DATA REDUCTION

3-Point Bending

Modulus

$$E_x = \frac{\sigma_x}{\varepsilon_x}$$

Strain Gage Method:

$$E_x = \frac{\frac{3PL}{2bh^2}}{\varepsilon_x}$$

Deflection Method:

$$E_x = \frac{PL^3}{4bh^3\delta}(1+S)$$

Where $S = \dfrac{3h^2 E_x}{2L^2 G_{xz}}$

δ = deflection of beam at L/2

ANALYSIS OF RESULTS

Four-Point Bending

Assumptions

- Homogeneous
- $E_c = E_t$
- Small deflection

Euler Beam Solution

$$\sigma = \frac{Mc}{I} \longrightarrow \sigma = \frac{3PL}{4bh^2}$$

DATA REDUCTION

4-Point Bending

Modulus $E_x = \frac{\sigma_x}{\varepsilon_x}$

Strain Gage Method $\longrightarrow$ $E_x = \dfrac{\frac{3PL}{4bh^2}}{\varepsilon_x}$

Deflection Method $\downarrow$

$$E_x = \frac{PL^3}{64\,bh^3\,\delta}\,(11 + 8S)$$

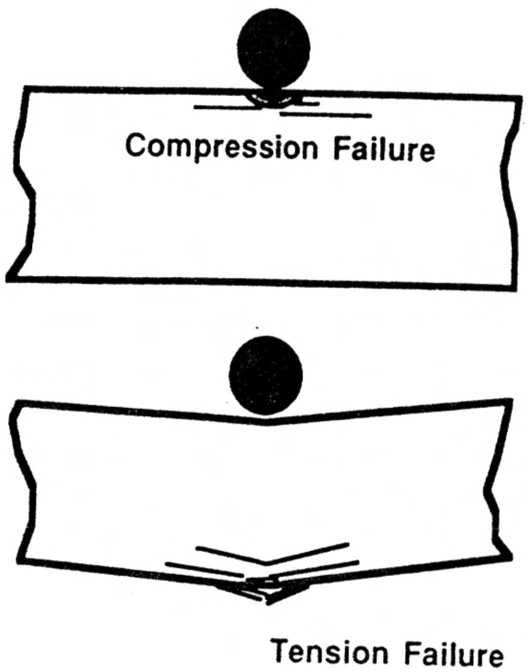
Where $S = \dfrac{3h^2 E_x}{2L^2 G_{xz}}$

δ = deflection of beam at L/2

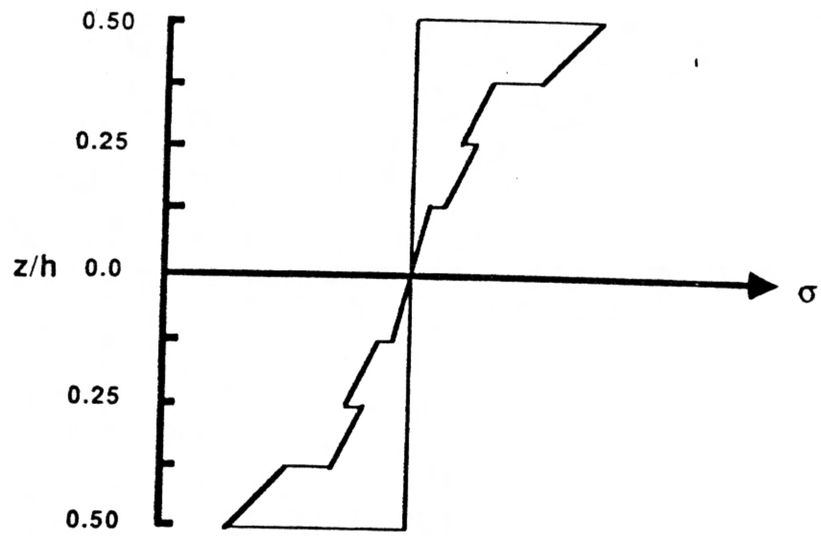
CHARACTERISTICS OF SHEAR CORRECTION

- Neglecting S $\longrightarrow$ $E_{apparent} < E_{tensile}$
- Minimizing S
  - Increasing L/h $\longrightarrow$ Decrease Influence of S
  - Decreasing G_{xz} (for E_x constant) $\longrightarrow$ Increasing Influence of S

FAILURE MODES



Laminate Stresses



[0 / 45 / -45 / 90]$_s$

COMPRESSION TESTS

ASTM D3410
ASTM D695

UNAXIAL COMPRESSION

0° Coupon Properites

E_1^c – Compression Modulus in Fiber Direction

S_1^c – Compression Strength in Fiber Direction

ε_1^c – Ultimate Compressive Strain in Fiber Direction

90° Coupon Properties

E_2^c – Compression Modulus Transverse to Fibers

S_2^c – Compression Strength Transverse to Fibers

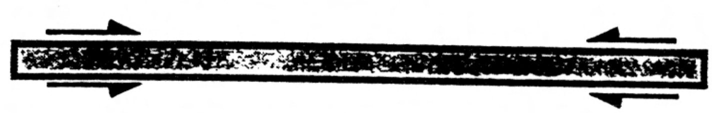
ε_2^c – Ultimate Compressive Strain Transverse to Fibers

CRITICAL ASPECTS OF COMPRESSION TESTING

- LOAD INTRODUCTION
  - Alignment
  - Damage Initiation
- TEST GEOMETRY
  - Uniform Stress
  - Fixity
  - Stability

