion.

Hygral Properties

The ply hygral properties predicted by micromechanics equation include diffusivity and moisture expansion. Additional equations have been derived to estimate moisture in the resin and composite as a function of the relative humidity ratio. An estimate for moisture expansion coefficient can be postulated analytically.

Hygrothermal Effects

The combined environmental effect of moisture and temperature is usually termed hygrothermal. All of the resin dominated properties are particularly influenced by hygrothermal phenomena. The degraded properties that are quantified include: glass transition temperature of wet resin, strength and stiffness mechanical characteristics, and thermal behavior.

Laminate Theory

Laminae or Plies

The most elementary level considered by macromechanic theory is the lamina or ply. This consists of a single layer of reinforcement and associated volume of matrix material. In aerospace applications, all specifications are expressed in terms of ply quantities. Marine applications typically involve thicker laminates and are usually specified according to overall thickness, especially when successive plies are identical.

For most polymer matrix composites, the reinforcement fiber will be the primary load carrying element because it is stronger and stiffer than the matrix. The mechanism for transferring load throughout the reinforcement fiber is the shearing stress developed in the matrix. Thus, care must be exercised to ensure that the matrix material does not become a strain limiting factor. As an extreme example, if a polyester reinforcement with an ultimate elongation of about 20% was combined with a polyester resin with 1.5% elongation to failure, cracking of the resin would occur before the fiber was stressed to a level that was 10% of its ultimate strength.

Laminates

A laminate consists of a series of laminae or plies that are bonded together with a material that is usually the same as the matrix of each ply. Indeed, with contact molding, the wet-out and laminating processes are continuous operations. A potential weak area of laminates is the shear strength between layers of a laminate, especially when the entire lamination process is not continuous.

A major advantage to design and construction with composites is the ability to vary reinforcement material and orientation throughout the plies in a laminate. In this way, the physical properties of each ply can be optimized to resist the loading on the laminate as a whole, as well as the out-of-plane (through thickness) loads that create unique stress fields in each ply. Figure 3-21 illustrates the concept of stress field discontinuity within a laminate.

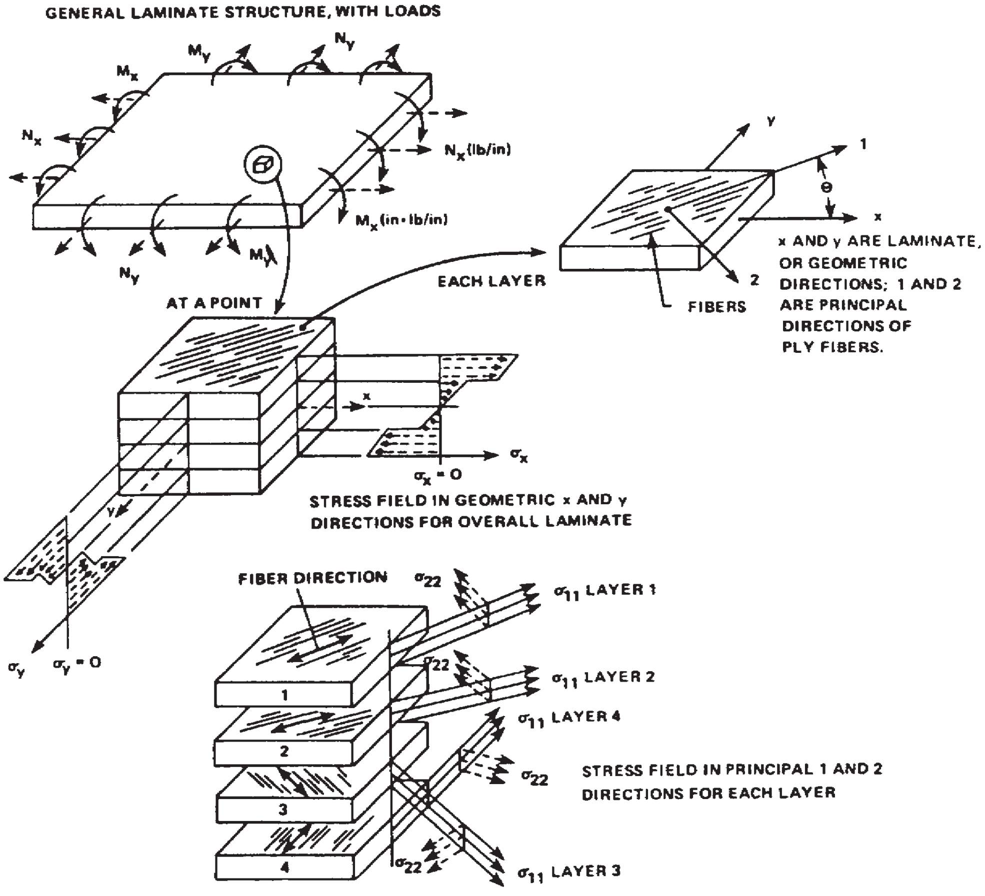


Figure 3-21 Elastic Properties of Plies within a Laminate [Schwartz, *Composite Materials Handbook*]

Laminate Properties

Predicting the physical properties of laminates based on published data for the longitudinal direction (1-axis) is not very useful, as this data was probably derived from samples fabricated in a very controlled environment. Conditions under which marine laminates are fabricated can severely limit the resultant mechanical properties. To date, safety factors have generally been sufficiently high to prevent widespread failure. However, instances of stress concentrations, resin-rich areas and voids can negate even large safety factors.

There are essentially three ways in use today to predict the behavior of a laminated structure under a given loading scenario. In all cases, estimates for Elastic properties are more accurate than those for Strength properties. This is in part due to the variety of failure mechanisms involved. The analytical techniques currently in use include:

- Property charts called “carpet plots” that provide mechanical performance data based on orientation composition of the laminate;
- Laminate analysis software that allows the user to build a laminate from a materials database and view the stress and strain levels within and between plies in each of the three mutually perpendicular axes; and
- Test data based on identical laminates loaded in a similar fashion to the design case.

