CHAPTER 10 THICK-SECTION COMPOSITES

10.1 INTRODUCTION AND DEFINITION OF THICK-SECTION

Thick-section composites are ones where the effect of geometry (thickness-to-span ratio), material constituents (matrix and fiber stiffness/strength properties), lamination scheme, processing, and service loading exhibit three-dimensional states of stress. For instance, all loadings induce multiaxial stresses into individual plies of composite materials that are made of multi-directional ply laminates (either woven or nonwoven), even though the overall loadings may only be uniaxial. When transverse (through-thickness) stresses and strains occur to a significant degree, they must be accounted for in analysis, design and testing. A significant degree is achieved when these effects contribute to failure (e.g., delamination), excessive deflection or vibration. Frequently, these stresses and strains induce failures that cannot be accurately predicted by conventional two-dimensional analyses for thin laminates. These two-dimensional analyses are usually based on material response data obtained from traditional shear and uniaxial tensile/compressive testing techniques. In thick section composites, where any one of six stress components may significantly contribute to failure, a failure criteria must distinguish between different types of failure modes by associating the contribution of each three-dimensional stress component to a unique mode of failure, be it fiber, matrix or interface dominated. An appropriate failure criteria for thick section composites must consider the following laminate failure modes:

Fiber Dominated	Matrix Dominated	Interface Dominated
. Fiber pull-out	. Transverse cracking	. Interface disbonding
. Fiber tensile failure	. Interlaminar cracking	. Interface delamination
. Fiber micro-buckling	. Intralaminar cracking	. Compressive delamination
. Fiber shear failure	. Edge delamination	

For example, thick-section composites made of high stiffness and strength fiber-reinforced plies often exhibit significant transverse shear and transverse normal deformations (the type of three-dimensional stress contributions that are negligibly small in thin laminates). The thickness effect can also be influenced by short wavelength loadings and, in dynamics, high frequency vibrations. These three-dimensional effects are considerably more pronounced in composites than in homogeneous isotropic materials due to their inherently high material compliances in the transverse direction relative to the axial fiber direction. Moreover, composite laminates exhibit much lower strength in the transverse direction, and at ply interfaces, making them particularly susceptible to matrix cracking and delamination.

Thick section composites can also be defined from the standpoint of fabrication effects associated with a large number of plies. Process induced stresses can be significant and, therefore, warrant special attention. Fabrication effects of special concern include residual stresses, wrinkling, micro-cracking, exotherm, volatile removal, compaction, machining, and mechanical joining and/or adhesive bonding. To minimize these effects, special resins, processing, tooling, and cure cycles may be necessary.

In thick laminates, typically two competing objectives are desired, namely, minimization of process induced residual stresses and maximization of production rates (i.e., minimization of the processing time required to achieve complete cure). Fast cure cycle times, involving steep heating and cooling rates, will generally lead to high process induced residual stresses. On the other hand, slowly bringing all part thicknesses up to complete cure simultaneously will minimize, if not eliminate, all process induced residual stresses. This, however, is accomplished at the expense of extended cure cycle times. It is also important to note that process induced residual stresses may in fact be intentionally introduced to cancel, or otherwise mitigate, large superimposed in-service stresses.

In thick laminate design, cure simulation plays a very important role in developing a deeper understanding of the cure kinetics and the degree of cure at any point in the time domain. Such simulation is also able to predict processing stresses even during the cure cycle. This can be an important tool for prediction and preventing in-process part fabrication failures where both stresses and associated strengths are low.

The structural analyst needs to know the multiaxial strength and deformation characteristics for efficient thick composite material design. The full potential of thick composites cannot be realized until the material response under multiaxial service loadings can be established. Technical progress in the design, analysis and associated material testing of thick composites remain much less developed than the generally accepted methodology associated with thin composite material characterizations and applications.

The step-by-step method for analysis of thick section composites is illustrated by the flow chart in Figure 10.1.

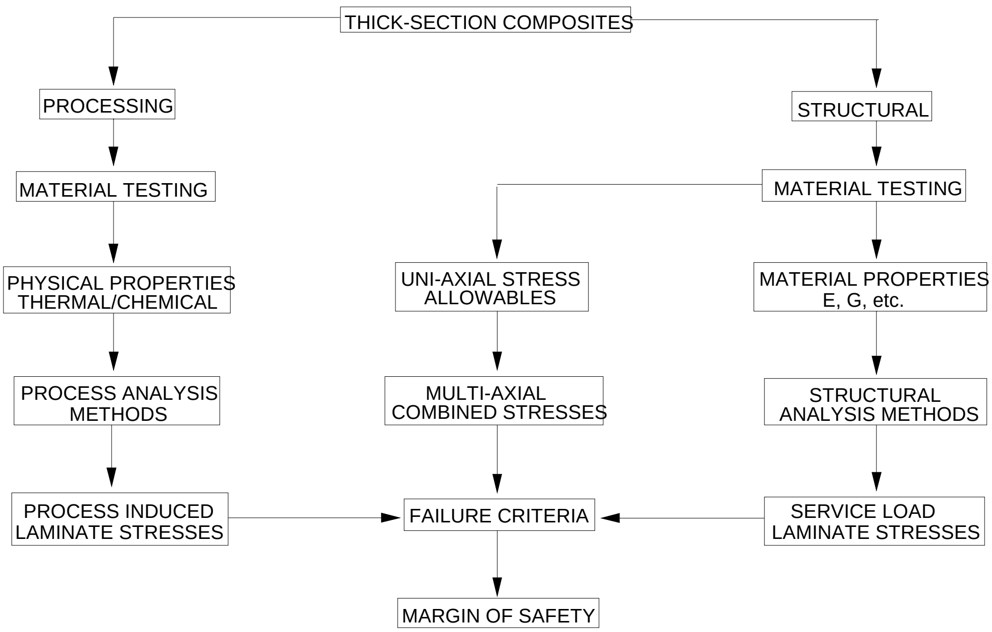


FIGURE 10.1 *Flowchart illustrating thick-section composites analysis method.*

10.2 MECHANICAL PROPERTIES REQUIRED FOR THICK-SECTION COMPOSITE THREE-DIMENSIONAL ANALYSIS

The purpose of this section is to define the three-dimensional (3-D) orthotropic stiffness properties necessary to conduct a 3-D point stress analysis, and the failure strength and strain allowables required to calculate a margin of safety. This section will:

a) Define the stiffness properties currently used to conduct a conventional two-dimensional (2-D) analysis (Volume 1, Section 6.7).

b) Define the additional stiffness properties needed to conduct a three-dimensional (3-D) stress analysis.

c) Define the testing required to experimentally determine the 3-D stiffness properties and the failure strengths and strains for uniaxial loading (Section 10.2.3.1) and multiaxial loading (Section 10.2.3.2)

d) Discuss the methodology for predicting laminate stiffness properties through the thickness using the 3-D lamina properties (Section 10.2.4).

The symbols and nomenclature used in the handbook (Volume 3, Section 1.3.1) apply to 2-D and 3-D composites and utilize 1, 2, 3 for lamina axes and x, y, z for an oriented laminate axis directions.

10.2.1 2-D composite analysis

The two-dimensional composite analysis procedures (Volume 3, Section 5.3.1) apply when the through the thickness stresses are not significant. For unidirectional laminates that have low stresses in the thickness or 3-direction $(\sigma_3 = \tau_{23} = \tau_{13})$, plane stress), the stress-strain relationship (Reference 10.2.1) is,

$$\{\varepsilon_{ij}\} =]\{\sigma_{ij}\} \tag{10.2.1(a)}$$

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \tag{10.2.1(b)}$$

In terms of the engineering elastic constants obtained by simple tests

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{12}}{E_1} & 0 \\ -\frac{\nu_{21}}{E_2} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \tag{10.2.1(c)}$$

The reciprocity relationships for stiffness is

$$\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2} \tag{10.2.1(d)}$$

For the plane stress two-dimensional analysis, the four independent elastic material properties are:

$$E_1,\ E_2,\ G_{12},\ \nu_{12}$$

In-plane failure stress and strain values can be obtained from the same test used for determining the stiffness as discussed in Section 10.2.3.1.

10.2.2 3-D composite analysis

When the stresses and strains in the thickness direction are significant, (applied values are approaching their allowables) the problem requires a three-dimensional orthotropic stress analysis. A 3-D analysis is frequently necessary as the section thickness of a composite increases or when thin sections have out-of-plane loading (bending moment, lateral pressures, etc.) which results in, for example, interlaminar tensile stresses in a corner radius or interlaminar shear stresses in a beam or plate.

10.2.2.1 Unidirectional lamina 3-D properties

For the orthotropic unidirectional lamina there are nine independent constants as shown by the following stress-strain relationship (Reference 10.2.1):

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} \qquad 10.2.2.1(a)$$

or in terms of the engineering constants,

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} \qquad 10.2.2.1(b)$$

There are three reciprocal relationships that must be satisfied for an orthotropic material. They are

$$\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2}, \qquad \frac{\nu_{13}}{E_1} = \frac{\nu_{31}}{E_3}, \qquad \frac{\nu_{23}}{E_2} = \frac{\nu_{32}}{E_3} \qquad 10.2.2.1(c)$$

There are nine independent elastic material properties required for an orthotropic lamina

$$E_1, E_2, E_3, G_{12}, G_{13}, G_{23}, \nu_{12}, \nu_{13}, \nu_{23}$$

When materials have a different stiffness in tension from in compression, it is common practice to use an average value when the difference is small. If the stiffness difference is significant, use the stiffness (tensile or compressive) that is representative of the application loading.

10.2.2.2 Oriented orthotropic laminate 3-D properties

The compliance matrix and associated nine elastic constants required to conduct a 3-D analysis are defined in this section and are for a oriented balanced and symmetric laminate loaded in the x, y, or z direction. Most practical composite laminate lay-ups generally are balanced and symmetric to prevent thermal warpage during processing. If the laminate is unbalanced and unsymmetric, or loaded "off-axis" to the principal orthogonal directions, then the matrix is fully populated with the Chentsov's coefficients $(\mu_{ij,kl})$ and coefficients of mutual influence $(\eta_{ij,i}, \eta_{i,ij})$ (see References 10.2.1, 10.2.2.2).