COMPRESSION TESTING

LOADING THROUGH SHEAR



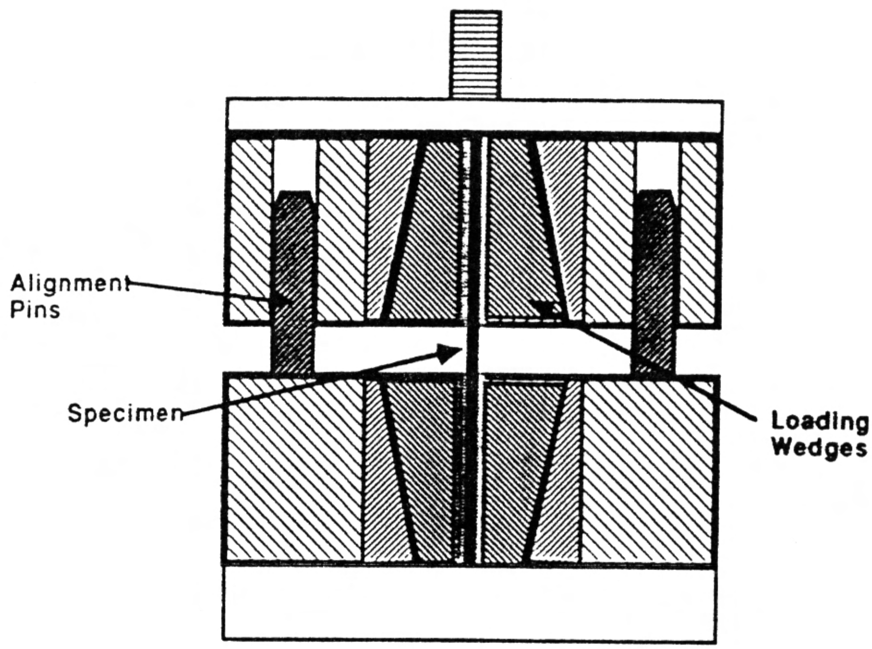
Positive

- Prevents loading damage

Negative

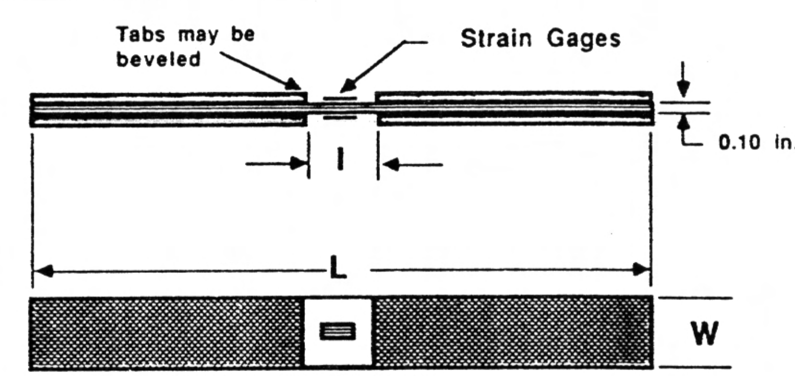
- Stress concentration
- Complex fixturing
- Potential tab bond failure

IITRI COMPRESSION FIXTURE



IITRI

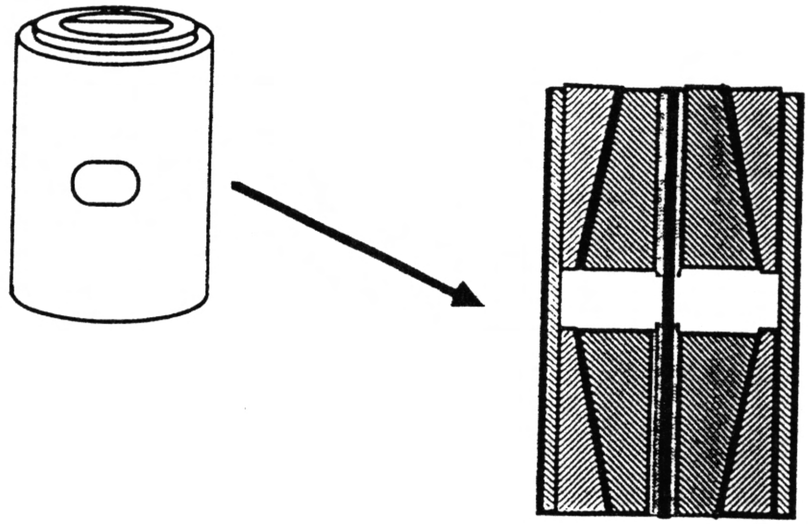
SPECIMEN GEOMETRY



W = 0.5 in. (90° Specimen)
W = 0.25 in. (0° Specimen)

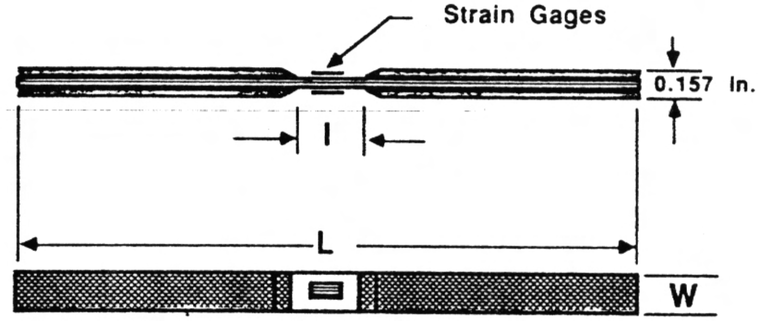
l = 0.5 in. (nominal)
L = 5 in. (nominal)