Carpet Plots

Examples of carpet plots based on a carbon fiber/epoxy laminate are shown in Figures 3-22, 3-23 and 3-24 for modulus, Poisson's ratio, and strength respectively. The bottom axis shows the percentage of ±45° reinforcement. “Iso” lines within the graphs correspond to the percentage of 0° and 90° reinforcement. The resultant mechanical properties are based on the assumption of uniaxial loading (hence, values are for longitudinal properties only) and assume a given design temperature and design criterion (such as B-basis where there is 90% confidence that 95% of the failures will exceed the value). [3-2] Stephen Tsai, an acknowledged authority on composites design, has dismissed the use of carpet plot data in favor of the more rigorous laminated plate theory. [3-12]

Carpet plots have been a common preliminary design tool within the aerospace industry where laminates typically consist of a large number of thin plies. Additionally, out-of-plane loads are not of primary concern as is the case with marine structures. An aerospace designer essentially views a laminate as a homogeneous engineering material with some degraded mechanical properties derived from carpet plots. Typical marine laminates consist of much fewer plies that are primarily not from unidirectional reinforcements. Significant out of plane loading and high aspect ratio structural panels render the unidirectional data from carpet plots somewhat meaningless for designing FRP marine structures.

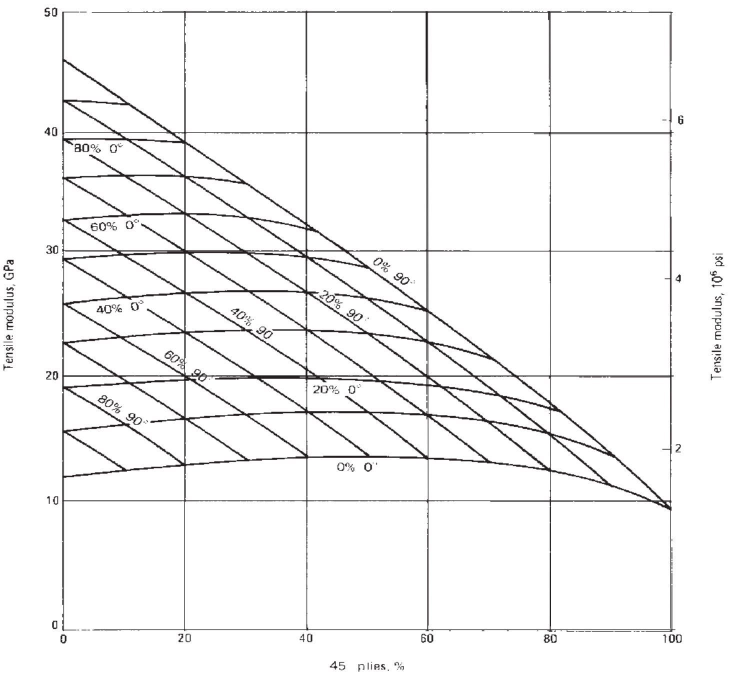


Figure 3-22 Carpet Plot Illustrating Laminate Tensile Modulus [*ASM Engineered Materials Handbook*]

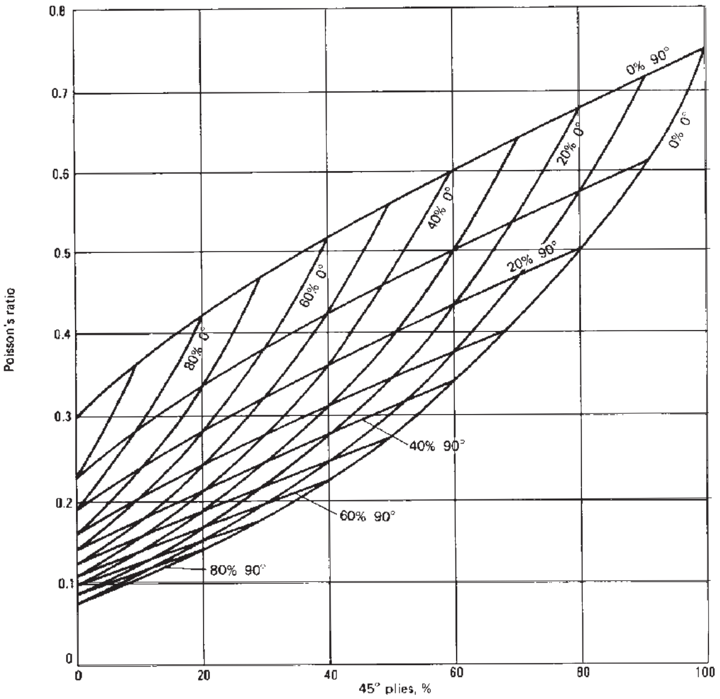


Figure 3-23 Carpet Plot Illustrating Poisson's Ratio [*ASM Engineered Materials Handbook*]

Computer Laminate Analysis

There are a number of structural analysis computer programs available for workstations or advanced PC computers that use finite-element or finite-difference numerical methods and are suitable for evaluating composites. In general, these programs will address:

- Structural response of laminated and multidirectional reinforced composites;
- Changes in material properties with temperature, moisture and ablative decomposition;
- Thin-shelled, thick-shelled, and/or plate structures;
- Thermal-, pressure- traction-, deformation- and vibration-induced load states;
- Failure modes;
- Non-linearity;
- Structural instability; and
- Fracture mechanics.

