Novel Methods for Testing and Modelling Composite Materials and Laminates

C. T. Sun
School of Aeronautics and Astronautics
Purdue University
West Lafayette, Indiana

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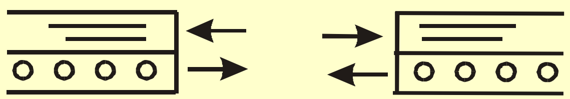
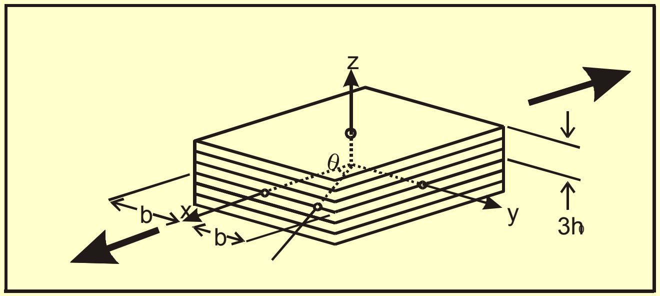
Composites Testing and Model Identification

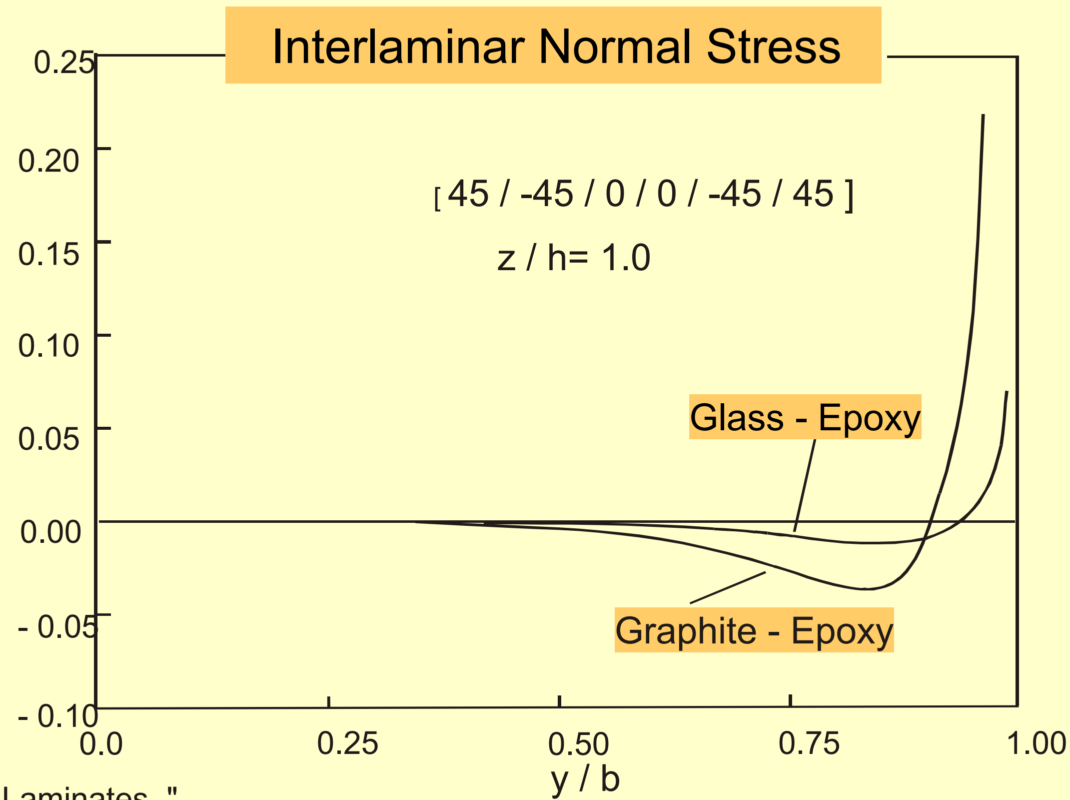
Outline

- Testing Notch Strength in Laminates
- Oblique End Tab for Off Axis Testing
- Testing and Modeling Nonlinear Behavior of Composites
- Testing and Modeling Compressive Strength of Composite
- Dynamic Interlaminar Fracture Toughness

Free Edge Stresses



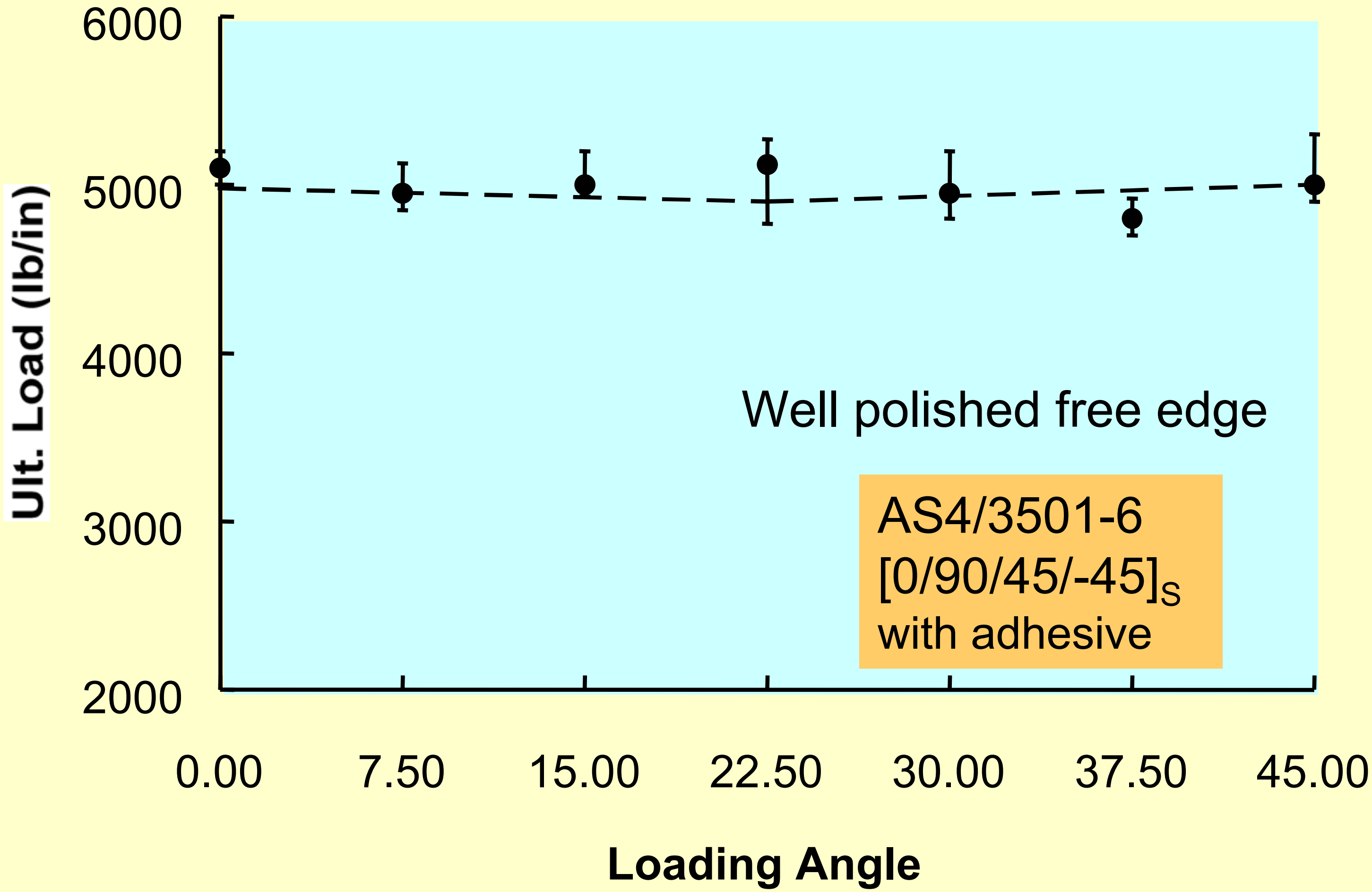




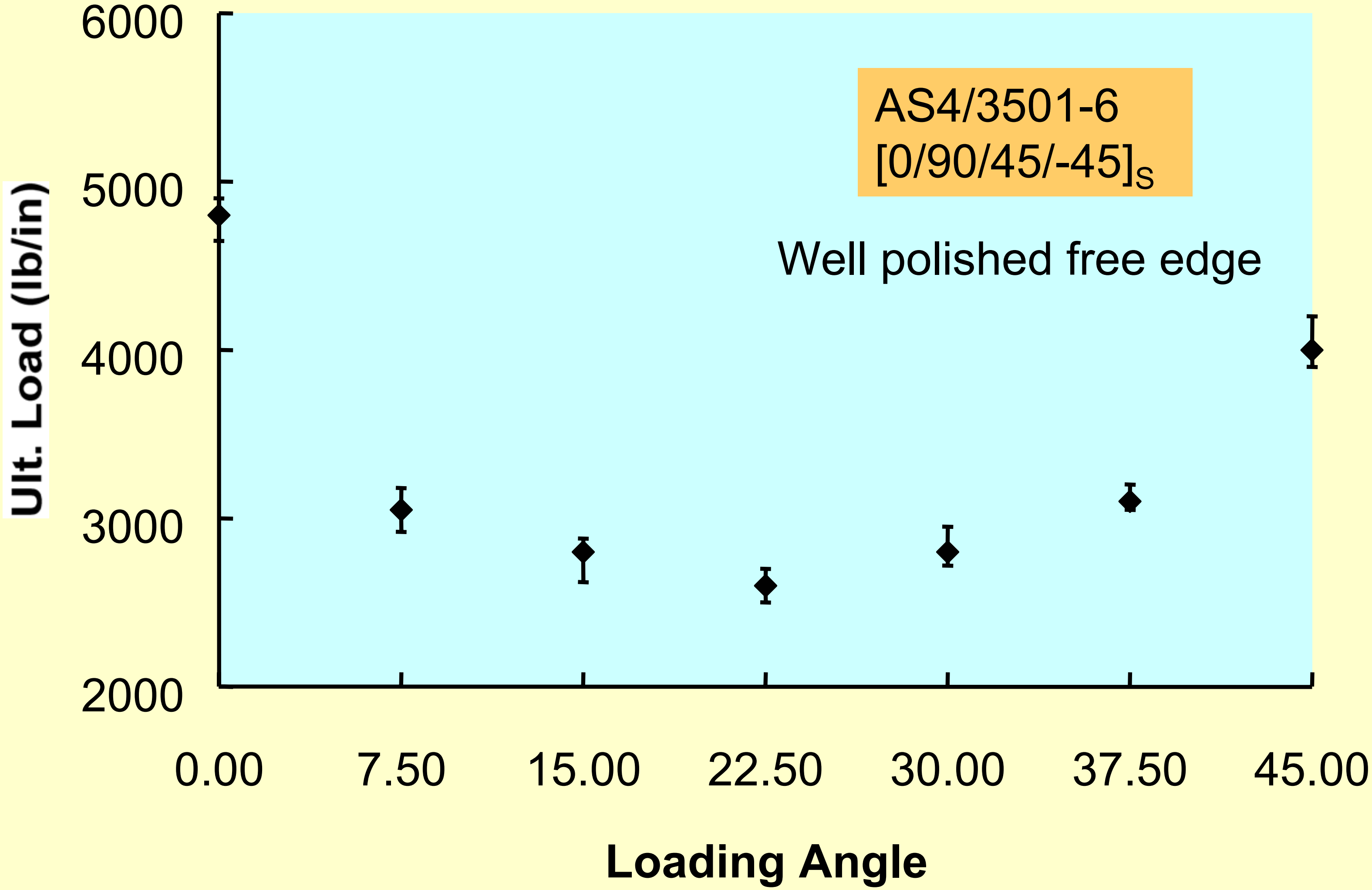
Air Force Materials Laboratory ,
Technical Report AFML -TR-72-18 , 1972

R.B Pipes , " Interlaminar Stresses in Composite Laminates ,"

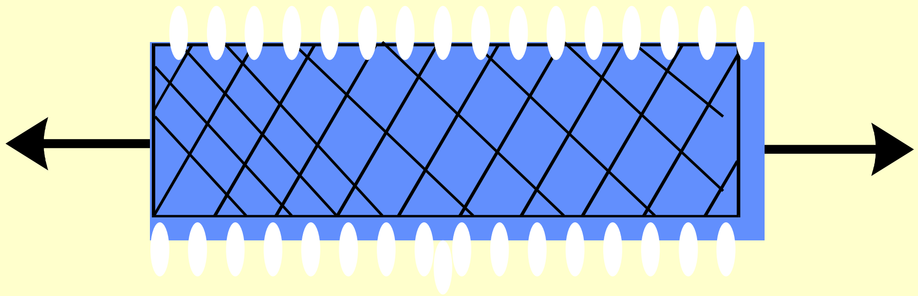
Strength without Edge Effect



Strength in Off-Axis Directions



Failure Loads of $[0/90/\pm 45]_S$ Laminate



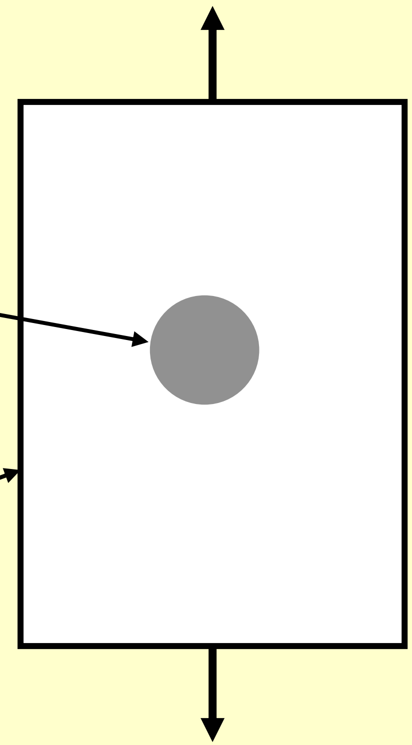
	Unnotched	Notch Type				
		1	2	3	4	5
0^o	4700 (lb/in)	3710	3730	3730	3705	3810
7.5^o	2730 (lb/in)	3350	3400	3220	3385	3540
15^o	2510 (lb/in)	3150	3200	3100	3300	3300