The compliance matrix for the balanced and symmetric laminate loaded in the x, y, or z direction is

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \bar{S}_{11} & \bar{S}_{12} & \bar{S}_{13} & 0 & 0 & 0 \\ \bar{S}_{12} & \bar{S}_{22} & \bar{S}_{23} & 0 & 0 & 0 \\ \bar{S}_{13} & \bar{S}_{23} & \bar{S}_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \bar{S}_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \bar{S}_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \bar{S}_{66} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{Bmatrix} \qquad 10.2.2.2(a)$$

In terms of the effective engineering elastic constants this relationship is,

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{yz}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{zx}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{Bmatrix} \qquad 10.2.2.2(b)$$

There are three reciprocal relationships that must be satisfied by the effective laminate stiffnesses. They are,

$$\frac{\nu_{xy}}{E_x} = \frac{\nu_{yx}}{E_y}, \qquad \frac{\nu_{xz}}{E_x} = \frac{\nu_{zx}}{E_z}, \qquad \frac{\nu_{yz}}{E_y} = \frac{\nu_{zy}}{E_z} \qquad 10.2.2.2(c)$$

There are nine independent effective elastic material constants required for analysis of the oriented laminate,

$$E_x, E_y, E_z, G_{xy}, G_{xz}, G_{yz}, \nu_{xy}, \nu_{xz}, \nu_{yz}$$

10.2.3 Experimental property determination

The current and most commonly used approach for failure analysis of 2-D composites is to experimentally determine the strength and stiffness values for the unidirectional lamina from simple uniaxial tests and use a failure criterion to account for the various load direction interactions to calculate the margin of safety. These uniaxial tests are defined in Section 10.2.3.1 for 2-D and 3-D composites. Another approach is to conduct multiaxial tests that provide loading in the proper proportions to simulate the actual load applications. The multiaxial testing and methodology are discussed in Section 10.2.3.2.

There are considerable challenges associated with both uniaxial and multiaxial, mechanical testing of thick section composite materials. A partial list of experimental testing considerations is presented below:

- Test system and load introduction
- Gripping system and fixturing
- Computer control and interface
- Adequate displacement control over specimen centroid location
- Specimen design and optimization
- Unknown states of stress within thick composites
- Multiaxial extensometry and other measurement devices and techniques

- Inclusion and treatment of environmental effects
- Data acquisition and analysis
- Multiaxial yield and failure criteria
- Size effect and scaling law
- Edge effects treatment
- Static and dynamic testing, including fatigue and impact loadings
- Sensitivity to stress concentrations
- NDE of damage

10.2.3.1 Uniaxial tests

The type of common tests conducted on the unidirectional laminate to obtain the conventional 2-D in-plane tensile, compressive, and shear stiffness, as well as failure strength and strains are summarized in Figures 10.2.3.1(a) through 10.2.3.1(c). These tests are also discussed in detail in Volume 1, Section 6.8. The additional unidirectional laminate design property tests needed when a 3-D (thick-section) analysis is required are summarized in Figure 10.2.3.1(d) and described in detail in Figures 10.2.3.1(e) and 10.2.3.1(f). Test methods available to obtain these properties are summarized in Table 10.2.3.1(a). Further test method development is needed for tension and compression testing in the 3 or through-thickness direction.

For oriented laminates, the additional design properties tests needed in addition to the 2-D tests for a 3-D analysis are summarized in Figure 10.2.3.1(g). The 3-D through the thickness stiffnesses can also be predicted from the unidirectional lamina stiffnesses by the methods discussed in Section 10.2.4 (Theoretical Property Determination). Table 10.2.3.1(b) summarizes the test methods available for determining 3-D properties for an oriented laminate. Furthermore, test method development is also needed for tension and compression testing in the z-thickness direction similar to the need for unidirectional laminate testing.

An example of representative thick-section composite properties for an intermediate modulus carbon/epoxy material system are presented in Tables 10.2.3.1(c) and (d) for the unidirectional lamina and [0/90] oriented laminate. The lamina properties were taken from Reference 10.2.3.1(a) and the [0/90] data were obtained by a Hercules test program from an 80-ply (t=0.59 in., 15mm) fiber-placed, autoclave-cured laminate (Reference 10.2.3.1(b)).

Tables 10.2.3.1(a) and (b) identify three uniaxial compressive test methods for testing composites greater than 0.250 inches (6.35 mm) in thickness. Both the David Taylor Research Center (DTRC) and the Alliant Techsystems testing fixtures, which are shown in Figures 10.2.3.1(h) and 10.2.3.1(i), respectively (see References 10.2.3.1(a) and 10.2.3.1(c), respectively), were developed for uniaxial compression testing of thick prismatic columnar shaped composite material specimens. The US Army Research Laboratory - Materials Directorate (ARL) (Reference 10.2.3.1(d)) test method utilizes a cubic specimen loaded directly between two steel platens with no associated fixturing. The development of compression data relative to the different material orientations identified in Tables 10.2.3.1(a) and (b) is accomplished through independent, successive uniaxial load applications. Successive uniaxial compression tests, that consist of one-directional load applications per material orientation, can be undertaken with conventional, medium-to-high capacity load frames. With proper care and specimen fixturing, these tests may also be used for determining unidirectional compressive material strengths and failure characteristics.

The primary feature that both the DTRC and the Alliant Techsystems test fixtures provide is that they have been developed for maintaining proper gripping and alignment of the test specimens as well as providing constraints to minimize any potential specimen end brooming (specimen splitting) under compressive load applications. Any potential onset of apparent, specimen end splitting and fixture-induced test specimen material cracking, may cause significant material strength reductions. Special tabbing as well as associated specimen-tabbing connection detail may be required for some uniaxial compression testing of thick composites.

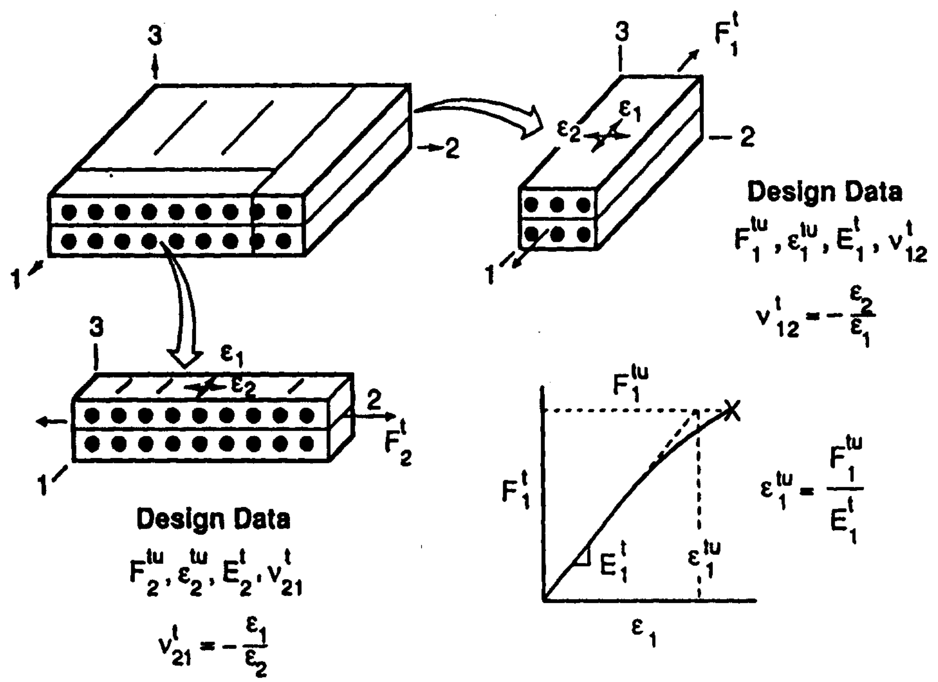


FIGURE 10.2.3.1(a) *Unidirectional laminate in-plane tensile design properties.*

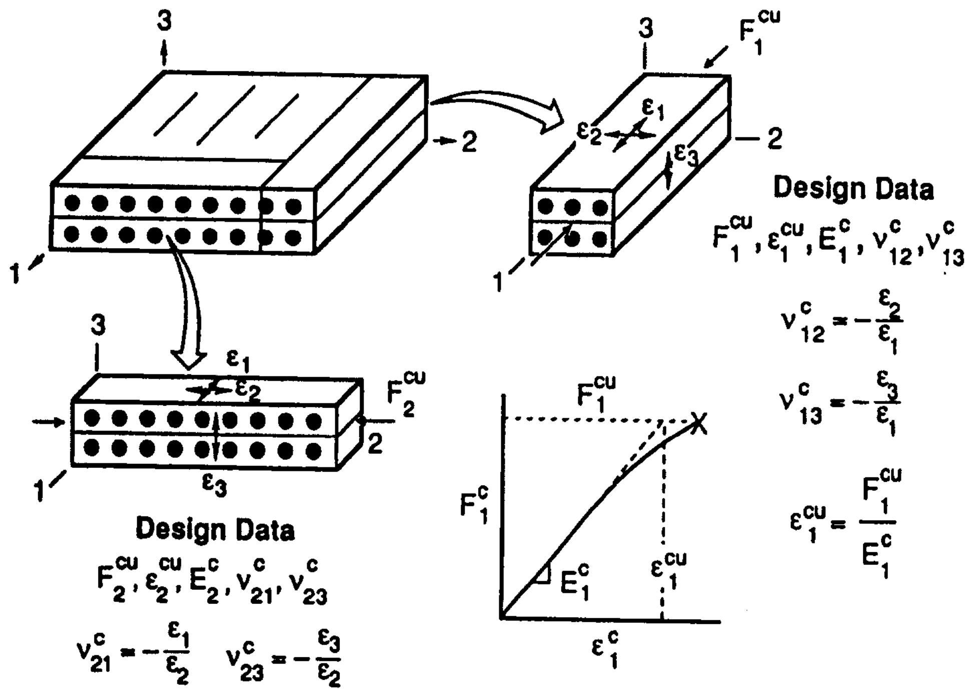


FIGURE 10.2.3.1(b) *Unidirectional laminate in-plane compressive design properties.*

