CEAC-TR-01-0103

MULTIAXIAL NONLINEAR DEFORMATION AND FAILURE STRENGTH OF FILAMENT-WOUND KEVLAR/EPOXY COMPOSITE

D. Miret, A. Miyase and S. S. Wang

Composites Engineering and Applications Center (CEAC), University of Houston, Houston, TX

April, 2001

TABLE OF CONTENTS

1. INTRODUCTION

A series of multiaxial loading experiments have been conducted on hoop-wound Kevlar/epoxy tubular composite specimens. The composite specimens provide the following advantages for the study of deformation and failure behavior of the composite [1,2,3]:

(1) Any state of combined normal and shear stresses at the ply level can be obtained in the most accurate manner.

(2) Ply composite properties can be determined accurately in the hoop-wound tubular specimens made with the same processing parameters as those for tubular composite laminate structural components.

(3) Undesirable stress concentrations, which occur in other test specimen geometries, do not exist in the tubular specimens.

The multiaxial experimental facilities, specimen preparation and design, gripping system, data acquisition techniques, and experimental procedure are described in this report. The results obtained from the experiments are given and discussed in Sections 4, 7 and 8.

2. OBJECTIVES

The overall objectives of the research are to:

(1) Establish non-linear constitutive equations for the hoop-wound Kevlar/epoxy fiber composite material.

(2) Determine deformation characteristics and failure behavior under various multiaxial loading states.

(3) Identify physical mechanisms responsible for various failure modes in the hoop-wound Kevlar/epoxy composite.

(4) Construct a multiaxial failure envelope for the Kevlar/epoxy composite system.

3. EXPERIMENTS

3.1 Kevlar/Epoxy Tubular Specimens

Hoop-wound composite specimens (see Fig. 1) were made of Kevlar/epoxy by a conventional filament-winding method. The composite tubes had a winding angle of approximately $\pm 1.5^0$ off the circumferential direction with twelve-ply thickness; i.e., the specimens had a $(\pm 88.5)_6$ lamination. The average of measured inner diameters was d_i = 2.0 in; the outer diameter, d_o = 2.47 in. An inner rubber layer was introduced and had a thickness dimension between 0.0025 and 0.0031 in. The length of the test specimen was 15 in. In Fig. 2 a typical microstructure of the hoop-wound Kevlar/epoxy specimen is shown.

The Kevlar/epoxy specimens were made with the following curing schedule: (a) 150°F for 10 hours and (b) 250°F for 12 hours under an ambient pressure.

The resin used was an aromatic-amine based epoxy, composed of Epon 862 cured with a EpiCure W agent. The mixing resin/curing agent ratio (by weight) was 100 parts of Epon 862 to 26.4 parts of EpiCure W.

Properly designed E-glass/epoxy tabs, also hoop-wound, were laid on each specimen to ensure load transfer without slippage in the gripping region during testing [11-15]. The tabs were machined to desired dimensions. The gage section was kept in an as-received condition.

(a) Specimen Geometry and Dimensions

Eleven Kevlar/epoxy specimens were tested in this research. The geometrical parameters of individual specimens were given in Table 1.

(b) Specimen Preparation

For each specimen tested, a total of six strain gages were used for different measurements. Specifically, the following arrangements were made for the strain gage measurements.

- Two in the hoop direction to measure ε_{yy} (Strain in the direction of fibers).
- Two in the axial direction to measure ε_{xx} (Strain in the transverse direction of fibers).
- Two along the 45^0 direction off the specimen axis to measure γ_{xy} (Engineering shear strain).

The surface where the strain gages were glued was first mechanically polished and cleaned using a fine sandpaper.

3.2 Experimental Program

(a) Experimental Facilities

The experimental facilities used for this study consisted of a closed-loop servo-hydraulic multiaxial loading system (Fig.3) with a desired, combined axial, pressure and torsional loading capacity. The axial, pressure and torsional loading actuators were independently controlled. The composite tubular specimens were subjected to various combinations of axial and torsional loading.

(b) Data acquisition and analysis

A computer-controlled data acquisition system was developed to record the applied axial load, torque and specimen deformation during each test. The axial and shear deformations were determined accurately from the strain gages mounted on the specimens. The strain signals were processed through a combination of eight-quarter and half Whetstone bridges, and then stored in a microcomputer for subsequent analysis.