CELANESE COMPRESSION FIXTURE



CELANESE

SPECIMEN GEOMETRY



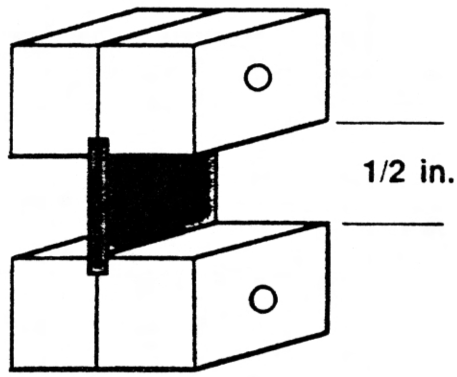
W = 0.25 In. (0° Specimen)

t = 0.10 In.

l = 0.5 In. (nominal)

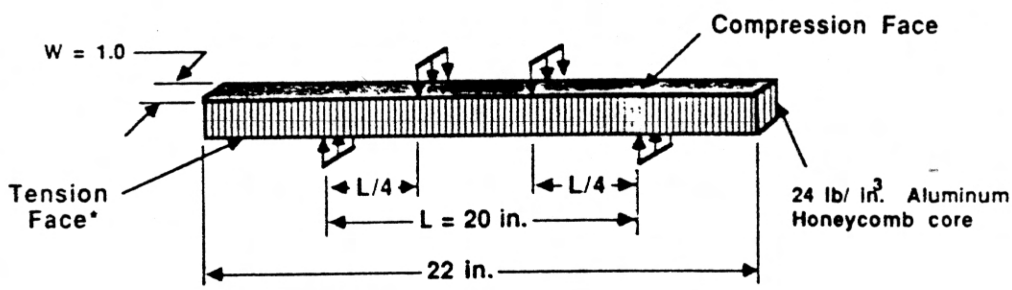
L = 5 In. (nominal)

RAE SPECIMEN



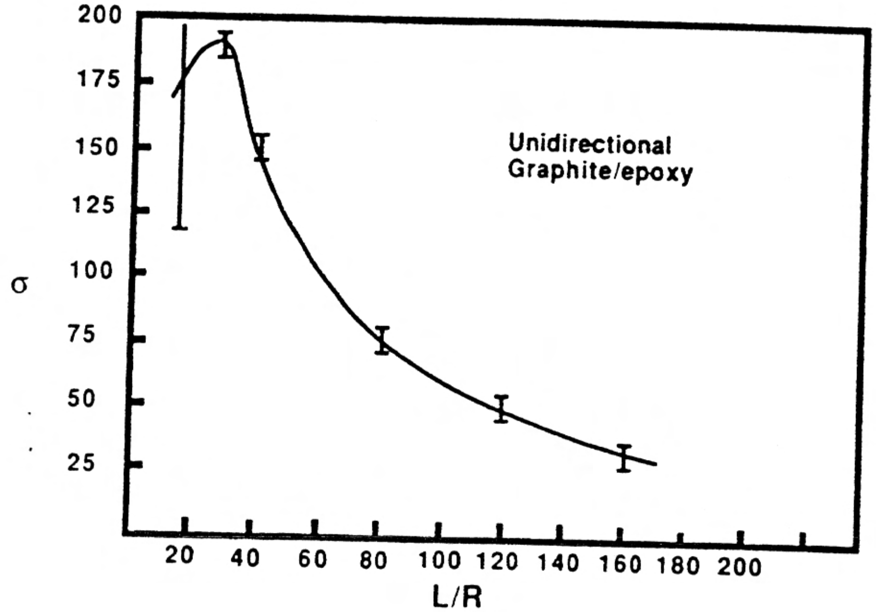
SANDWICH BEAM METHOD

Four-Point Bending

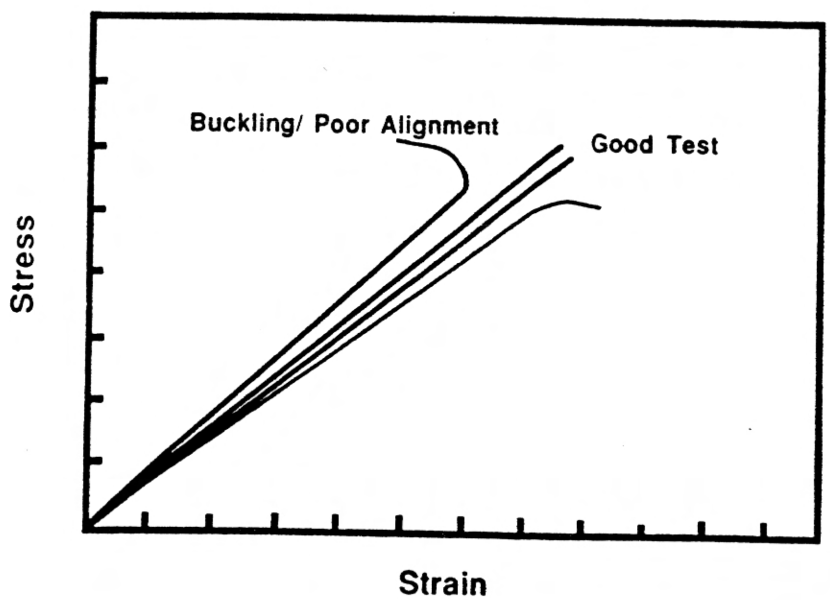


*Tension face is designed to be stronger than the compression face.