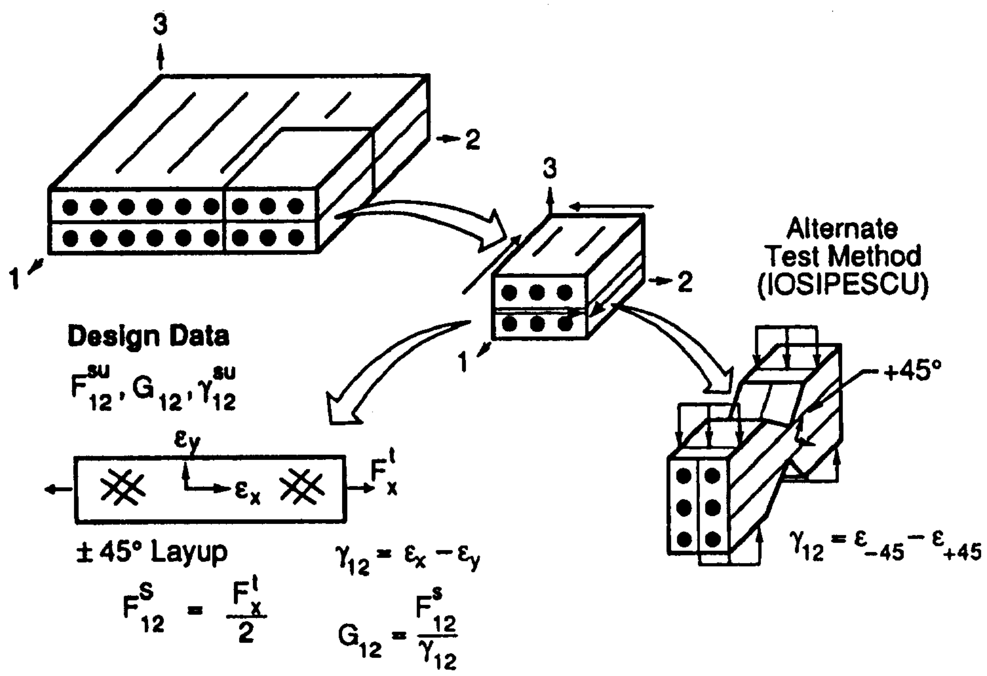


FIGURE 10.2.3.1(c) *Unidirectional laminate in-plane shear design properties.*

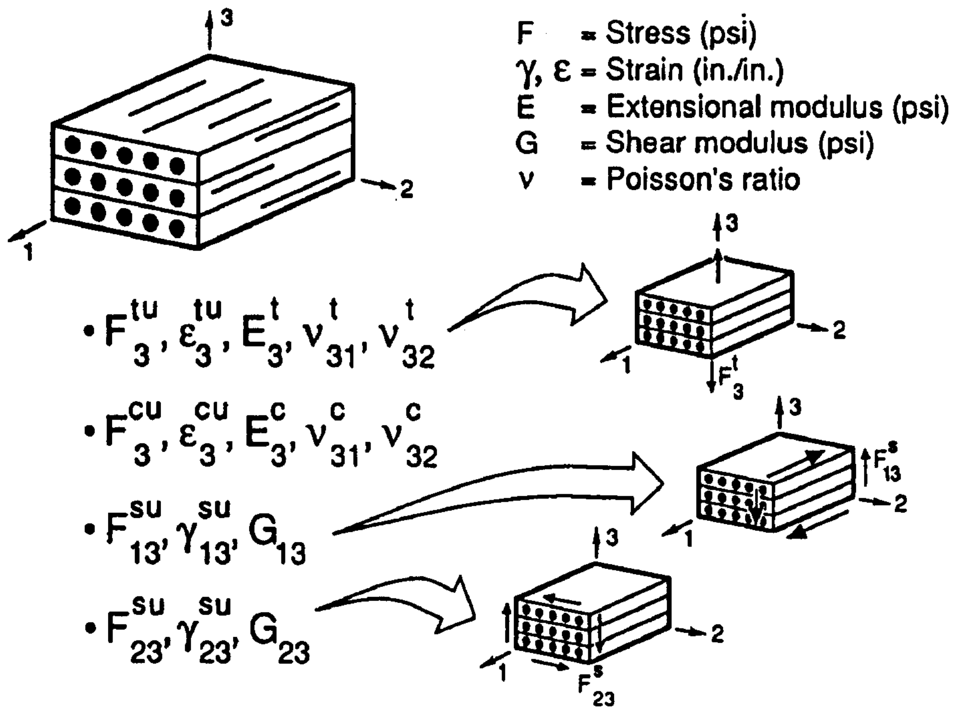


FIGURE 10.2.3.1(d) *Unidirectional laminate thickness direction design properties.*

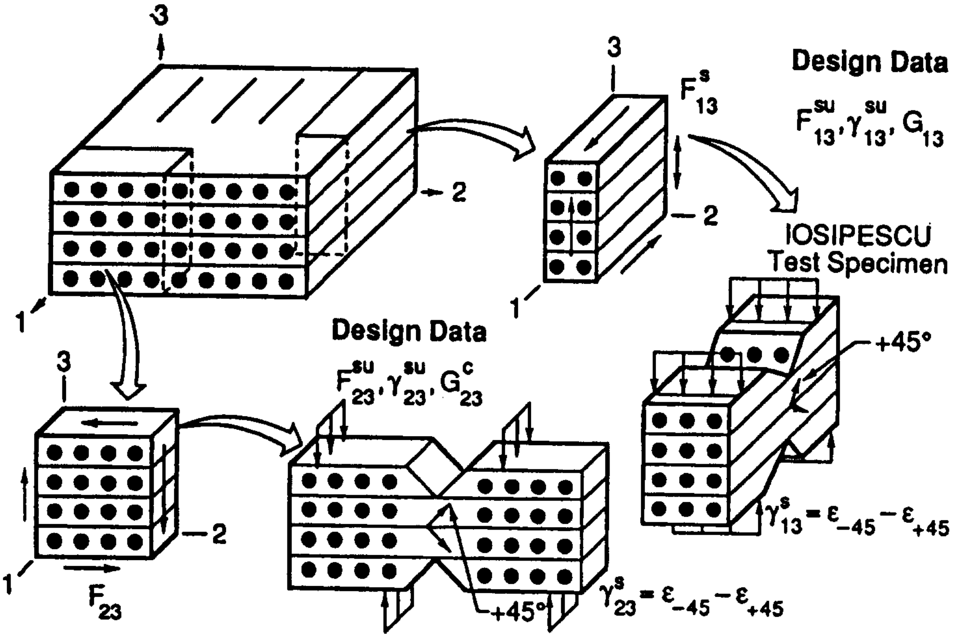


FIGURE 10.2.3.1(e) *Unidirectional laminate design properties for shear thickness direction.*

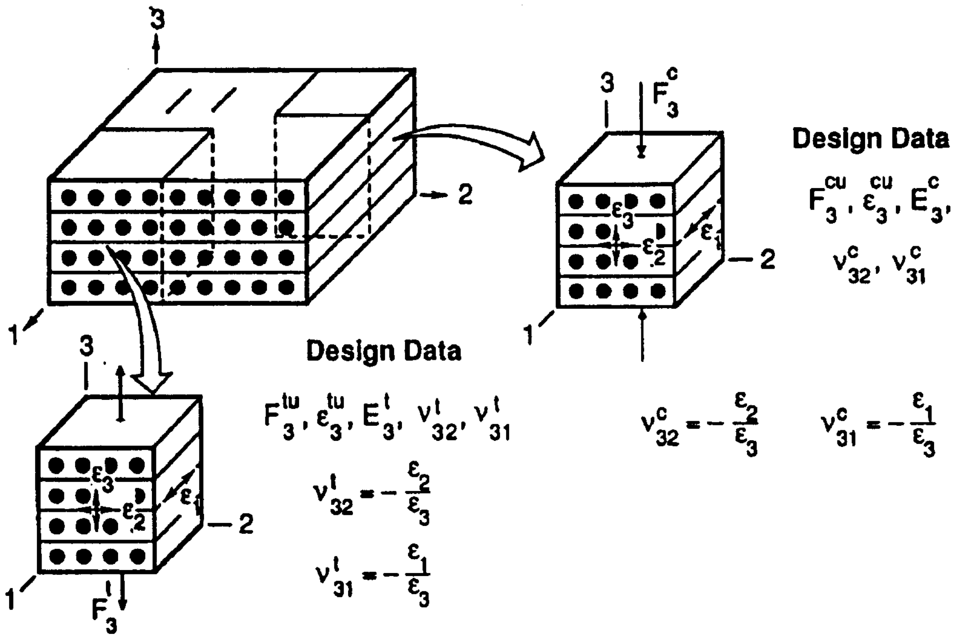
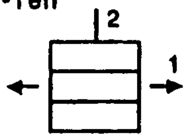
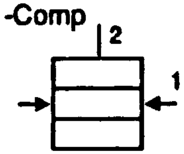
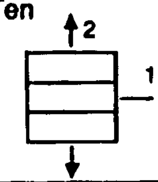
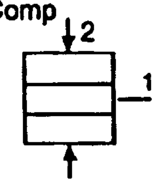
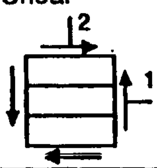
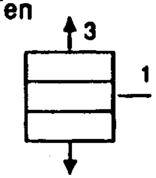
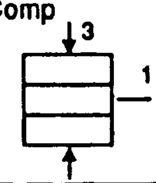
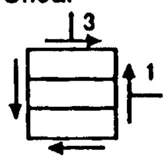
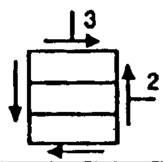


FIGURE 10.2.3.1(f) *Unidirectional laminate tensile and compressive design properties in thickness direction.*

TABLE 10.2.3.1(a) *Test methods available for determining 3-D laminate properties.*

Loading	Inplane Property	Test Method
1-Ten 	F_1^{tu} ε_1^{tu} E_1^t ν_{12}^t	ASTM D3039 SACMA SRM-4
1-Comp 	F_1^{cu} ε_1^{cu} E_1^c ν_{12}^c ν_{13}^c	ASTM D3410 SACMA SRM-1 ALLIANT TECHSYSTEMS DTRC ARL
2-Ten 	F_2^{tu} ε_2^{tu} E_2^t ν_{21}^t	ASTM D3039 SACMA SRM-4
2-Comp 	F_2^{cu} ε_2^{cu} E_2^c ν_{21}^c ν_{23}^c	ASTM D3410 SACMA SRM-1 ALLIANT TECHSYSTEMS DTRC ARL
12-Shear 	F_{12}^{su} γ_{12}^{su} G_{12}	ASTM D3518 SACMA SRM-7

Loading	Out-of-plane Property	Test Method
3-Ten 	F_3^{tu} ε_3^{tu} E_3^t ν_{31}^t ν_{32}^t	To Be Developed
3-Comp 	F_3^{cu} ε_3^{cu} E_3^c ν_{31}^c ν_{32}^c	To Be Developed
13-Shear 	F_{13}^{su} γ_{13}^{su} G_{13}^t	ASTM D2344 SACMA SRM-8 IOSIPESCU
23-Shear 	F_{23}^{su} γ_{23}^{su} G_{23}	IOSIPESCU