(c) Experimental Method and Procedure

(i) Evaluation of Composite Elastic Constants

Various mechanical tests were conducted on the hoop-wound Kevlar/epoxy tubular composite specimens to determine their elastic constants. The following loading cases and loading rates were applied to individual test specimens:

(a) *Axial tension* was applied to determine transverse tensile modulus and Poisson's ratio.

- Two tests were run in a load-control mode for each specimen.
- Loading rate: 0.75 kip/min with maximum load, F_{xx} = 0.75 kip.

(b) *Axial compression* was applied to determine transverse compressive modulus and Poisson's ratio.

- One test was run in a load control mode for each specimen.
- Loading rate: 2 kip/min with maximum load, F_{xx} = -2 kip.

(c) *Pure shear* was applied to determine shear modulus.

- Two tests were run in a torque control mode for each specimen.
- Loading rate: 2.5 kip-in/min with maximum torque, T = 2.5 kip-in.

(ii) Evaluation of Composite Strength and Failure Strain

After the previously described elastic-property-evaluation experiments were conducted, each specimen was then tested until failure in order to determine the failure strength and strain of the Kevlar/epoxy composite. The loading modes and loading rates used for the failure strength evaluation are described below:

(a) *Axial tension* was applied until specimen failure to determine transverse tensile strength and failure strain.

- Loading mode: load-controlled mode.
- Loading rate: 3.5 kip/min until failure.

(b) *Axial compression* was applied until specimen failure to determine transverse compressive strength and failure strain.

- Loading mode: load-controlled mode.
- Loading rate: 3.5 kip/min until failure.

(c) *Pure Shear* was applied until specimen failure to determine shear strength and failure strain.

- Loading mode: torque-controlled mode.
- Loading rate: 2.5 kip-in/min until failure.

(d)*Combined torsion and axial loading* was applied until specimen failure. First, an axial stress was applied up to a prescribed level, and then, shear was added and monotonically increased until failure.

- Loading modes: Load and torque controlled mode, respectively.
- Loading rate: Prescribed axial load level reached in one minute and 2.5 kip-in/min until failure.

(d) Composite Constitutive Equations

(i) Evaluation of Composite Elastic Constants

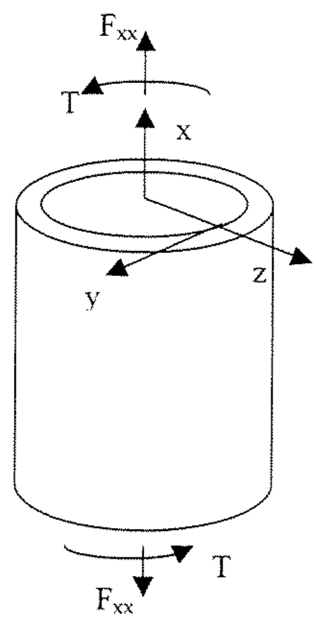
The following basic equations were applied to evaluate the elastic responses of the hoop-wound Kevlar/epoxy tubes subjected to individual axial tension, axial compression and pure shear.

Axial Tension (and Compression) Tests

Transverse Elastic Modulus: $E_{xx} = \sigma_{xx} / \varepsilon_{xx}$

Poisson's Ratio: $\nu_{xy} = - \varepsilon_{yy} / \varepsilon_{xx}$

Axial Stress: $\sigma_{xx} = F_{xx} / A$



Torsion Tests

Shear Modulus: $G_{xy} = \tau_{xy} / \gamma_{xy}$

Shear Stress: $\tau_{xy} = T * (R_o / J)$

Note that all the results are shown in the structural coordinates [x, y, z], where x represents the transverse direction of fibers, and y, the longitudinal direction of fibers.

(ii) Nonlinear Composite of Constitutive Equations

A nonlinear constitutive equation derived based on the well-known complementary strain energy density function formulation [4,5] has been used here to describe the nonlinear behavior of the Kevlar/epoxy composite. The nonlinear shear constitutive equation of the Kevlar/epoxy composite is expressed as

$$\gamma_{xy} = \tau_{xy} / G_{xy} + S_{xyxy} (\tau_{xy})^3$$

where S_{xyxy} is the high-order coefficient to describe the nonlinear part of shear behavior of the Kevlar/epoxy composite. Its value has been obtained from the pure shear experiments and will be discussed in the next section.