Notch Strength of Composite Laminates

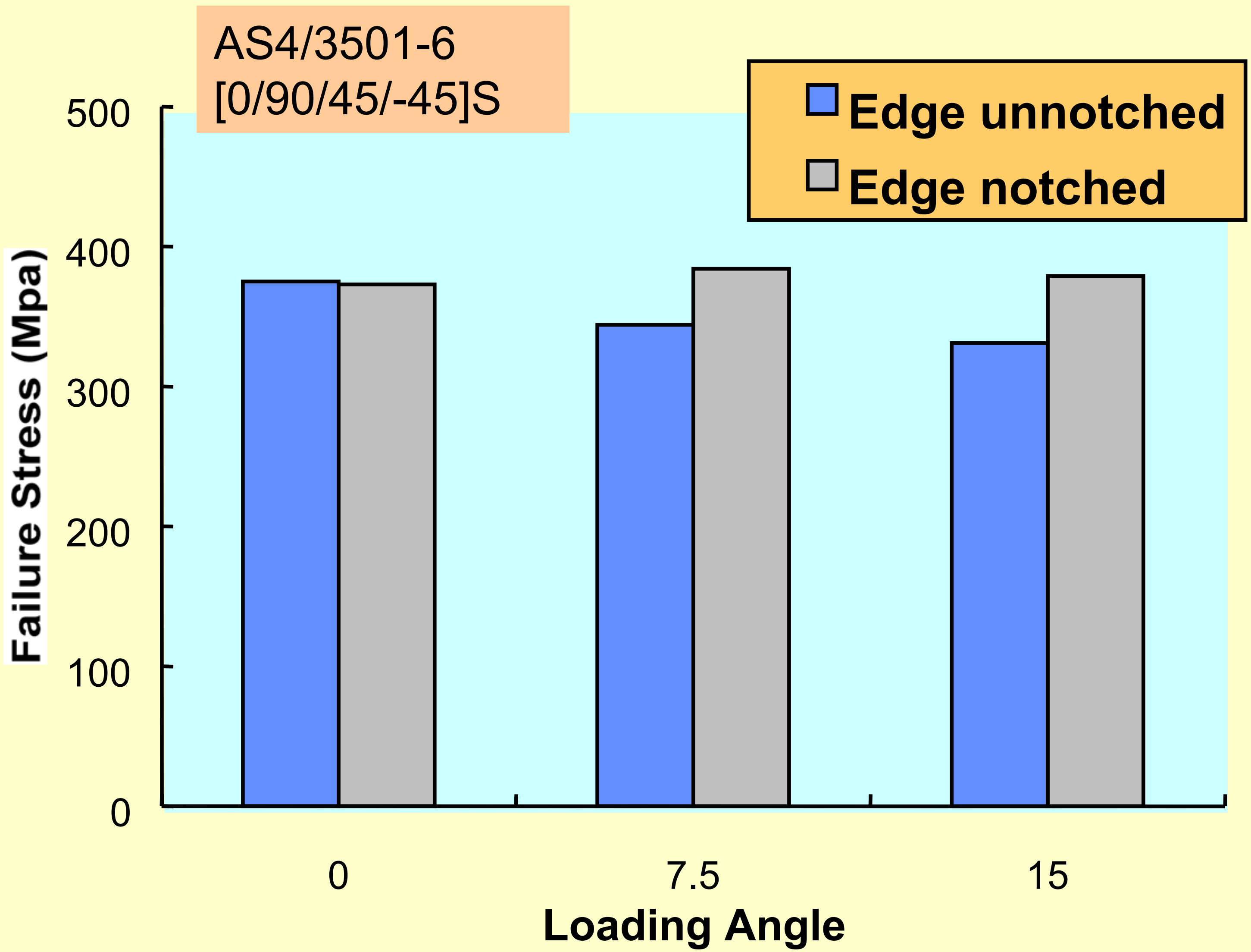
Two Failure Mechanisms

•Stress Concentration

•Free Edge Stress

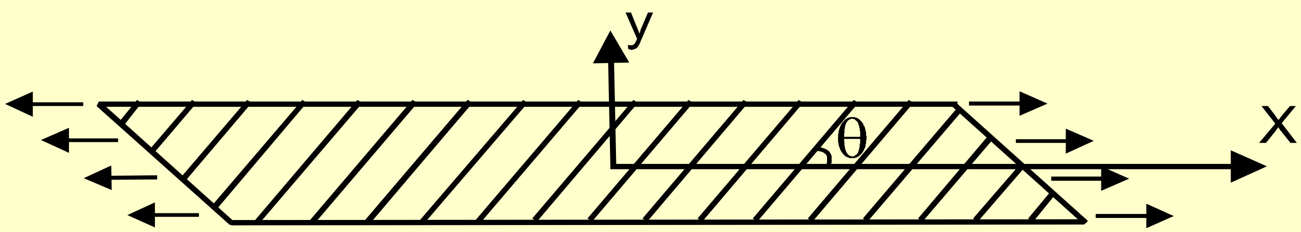


Net-section Strength



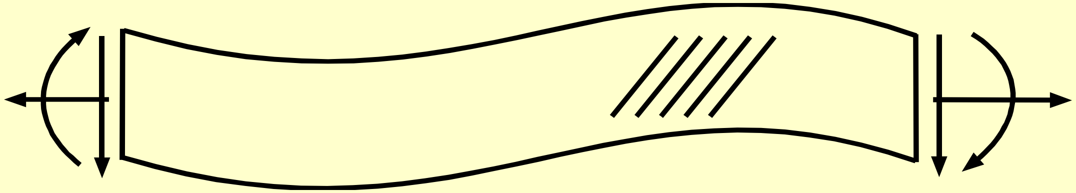
Off-Axis Tension

Simple Tension



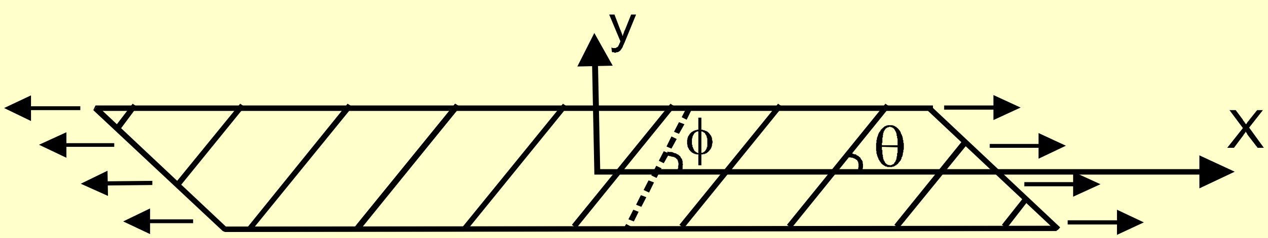
$$\sigma_{xx} = \sigma_0, \quad \sigma_{yy} = \sigma_{xy} = 0$$

Clamped End



$$\sigma_{xx} \neq 0, \quad \sigma_{xy} \neq 0$$

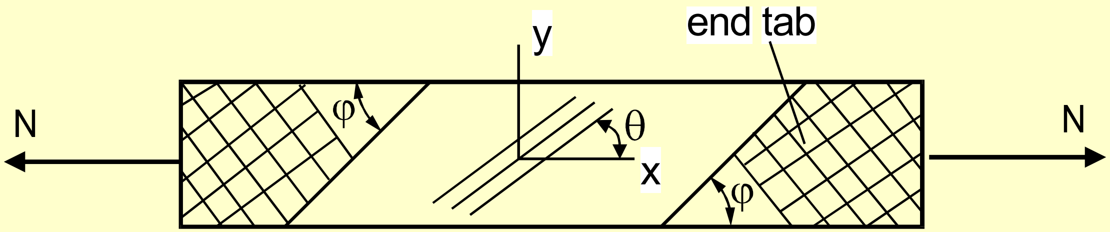
Displacements in Off-Axis Tension

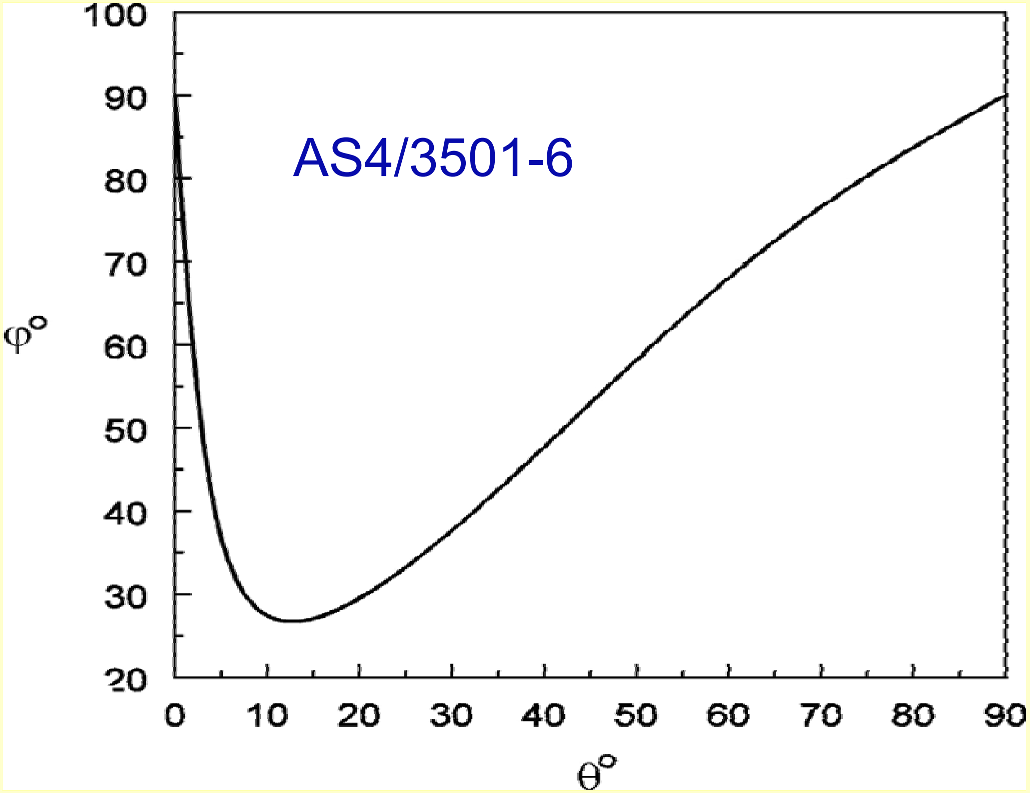


$$U_x = \bar{S}_{11}\sigma_{xx}x + \bar{S}_{16}\sigma_{xx}y$$

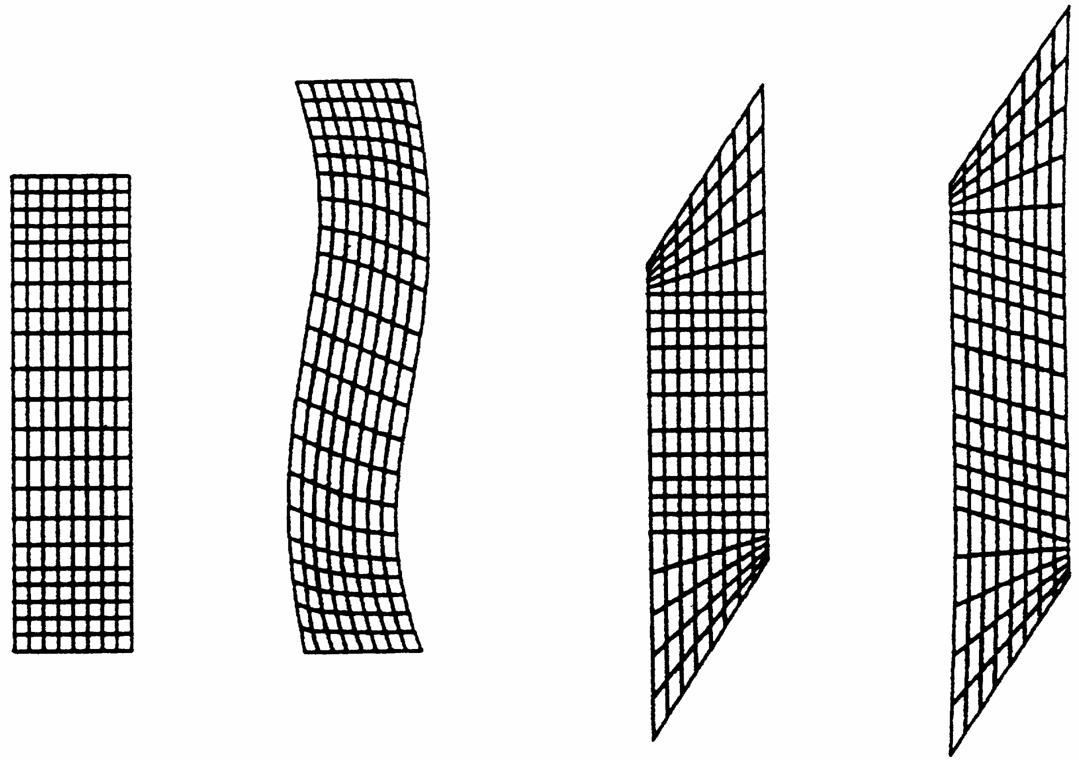
$$\frac{dx}{dy} = \cot\phi = -\frac{\bar{S}_{16}}{\bar{S}_{11}}$$