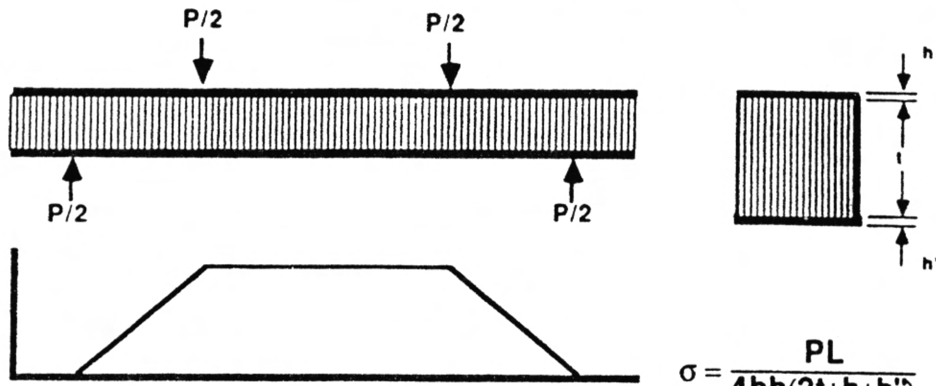
ULTIMATE STRENGTH VERSUS ASPECT RATIO



TYPICAL STRESS-STRAIN BEHAVIOR



SANDWICH BEAM COMPRESSION



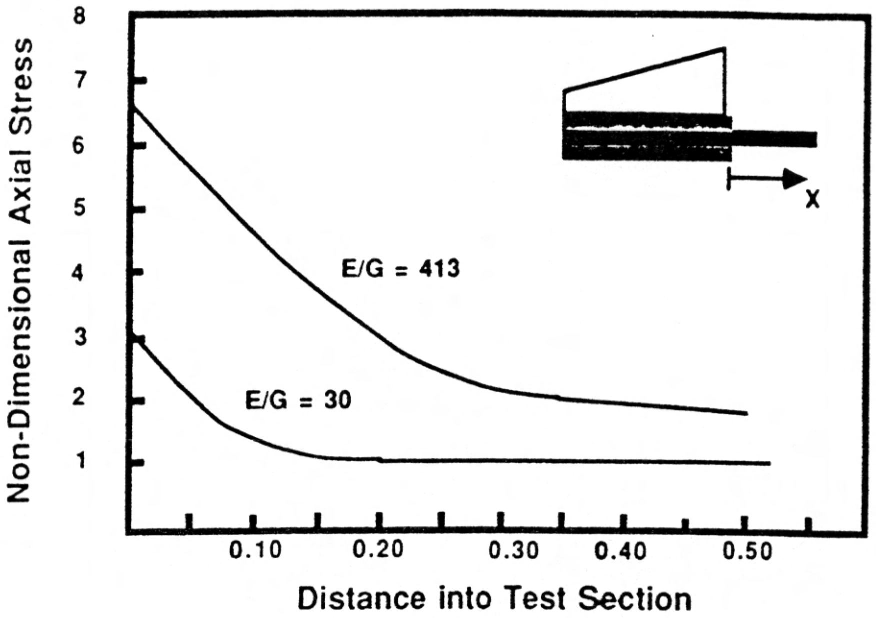
$$\sigma = \frac{PL}{4bh(2t+h+h')}$$

COMPRESSION STRENGTH AND MODULUS

METHOD COMPARISON T300/5208

METHOD	MODULUS		STRENGTH	
	Msi	GPa	Ksi	MPa
Sandwich Beam	20.3 ±1.04	139.0 ±8.72	222.0 ±40.5	1536.0 ±273
Pyrimidal Wedge	19.2 ±0.20	132.3 ±1.53	190.0 ±5.6	1308.0 ±38.9
Conical Wedge	20.3 ±0.45	139.6 ±3.21	250.0 ±31.3	1723.0 ±215

VARIATION OF STRESS IN THE TEST SECTION

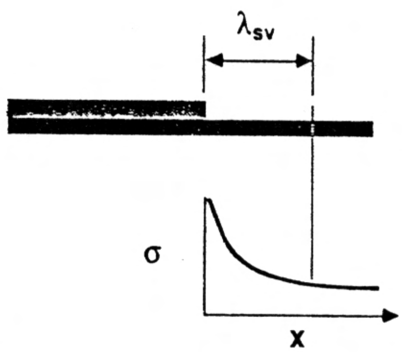


DECAY OF STRESS CONCENTRATION

St. Venant's Approximation:

$$\lambda_{sv} \leq \frac{4.6t}{2\pi}\left(\frac{E_x}{G_{xz}}\right)^{1/2}$$

$$\lambda_{\frac{F}{E}} < \frac{t}{2}\left(\frac{F_x}{G_{xz}}\right)^{1/2}$$



t = thickness

E_x = Axial Young's Modulus

G_{xz} = Interlaminar Shear Modulus

$$L \geq 2\lambda_{FE}$$

$$\frac{L}{t} \geq \frac{1}{2}\left(\frac{E_x}{G_{xz}}\right)^{1/2}$$

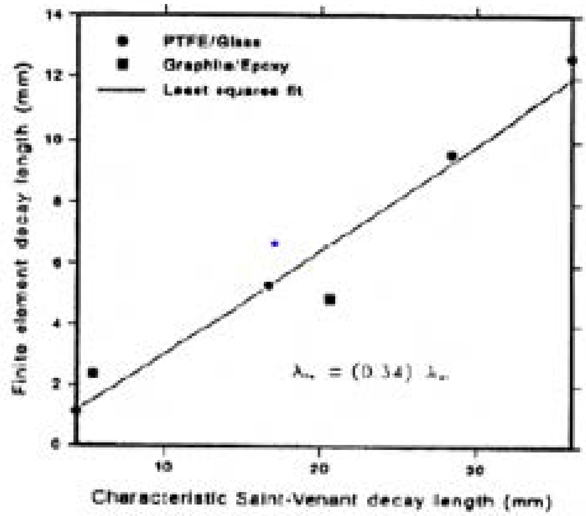


Figure (6) : Decay Length Correlation

Figure (6) : Decay Length Correlation

STABILITY REQUIREMENTS

For Compressive Failure Prior to Buckling

$$\sigma_b = \frac{E_x}{\frac{12}{\pi^2}\left(\frac{l}{t}\right)^2 + 1{\cdot}2\left(\frac{E_x}{G_{xz}}\right)} \tag{5}$$