4. RESULTS AND DISCUSSION

4.1 Nonlinear Composite Material Constitutive Equations

The stress-strain behavior of the hoop-wound Kevlar/epoxy subjected to individual axial tension, pure shear and axial compression is shown in Figs. 4, 5, 6 and 7, respectively.

The multiaxial deformation behavior of the hoop-wound Kevlar/epoxy subjected to combined torque and axial load are given in Figs. 8 and 9.

In Tables 2 and 3, various mechanical properties of the hoop-wound Kevlar/epoxy composite obtained from the experiments are summarized.

The nonlinear material parameter in the shear constitutive equation of the Kevlar/epoxy composite was found as: $S_{xyxy} = 2 * 10^{-14}$ (psi)$^{-3}$. In Fig. 10 the nonlinear shear equation for the composite and the experimental data obtained are shown.

4.2 Multiaxial Failure Strength Envelope and Failure Modes

The multiaxial failure strength envelope of the hoop-wound Kevlar/epoxy composite has been determined, based on the multiaxial strength experiments. The complete failure strength envelope for the Kevlar/epoxy composite is shown in Fig. 11.

Note that distinct characteristics of the failure envelope are observed in the transverse tension-shear and transverse compression-shear regions. Similar to other composite systems [1, 6-8], three different regions can be clearly defined, based on the three different failure modes observed in the Kevlar/epoxy composite. Under combined compression and shear, applying low transverse compressive stress increases the composite failure strength considerably (Region II), whereas applying a high compressive stress (Region III) dictates the failure mode and reduces the composite strength. For the cases under combined transverse tension and shear (Region I), the Kevlar/epoxy strength envelope follows the well-known Hashin's failure theory [9, 10].

In the Kevlar/epoxy composite under multiaxial loading, the aforementioned matrix-dominated failure modes are governed by the following equations, depending on the stress state in the composite:

(1) *REGION I: Matrix-dominated transverse tensile failure:*

$$\sigma_2 > 0 \quad \Rightarrow \quad F_I(\sigma_i) = \left(\frac{\sigma_2}{X_2^+}\right)^2 + \left(\frac{\sigma_6}{X_6}\right)^2 = 1$$

(2) *REGION II: Matrix-dominated shear failure:*

$$\sigma_2 > (X_2^- + X_6) \quad \Rightarrow \quad F_{II}(\sigma_i) = \frac{\frac{\sigma_2}{2} + \sqrt{\frac{\sigma_2^2}{4} + \sigma_6^2}}{D_2} = 1$$

(3) *REGION III: Matrix-dominated compressive failure :*

$$\sigma_2 < (X_2^- + X_6) \quad \Rightarrow \quad F_{III}(\sigma_i) = \frac{\frac{\sigma_2}{2} - \sqrt{\frac{\sigma_2^2}{4} + \sigma_6^2}}{D_3} = 1$$

where $\sigma_2 \cong \sigma_{xx}$ and $\sigma_6 \cong \tau_{xy}$.

For the hoop wound Kevlar/epoxy composite, D_2 and D_3 are selected to be $X_6 \cong [\tau_{xy}(f)]$ and $X_2^- \cong [\sigma_{xx}(f)$ in compression], respectively.

5. SUMMARY AND CONCLUSIONS

(1) The mechanical behavior of a filament-wound Kevlar/Epoxy composite subject to individual axial tension, pure shear, and axial compression as well as combined loading has been studied. Extensive multiaxial mechanical tests were also conducted. The composite elastic moduli, strength, and strain to failure are summarized below:

(a) *Elastic Constants of the hoop-wound Kevlar/epoxy composite:*

Transverse tensile Young's modulus:	$E_{xx}(+) = 0.596$ msi
Transverse compressive Young's modulus:	$E_{xx}(-) = 0.606$ msi
Poisson's ratio (in tension):	$\nu_{xy}(+) = 0.077$
Poisson's ratio (in compression):	$\nu_{xy}(-) = 0.080$
Shear modulus:	$G_{xy} = 0.257$ msi