Oblique Tab Angle



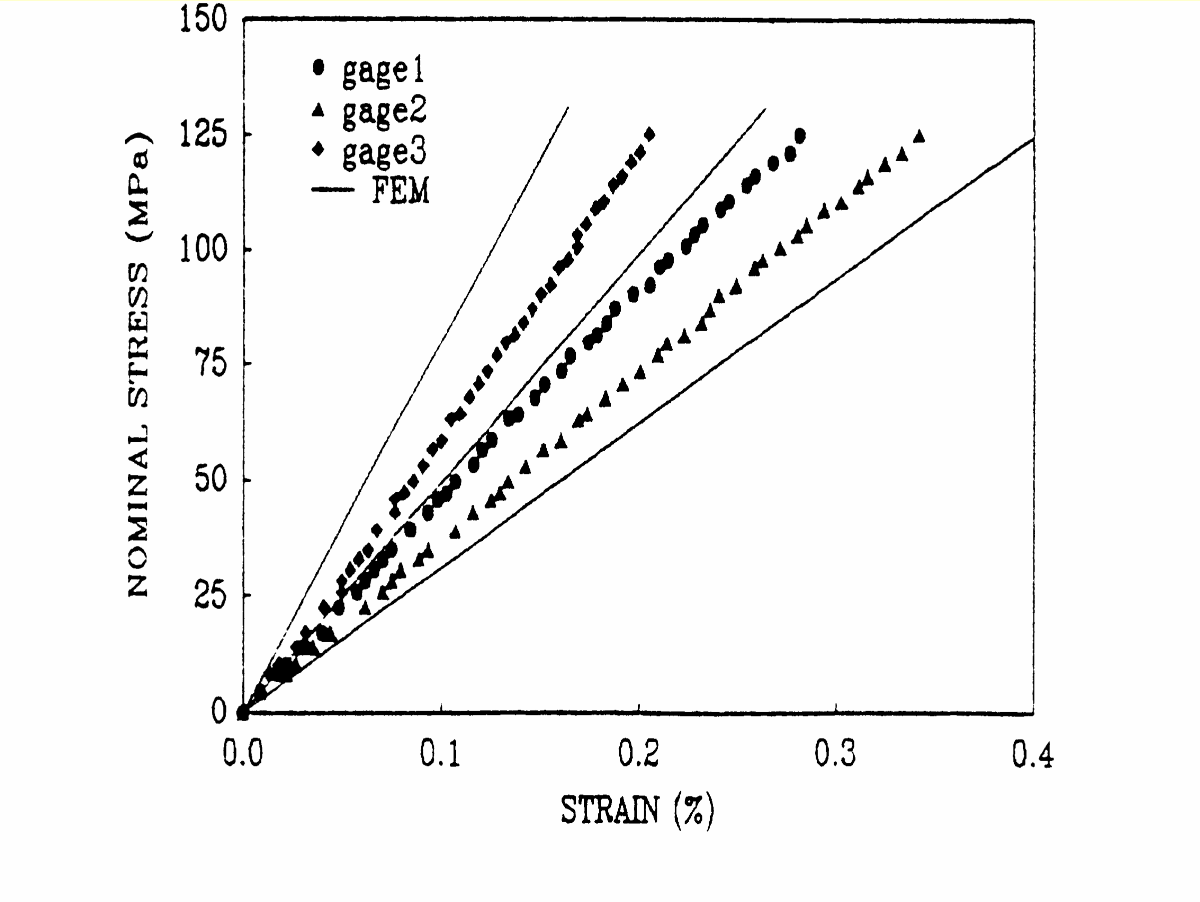


Undeformed (a) and (c) and deformed shapes (b) and (d) of 20° off-axis carbon/ epoxy specimens

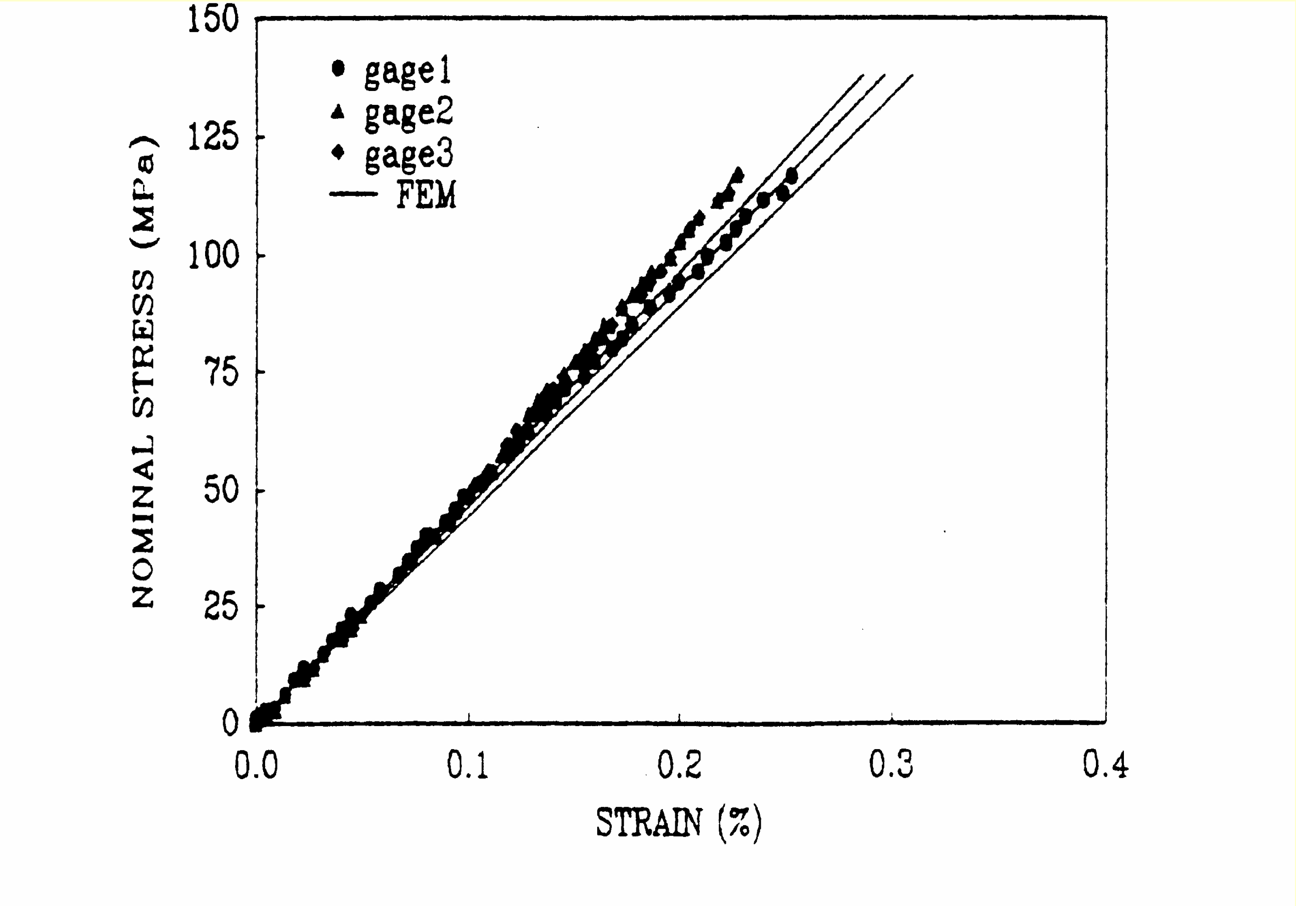


(a) (b) (c) (d)

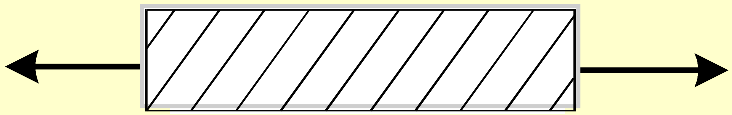
Axial strains in 20 deg off-axis specimen with rectangular end tabs



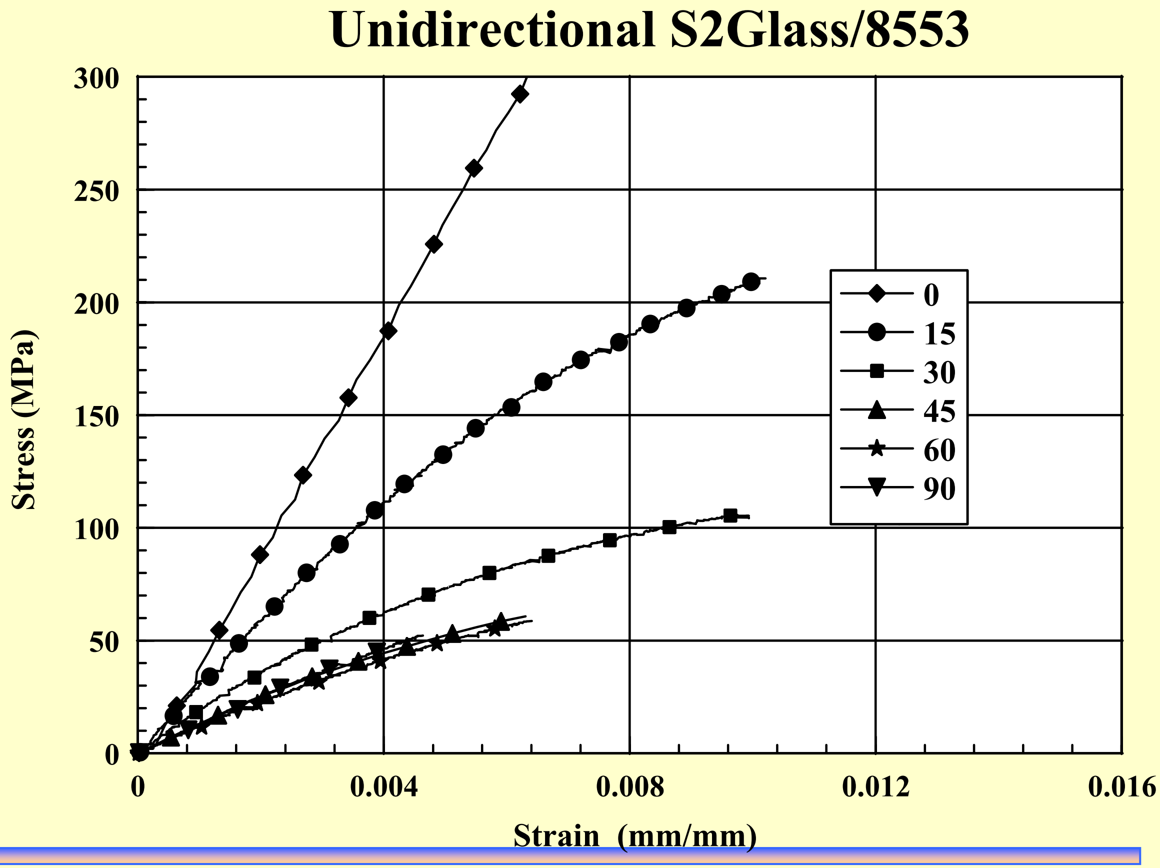
Strain Distribution in 20 deg Specimen with Oblique Tabs



Nonlinear Behavior in Fiber Composites



- Off-Axis Stress-Strain Curves



Anisotropic
Nonlinear

Plastic Potential and Flow Rule

- Flow Rule

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p}$$

$$d\varepsilon_{ij}^{p} = \frac{\partial f}{\partial \sigma_{ij}} d\lambda$$

$$\bar{\sigma} = \sqrt{3f}$$

$$dW^{p} = \sigma_{ij} d\varepsilon_{ij}^{p} = \bar{\sigma} d\bar{\varepsilon}^{p}$$

$$d\lambda = \frac{3}{2}\left(\frac{d\bar{\varepsilon}^{p}}{d\bar{\sigma}}\right)\left(\frac{d\bar{\sigma}}{\bar{\sigma}}\right)$$

- One-Parameter Plastic Potential

Transversely isotropic

$$f(\sigma_{ij}) = \frac{1}{2}\left[(\sigma_{22} - \sigma_{33})^2 + 4\sigma_{23}^2 + 2a_{66}(\sigma_{13}^2 + \sigma_{12}^2)\right]$$

- No plastic strain in the fiber direction

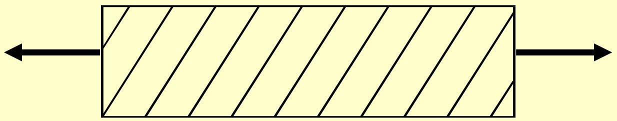
- Satisfies transverse isotropy

Off-Axis Test-Plane Stress

$$\sigma_{11} = \cos^2\theta\,\sigma_x$$

$$\sigma_{22} = \sin^2\theta\,\sigma_x$$

$$\sigma_{12} = -\sin\theta\cos\theta\,\sigma_x$$



$$\bar{\sigma} = h(\theta)\sigma_x$$

$$h(\theta) = \left[\frac{3}{2}(\sin^4\theta + 2a_{66}\sin^2\theta\cos^2\theta\right]^{1/2}$$

$$d\varepsilon_x^p = \cos^2\theta\, d\varepsilon_{11}^p + \sin^2\theta\, d\varepsilon_{22}^p - \sin\theta\cos\theta\, d\gamma_{12}^p$$