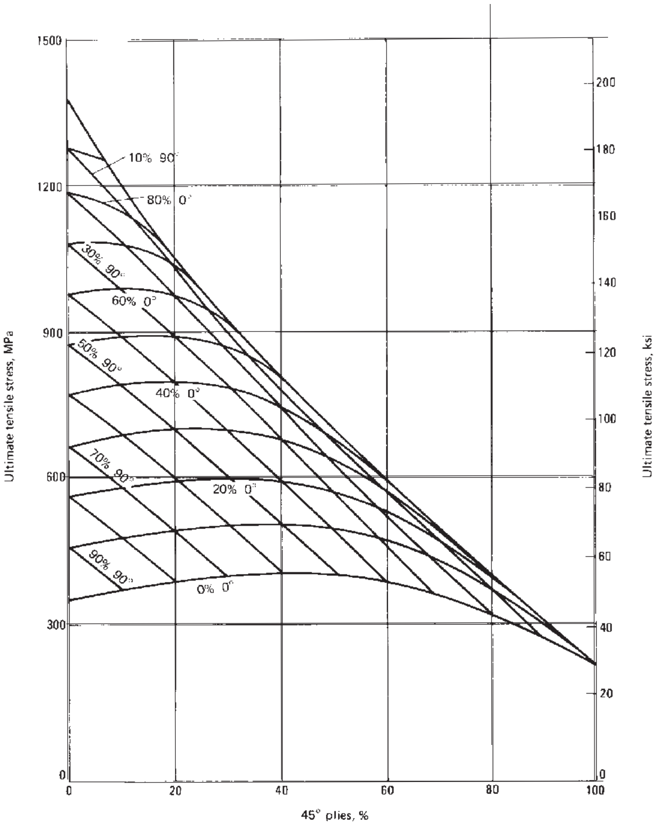


Figure 3-24 Carpet Plot Illustrating Tensile Strength [*ASM Engineered Materials Handbook*]

The majority of these codes for mainframes are quite expensive to acquire and operate, which precludes their use for general marine structures. Specialized military applications such as a pressure hull for a torpedo or a highly stressed weight critical component might justify analysis with these sort of programs. [3-2]

More useful to the marine designer, are the PC-based laminate analysis programs that allow a number of variations to be evaluated at relatively low cost. The software generally costs less than $500 and can run on hardware that is probably already integrated into a design office. The better programs are based on laminated plate theory and do a reasonable job of predicting first ply failure in strain space. Prediction of ultimate strengths with materials that enter non-elastic regions, such as foam cores, will be of limited accuracy. Some other assumptions in laminated plate theory include: [3-2]

- The thickness of the plate is much smaller than the in-plane dimensions;
- The strains in the deformed region are relatively small;
- Normal to the undeformed plate surface remain normal to the deformed plate surface;
- Vertical deflection does not vary through the thickness; and
- Stress normal to the plate surface is negligible.

For a detailed description of laminated plate theory, the reader is advised to refer to ***Introduction to Composite Materials***, by S.W. Tsai and H.T. Hahn, Technomic, Lancaster, PA (1985).

Table 3-2 illustrates a typical range of input and output variables for computer laminate analysis programs. Some programs are menu driven while others follow a spreadsheet format. Once material properties have been specified, the user can “build” a laminate by selecting materials and orientation. As a minimum, stresses and strain failure levels for each ply will be computed. Some programs will show stress and strain states versus design allowables based on various failure criteria. Most programs will predict which ply will fail first and provide some routine for laminate optimization. In-plane loads can usually be entered to compute predicted states of stress and strain instead of failure envelopes.

Table 3-2 Typical Input and Output Variables for Laminate Analysis Programs

Input		Output	
Load Conditions	**Material Properties**	**Ply Properties**	**Laminate Response**
Longitudinal In-Plane Loads	Modulus of Elasticity	Thicknesses*	Longitudinal Deflection
Transverse In-Plane Loads	Poisson's Ratio	Orientation*	Transverse Deflection
Vertical In-Plane Loads (shear)	Shear Modulus	Fiber Volume*	Vertical Deflection
Longitudinal Bending Moments	Longitudinal Strength	Longitudinal Stiffness	Longitudinal Strain
Transverse Bending Moments	Transverse Strength	Transverse Stiffness	Transverse Strain
Vertical Moments (torsional)	Shear Strength	Longitudinal Poisson's Ratio	Vertical Strain
Failure Criteria	Thermal Expansion Coefficients	Transverse Poisson's Ratio	Longitudinal Stress per Ply
Temperature Change		Longitudinal Shear Modulus	Transverse Stress per Ply
		Transverse Shear Modulus	Vertical Stress (shear) per Ply
			First Ply to Fail
			Safety Factors

*These ply properties are usually treated as input variables

Failure Criteria

Failure criteria used for analysis of composites structures are similar to those in use for isotropic materials, which include maximum stress, maximum strain and quadratic theories. [3-12] These criteria are empirical methods to predict failure when a laminate is subjected to a state of combined stress. The multiplicity of possible failure modes (i.e. fiber vs. laminate level) prohibits the use of a more rigorously derived mathematical formulation. Specific failure modes are described in Chapter Four. The basic material data required for two-dimensional failure theory is longitudinal and transverse tensile, and compressive as well as longitudinal shear strengths.

Maximum Stress Criteria

Evaluation of laminated structures using this criteria begins with a calculation of the strength/stress ratio for each stress component. This quantity expresses the relationship between the maximum, ultimate or allowable strength, and the applied corresponding stress. The lowest ratio represents the mode that controls ply failure. This criteria ignores the complexities of composites failure mechanisms and the associated interactive nature of the various stress components.

Maximum Strain Criteria

The maximum strain criteria follows the logic of the maximum stress criteria. The maximum strain associated with each applied stress field is calculated by dividing strengths by moduli of elasticity, when this is known for each ply. The dominating failure mode is that which produces the highest strain level. Simply stated, failure is controlled by the ply that first reaches its elastic limit. This concept is important to consider when designing hybrid laminates that contain low strain materials, such as carbon fiber. Both the maximum stress and maximum strain criteria can be visualized in two-dimensional space as a box with absolute positive and negative values for longitudinal and transverse axes. This failure envelope implies no interaction between the stress fields and material response. Structural design considerations (strength vs. stiffness) will dictate whether stress or strain criteria is more appropriate.

Quadratic Criteria for Stress and Strain Space

One way to include the coupling effects (Poisson phenomena) in a failure criteria is to use a theory based on distortional energy. The resultant failure envelope is an ellipse which is very oblong. A constant, called the normalized empirical constant, which relates the coupling of strength factors, generally falls between $-\frac{1}{2}$ (von Mises criteria) and 0 (modified Hill criteria). [3-12] A strain space failure envelope is more commonly used for the following reasons:

- Plotted data is less oblong;
- Data does not vary with each laminate;
- Input properties are derived more reliably; and
- Axes are dimensionless.