(b) *Strength and Failure Strain of the hoop-wound Kevlar/epoxy composite:*

Transverse tensile strength:	$\sigma_{xx}(f) = 2.2$ ksi
Transverse tensile strain to failure:	$\varepsilon_{xx}(f) = 0.0036$
Transverse compressive strength:	$\sigma_{xx}(f) = -12.88$ ksi
Transverse compressive strain to failure:	$\varepsilon_{xx}(f) = -0.0270$
Pure shear failure strength:	$\tau_{xy}(f) = 6.86$ ksi
Pure shear strain to failure:	$\gamma_{xy}(f) = 0.0320$

(2) The nonlinear composite constitutive equation, based on the complementary strain energy formulation, has been found to describe well the nonlinear shear behavior of the Kevlar/epoxy composite. The nonlinear shear parameter obtained for the filament-wound Kevlar/epoxy composite was:

$$S_{xyxy} = 2 * 10^{-14} \text{ (psi)}^{-3}$$

(3) Multiaxial load-controlled strength experiments were performed to study in detail the failure envelope of the Kevlar/epoxy composite under various combinations of loads. Hashin's failure theory [9] is found to be suitable to describe the composite failure under combined transverse tension and shear. Currently developed multiaxial strength theories [1, 6, 10] are necessary to describe the strength behavior of the Kevlar/epoxy composite under combined shear and compressive loading.

5. ACKNOWLEDGEMENTS

This research was supported in part by Offshore Technology, Shell Global Solutions US. The authors wish to express their gratitude to Shell for the support, and to Dr. K. H. Lo for the technical discussion and encouragement.

6. REFERENCES

(1) Wang, S.S., Srinivasan, S., 1996, *"Long-term leakage failure of filament-wound fiberglass composite laminate tubing under combined internal pressure and axial loading"*. Technical Report CEAC-TR-96-0101, University of Houston, Houston, TX.

(2) Daniel, I.M. and Ishai, O., 1994, *Engineering Mechanics of Composite Materials,* Oxford University Press, New York.

(3) Swanson, S.R, Messick M.J. and Tian, Z.,1987, *"Failure of carbon/epoxy lamina under combined stress"*, Journal of Composite Materials, vol. 21, pp. 619-630.

(4) Hahn, Z., and Tsai, S.W., 1973, *"Nonlinear elastic behavior of unidirectional composite laminae"*, Journal of Composite Materials, vol. 7, pp. 102-118.

(5) Hashin, Z., Bagchi, D., and Rosen, B.W., 1974, *"Nonlinear behavior of fiber composite laminate"*, Technical Report NASA CR 2313, Washington, D.C.

(6) Puck, A. and Schneider, W., 1960, *"On failure mechanisms and failure criteria of filament-wound glass-fiber/resin compoistes,"* Plastics and Polymers, pp.33-44.

(7) Christensen, R.M., 1988, *"Tensor transformations and failure criteria for analysis of fiber composite materials,"* Journal of Composite Materials, vol. 22, pp. 874-897.

(8) Hahn, H.T. Eriksson, J.B., and Tsai, S.W., 1982, *"Characterization of matrix interface-controlled strength of unidirectional composites,"* Fracture of Composite Materials, Eds. Matinus Nijhoff, the Netherlands, pp. 197-214.

(9) Hashin, Z. 1980, *"Failure criteria for unidirectional fiber composites,"* Journal of Applied Mechanics, ASME Trans.

(10) Skundra, A. M., 1984, *"Micromechanics of failure of reinforced plastics"*, Failure Mechanics of Composites, Eds. North-Holland, New York, pp. 1-68.

(11) Whitney, J.M. and Halpin, J.C. 1968, *"Analysis of laminated anisotropic tubes under combined loading,"* Journal of Composite Materials, vol. 2, no.3, pp.360-367.

(12) Whitney, J.M., 1971, *"On the use of shell theory for determining stresses in composite cylinders,"* Journal of Composite Materials, vol.5, no. 3, pp. 340-353.