Notes:

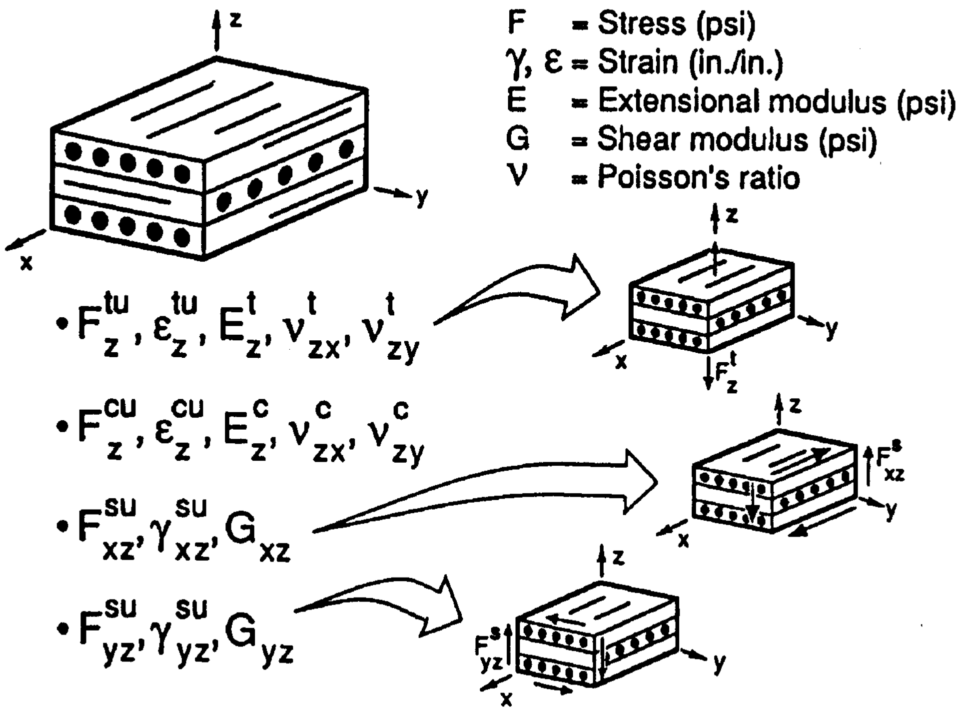
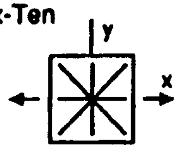
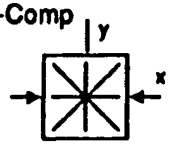
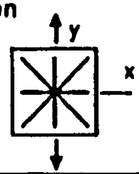
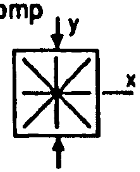
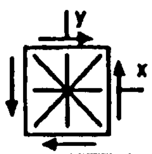
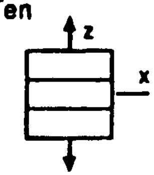
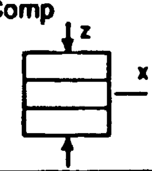
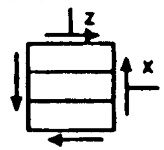
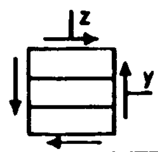


FIGURE 10.2.3.1(g) *Oriented laminate thickness direction design properties.*

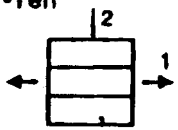
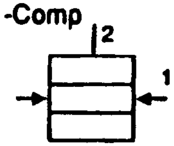
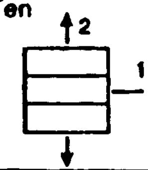
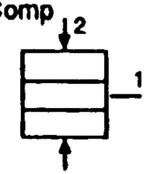
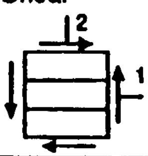
TABLE 10.2.3.1(b) *Test methods available for determining 3-D lamina properties.*

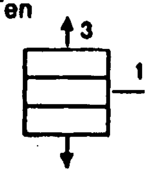
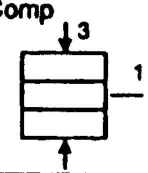
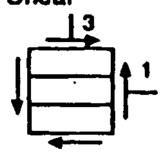
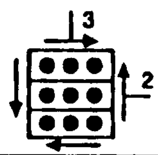
Loading	Inplane Property	Test Method
x-Ten 	F_x^{tu} ε_x^{tu} E_x^t ν_{xy}^t	ASTM D3039? SACMA SRM-4?
x-Comp 	F_x^{cu} ε_x^{cu} E_x^c ν_{xy}^c ν_{xz}^c	ASTM D3410? SACMA SRM-1? ALLIANT TECHSYSTEMS DTRC ARL
y-Ten 	F_y^{tu} ε_y^{tu} E_y^t ν_{yx}^t	ASTM D3039? SACMA SRM-1?
y-Comp 	F_y^{cu} ε_y^{cu} E_y^c ν_{yx}^c ν_{yz}^c	ASTM D3410? SACMA SRM-1? ALLIANT TECHSYSTEMS DTRC ARL
xy-Shear 	F_{xy}^{su} γ_{xy}^{su} G_{xy}	ASTM D4255? IOSIPESCU

Loading	Out-of-Plane Property	Test Method
z-Ten 	F_z^{tu} ε_z^{tu} E_z^t ν_{zx}^t ν_{zy}^t	To Be Developed
z-Comp 	F_z^{cu} ε_z^{cu} E_z^c ν_{zx}^c ν_{zy}^c	To Be Developed
xz-Shear 	F_{xz}^{su} γ_{xz}^{su} G_{xz}	ASTM D2344? SACMA SRM-8? IOSIPESCU
yz-Shear 	F_{yz}^{su} γ_{yz}^{su} G_{yz}	IOSIPESCU

Notes:
? - Applicability depends on laminate layup configuration.

TABLE 10.2.3.1(c) *Intermediate modulus carbon/epoxy lamina typical 3-D properties.*

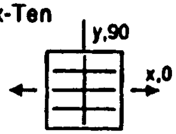
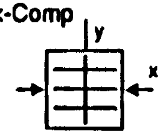
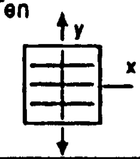
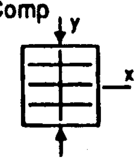
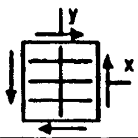
Loading	Inplane Property	RT/ Dry
1-Ten 	F_1^{tu} ε_1^{tu} E_1^t ν_{12}^t	250. ksi (1720 MPa) 15200 με 16.5 Msi (114 GPa) 0.33
1-Comp 	F_1^{cu} ε_1^{cu} E_1^c ν_{12}^c ν_{13}^c	170. ksi (1170 MPa) 10300 με 16.5 Msi (114 GPa)
2-Ten 	F_2^{tu} ε_2^{tu} E_2^t ν_{21}^t	8.00 ksi (55.2 MPa) 5700 με 1.40 Msi (9.65 GPa)
2-Comp 	F_2^{cu} ε_2^{cu} E_2^c ν_{21}^c ν_{23}^c	30.0 ksi (207 MPa) 21500 με 1.40 Msi (9.65 GPa)
12-Shear 	F_{12}^{su} γ_{12}^{su} G_{12}	15.0 ksi (103 MPa) 17000 με 0.87 Msi (6.0 GPa)

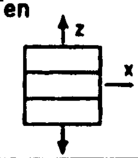
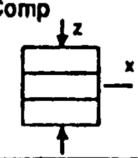
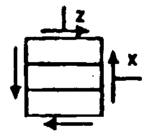
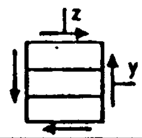
Loading	Out-of-plane Property	RT/ Dry
3-Ten 	F_3^{tu} ε_3^{tu} E_3^t ν_{31}^t ν_{32}^t	8.00 ksi (55.2 (MPa) 5700 με 1.40 Msi (9.65 GPa)
3-Comp 	F_3^{cu} ε_3^{cu} E_3^c ν_{31}^c ν_{32}^c	30.0 ksi (207 MPa) 21500 με 1.40 Msi (9.65 GPa)
13-Shear 	F_{13}^{su} γ_{13}^{su} G_{13}^t	12.0 ksi (82.7 MPa) 4000 με 0.87 Msi (6.0 GPa)
23-Shear 	F_{23}^{su} γ_{23}^{su} G_{23}	12.0 ksi (82.7 MPa) 22000 με 0.55 Msi (3.8 GPa)

Notes:

1. **Transverse isotropy assumed in 2-3 plane for stiffness, strength, strain.**
2. **Failure strain = strength/modulus.**
3. **60% fiber volume.**

TABLE 10.2.3.1(d) *Intermediate modulus carbon/epoxy [0_3,90] laminate typical 3-D properties.*

Loading	Inplane Property	RT/ Dry
x-Ten 	F_x^{tu} ε_x^{tu} E_x^t ν_{xy}^t	140. ksi (965 MPa) 9330 με 15.0 Msi (103 GPa) 0.10
x-Comp 	F_x^{cu} ε_x^{cu} E_x^c ν_{xy}^c ν_{xz}^c	111 ksi (765 MPa) 8600 με 12.9 Msi (88.9 GPa) 0.12
y-Ten 	F_y^{tu} ε_y^{tu} E_y^t ν_{yx}^t	35.0 ksi (241 MPa) 6210 με 5.64 Msi (38.9 GPa) 0.03
y-Comp 	F_y^{cu} ε_y^{cu} E_y^c ν_{yx}^c ν_{yz}^c	72.9 ksi (503 MPa) 12900 με 5.66 Msi (39.0 GPa) 0.029
xy-Shear 	F_{xy}^{su} γ_{xy}^{su} G_{xy}	15.3 ksi (105 MPa) 22000 με 0.70 Msi (4.8 GPa)

Loading	Out-of-Plane Property	RT/ Dry
z-Ten 	F_z^{tu} ε_z^{tu} E_z^t ν_{zx}^t ν_{zy}^t	3.40 ksi (23.4 MPa) 3040 με 1.12 Msi (7.72 GPa)
z-Comp 	F_z^{cu} ε_z^{cu} E_z^c ν_{zx}^c ν_{zy}^c	60.0 ksi (414 MPa) 3660 με 1.64 Msi (11.3 GPa)
xz-Shear 	F_{xz}^{su} γ_{xz}^{su} G_{xz}	4.06 ksi (28.0 MPa) 7700 με 0.53 Msi (3.7 GPa)
yz-Shear 	F_{yz}^{su} γ_{yz}^{su} G_{yz}	6.15 ksi (42.4 MPa) 9300 με 0.66 Msi (4.6 GPa)

Notes:
1. [0_3,90] laminate (t =.59 in.) average properties from reference 4, fiber volume = 61.4%, void = 0.04%.
2. Fiber placed, autoclave cured, flat panel data, 5-7 specimen average.
3. Failure strain = strength/modulus.