First- and Last-Ply to Failure Criteria

These criteria are probably more relevant with aerospace structures where laminates may consist of over 50 plies. The theory of first-ply failure suggests an envelope that describes the failure of the first ply. Analysis of the laminate continues with the contribution from that and successive plies removed. With the last ply to failure theory, the envelope is developed that corresponds to failure of the final ply in what is considered analogous to ultimate failure. Each of these concepts fail to take into account the contribution of a partially failed ply or the geometric coupling effects of adjacent ply failure.

Laminate Testing

Laminates used in the marine industry are typically characterized using standard ASTM tests. Multiple laminates, usually a minimum of ⅛ inch (3 mm) thick, are used for testing and results are reported as a function of cross-sectional area, i.e. width × thickness. Thus, thickness of the laminate tested is a critical parameter influencing the reported data. High fiber laminates that are consolidated with vacuum pressure will be thinner than standard open mold laminates, given the same amount of reinforcement. Test data for these laminates will be higher, although load carrying capability may not be. The following ASTM tests were used to generate the laminate data presented in Appendix A. Comments regarding the application of these tests to typical marine laminates is also included. ISO and SACMA tests are also cited.

Tensile Tests

These test methods provide procedures for the evaluation of tensile properties of single-skin laminates. The tests are performed in the axial, or in-plane orientation. Properties obtained can include tensile strength, tensile modulus, elongation at break (strain to failure), and Poisson’s ratio.

For most oriented fiber laminates, a rectangular specimen is preferred. Panels fabricated of resin alone (resin casting) or utilizing randomly oriented fibers (such as chopped strand) may be tested using dog-bone (dumbbell) type specimens. Care must be taken when cutting test specimens to assure that the edges are aligned in the axis under test. The test axis or orientation must be specified for all oriented-fiber laminates.

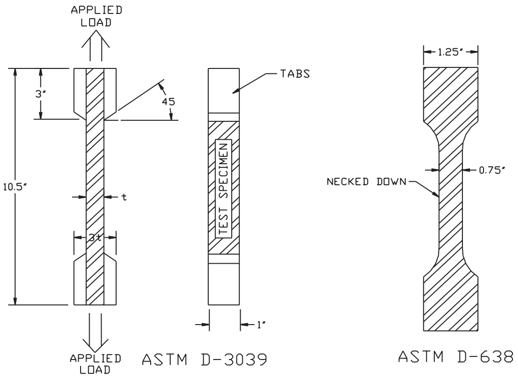


Figure 3-25 Test Specimen Configuration for ASTM D-3039 and D-638 Tensile Tests (Structural Composites, Inc.)

Tensile Test Methods	
ASTM D 3039	Tensile Properties of Polymer Matrix Composite Materials Specimen Type: Rectangular, with tabs
ASTM D 638	Tensile Properties of Plastics Specimen Type: Dumbbell
ISO 3268	Plastics - Glass-Reinforced Materials - Determination of Tensile Properties Specimen Type: Type I Dumbbell Type II Rectangular, no tabs Type III Rectangular, with tabs
SACMA SRM 4	Tensile Properties of Oriented Fiber-Resin Composites Specimen Type: Rectangular, with tabs
SACMA SRM 9	Tensile Properties of Oriented Cross-Plied Fiber-Resin Composites Specimen Type: Rectangular, with tabs

Compressive Tests

Several methods are available for determination of the axial (in-plane, edgewise, longitudinal) compression properties. The procedures shown are applicable for single-skin laminates. Other methods are utilized for determination of "edgewise" and "flatwise" compression of sandwich composites. Properties obtained can include compressive strength and compressive modulus.

For most oriented fiber laminates, a rectangular specimen is preferred. Panels fabricated of randomly oriented fibers such as chopped strand may be tested using dog-bone (dumbbell) type specimens.

Compressive Test Methods

ASTM D 3410	Compressive Properties of Unidirectional or Crossply Fiber-Resin Composites Specimen Type: Rectangular, with tabs
ASTM D 695	Compressive Properties of Rigid Plastics Specimen Type: Rectangular or dumbbell
ISO 604	Plastics - Determination of Compressive Properties Specimen Type: Rectangular
SACMA SRM 1	Compressive Properties of Oriented Fiber-Resin Composites Specimen Type: Rectangular, with tabs
SACMA SRM 6	Compressive Properties of Oriented Cross-Plied Fiber-ResinComposites Specimen Type: Rectangular, with tabs