$$d\bar{\varepsilon}^p = d\varepsilon_x^p / h(\theta)$$

$$\bar{\varepsilon}^p = \varepsilon_x^p / h(\theta)$$

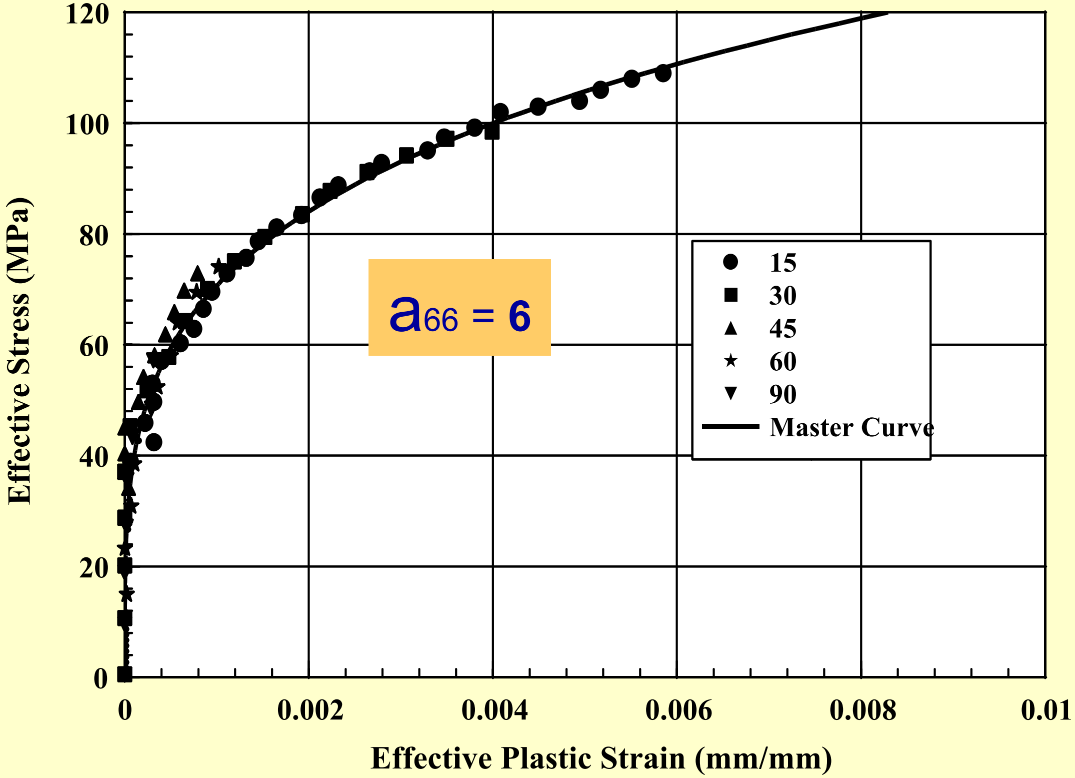
Power Law

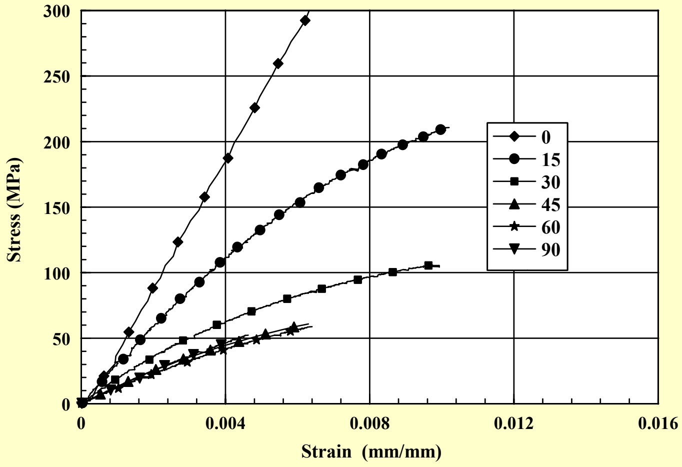
$$\bar{\varepsilon}^p = A\left(\bar{\sigma}\right)^n$$

Master Curve in Effective Stress and Effective Plastic Strain

$$\bar{\varepsilon}^{p} = A\left(\bar{\sigma}\right)^{n}$$

$$d\varepsilon_{ij}^{p} = \frac{\partial f}{\partial \sigma_{ij}} d\lambda$$

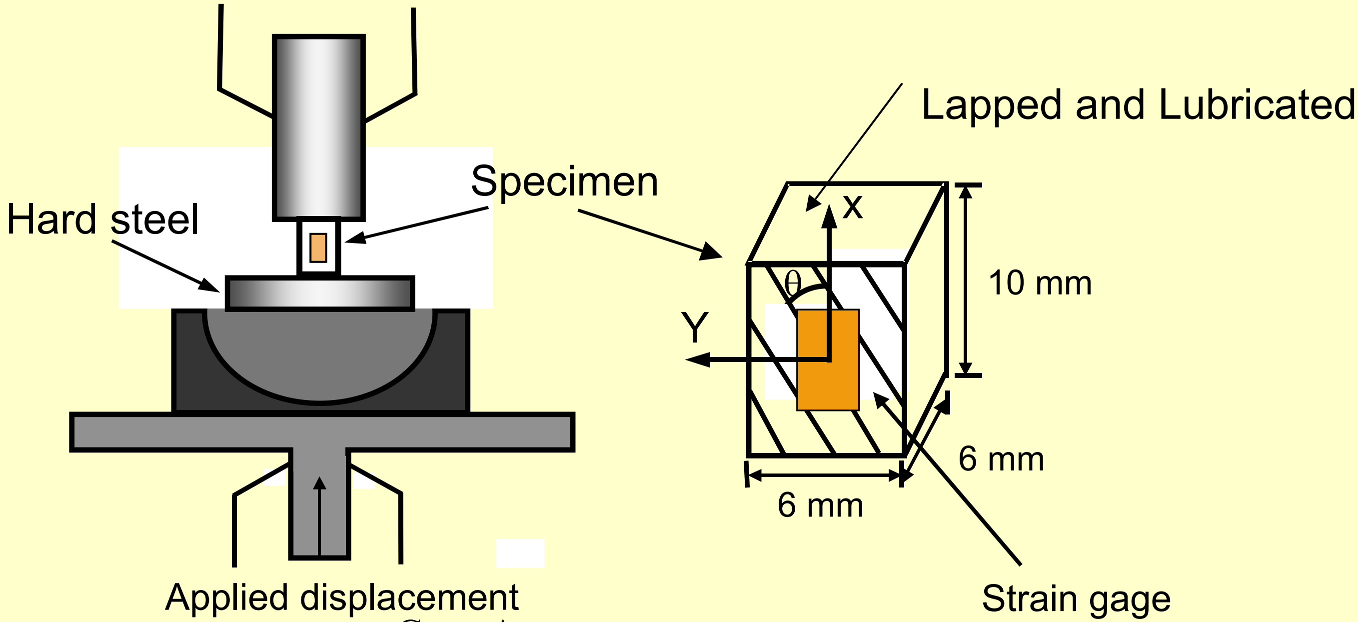




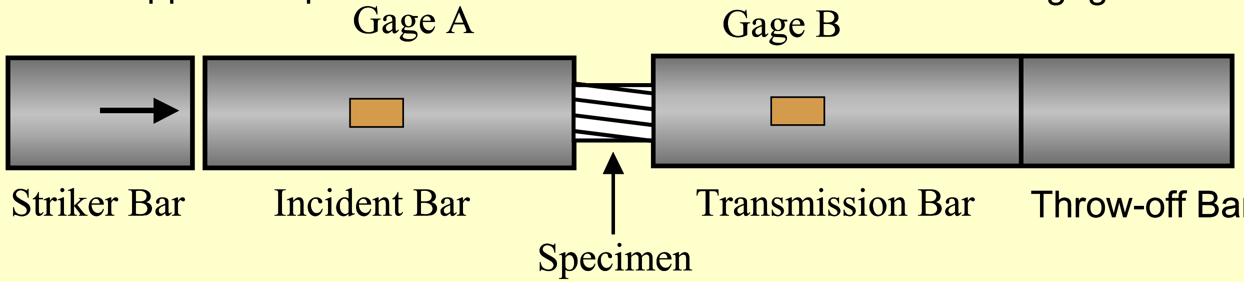
Compression Test of Off-Axis Composites

Compression tests were performed on off-axis S2/8552 glass/epoxy composites at strain rates from 10^{-4}/s to 1000/s.

Quasi-Static
(MTS machine)

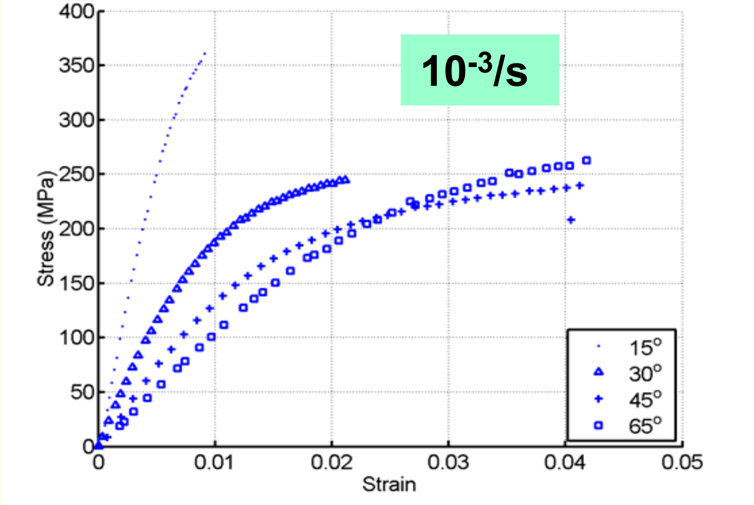


Dynamic
(Hopkinson bar)

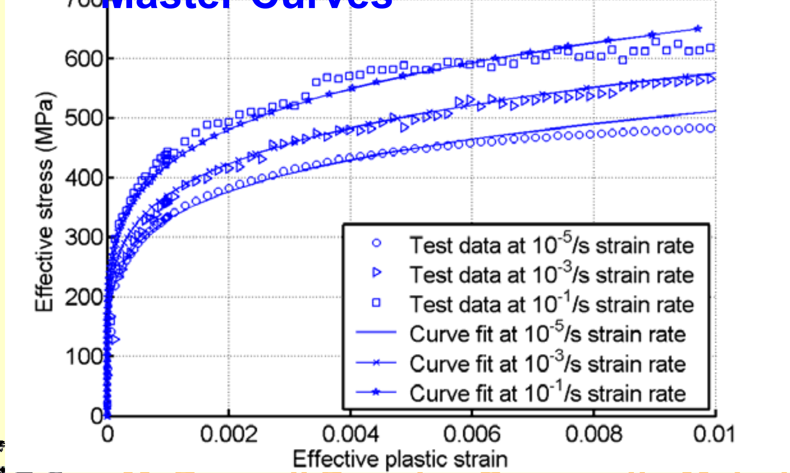


A Model for Rate –Dependent Nonlinear Behavior Of Fiber Composites

Off-Axis Curves



Master Curves

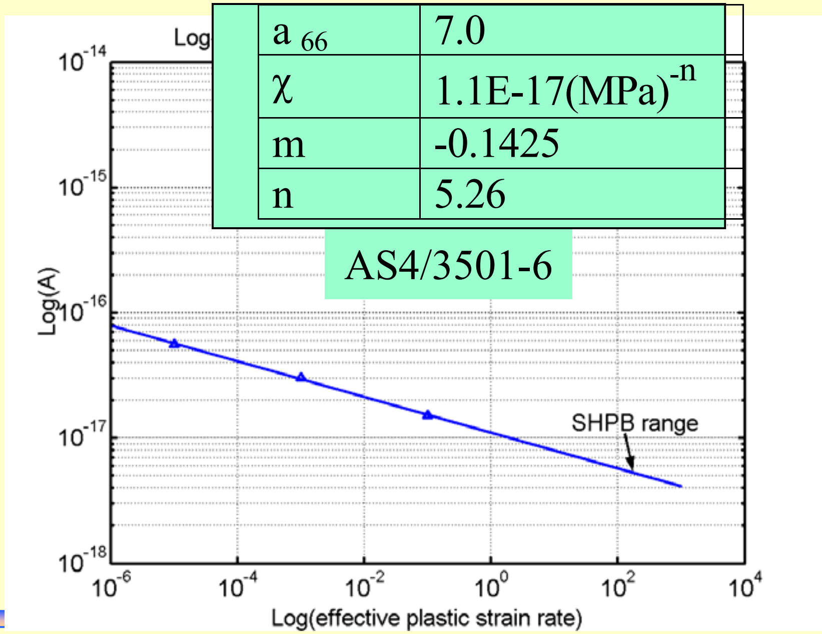


$$\dot{\bar{\varepsilon}}^{p} = A(\bar{\sigma})^{n}$$

$$\bar{\sigma} = \sqrt{3f} \qquad \dot{\varepsilon}_{ij}^{p} = \frac{\partial f}{\partial \sigma_{ij}}\dot{\lambda}$$

$$A = \chi(\dot{\bar{\varepsilon}}^{p})^{m}$$

$$f = \frac{1}{2}[(\sigma_{22}-\sigma_{33})^2 + 4\sigma_{23}^2 + 2a_{66}(\sigma_{12}^2 - \sigma_{13}^2)]$$



a_{66}	7.0
χ	1.1E-17(MPa)$^{-n}$
m	-0.1425
n	5.26

AS4/3501-6

Failure Modes Produced in Off-Axis Test

- **Fiber Microbuckling Failure** - fiber orientation equal or less than 15°.

$$\sigma_{cr} = \frac{G_m^{ep}}{1 - V_f} = G_{12}^{ep} \quad \text{(Microbuckling model)}$$

- **In-plane Shear Failure** –between 15° and 45°.

- **Out-of-plane Shear Failure** – greater than 45° .

Strain Rate Effect on Failure Mode

15 degree AS4/3501-6

Uncoated | **Coated withTi**

Microbuckling at 10^{-5}/s strain rate

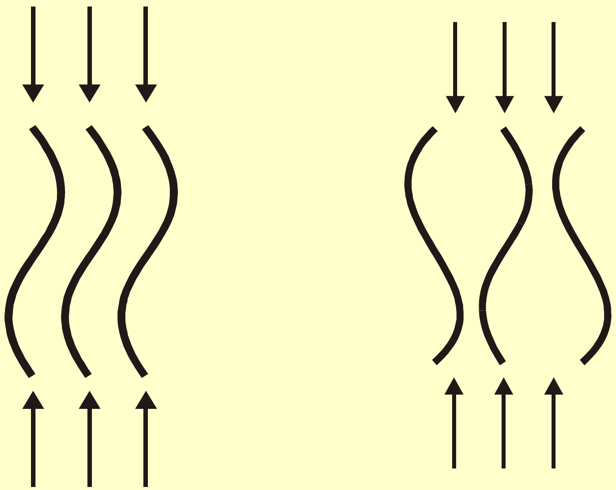
Shear failure at 1/s strain rate

Microbuckling Model

Rosen (1965):

•Idealize the composite as a series of perfectly aligned beam embedded in elastic matrix.

•Two modes of failure: extension and shear.