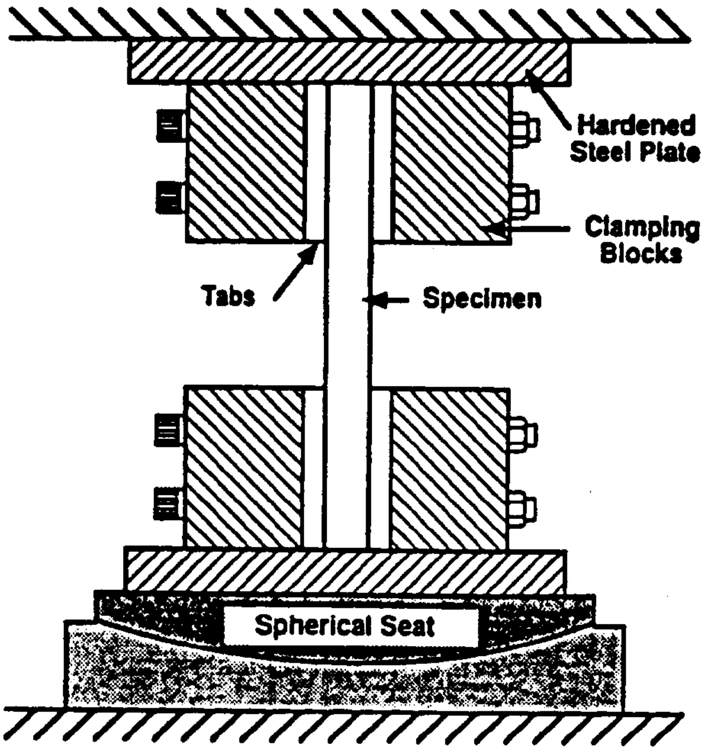


FIGURE 10.2.3.1(h) *Uniaxial thick-section compression test fixture - David Taylor Research Center (DTRC).*

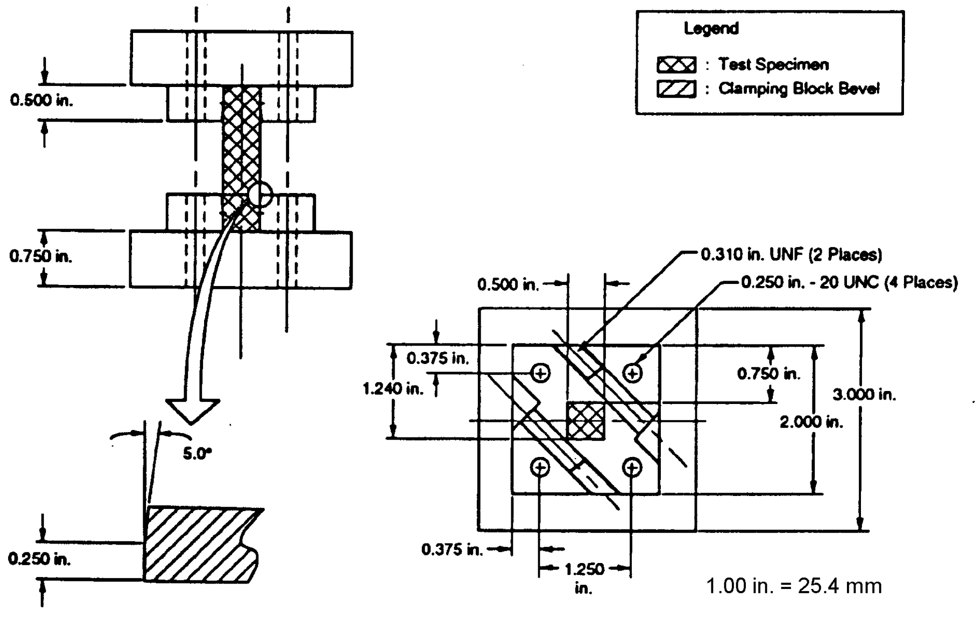


FIGURE 10.2.3.1(i) *Uniaxial thick-section compression test fixture - Alliant Techsystems Inc.*

10.2.3.2 Multiaxial tests

The purpose of this section is to provide information regarding multiaxial material testing methods. Some of these techniques, such as the two-dimensional methods (biaxial load applications), may be used for testing both thick and thin section composite materials. *However, the three-dimensional tests are primarily aimed at evaluating thick-section composite specimen material properties.* The importance of multiaxial testing becomes apparent when considering the need to evaluate the response of lamina and laminates to complex three-dimensional loads that result from service conditions. Multiaxial testing can help identify actual material strengths and failure mechanisms under properly proportioned loadings that simulate actual service conditions. Furthermore, multiaxial testing is recommended since the ability to predict the response of composites to multiaxial loadings has not been validated.

Currently, there is only limited experimental testing capability available to undertake all of the necessary work that is required to obtain a multidirectional material response data base. The testing procedures for thick composites are somewhat difficult to execute, have not yet been fully verified, and as such represent a major part of current and future research in themselves. However, the recently developed multiaxial testing techniques have been shown to be necessary in the determination of basic thick composite material parameters and actual material responses. These tests are also important in that the test results support the development of general and reliable three-dimensional numerical modeling, design, and analysis capabilities (i.e., finite element, boundary element, etc.) and failure theories for thick section composites in structural applications.

There are in current use two distinctively different multiaxial composite material testing techniques, associated mechanical testing load frames, and specimen fixturing arrangements. One method utilizes testing machines that apply loads/displacements along primary, mutually orthogonal coordinate axes to lineal test specimens. This broad class of machines consists of planar biaxial machines (Figure 10.2.3.2(a)), and true triaxial test frames (Figure 10.2.3.2(b)). The second method employs a class of machines that apply loads/displacements on tubular test specimens. The biaxial machines consist of a basic uniaxial - universal testing machine that has the additional capability to also apply a torque about the primary axis of the cylindrical specimen. The corresponding triaxial machine (Figure 10.2.3.2(c)) is similar to the biaxial test frame except that it has the added capacity to also apply either an internally or externally induced pressure differential across the wall of the cylindrical test specimen.