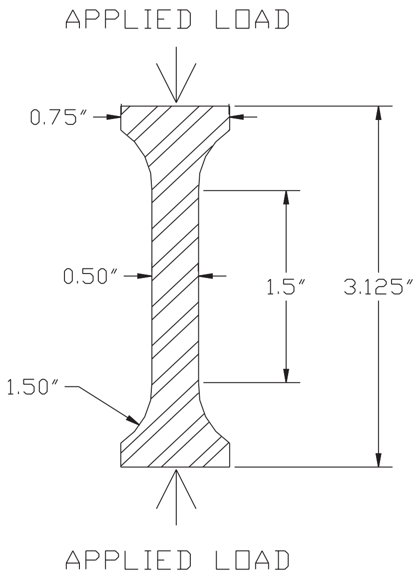


Figure 3-26 Test Specimen Configuration for ASTM D-695 Compression Test

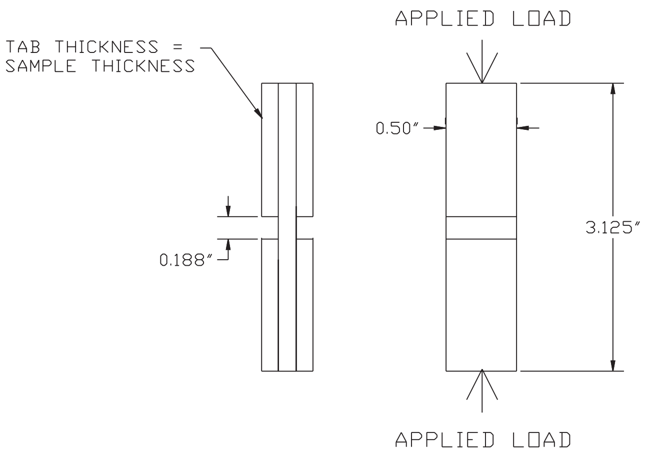
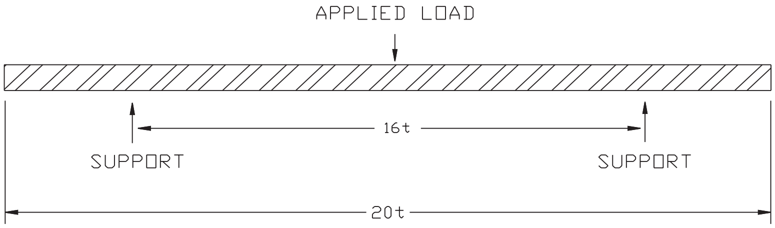


Figure 3-27 Test Specimen Configuration for SACMA SRM-1 Compression Test

Flexural Tests

For evaluation of mechanical properties of flat single-skin laminates under bending (flexural) loading, several standard procedures are available. The methods all involve application of a load which is out-of-plane, or normal to, the flat plane of the laminate. Properties obtained include flexural strength and flexural modulus.

Rectangular specimens are required regardless of reinforcement type. Unreinforced resin castings may also be tested using these procedures. Generally, a support span-to-sample depth ratio of between 14:1 and 20:1 is utilized (support span is 14-20 times the average laminate thickness). Load may be applied at the midpoint of the beam (3-point loading), or a 4-point loading scheme may be used. Flexural tests are excellent for comparing laminates of similar geometry and are often used in Quality Assurance programs.



NOTES: 1) SAMPLE WIDTH = 1″
2) LOAD APPLIED IN MIDDLE OF SUPPORT SPAN

Figure 3-28 Test Specimen Configuration for ASTM D-790 Flexural Test, Method I, Procedure A

Flexural Test Methods	
ASTM D 790	Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials Method I 3-point bending Method II 4-point bending
ISO 178	Plastics - Determination of Flexural Properties 3-point bending

Shear Tests

Many types of shear tests are available, depending on which plane of the single-skin laminate is to be subjected to the shear force. Various “in-plane” and “interlaminar” shear methods are commonly used. Confusion exists as to what properties are determined by the tests, however. The “short-beam” methods also are used to find “interlaminar” properties.

Through-plane shear tests are utilized for determination of out-of-plane shear properties, such as would be seen when drawing a screw or a bolt out of a panel. The load is applied perpendicular to, or “normal” to, the flat plane of the panel.

Properties obtained by these tests are shear strength, and in some cases, shear modulus.

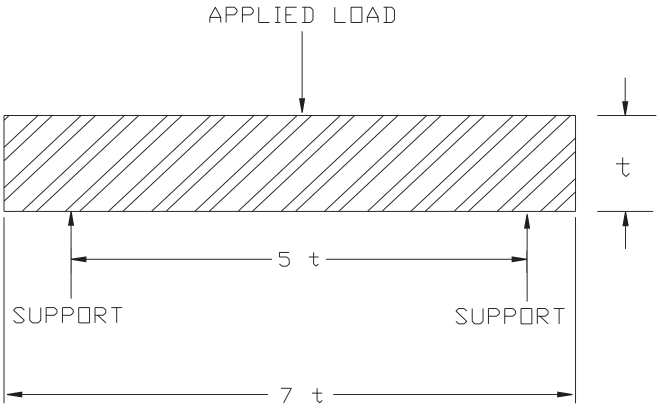


Figure 3-29 Test Specimen Configuration for ASTM D-2344 Short Beam Shear Test

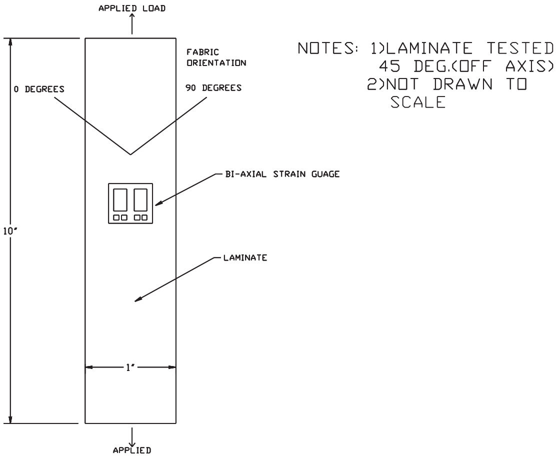


Figure 3-30 Test Specimen Configuration for ASTM D-3518 In-Plane Shear Test

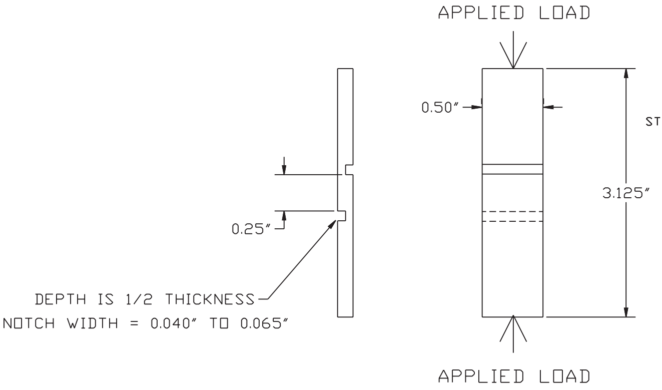


Figure 3-31 Test Specimen Configuration for ASTM D-3846 In-Plane Shear Test

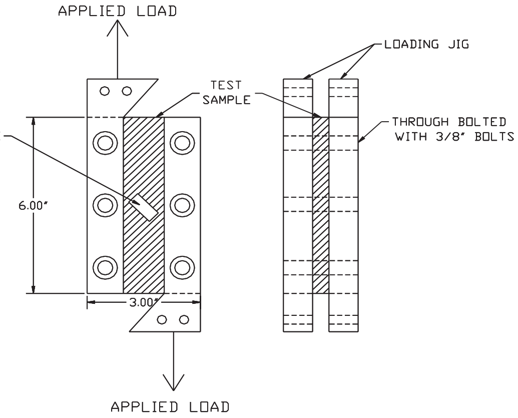


Figure 3-32 Test Specimen Configuration for ASTM D-4255 Rail Shear Test, Method A