For linear-elastic material behavior, the critical buckling strain is defined by:

$$\epsilon_b = \frac{\sigma_b}{E_x} \tag{6}$$

Combining eqns (5) and (6), the critical buckling strain was found to be a function of the specimen geometry and material anisotropy. The relationship is given by:

$$\epsilon_b = \left[\frac{12}{\pi^2}\left(\frac{l}{t}\right)^2 + 1{\cdot}2\left(\frac{E_x}{G_{xz}}\right)\right]^{-1} \tag{7}$$

Specimen geometries ensuring that material failure will occur prior to buckling-induced failure correspond to l/t ratios which make the critical buckling strain in eqn (7) greater than the anticipated failure strain for a given material system.

$$\frac{l}{t} = \left[\frac{\pi^2\left(\frac{1}{\epsilon_b} - 1{\cdot}2\left(\frac{E_x}{G_{xz}}\right)\right)}{12}\right]^{1/2} \tag{12}$$

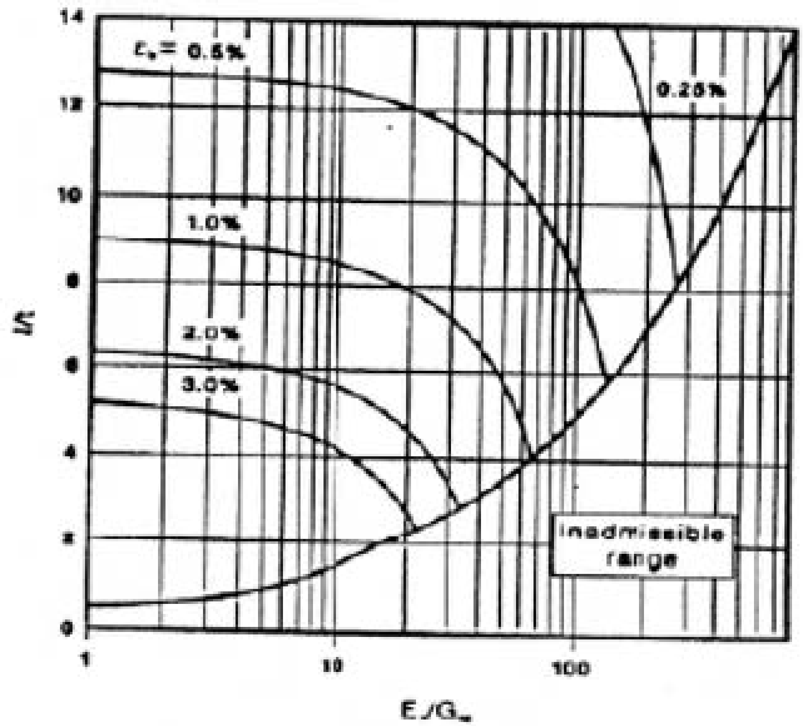
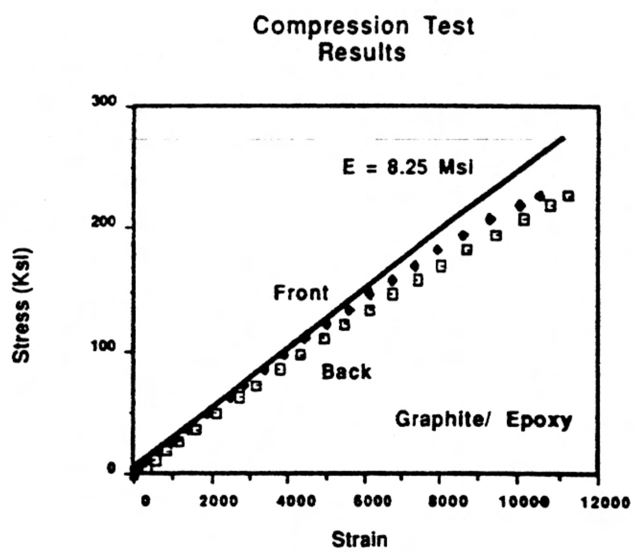


Figure (8) : Specimen Design for Accurate Modulus Determination and Strength Measurement

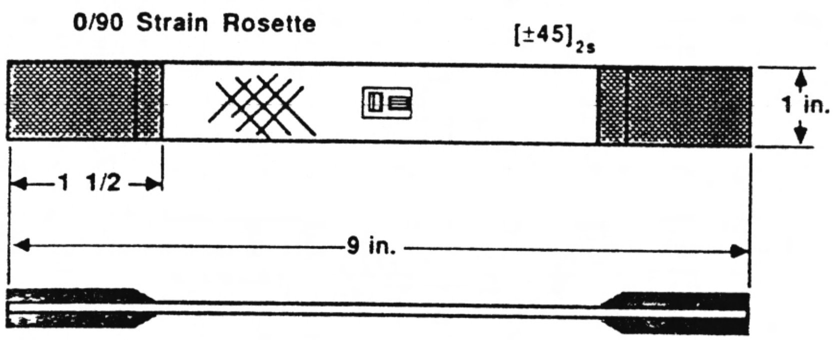


SHEAR TESTING

- Inplane Shear Stress-Strain Response
  - ASTM D3515
- Rail Shear Test for Inplane Shear
  - ASTM D4055
- 10° Off-Axis Test
- Short Beam Shear Test (Interlaminar Strength)
- V-Notched Beam shear Tests
  - Iosipescu
  - Asymmetric Four Point Bending Test (AFPB)
  - Arcan