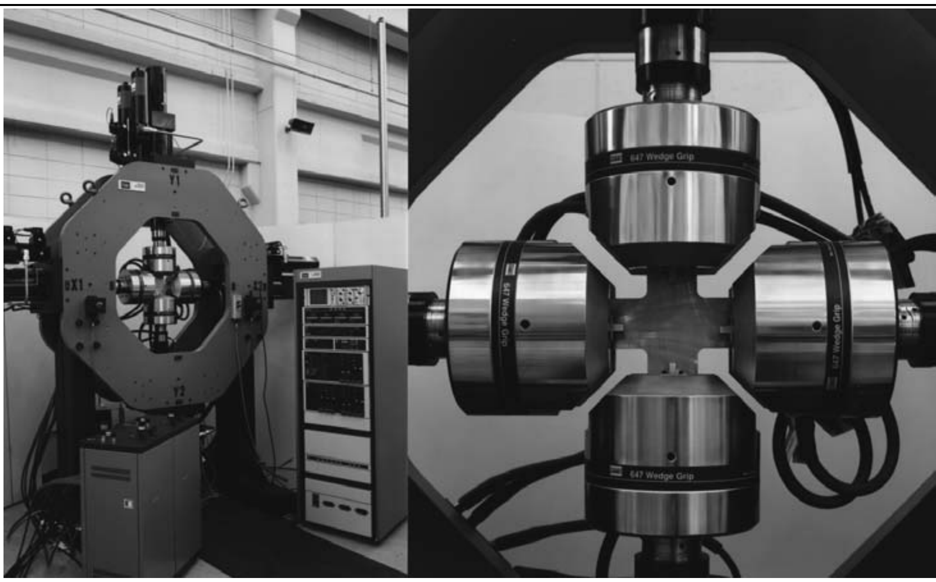


FIGURE 10.2.3.2(a) *MTX biaxial tension/compression testing system.*

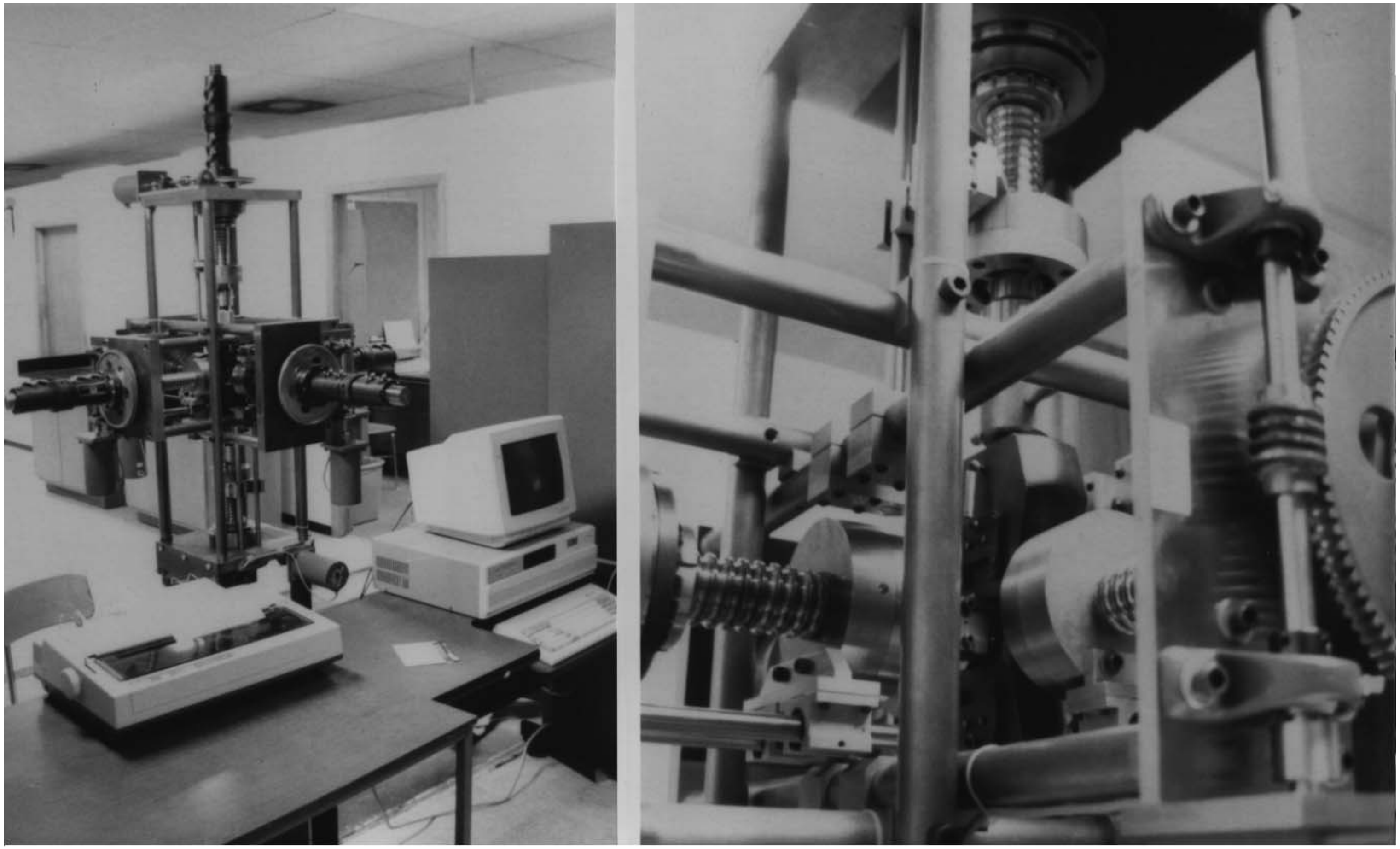


FIGURE 10.2.3.2(b) *Alliant Techsystems - University of Wyoming triaxial tension/compression testing system.*

FIGURE 10.2.3.2(c) *Three-dimensional axial/torsion pressure testing systems.*

10.2.3.2.1 Lineal test specimens/techniques

This material testing method utilizes the lineal test specimens, shown in Figure 10.2.3.2.1, such as cruciform or plate configured specimens for biaxial testing, and cubes or parallelopipeds for three-dimensional load applications.

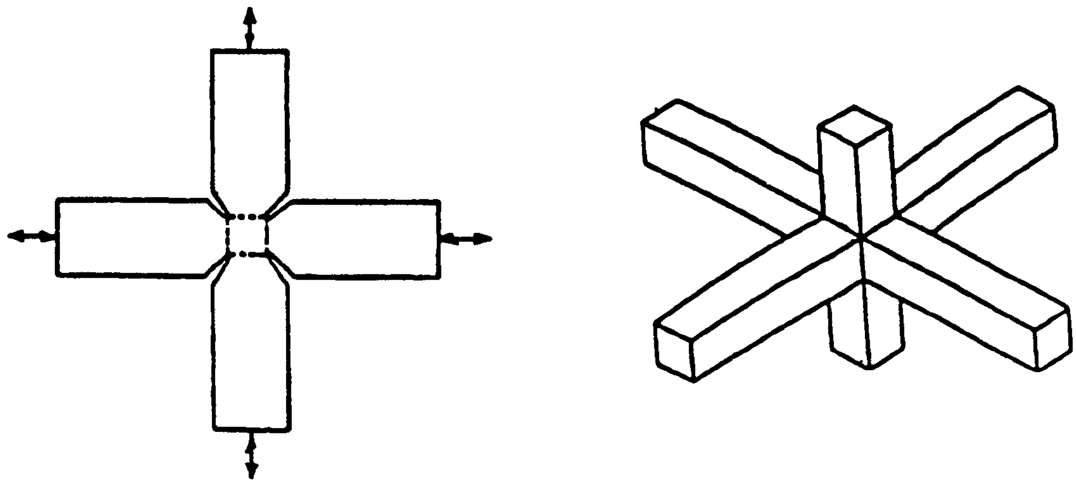


FIGURE 10.2.3.2.1 *Lineal biaxial test specimen geometries.*

Simultaneous, multiaxial tension/compression testing may be undertaken by applying loads along the principal, mutually orthogonal axes of the 2-D and 3-D specimens. Multiaxial testing is necessary for determining actual material strength/failure envelopes as well as for identifying failure mechanisms. This data is required in developing true multidirectional material constitutive equations and appropriate failure criteria.

There are available commercially fabricated, true biaxial machines for testing cruciform or plate configured material test specimens. These machines are typically of the servohydraulic-actuated type. There also exist special, non-commercially built, screw driven biaxial load frames. Both of these biaxial machine types are capable of simultaneously inducing tensile and/or compressive loads along two orthogonal axes. Thus, these load frames can be used to develop any general biaxial normal stress field within the test region of the material specimen. Special specimen fixturing, such as brush/comb flexible tabbing, has been developed and may be required to permit unrestricted in-plane movement and transverse constraints in order to minimize out-of-plane bending in biaxial tension/compression testing. This flexible specimen tabbing operates in a similar fashion as the brush/bearing platens typically used in compression testing of concrete.

True triaxial machines have also become available. These load frames have the capability of testing cubic anisotropic material specimens. These multidirectional, material testing machines may be either servo-hydraulically actuated or screw driven. Both of these types of three-dimensional machines may be used to apply any general combination of three-dimensional normal stress states to tabbed cubic test specimens. To the best of our knowledge, no comprehensive three-dimensional composite material testing has yet been undertaken with this equipment since special test specimen fixturing for these machines is currently under development and calibration of the load frames is in progress.

Both biaxial and triaxial machines require control systems that essentially maintain the test specimen centroid in a stationary position. This computer software - load frame control is a necessary feature in that it is recommended that the specimen not be subjected to unwanted eccentric loading conditions. Lack of proper test frame displacement or load control may produce erroneous test measurements, inappropriate material failure mechanisms, as well as failures occurring outside the instrumented gage areas. In summary, the proper utilization of these one-, two-. and three-dimensional load frames requires special test specimen holding fixtures, well-designed specimen geometries, and effective tabbing and/or specimen end constraining methods. Extreme care has to be exercised in designing test specimens, fixtures, tabbing, and load application methods in order to avoid developing undesirable edge or end effects along with stress concentrations. The three-dimensional test method, described above, is often referred to as a true triaxial method since the cubical test specimen geometry permits complete freedom as to the fiber lay-up orientations in relation to the load application axes.

10.2.3.2.2 Cylindrical test specimens/techniques

To date, the most frequently used multiaxial, two- and three-dimensional, composite material testing method utilizes cylindrical test specimens shown in Figure 10.2.3.2.2. Predominantly, these test specimens are thin-walled tubes. There are well over a hundred commercially built biaxial machines which can apply an axial load (tension or compression) in conjunction with a torsional twisting loading about the longitudinal axis of cylindrical test specimens.

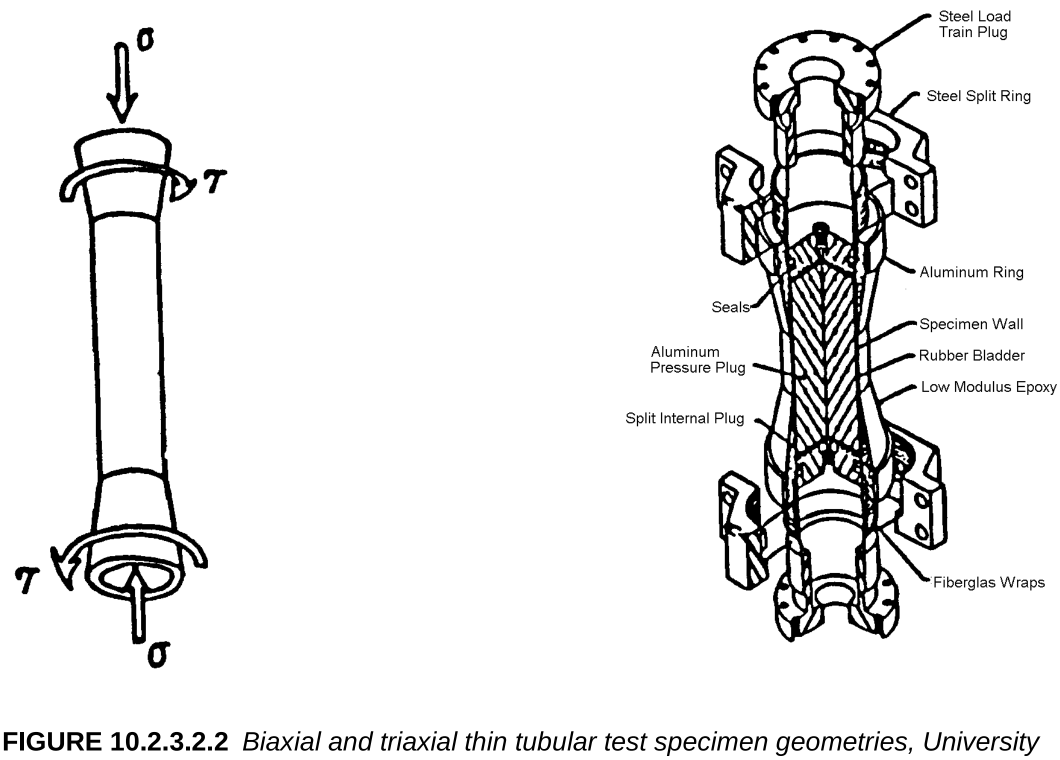


FIGURE 10.2.3.2.2 *Biaxial and triaxial thin tubular test specimen geometries, University of Utah triaxial specimen fixturing.*

The triaxial machines are similar to the 2-D test frames in their axial and torsional loads application utility. However, these load frames also have the additional capability of applying either an internal or external hydraulic pressurization across the wall thickness of hollow cylindrical specimens. By the very nature of hoop construction lay-ups of composite material cylinders, it would appear that this testing technique is very well suited for investigating material parameters and failure mechanisms of filament-wound test specimens. Typically, these cylindrical specimens do not exhibit edge effects in the gage section due to the geometric hoop continuity of cylindrical specimens. However, end effects such as brooming and shearing may be a problem and require careful structural design and analyses of the connection detail and specimen configuration. The potential occurrence of structural instability such as buckling of the cylindrical test specimens, that are subjected to either an individual or a combination of axial, torsional, and pressurization loadings is a major consideration with this testing method. The development of any structural buckling of the test cylinders would mask material strength measurements. It should also be noted that this multiaxial testing technique has been used primarily for investigating only thin-walled tubular specimens.