Shear Test Methods	
ASTM D 3846	In-Plane Shear Strength of Reinforced Plastics
ASTM D 4255	Inplane Shear Properties of Composites Laminates
ASTM D 2344	Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method
ASTM D 3518	In-Plane Shear Stress-Strain Response of Unidirectional Polymer Matrix Composites
ASTM D 732	Shear Strength of Plastics by Punch Tool
ISO 4585	Textile Glass Reinforced Plastics - Determination of Apparent Interlaminar Shear Properties by Short-Beam Test
SACMA SRM 7	Inplane Shear Stress-Strain Properties of Oriented Fiber-Resin Composites
SACMA SRM 8	Short Beam Shear Strength of Oriented Fiber-Resin Composites

Impact Tests

Two basic types of impact tests are available for single-skin laminates. The “Izod” and “Charpy” tests utilize a pendulum apparatus, in which a swinging hammer or striker impacts a gripped rectangular specimen. The specimen may be notched or unnotched. Also, the specimen may be impacted from an edgewise face or a flatwise face.

Drop weight tests are performed by restraining the edges of a circular or rectangular specimen in a frame. A “tup” or impactor is dropped from a known height, striking the center of the specimen. The drop test is more commonly used for composite laminates

Impact Test Methods	
ASTM D 256	Impact Resistance of Plastics and Electrical Insulating Materials
ASTM D 3029	Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Tup (Falling Weight)
ISO 179	Plastics - Determination of Charpy Impact Strength
ISO 180	Plastics - Determination of Izod Impact Strength

Resin/Reinforcement Content

The simplest method used to determine the resin content of a single-skin laminate is by a resin burnout method. The procedure is only applicable to laminates containing E-glass or S-glass reinforcement, however. A small specimen is placed in a pre-weighed ceramic crucible, then heated to a temperature where the organic resin decomposes and is burned off, leaving the glass reinforcement intact.

Laminates containing carbon or Kevlar® fibers cannot be analyzed in this way. As carbon and Kevlar® are also organic materials, they burn off together with the resin. More complicated resin “digestion” methods must be used. These methods attempt to chemically dissolve the resin with a strong acid or strong base. As the acid or base may also attack the reinforcing fibers, the accuracy of the results may be questionable if suitable precautions are not taken.

Fiber volume (%) may be calculated from the results of these tests if the dry density of the reinforcement is known.

Resin/Reinforcement Test Methods	
ASTM D 2584	Ignition Loss of Cured Reinforced Resins
ASTM D 3171	Fiber Content of Resin-Matrix Composites by Matrix Digestion
ISO 1172	Textile Glass Reinforced Plastics - Determination of Loss on Ignition

Hardness/Degree of Cure

The surface hardness of cured resin castings or reinforced plastics may be determined using “impressor” methods. A steel needle or cone is pushed into the surface and the depth of penetration is indicated on a dial gauge.

For cured polyester, vinyl ester, and DCPD type resins, the "Barcol" hardness is generally reported. Epoxy resins may be tested using either the "Barcol" or "Shore" type of test.

Hardness/Degree of Cure Test Methods	
ASTM D 2583	Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor
ASTM D 2240	Rubber Property - Durometer Hardness

Water Absorption

Cured resin castings or laminates may be tested for resistance to water intrusion by simple immersion methods. A rectangular section is placed in a water bath for a specified length of time. The amount of water absorbed is calculated from the original and post-immersion weights. Tests may be performed at ambient or elevated water temperatures.

Water Absorption Test Methods	
ASTM D 570	Water Absorption of Plastics
ISO 62	Plastics - Determination of Water Absorption

Core Flatwise Tensile Tests

The tensile strength of a core material or sandwich structure may be evaluated using a "flatwise" test. Load is applied to the flat faces of a rectangular or circular specimen. This load is perpendicular to, or normal to, the flat plane of the panel.

Test specimens are bonded to steel blocks using a high strength adhesive. The assembly is then placed in a tensile holding fixture, through which load is applied to pull the blocks apart. Failures may be within the core material (cohesive), or between the core and FRP skin (adhesive), or a combination of both.

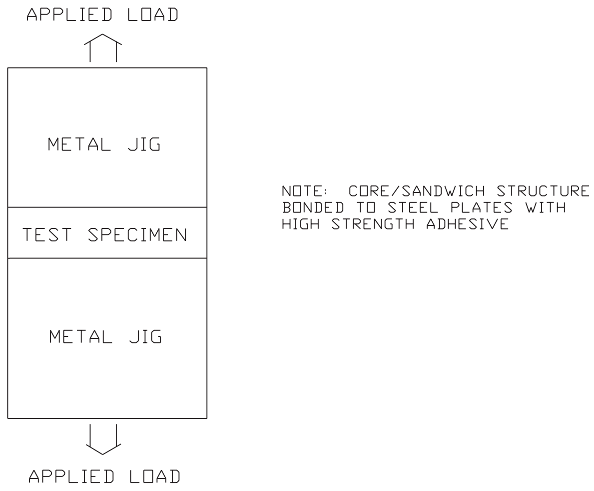


Figure 3-33 Test Specimen Configuration for ASTM C-297 Core Flatwise Tensile Test

Core Flatwise Tensile Test Methods	
ASTM C 297	Tensile Strength of Flat Sandwich Constructions in Flatwise Plane

Core Flatwise Compressive Tests

The compressive properties of core materials and sandwich structures are determined by loading the faces of flat, rectangular specimens. The specimen is crushed between two parallel steel surfaces or plates.