±45 TENSION TEST

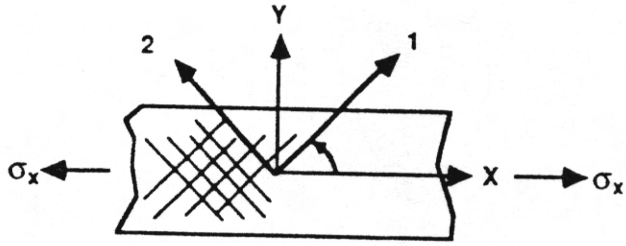
Inplane Shear Coupon Geometry



DATA REDUCTION

$\{\sigma_i\} = [T_{ij}]\{\sigma_j\}$

For $\theta = 45$



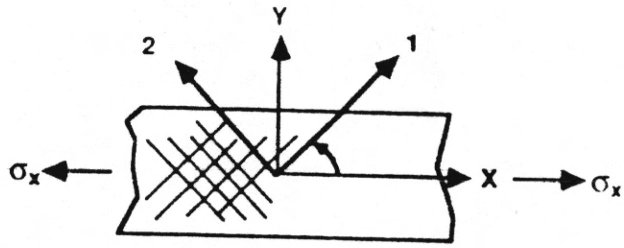
$$\tau_{12} = \pm \frac{\sigma_x}{2}$$

DATA REDUCTION

Strain Transformation

$\{\varepsilon_i\} = [T_{ij}]\{\varepsilon_j\}$

For $\theta = 45$



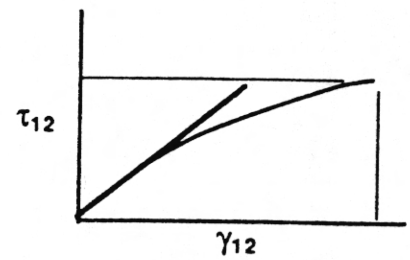
$$\gamma_{12} = (\varepsilon_x - \varepsilon_y)$$