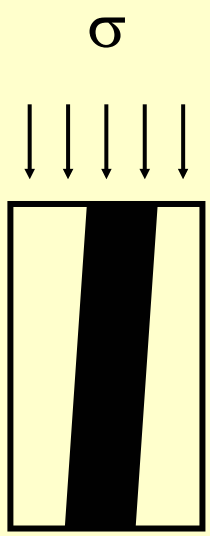
Shear mode

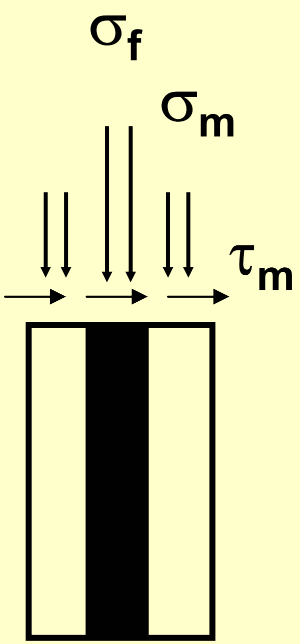
$$\sigma_c = \frac{G_m}{1 - V_f} \approx G_{12}$$

Microbuckling Model with Nolinear Matrix Behavior an Misalignments

Sun and Jun (1994)

- Fiber microbuckling in nonlinear matrix including fiber misalignment effect





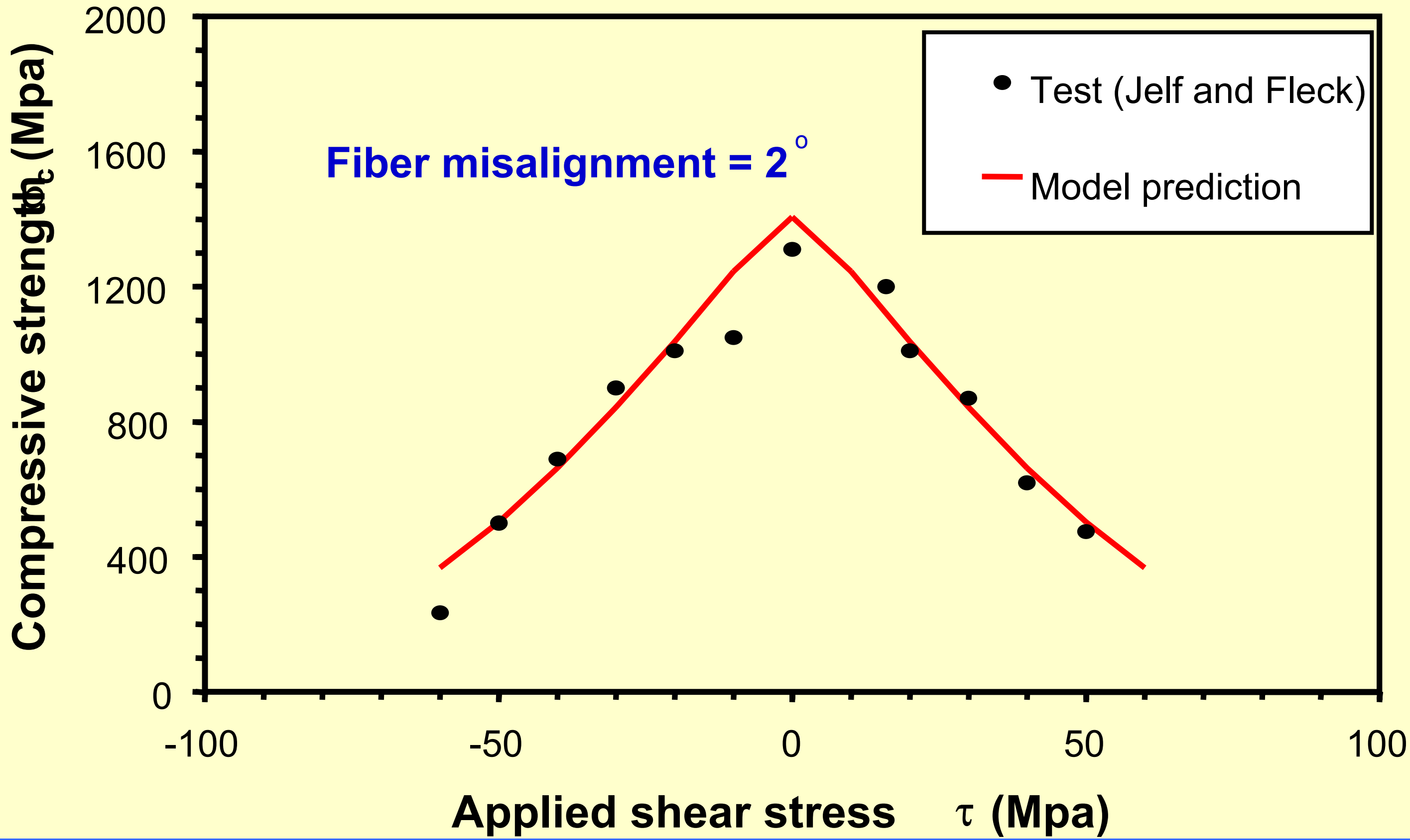
$$\sigma_{cr} = \frac{G_m^{ep}}{1 - V_f}$$

$$\approx G^{ep}(\sigma_{cr}, \phi)$$

EFFECT OF SHEAR STRESS

Compression-Torsion Test

EXAS HIS/DX6002 Carbon/epoxy composites, V_f =65%



Model Predictions and Test Data

AS4/3501-6 (misalignment angle = 2.5 deg)

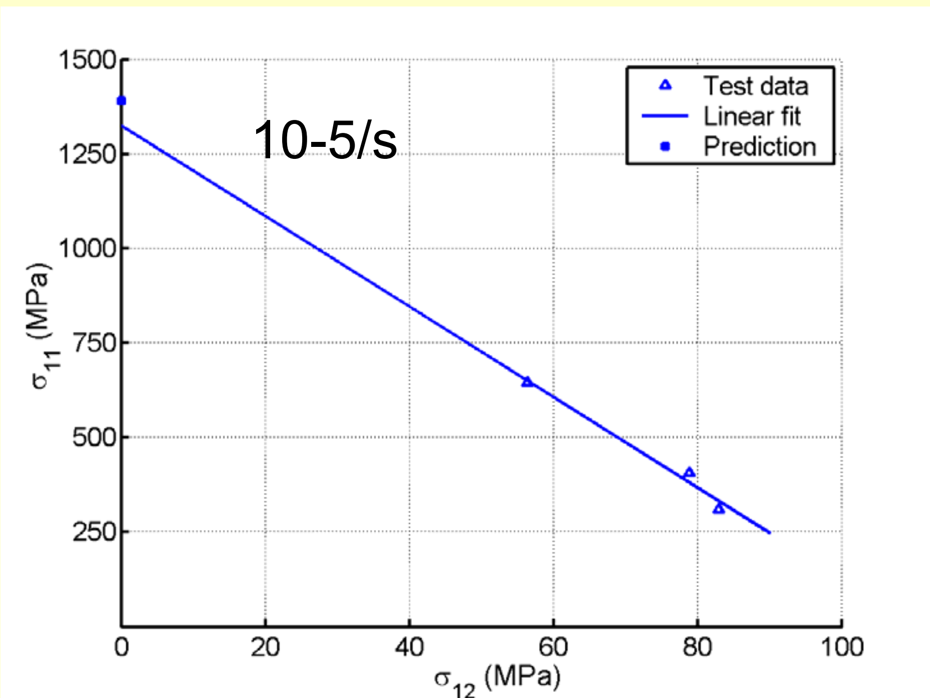
$$\boxed{\sigma_{cr} = G_{12}^{ep}}$$

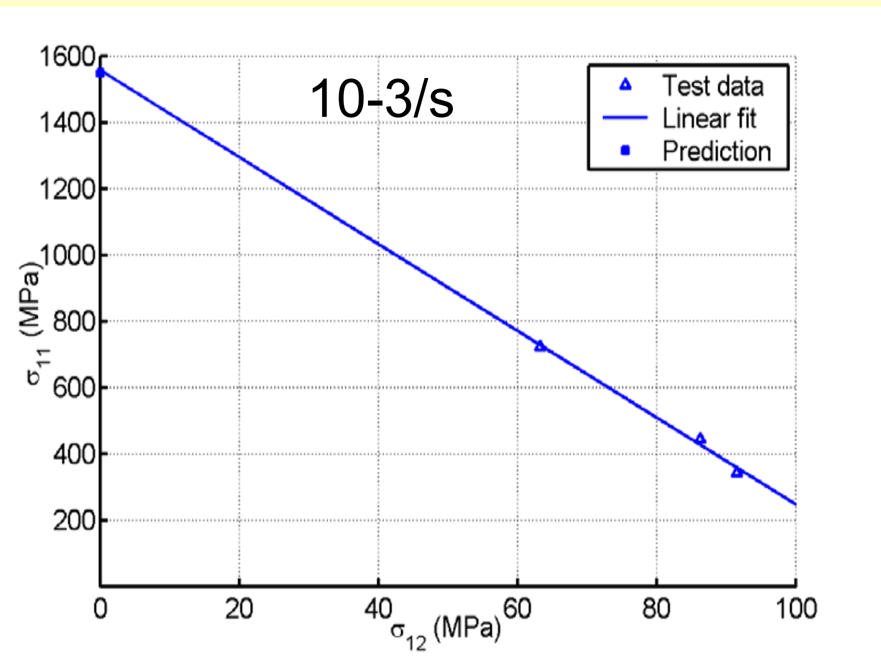
$$\sigma_{xc}\cos^2(\bar{\theta}+\gamma_{12}) = \left[\frac{1}{G_{12}^{e}} + \frac{6a_{66}^{2}\cos^2(\bar{\theta}+\gamma_{12})}{H_p(\sin^2(\bar{\theta}+\gamma_{12})+2a_{66}\cos^2(\bar{\theta}+\gamma_{12}))}\right]^{-1}$$

Strain Rate	Off-axis Angle (°)	Test Result (MPa)	Model Prediction (MPa)
10^{-5}/s	5	649.7	627
	11	420.9	419
	15	331.7	355
10^{-3}/s	5	729.4	706
	11	460.9	472
	15	366.4	401
10^{-1}/s	5	837.7	801
	11	487.0	530
~150/s	5	934.9	940
	11	597.2	626

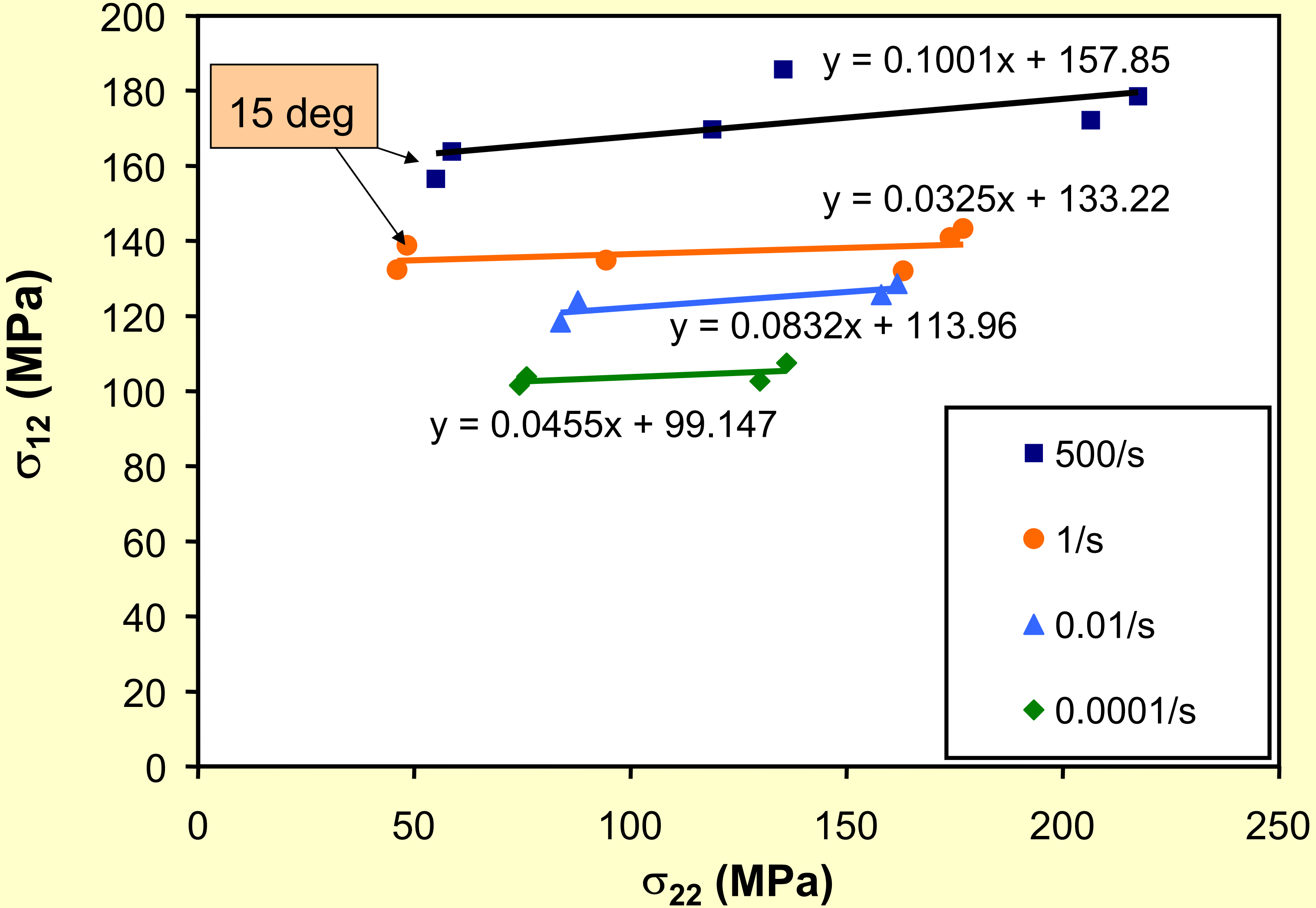
Longitudinal Compressive Strength

Strain rate	10^{-5}/s	10^{-3}/s
Strength projection from test data (MPa)	1324	1557
Model prediction (MPa)	1392	1547