10.2.4 Theoretical property determination

In considering the use of theoretical procedures to determine the mechanical properties of composite materials the most fundamental level that can be addressed is that of the individual constituents, or the micromechanics level. A theoretical development of composite micromechanics is summarized in Volume 3 Section 5.2.2.1 of this Handbook and in Section 4 of Reference 10.2.4. 3-D laminate properties can be determined from constituent data using micromechanical analyses and these references should be consulted for additional information and references on this topic.

Since properties at the lamina or laminate level are typically used for the analysis of a composite structure, only these properties will be discussed in this section and all analyses considered are linear elastic.

10.2.4.1 3-D lamina property determination

In Section 10.2, the nine independent elastic material properties required for a 3D lamina based analysis were listed as:

$$E_1, E_2, E_3, G_{12}, G_{13}, G_{23}, \nu_{12}, \nu_{13}, \nu_{23} \qquad 10.2.4.1(a)$$

Of these properties E_1, E_2, G_{12} and ν_{12} can be readily generated by conventional experimental methods. Methods for determining out-of-plane properties are discussed in Section 10.2.3. In the absence of experimental data for these properties, the assumption of transverse isotropy in the 2-3 plane is often reasonable. The validity of this assumption has been demonstrated by the experimental data available in References 10.2.4.1(a) - (c). The assumption of transverse isotropy implies

$$E_3 = E_2, \quad G_{13} = G_{12}, \quad \nu_{13} = \nu_{12}, \quad \text{and} \quad G_{23} = \frac{E_2}{2(1+\nu_{23})} \qquad 10.2.4.1(b)$$

Even with this simplifying assumption ν_{23} must be measured or estimated for full knowledge of the nine independent elastic material properties.

Values for ν_{23} that have been experimentally determined have been reported in References 10.2.4.1(a) - (c). A value for ν_{23} determined in compression for T300/5208 is reported in Reference 10.2.4.1(a). A value for ν_{23} determined in tension and compression for T300/5208 is reported in Reference 10.2.4.1(b). Values for ν_{23} determined in compression for AS4/3501-6 and S2/3501-6 are reported in 10.2.4.1(c) and can be found in Table 10.2.4.1.

The need for all nine independent elastic constants does not imply that a 3-D analysis will be sensitive to the choice of the through-thickness material properties just discussed. For instance, a choice of ν_{23} of 0.50 versus 0.40 (a 20% difference) may only result in a 2% difference in the stress or strain results from a laminate or structural analysis. This sensitivity of a particular analysis to a particular material property should be evaluated through a parametric study if the value of the property is uncertain.

TABLE 10.2.4.1 *3-D elastic constants for carbon and S2 glass reinforced epoxy (Reference 10.2.4.1(c)), E and G in Msi (GPa).*

	AS4/3501-6 59.5% FVF	S2/3501-6 56.5% FVF
E_1 [1]	16.48 (113.6) (3.7)[2]	7.15 (49.3) (4.0)
E_2 [1]	1.40 (9.65) (3.6)	2.13 (14.7) (2.2)
E_3 [1]	1.40[3] (9.65)	2.13[3] (14.7)
ν_{12} [1]	0.334 (3.0)	0.296 (4.1)
ν_{13} [1]	0.328 (1.2)	0.306 (2.8)
ν_{23} [1]	0.540 (1.6)	0.499 (1.4)
G_{12}	0.87[4] (6.0)	0.98[4] (6.8)
G_{13}	0.87[5] (6.0)	0.98[4] (6.8)
G_{23}	0.45[6] (3.1)	0.71[4] (4.9)

1 E_1, E_2, ν_{12}, ν_{13}, and ν_{23} determined from thick, flat, compression test specimens
2 coefficient of variation (%)
3 E_3 assumed equal to E_2
4 G_{12} determined from $[\pm 45]_{2s}$ tension test
5 G_{13} assumed equal to G_{12}
6 G_{23} from assumption of transverse isotropy

Likewise, the use of a linear analysis when certain material properties are extremely nonlinear (i.e., in-plane and through-thickness shear modulus) may not affect laminate or structural analysis and this too should be considered in 3-D analysis.

10.2.4.2 3-D laminate property determination

As for the case of a 3-D lamina properties, Section 10.2 lists the nine independent elastic material properties required for a 3-D laminate based analysis as:

$$E_x, E_y, E_z, G_{xy}, G_{xz}, G_{yz}, \nu_{xy}, \nu_{xz}, \nu_{yz} \qquad 10.4.2.2(a)$$

E_x, E_y, G_{xy}, ν_y can be readily determined by conventional experimental or theoretical methods. Theoretically they can be determined using classical lamination theory as presented in Volume 3 Section 5.3.2 of this Handbook. The determination of the remaining out-of-plane laminate properties present a much greater challenge than for the in-plane properties. Little experimental data exists for out-of-plane laminate properties and the test methodologies used to generate them can be described as very specific to the programs they have been used for, such as those in References 10.2.4.1(a) - (c).

A number of methods have been developed to theoretically predict the out-of-plane properties based on in-plane lamina properties (References 10.2.4.2(a) - (h)). These methods basically replace a layered inhomogeneous media of orthotropic layers with a homogeneous anisotropic media. This replacement is termed "smearing" and the resulting effective material properties are referred to as "smeared properties". These smeared anisotropic properties are commonly used in the analysis of composite structures. If average, global stress states or average displacements are sufficient for the analysis being conducted then an analysis with smeared properties is all that would be needed. If local stress states are needed then other analyses techniques must be employed such as a "global-local" technique. In this approach smeared anisotropic properties are used to determine global stress states, then this information is used to interrogate stress states in specific regions of concern on a ply-by-ply basis, therefore avoiding the costly use of a ply-by-ply analysis for an entire structure made of a thick-section composite material. The use of this global-local analysis technique is commonly referred to as the most rational way to approach the problem of design and analysis for thick composite materials.

The solution methods available to generate smeared anisotropic 3-D properties range from approximate formulations (Reference 10.2.4.2(a)) to exact formulations not including bending-extensional coupling (Reference 10.2.4.2(c)). The exact solutions by Pagano (Reference 10.2.4.2(c)) and Sun (Reference 10.2.4.2(b)) lend themselves to simple programming on personal computers. In fact Trethewey et al. (Reference 10.2.4.2(d)) and Peros (Reference 10.2.4.2(e)) have encoded the Pagano solution while Sun has encoded his own solution for a personal computer.

Tables 10.2.4.2(a) and (b) contain 3D laminate elastic constants for six laminate configurations and two materials as determined by laminate plate theory (LPT), and by the Pagano, Sun, and Roy solutions (Reference 10.2.4.2(g), (h)). Table 10.2.4.1 lists the lamina input properties used in each of the analyses. The three exact solutions (LPT, Pagano, Sun) yield identical results for both in-plane and through thickness properties for all of the cases presented. The results from the approximate solution by Roy differ from the others in the z-direction properties up to 12% in some cases.

Data verifying the results of these analyses are limited due to the difficulty in generating 3D experimental data. Data that does exist is documented in References 10.2.4.1(a) - (c), 10.2.4.2(h) and (i). Table 10.2.4.2(c) contains a comparison of theoretical predictions using the linear elastic theory by Pagano and experimental data from Reference 10.2.4.1(c) and Reference 10.2.4.2(i).

TABLE 10.2.4.2(a) *3-D effective properties of various AS4/3501-6 laminates, continued on next page.*

Laminate Properties for AS4/3501-6, E and G in Msi												
	$[0_2/90]_s$				$[0/90]_{2s}$				$[0/90/\pm45]_s$			
	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy
E_x	11.5	11.5	11.5	11.5	9.01	9.00	9.00	9.00	6.68	6.68	6.68	6.67
E_y	6.48	6.47	6.47	6.47	9.01	9.00	9.00	9.00	6.68	6.68	6.68	6.68
E_z	--	1.80	1.80	1.65	--	1.82	1.82	1.60	--	1.82	1.82	1.61
ν_{xy}	0.073	0.073	0.074	0.072	0.052	0.052	0.053	0.052	0.297	0.297	0.298	0.296
ν_{xz}	--	0.488	0.489	0.402	--	0.506	0.507	0.438	--	0.375	0.376	0.318
ν_{yz}	--	0.519	0.520	0.465	--	0.506	0.508	0.427	--	0.375	0.376	0.317
G_{xy}	0.870	0.870	0.870	0.870	0.870	0.870	0.870	0.870	2.58	2.57	2.57	2.57
G_{xz}	--	0.664	0.664	0.780	--	0.593	0.593	0.612	--	0.593	0.593	0.627
G_{yz}	--	0.536	0.536	0.503	--	0.593	0.593	0.573	--	0.593	0.593	0.519

Laminate Properties for AS4/3501-6, E and G in Msi												
	$[\pm30]_{2s}$				$[\pm45]_{2s}$				$[\pm60]_{2s}$			
	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy
E_x	6.84	6.84	6.84	6.84	2.94	2.94	2.94	2.94	1.77	1.77	1.77	1.77
E_y	1.77	1.77	1.77	1.77	2.94	2.94	2.94	2.94	6.84	6.84	6.83	6.85
E_z	--	1.66	1.66	1.50	--	1.82	1.82	1.71	--	1.66	1.66	1.74
ν_{xy}	1.14	1.41	1.41	1.13	0.691	0.691	0.691	0.689	0.295	0.295	0.295	0.294
ν_{xz}	--	-0.095	-0.094	-0.197	--	0.165	0.165	0.211	--	0.390	0.390	0.434
ν_{yz}	--	0.390	0.390	0.434	--	0.165	0.165	0.211	--	-0.095	-0.095	-0.197
G_{xy}	3.43	3.43	3.42	3.42	4.28	4.28	4.27	4.27	3.43	3.43	3.42	3.42
G_{xz}	--	0.705	0.705	0.708	--	0.593	0.593	0.596	--	0.512	0.512	0.515
G_{yz}	--	0.512	0.512	0.515	--	0.593	0.593	0.596	--	0.705	0.705	0.708

TABLE 10.2.4.2(a) *3-D effective properties of various AS4/3501-6 laminates, concluded.*