DATA REDUCTION

±45 Inplane Shear

$$\tau_{12} = \pm \frac{\sigma_x}{2}$$

$$\gamma_{12} = (\varepsilon_x - \varepsilon_y)$$



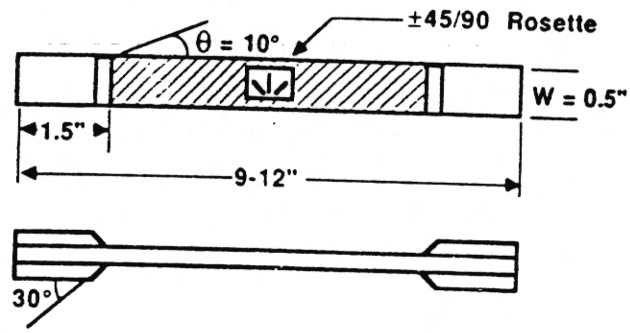
Ultimate Strength

$$\tau_{12}^{ult} = \frac{P^{ult}}{2A}$$

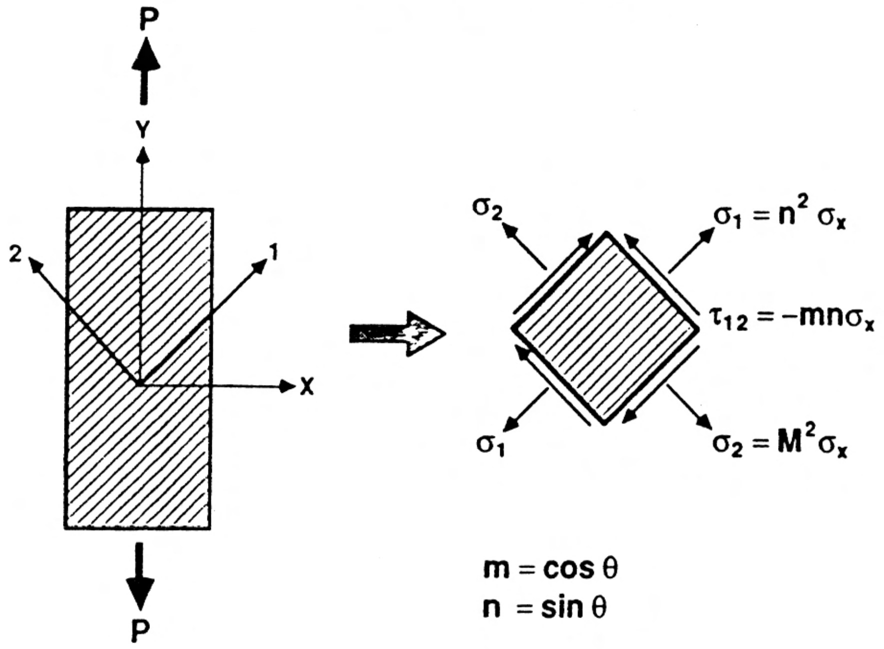
Modulus

$$G_{12} = \frac{\tau_{12}}{\gamma_{12}}$$

10° Off Axis Test

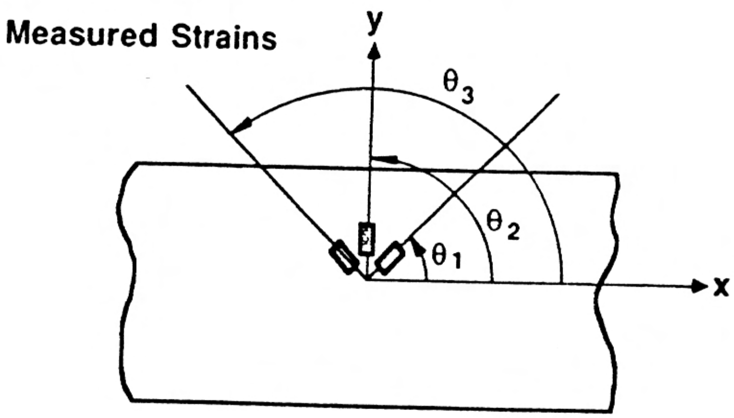


BIAXIAL STRESSES



$m = \cos\theta$
$n = \sin\theta$

STRAIN ANALYSIS



STRAIN ANALYSIS

Determing Strain Components

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} m_1^2 & n_1^2 & m_1 n_1 \\ m_2^2 & n_2^2 & m_2 n_2 \\ m_3^2 & n_3^2 & m_3 n_3 \end{bmatrix}^{-1} \begin{Bmatrix} \varepsilon_{\theta_1} \\ \varepsilon_{\theta_2} \\ \varepsilon_{\theta_3} \end{Bmatrix}$$

STRAIN TRANSFORMATION

Knowing ε_x, ε_y and γ_{xy}, we find.

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} m^2 & n^2 & mn \\ n^2 & m^2 & -mn \\ -2mn & 2mn & (m^2-n^2) \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

$m = \cos\theta$

$n = \sin\theta$

Thus

$$\boxed{\gamma_{12} = -2mn\,\varepsilon_x + 2mn\,\varepsilon_y + (m^2 - n^2)\,\gamma_{xy}}$$

DATA REDUCTION

Strength

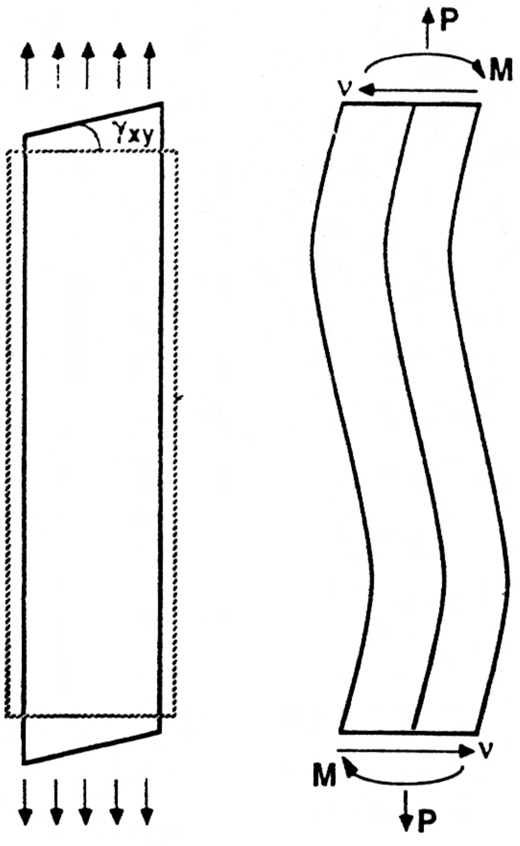
$$\tau_{12} = -mn\,\sigma_x^{ULT}$$

$$\sigma_x^{ULT} = P^{ULT}/A$$

Modulus

$$G_{12} = \frac{\tau_{12}}{\gamma_{12}} = \frac{-mn\,\sigma_x}{[-2mn\,\varepsilon_x + 2mn\,\varepsilon_y + (m^2-n^2)\,\gamma_{xy}]}$$

OFF AXIS SHEAR



OFF-AXIS TENSION

For Uniaxial Tension

$$\varepsilon_x = \frac{1}{E_x}\sigma_x$$

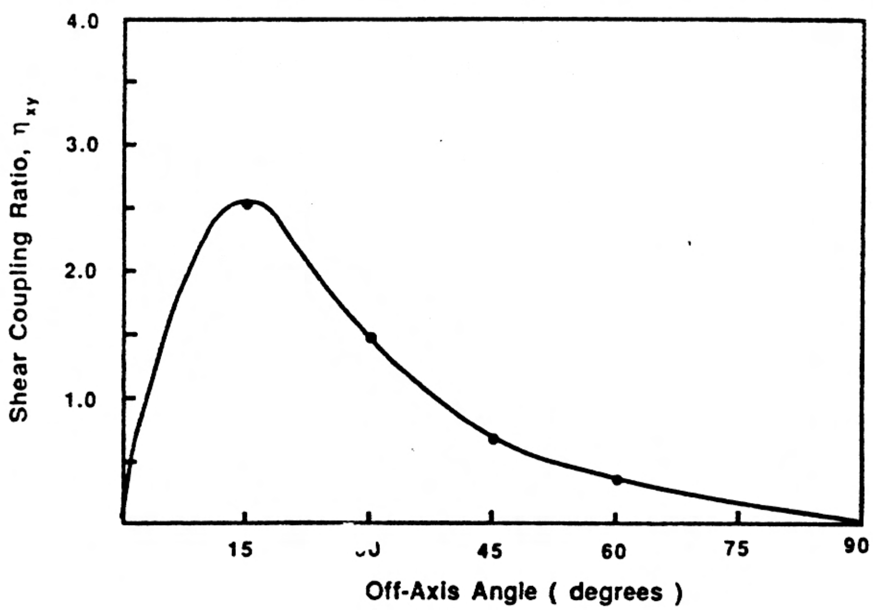
$$\varepsilon_y = \frac{-\nu_{xy}}{E_x}\sigma_x$$