Typically, load is applied until a 10% deformation of the specimen has occurred (1.0" thick core compressed to 0.9", for example). The peak load recorded within this range is used to calculate compressive strength. Deformation data may be used for compressive modulus determination.

Core Flatwise Compressive Test Methods	
ASTM C 365	Flatwise Compressive Strength of Sandwich Cores
ASTM D 1621	Compressive Properties of Rigid Cellular Plastics

Sandwich Flexure Tests

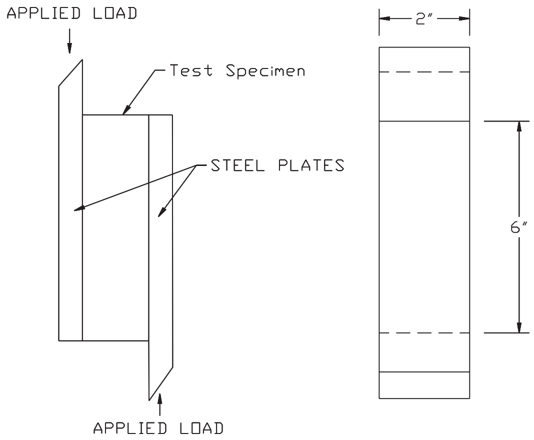
The bending properties of sandwich panels can be evaluated using flexural methods similar to those utilized for single-skin laminates. A 3 or 4-point loading scheme may be used. Generally, the test is set up as a simply-supported beam, loaded at the midpoint (3-point). A 4-point setup can be selected if it is desired to produce higher shear stresses within the core.

Properties obtained from sandwich flexure tests include flexural modulus and panel stiffness, *EI*.

Sandwich Flexure Test Methods	
ASTM C 393	Flexural Properties of Flat Sandwich Constructions

Sandwich Shear Tests

The shear properties of sandwich panels and core materials are determined by a parallel plate test. Steel plates are bonded to the flat faces of rectangular sections. Load is applied to the plates so as to move them in opposing directions, causing shear stress in the specimen between the plates. Core shear strength is found from the load at failure. Shear modulus may be determined if plate-to-plate displacement is measured during the test.



NOTE: CORE/SANDWICH STRUCTURE BONDED TO STEEL PLATES WITH HIGH STRENGTH ADHESIVE

Figure 3-34 Test Specimen Configuration for ASTM C-273 Core Shear Test

Sandwich Shear Test Methods	
ASTM C 273	Shear Properties in Flatwise Plane of Flat Sandwich Constructions or Sandwich Cores

Peel Tests

The adherence of the FRP skins to a core in a sandwich structure may be evaluated using peel test methods. One FRP skin is restrained, while the opposite skin is loaded at an angle (starting at one edge of the specimen), to peel the skin away from the core. These methods may be utilized to determine optimum methods of bedding or adhesively bonding skins to sandwich cores.

Peel Test Methods	
ASTM D 1062 (modified)	Cleavage Strength of Metal-to-Metal Adhesive Bonds
ASTM D 1781	Climbing Drum Peel Test for Adhesives

Core Density

The density of core materials used in sandwich constructions is typically determined from a sample of raw material (unlaminated). A rectangular section is weighed, with the density calculated from the mass and volume of the specimen.

Core Density Test Methods	
ASTM D 1622	Apparent Density of Rigid Cellular Plastics
ASTM C 271	Density of Core Materials for Structural Sandwich Constructions

Machining of Test Specimens

A variety of tools are available which are suitable for cutting and machining of test specimens. These methods may be used for both single-skin laminates and sandwich structures. The tools normally utilized for specimen preparation include :

- Milling machine;
- Band saw;
- Wet saw, with abrasive blade (ceramic tile saw);
- Water jet cutter;
- Router, with abrasive bit; and
- Drum sander.

The wet cutting methods are preferred to reduce heating of the sample, and also reduce the amount of airborne dust generated. However, for necking down dumbbell specimens, a drum sander of the proper radius is often employed (with appropriate dust control).

Great care must be taken to assure that the specimens are cut in the correct orientation when directional fibers are present.

Machining Method	
ISO 2818	Plastics - Preparation of Test Specimens by Machining
ASTM D 4762	Testing Automotive/Industrial Composite Materials (Section 9 - Test Specimen Preparation)

Typical Laminate Test Data

Ideally, all testing should be conducted using standardized test methods. The standardized test procedures described above have been established by the American Society for Testing and Materials (ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959) and the Suppliers of Advanced Composite Materials Association (SACMA, 1600 Wilson Blvd., Suite 1008, Arlington, VA 22209). SACMA has developed a set of recommended test methods for oriented fiber resin composites. These tests are similar to ASTM standard tests, and are either improvements on the corresponding ASTM standard tests or are new tests to obtain data not covered by ASTM standard tests. The tests are intended for use with prepreg materials, thus some modifications may be necessary to accommodate common marine laminates. Also, the tolerances on fiber orientations (1°) and specimen size (approximately 0.005 inch) are not realistic for marine laminates. The individual tests have been established for specific purposes and applications. The tests may or may not be applicable to other applications and must be evaluated on a case by case basis.

There are three major types of testing: 1) tests of the FRP laminates, 2) tests of the individual FRP components, 3) tests of the FRP structure. In general, the tests of individual FRP components tend to be application dependent, however, some of the properties may not be useful in certain applications. Tests of the FRP laminates tend to be more application independent, and tests of FRP structures are heavily application dependent.

Appendix A contains test data on a variety of common marine reinforcements tested with ASTM methods by Art Wolfe at Structural Composites, Inc.; Dave Jones at Sigma; Tom Juska from the Navy’s NSWC; and Rick Strand at Comtrex. In limited cases, data was supplied by material suppliers. Laminates were fabricated using a variety of resin systems and fabrication methods, although most were made using hand lay-up techniques. In general, test panels made on flat tables exhibit properties superior to as-built marine structures. Note that higher fiber content laminates will be thinner for the same amount of reinforcement used. This will result in higher mechanical values, which are reported as a function of cross sectional area. However, if the same amount of reinforcement is present in high- and low-fiber content laminates, they may both have the same “strength” in service. Indeed, the low-fiber content may have superior flexural strength as a result of increased thickness. Care must always be exercised in interpreting test data. Additionally, samples should be fabricated by the shop that will produce the final part and tested to verify minimum properties.