Shear Failure Mode

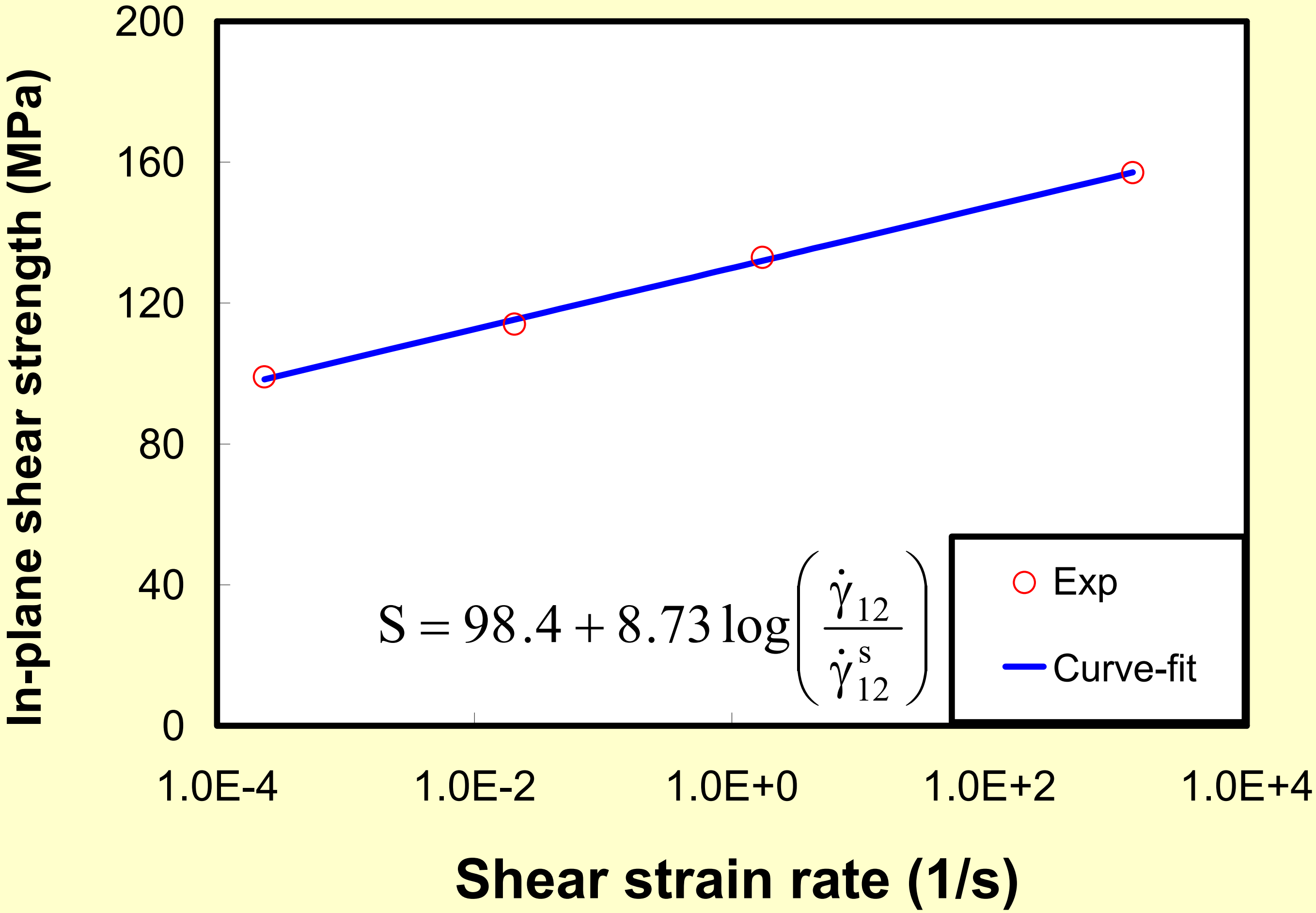


In-Plane Shear Strength

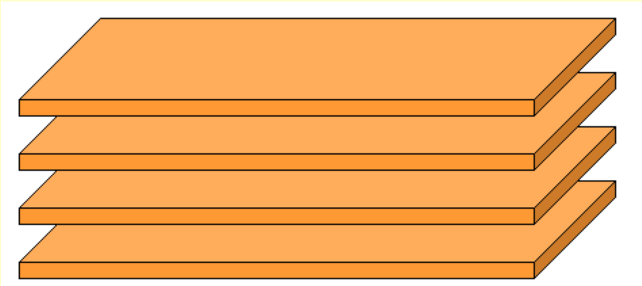
Transverse normal stress $\sigma_{22} = 0$

Pure shear strength (MPa)	Nominal axial strain rate (1/s)	Shear strain rate (1/s)
99	0.0001	0.00023
114	0.01	0.02
133	1	1.73
158	600	1300

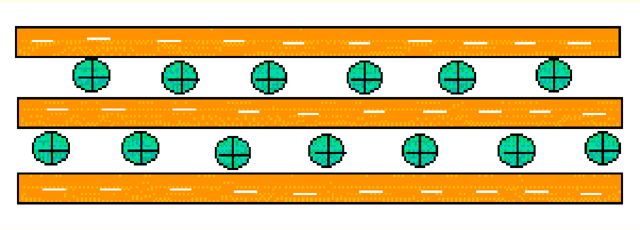
Shear Strength vs Shear Strain Rate



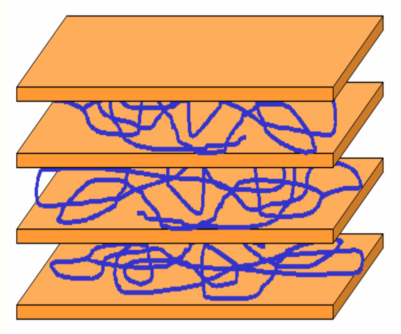
Montmorillonite Clay Structure



Layer dimension length (width) = 0.5 ~ 1 micron, thickness =1nm

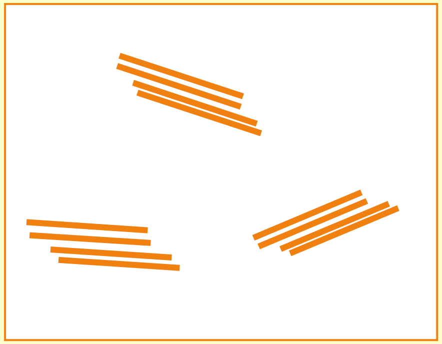


= Sodium ions



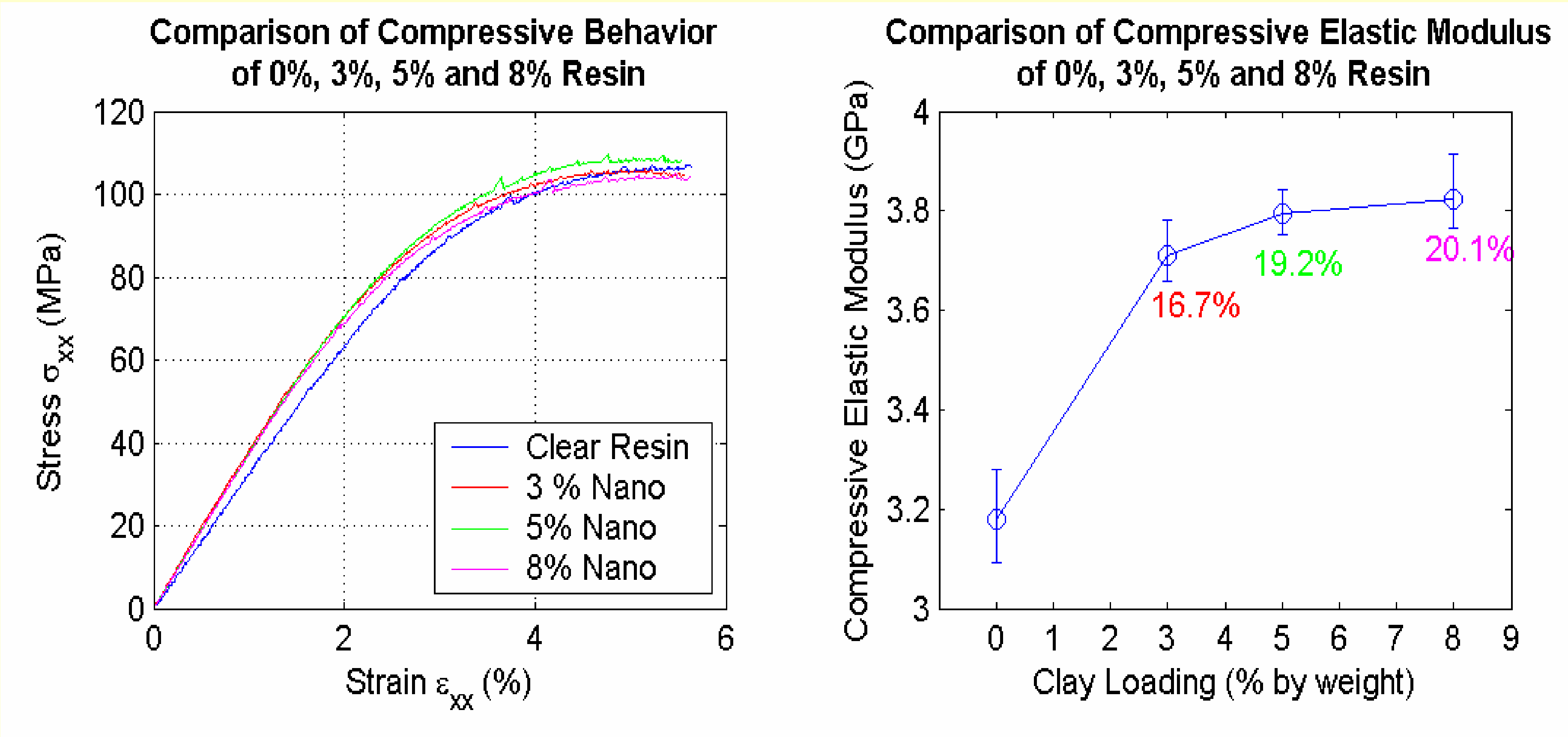
Intercalated

Exfoliated

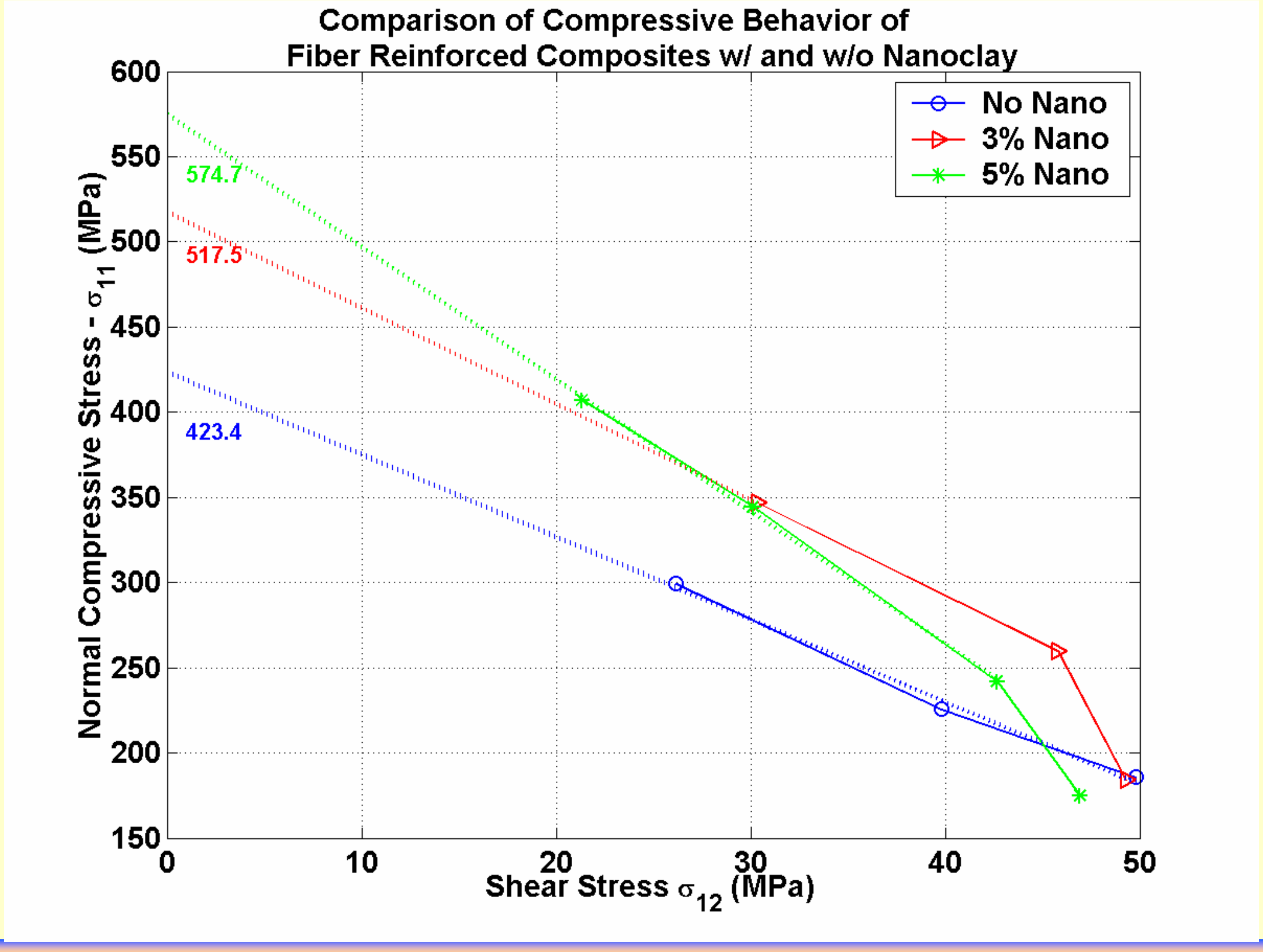


Unseparated (Tactoids)