$$\gamma_{xy} = \frac{\eta_{xy}}{E_x}\sigma_x$$

where

$$\eta_{xy} = \frac{S_{16}}{S_{11}}$$

SHEAR COUPLING RESPONSE



OFF-AXIS TEST SPECIMEN DESIGN

Slenderness Ratio

Assume

$$E_x = (1 - \eta)\, E_x^*$$

where

E_x^* = measured apparent modulus

η = error term

SLENDERNESS RATIO

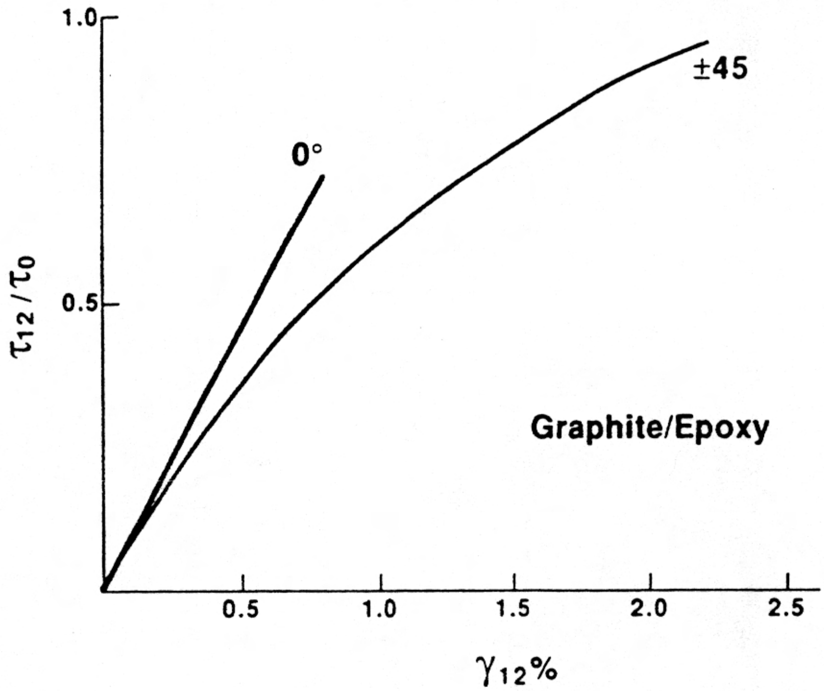
$$\eta = \frac{3\,\eta_{xy}}{\left[\dfrac{3E_x}{G_{xy}} + \dfrac{2L^2}{W^2}\right]}$$

$\eta \to 0$ if $\eta_{xy} \to 0$

or

L/W is large

COMPARISON OF ±45 AND 10° OFF-AXIS TEST RESULTS



RAIL SHEAR TEST

- Two-Rail
- Three-Rail
- Measures Strength and Modulus

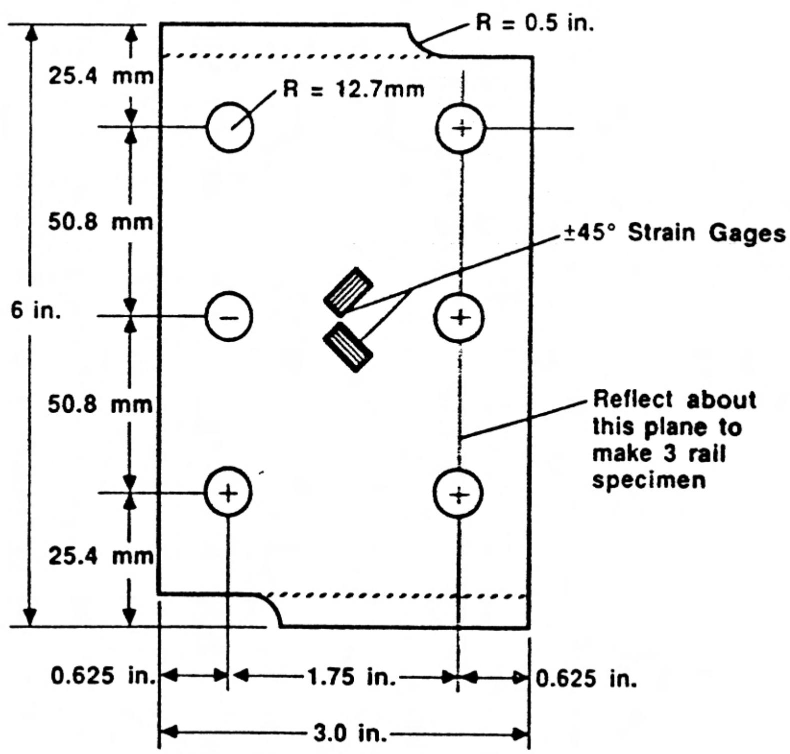
RAIL SHEAR

Test Specimen Design

- Unidirectional
  - 0°
  - 90°
- Laminate
  - 0/90 $(A_{16}, A_{26} = 0)$
- Discontinuous Fiber
  - random inplane
  - oriented

TEST SPECIMEN

Two Rail



TEST SPECIMEN CONSIDERATIONS

- Length to width ratio for test section is 8:1.
- Bolts do not carry load.
- Rails act perfectly clamped.

DATA REDUCTION

STRESS

$\tau_{xy} = \frac{P}{bh}$ (2-rail

$\tau_{xy} = \frac{P}{2bh}$ (3-rail)

STRAIN

$\gamma_{xy} = \varepsilon_{45} - \varepsilon_{-45}$

Shear Strength

$\tau_{xy}^{ult} = \frac{P^{ult}}{bh}$

Shear Modulus

$G_{xy} = \frac{\tau_{xy}}{\gamma_{xy}}$