As can be seen in Appendix A, complete data sets are not available for most materials. Where available, data is presented for properties measured in 0°, 90° and ±45° directions. Shear data is not presented due to the wide variety in test methods used. Values for Poission's ratio are seldom reported. Lu and Jin reported on materials used for the construction of a 126 foot (38.5 meter) commercial fishing vessel built in China during the 1970's. [3-13] The mechanical data determined in their test program is presented here as typical of what can be expected using general purpose polyester resin and hand lay-up techniques.

Table 3-3 Ultimate Strengths and Elastic Constants for Polyester Resin Laminates [X.S. Lu & X.D. Jin, "*Structural Design and Tests of a Trial GRP Hull*," Marine Structures, Elsever, 1990]

	Test Angle	Quasi-Isotropic WR & Twill @ 0°/90°		Quasi-Isotropic WR & Twill @ 0°/90°/±45°		Unidirectional		Balanced WR & Twill @ 0°		Mostly WR & Twill @ 0°	
		ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
Tensile Strength	0°	30.0	207	27.4	189	42.3	292	29.1	201	36.5	252
	90°	25.9	179	26.5	183	10.7	74	28.0	193	n/a	
	±45°	17.5	121	19.6	135	n/a		17.8	123	n/a	
Compress Strength	0°	21.2	146	20.1	139	n/a		23.9	165	21.6	149
	90°	17.8	123	20.3	140	n/a		21.6	149	n/a	
	±45°	n/a		n/a		n/a		n/a		n/a	
Flexural Strength	0°	36.7	253	36.1	249	n/a		39.7	274	40.3	278
	90°	39.6	273	38.4	265	n/a		35.8	247	n/a	
	±45°	n/a		n/a		n/a		n/a		n/a	
In-Plane Shear	0°	n/a		n/a		n/a		n/a		n/a	
	90°	10.4	72	11.4	79	n/a		10.7	74	n/a	
	±45°	n/a		n/a		n/a		n/a		n/a	
Out-of-Plane Shear	0°	14.3	99	14.3	99	n/a		14.6	101	15.1	104
	90°	14.3	99	13.8	95	n/a		13.6	94	n/a	
	±45°	n/a		n/a		n/a		n/a		n/a	
		msi	GPa	msi	GPa	msi	GPa	msi	GPa	msi	GPa
Tensile Modulus	0°	2.22	15.3	1.94	13.4	3.06	21.1	2.26	15.6	2.29	15.8
	90°	2.19	15.1	1.85	12.8	1.35	9.3	2.14	14.8	n/a	
	±45°	1.07	7.4	1.38	9.5	n/a		1.01	7.0	n/a	
Shear Modulus	In-Plane	0.44	3.03	0.65	4.51	n/a		0.36	2.45	n/a	
Poisson's Ratio	0°	0.15		0.23		0.19		0.14		n/a	
	90°	0.13		0.22		0.12		0.12		n/a	
	±45°	0.62		0.50		n/a		0.60		n/a	

Material Testing Conclusions

In the previous text there is a review of ASTM and SACMA test procedures for determining physical and mechanical properties of various laminates. In order to properly design a boat or a ship, the designer must have accurate mechanical properties. The properties important to the designer are the tensile strength and modulus, the compressive strength and modulus, the shear strength and modulus, the interply shear strength, and the flexural strength and modulus.

The ASTM and SACMA tests are all uniaxial tests. There are some parts of a boat's structure that are loaded uniaxially, however, much of the structure, the hull, parts of the deck and bulkheads, etc., receive multiaxial loads. Multiaxial tests are difficult to conduct and typically are only done with panel “structures,” (i.e. sandwich or stiffened panels).

The marine industry has yet to develop a set of tests which yield the right type of data for the marine designer. Once this has been accomplished and an industry wide set of accepted tests has been developed, then a comprehensive testing program, testing all the materials that are commonly used in the marine industry, would be very beneficial to the designers to try to yield some common data. Meanwhile, until these tests are developed, there is still a need for some common testing. In particular, the minimum tests recommended to be performed on laminates are the ASTM D3039 tensile test or the appropriate SACMA variation of that, SRM 4-88.

The ASTM compressive tests all leave something to be desired for marine laminates. However, the SACMA compression test looks like it might yield some useful uniaxial compressive load data for marine laminates, and therefore, at this time would probably be the recommended test for compression data. Flexural data should be determined using ASTM D790. This is a fairly good test.

As far as shear is concerned, there is really no good test for determining inplane shear properties. The ASTM test (D3518) is basically a 3039 tensile test performed on a fabric that has been laid up at a bias so that all the fibers are at ± 45°. This has a number of problems, since the fibers are not continuous, and the results are heavily dependent on the resin, much more so than would be in a continuous laminate. Some recent investigations at Structural Composites, Inc. has shown that wider samples with associated wider test grips will yield higher test values.

Therefore, there is currently not a test that would yield the right type of data for the inplane shear properties. For interply shear, about the only test that's available is the short beam shear test (ASTM D2344). The data yielded there is more useful in a quality control situation. It may be, however, that some of the other tests might yield some useful information. There's a shear test where slots are cut half way through the laminate on opposite sides of the laminate (ASTM D3846). This one might yield some useful information, but because the laminate is cut with the inherent variability involved, it difficult to come up with consistent data.

In summary, what is recommended as a comprehensive laminate test program is the ASTM D3039 tensile test, the SACMA compressive test, ASTM D790 flexural test and a panel test that realistically models the edge conditions. This type of test will be discussed further under “sandwich panel testing (page 177). A laminate test program should always address the task objectives, i.e. material screening, preliminary design, detail design and the specific project needs.