Laminate Properties for AS4/3501-6, E and G in GPa												
	$[0_2/90]_s$				$[0/90]_{2s}$				$[0/90/\pm45]_s$			
	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy
E_x	79.3	79.3	79.3	79.3	62.1	62.1	62.1	62.1	46.1	46.1	46.1	46.0
E_y	44.7	44.6	44.6	44.6	62.1	62.1	62.1	62.1	46.1	46.1	46.1	46.1
E_z	--	12.4	12.4	11.4	--	12.5	12.5	11.0	--	12.5	12.5	11.1
ν_{xy}	0.073	0.073	0.074	0.072	0.052	0.052	0.053	0.052	0.297	0.297	0.298	0.296
ν_{xz}	--	0.488	0.489	0.402	--	0.506	0.507	0.438	--	0.375	0.376	0.318
ν_{yz}	--	0.519	0.520	0.465	--	0.506	0.508	0.427	--	0.375	0.376	0.317
G_{xy}	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	17.8	17.7	17.7	17.7
G_{xz}	--	4.58	4.58	5.38	--	4.09	4.09	4.22	--	4.09	4.09	4.32
G_{yz}	--	3.70	3.70	3.47	--	4.09	4.09	3.95	--	4.09	4.09	3.58

Laminate Properties for AS4/3501-6, E and G in GPa												
	$[\pm30]_{2s}$				$[\pm45]_{2s}$				$[\pm60]_{2s}$			
	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy
E_x	47.2	47.2	47.2	47.2	20.3	20.3	20.3	20.3	12.2	12.2	12.2	12.2
E_y	12.2	12.2	12.2	12.2	20.3	20.3	20.3	20.3	47.2	47.2	47.1	47.2
E_z	--	11.4	11.4	10.3	--	12.5	12.5	11.8	--	11.4	11.4	12.0
ν_{xy}	1.14	1.41	1.41	1.13	0.691	0.691	0.691	0.689	0.295	0.295	0.295	0.294
ν_{xz}	--	-0.095	-0.094	-0.197	--	0.165	0.165	0.211	--	0.390	0.390	0.434
ν_{yz}	--	0.390	0.390	0.434	--	0.165	0.165	0.211	--	-0.095	-0.095	-0.197
G_{xy}	23.6	23.6	23.6	23.6	29.5	29.5	29.4	29.4	23.6	23.6	23.6	23.6
G_{xz}	--	4.86	4.86	4.88	--	4.09	4.09	4.11	--	3.53	3.53	3.55
G_{yz}	--	3.53	3.53	3.55	--	4.09	4.09	4.11	--	4.86	4.86	4.88

TABLE 10.2.4.2(b) *3-D effective properties of various S2/3501-6 laminates, continued on next page.*

Laminate Properties for S2/3501-6, E and G in Msi												
	$[0_2/90]_s$				$[0/90]_{2s}$				$[0/90/\pm45]_s$			
	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy
E_x	5.52	5.52	5.52	5.52	4.68	4.68	4.68	4.68	3.89	3.89	3.89	3.89
E_y	3.83	3.83	3.83	3.83	4.68	4.68	4.68	4.68	3.89	3.89	3.89	3.89
E_z	--	2.38	2.38	2.30	--	2.40	2.40	2.29	--	2.40	2.40	2.32
ν_{xy}	0.166	0.166	0.166	0.165	0.136	0.136	0.136	0.135	0.281	0.281	0.281	0.280
ν_{xz}	--	0.405	0.405	0.359	--	0.435	0.435	0.393	--	0.362	0.362	0.329
ν_{yz}	--	0.459	0.459	0.427	--	0.435	0.435	0.392	--	0.362	0.362	0.329
G_{xy}	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	1.52	1.52	1.52	1.52
G_{xz}	--	0.870	0.870	0.918	--	0.823	0.823	0.830	--	0.823	0.823	0.838
G_{yz}	--	0.782	0.782	0.754	--	0.823	0.823	0.811	--	0.823	0.823	0.781

Laminate Properties for AS4/3501-6, E and G in Msi												
	$[\pm30]_{2s}$				$[\pm45]_{2s}$				$[\pm60]_{2s}$			
	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy
E_x	4.45	4.45	4.45	4.45	2.88	2.88	2.88	2.88	2.26	2.26	2.26	2.26
E_y	2.26	2.26	2.26	2.26	2.88	2.88	2.88	2.88	4.45	4.45	4.45	4.45
E_z	--	2.30	2.30	2.16	--	2.40	2.40	2.33	--	2.30	2.30	2.44
ν_{xy}	0.546	0.546	0.546	0.545	0.468	0.468	0.468	0.467	0.278	0.278	0.278	0.277
ν_{xz}	--	0.200	0.200	0.136	--	0.267	0.267	0.284	--	0.387	0.387	0.406
ν_{yz}	--	0.387	0.387	0.406	--	0.267	0.267	0.284	--	0.200	0.200	0.136
G_{xy}	1.79	1.79	1.79	1.79	2.06	2.06	2.06	2.06	1.79	1.79	1.79	1.79
G_{xz}	--	0.895	0.895	0.895	--	0.823	0.823	0.823	--	0.762	0.762	0.763
G_{yz}	--	0.762	0.762	0.763	--	0.823	0.823	0.823	--	0.985	0.985	0.895

TABLE 10.2.4.2(b) *3-D effective properties of various S2/3501-6 laminates, concluded.*

Laminate Properties for S2/3501-6, E and G in GPa												
	$[0_2/90]_s$				$[0/90]_{2s}$				$[0/90/\pm45]_s$			
	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy
E_x	38.1	38.1	38.1	38.1	32.3	32.3	32.3	32.3	26.8	26.8	26.8	26.8
E_y	26.4	26.4	26.4	26.4	32.3	32.3	32.3	32.3	26.8	26.8	26.8	26.8
E_z	--	16.4	16.4	15.9	--	16.5	16.5	15.8	--	16.5	16.5	16.0
ν_{xy}	0.166	0.166	0.166	0.165	0.136	0.136	0.136	0.135	0.281	0.281	0.281	0.280
ν_{xz}	--	0.405	0.405	0.359	--	0.435	0.435	0.393	--	0.362	0.362	0.329
ν_{yz}	--	0.459	0.459	0.427	--	0.435	0.435	0.392	--	0.362	0.362	0.329
G_{xy}	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	10.5	10.5	10.5	10.5
G_{xz}	--	6.00	6.00	6.33	--	5.67	5.67	5.72	--	5.67	5.67	5.78
G_{yz}	--	5.39	5.39	5.20	--	5.67	5.67	5.59	--	5.67	5.67	5.04

Laminate Properties for AS4/3501-6, E and G in GPa												
	$[\pm30]_{2s}$				$[\pm45]_{2s}$				$[\pm60]_{2s}$			
	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy	LPT	Pagano	Sun	Roy
E_x	30.7	30.7	30.7	30.7	19.9	19.9	19.9	19.9	15.6	15.6	15.6	15.6
E_y	15.6	15.6	15.6	15.6	19.9	19.9	19.9	19.9	30.7	30.7	30.7	30.7
E_z	--	15.9	15.9	14.9	--	16.5	16.5	16.1	--	15.9	15.9	16.8
ν_{xy}	0.546	0.546	0.546	0.545	0.468	0.468	0.468	0.467	0.278	0.278	0.278	0.277
ν_{xz}	--	0.200	0.200	0.136	--	0.267	0.267	0.284	--	0.387	0.387	0.406
ν_{yz}	--	0.387	0.387	0.406	--	0.267	0.267	0.284	--	0.200	0.200	0.136
G_{xy}	12.3	12.3	12.3	12.3	14.2	14.2	14.2	14.2	12.3	12.3	12.3	12.3
G_{xz}	--	6.17	6.17	6.17	--	5.67	5.67	5.67	--	5.25	5.25	5.26
G_{yz}	--	5.25	5.25	5.26	--	5.67	5.67	5.67	--	6.79	6.79	6.17

TABLE 10.2.4.2(c) *Comparison of theoretical and experimental laminate results $[0_2/90]_{ns}$ from Reference 10.2.4.1(c), $[0_3/90]_{ns}$ from Reference 10.2.4.2(i), E and G in Msi (GPa).*

	AS4/3501-6$[0_2/90]_{ns}$		S2 glass/3501-6$[0_2/90]_{ns}$		AS4/3501-6$[0_3/90]_{ns}$	
	Theoretical	Experimental	Theoretical	Experimental	Theoretical	Experimental
E_x	11.53 (79.5)	11.63[A] (80.2) [4.0][B][32]	5.52 (38.1)	5.82 (40.1) [6.9][32]	12.80 (88.3)	12.90[A] (88.9)
E_y	6.47 (44.6)		3.83 (26.4)		5.27 (36.3)	5.66[A] (39.0)
E_z	1.80 (12.4)		2.38 (16.4)		1.63 (11.2)	1.64[A] (11.3)
ν_{xy}	0.073	0.069[A] [6.7][7][C]	0.166	0.166 [4.3][7]	0.090	0.120[A]
ν_{xz}	0.488	0.469[A] [3.0][14]	0.405	0.363 [2.7][14]	0.440	---
ν_{yz}	0.519		0.459		0.452	---
G_{xy}	0.87 (6.0)		0.98 (6.8)		0.87 (6.0)	0.70[D] (4.8)
G_{xz}	0.73 (5.0)		0.78 (5.4)		0.72 (5.0)	0.53[D] (3.7)
G_{yz}	0.63 (4.3)		0.64 (4.4)		0.54 (3.7)	0.66[D] (4.6)

[A] data from thick, flat, compression test specimens
[B] coefficient of variation (%)
[C] number of data points in average
[D] data from Iosipescu shear test specimens

10.2.5 Test specimen design considerations

This section is reserved for future work.

10.3 STRUCTURAL ANALYSIS METHODS FOR THICK-SECTION COMPOSITES

This section is reserved for future work.

10.4 PHYSICAL PROPERTY ANALYSIS REQUIRED FOR THICK-SECTION COMPOSITE THREE-DIMENSIONAL ANALYSIS

This section is reserved for future work.

10.5 PROCESS ANALYSIS METHODS FOR THICK-SECTION COMPOSITES

This section is reserved for future work.

10.6 FAILURE CRITERIA

This section is reserved for future work.

10.7 FACTORS INFLUENCING THICK-SECTION ALLOWABLES (I.E., SAFETY MARGINS)

This section is reserved for future work.

10.8 THICK LAMINATE DEMONSTRATION PROBLEM

This section is reserved for future work.

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