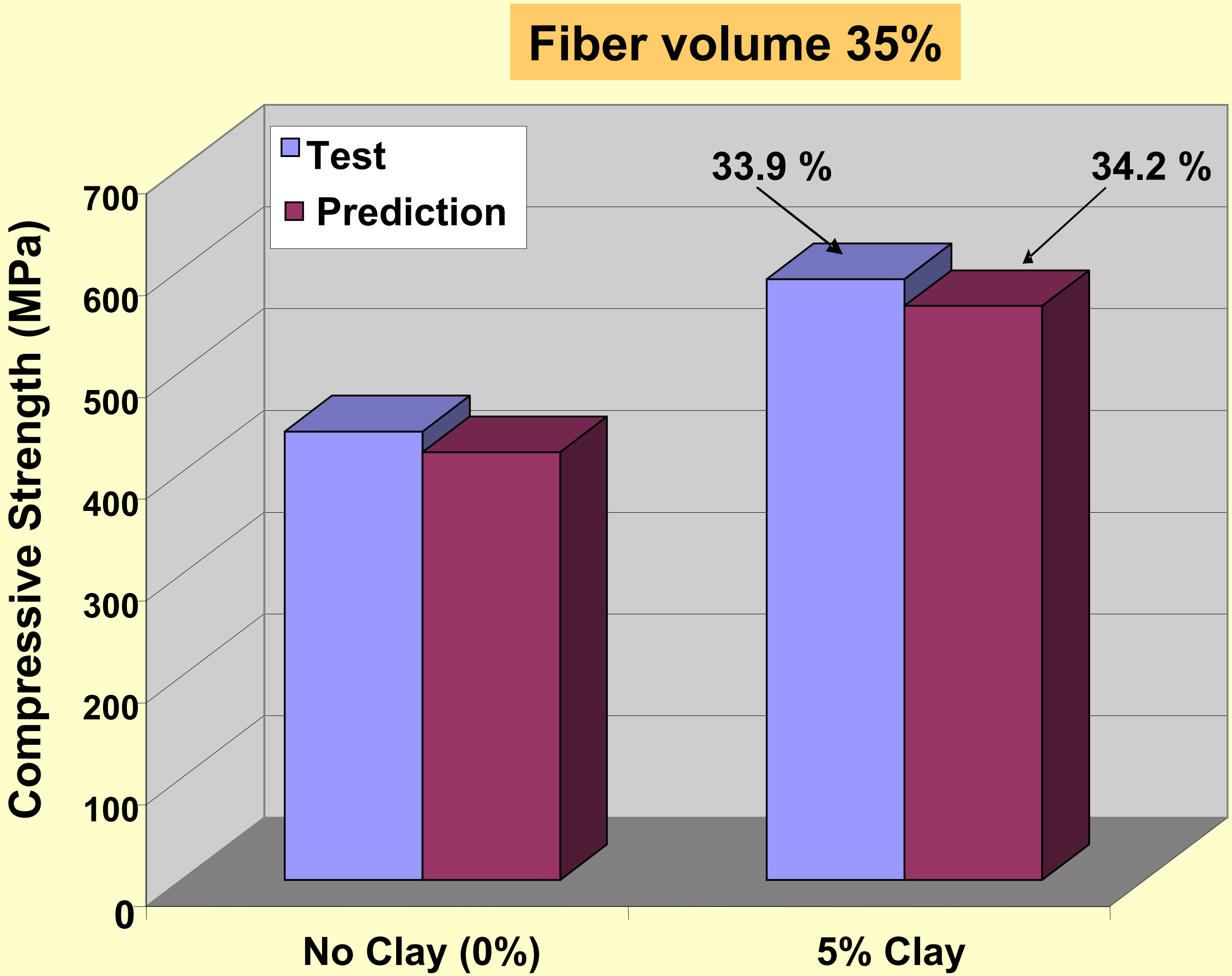
Comparison of Stress-Strain Behavior of Resin with Different Clay Loadings



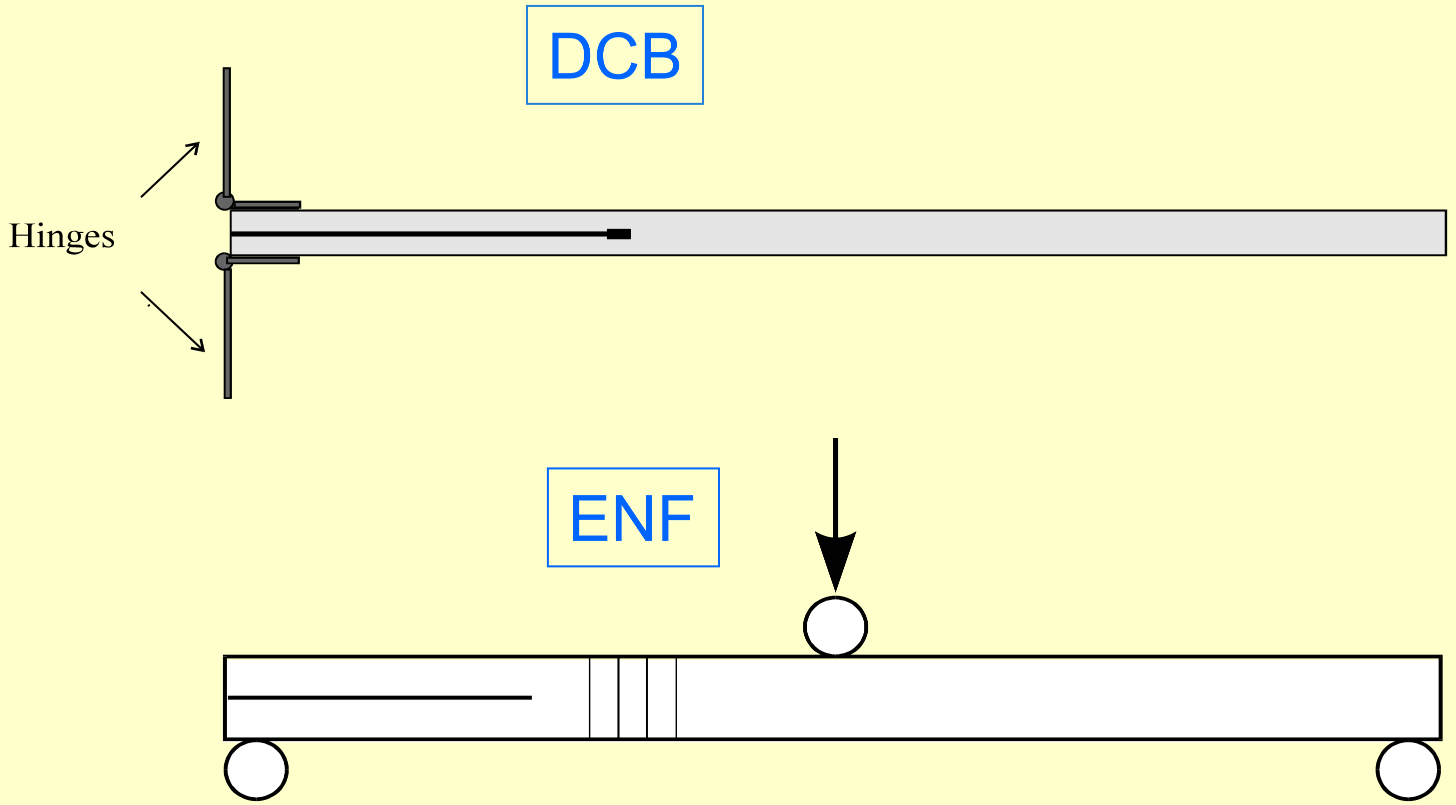
Compressive Strength of 0 Degree Composites



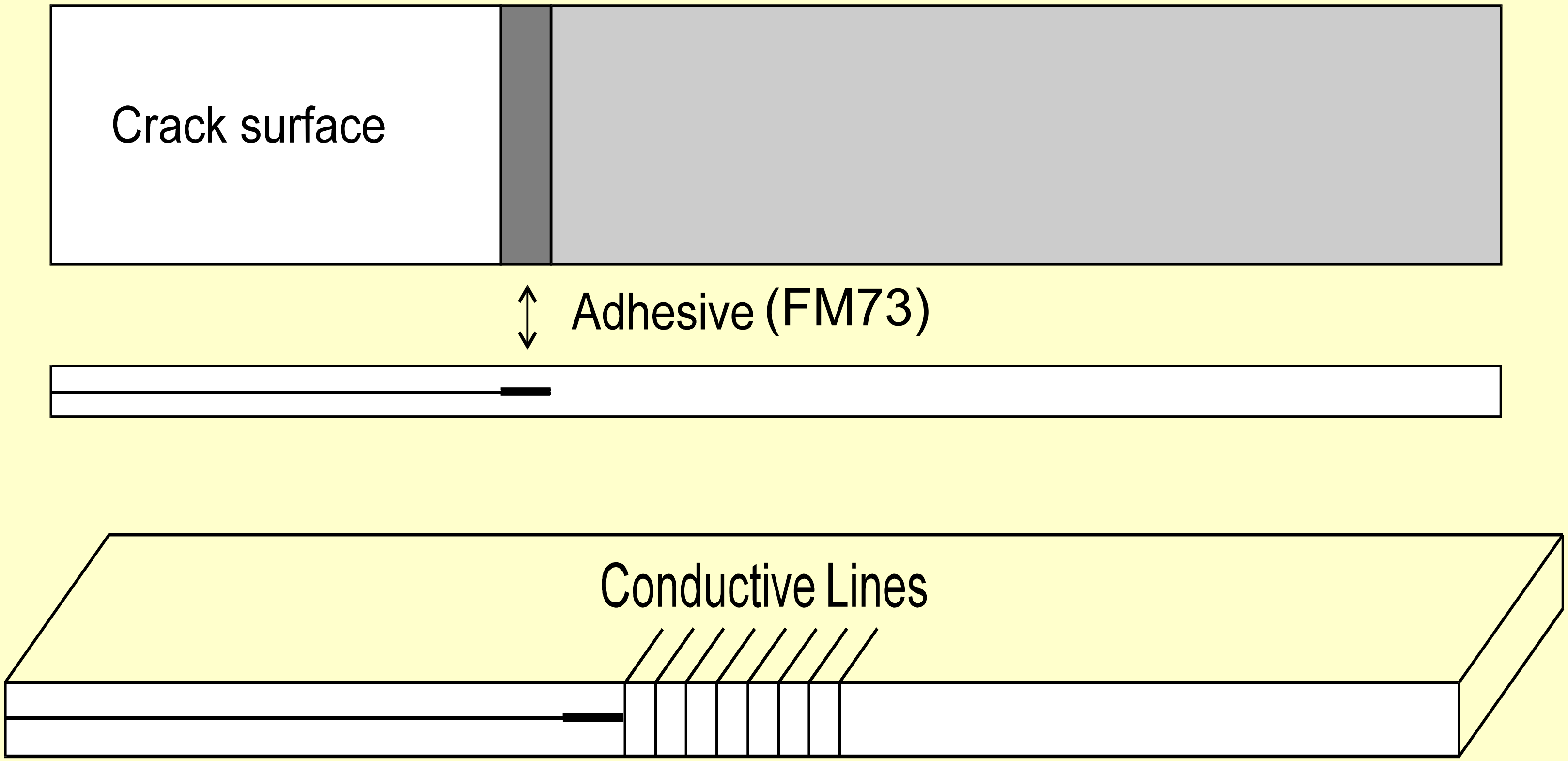
Longitudinal (0 deg) Compressive Strength



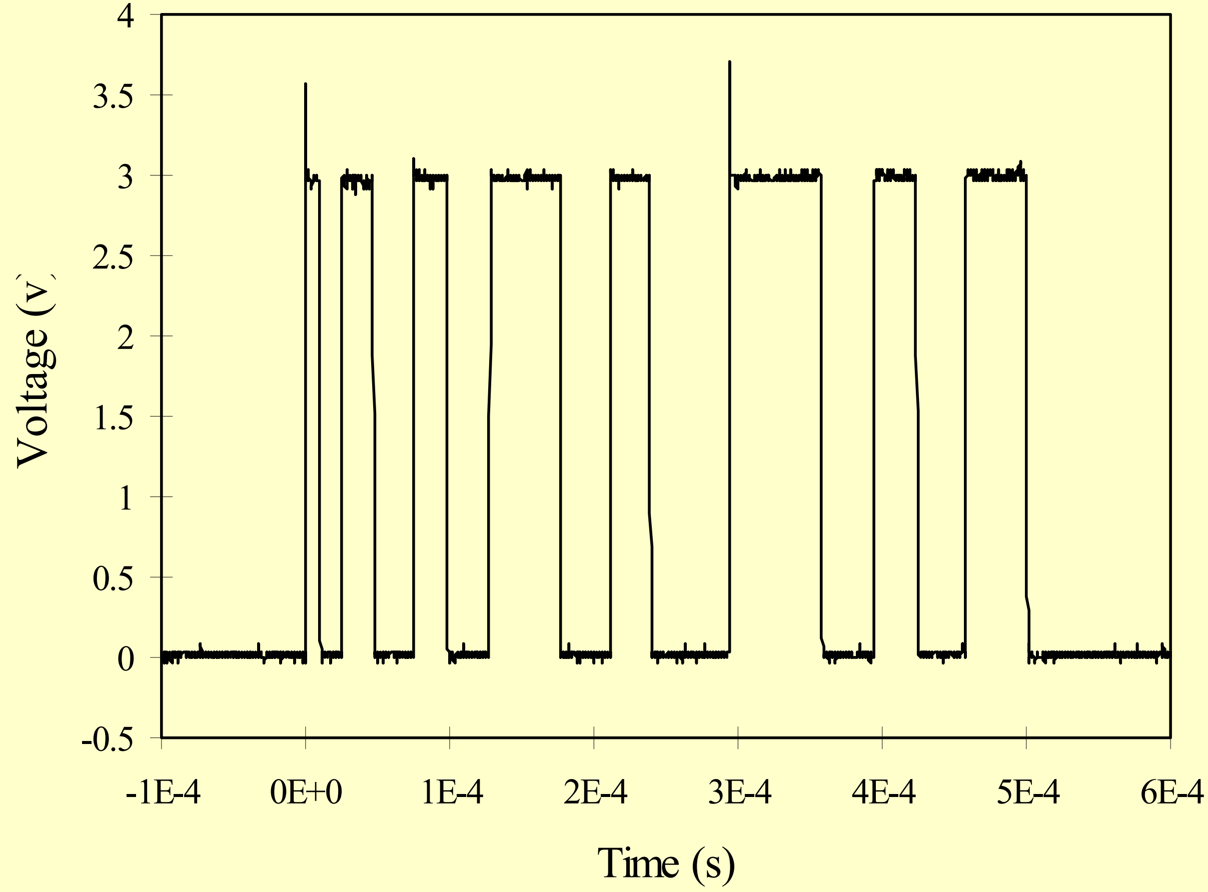
Interlaminar fracture Test



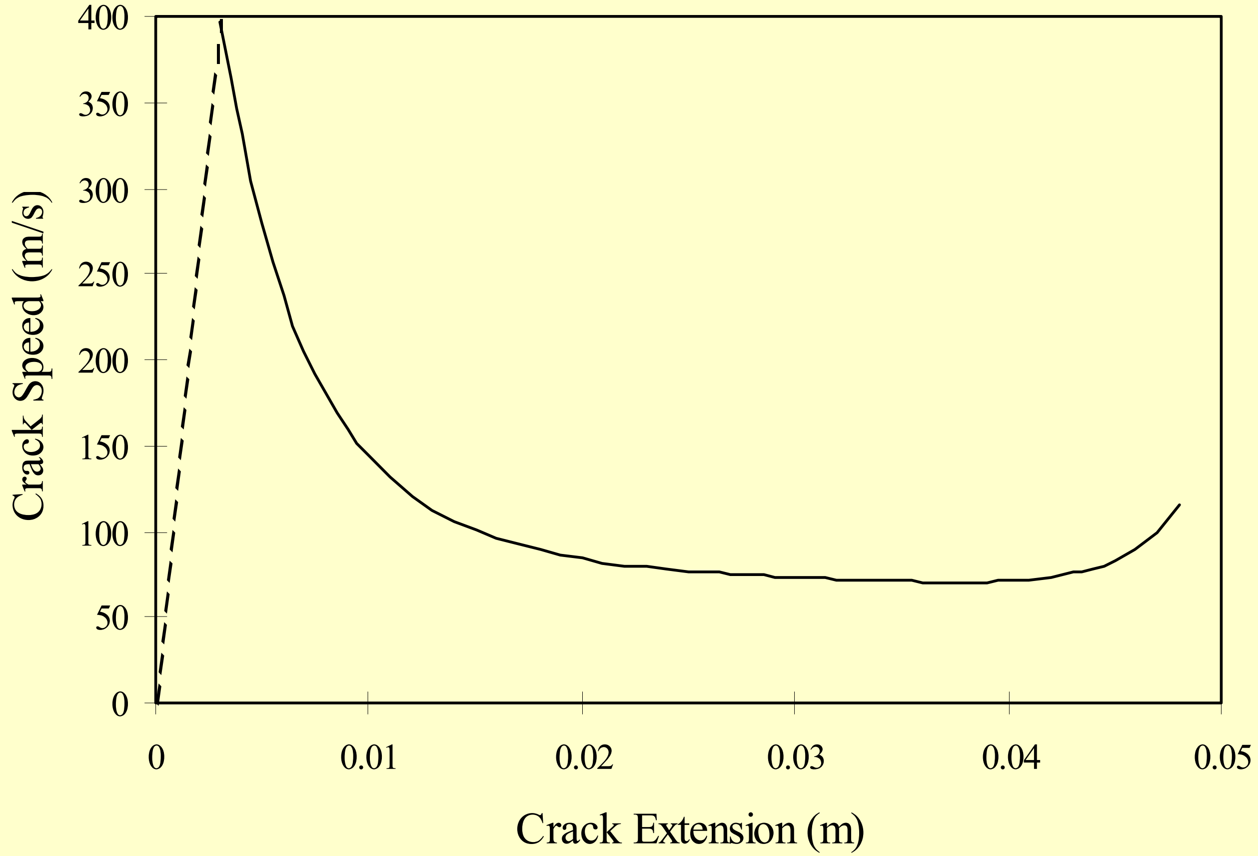
Delayed Crack Initiation



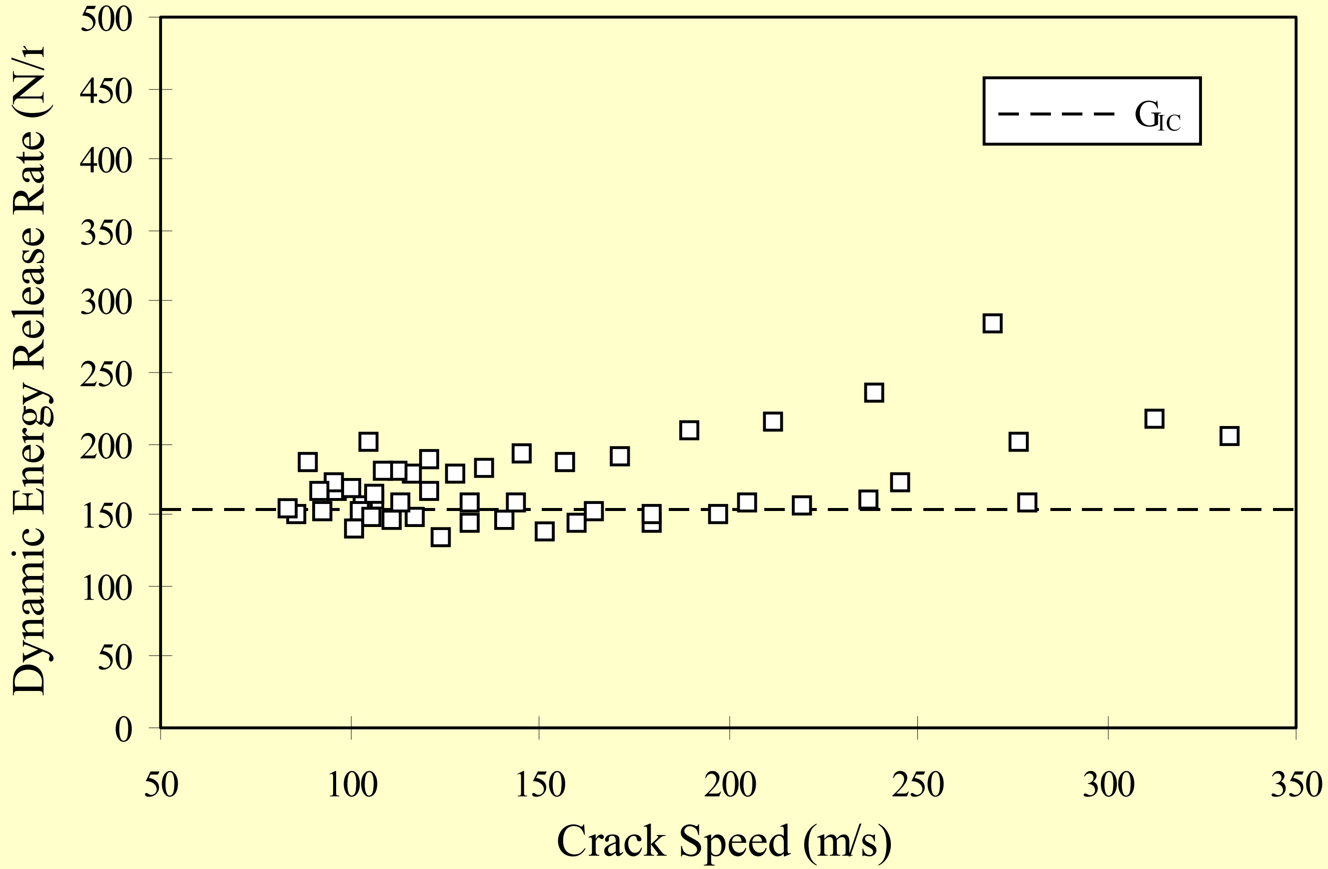
Crack Extension History



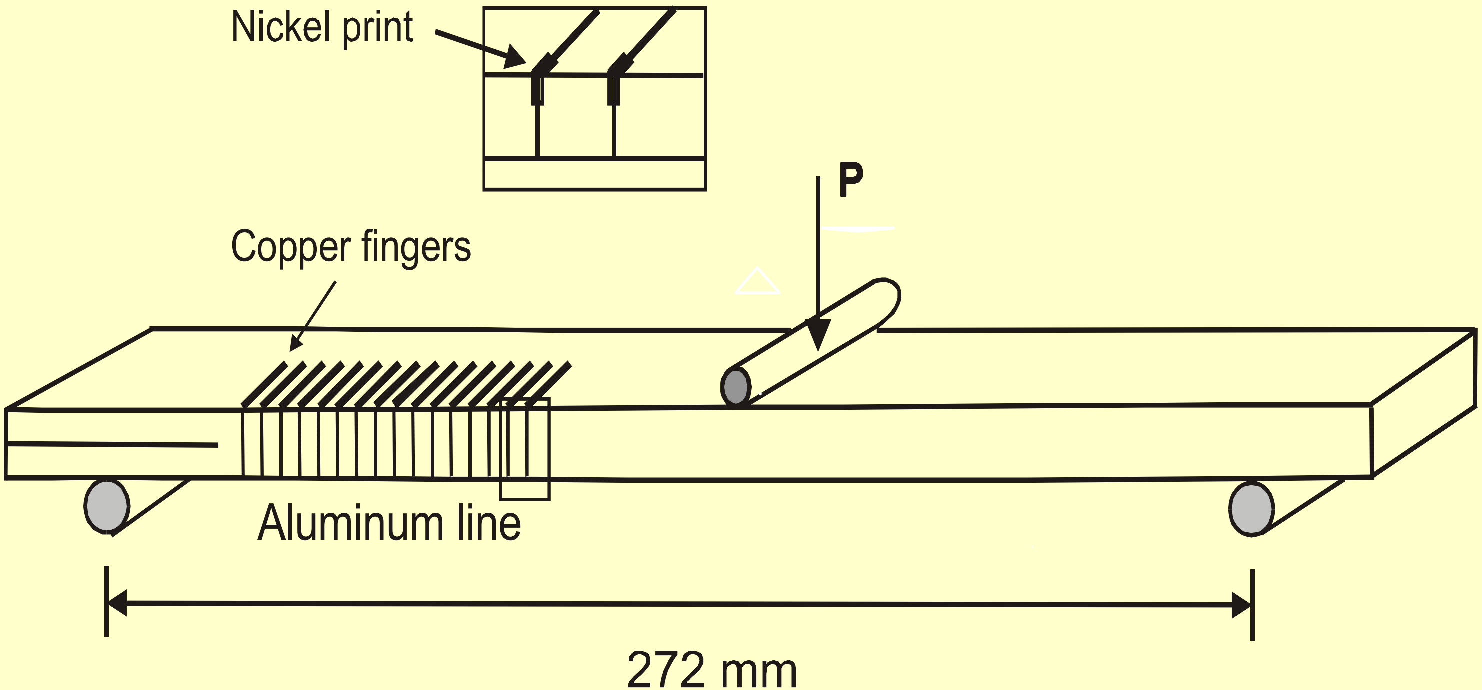
Typical Crack Speed History
Mode I



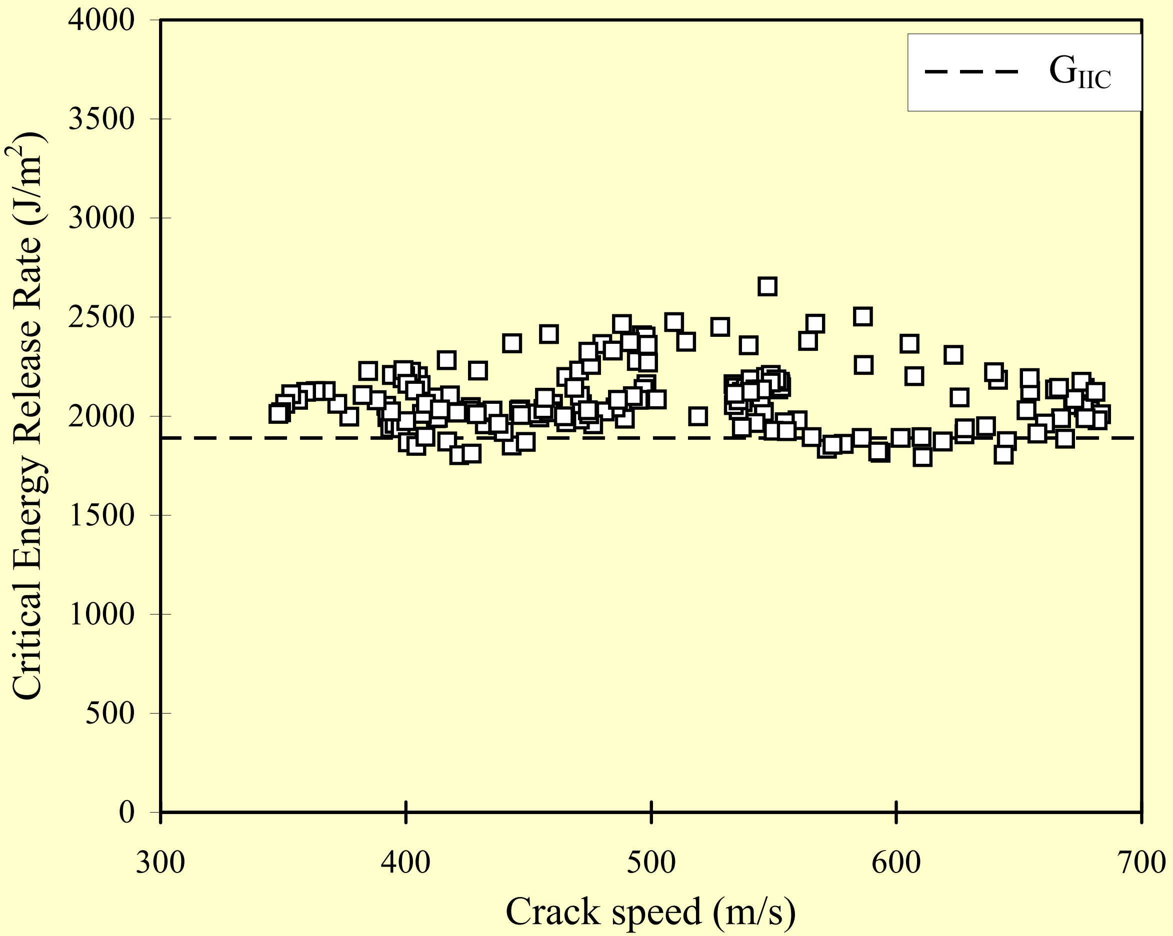
Mode I Fracture Toughness for AS4/3501-4



ENF Test for Mode II Fracture



Mode II Dynamic Fracture Toughness for S2/8553



Mixed Mode Dynamic Fracture Toughness