(13) Leknitskii, S.G., 1981, *Theory of an anisotropic body*. Mir publications, Moscow.

(14) Pagano, N.J. and Whitney, J.M., 1970. *"Geometric design of composite cylindrical characterization specimens"*, Journal of Composite Materials, vol. 4, pp. 360-378.

(15) Roy, A.K. and Tsai, S.W., 1987, *"Design of thick composite cylinders". Design and Analysis of Compostie Material Vessels"*. Presented at the Pressure Vessels and Piping Conference, June 28. San Diego, California. Eds. PVP vol. 121, pp. 75-85.

7. TABLES

Spec. ID #	O.D. (in)	A (in^2)	t (in)	J (in^4)	Ro/J (in^3)
9-1-1	2.469	1.455	0.0300	1.880	0.656
-2	2.473	1.474	0.0294	1.908	0.648
-4	2.496	1.564	0.0297	2.048	0.609
-5	2.464	1.411	0.0317	1.824	0.675
-6	2.473	1.467	0.0302	1.900	0.650
-7	2.464	1.433	0.0302	1.848	0.666
9-2-2	2.468	1.448	0.0302	1.870	0.659
-4	2.457	1.401	0.0309	1.801	0.682
9-3-2	2.463	1.447	0.0250	1.861	0.660
9-4-7	2.451	1.425	0.0238	1.817	0.674
9-8-2	2.491	1.502	0.0358	1.970	0.632
Average	**2.466**	**1.442**	**0.0297**	**1.861**	**0.662**
Stand. Desv	**0.012**	**0.032**	**0.0038**	**0.054**	**0.016**

Table 1. Geometric Parameters of the Kevlar/Epoxy Composite Specimens.

where: **J** is the Polar Moment of Inertia. $J = [R_o^4 - (R_i + t)^4]*\pi / 2$

A is the Cross Sectional Area. $A = [R_o^2 - (R_i + t)^2]*\pi$

$\mathbf{R_o}$ is the outer radius. $R_0 = O.D./2$

$\mathbf{R_i}$ is the inner radius

t is the thickness of inner rubber layer.

Table 2. Elastic Material Properties of the Kevlar/Epoxy Composite

Spec. ID #	Loading Mode	Composite Elastic Constants				
		$E_{xx}^{(+)}$ (Msi)	$E_{xx}^{(-)}$ (Msi)	ν_{xy} (+)	ν_{xy} (-)	G_{xy} (Msi)
9-1-1	tension	0.579		0.074		0.251
-2	shear					0.272
-4	compres.		0.634		0.086	
-5	tension	0.617	0.615			0.273
-6	75%C-Sh	0.606	0.617	0.072	0.072	0.241
-7	30%C-Sh	0.573	0.577	0.071	0.074	0.247
9-2-2	50%T-Sh	0.586	0.589	0.074	0.074	0.257
-4	50%C-Sh	0.607	0.612	0.077	0.085	0.256
9-3-2	shear	0.617	0.617	0.078	0.078	0.274
9-4-7	compres.	0.588	0.594	0.091	0.093	0.245
9-8-2	75%C-Sh	0.593	0.599	0.077	0.076	
Average		**0.596**	**0.606**	**0.077**	**0.080**	**0.257**
Std.Desv.		**0.016**	**0.018**	**0.006**	**0.007**	**0.013**

Table 3. Kevlar/Epoxy Composite Strength and Failure Strain

Spec. ID #	Loading Mode	Failure Strength		Failure Strain	
		σ_{xx} (ksi)	τ_{xy} (ksi)	ε_{xx}	ε_{xy}
9-1-1	tension	2.12		0.0036	
-2	shear		6.87		0.0330
-4	compres.	-13.12		-0.0256	
-5	tension	2.28		0.0037	
-7	30%C-Sh	-4.2	7.87	-0.0070	0.0510
9-2-2	50%T-Sh	1.03	5.61	0.0017	0.0240
-4	50%C-Sh	-5.73	8.62	-0.0090	0.0570
9-3-2	shear		6.85		0.0310
9-4-7	compres.	-12.64		-0.0290	
9-8-2	75%C-Sh	-10.00	6.54	-0.0200	0.034

8. FIGURES

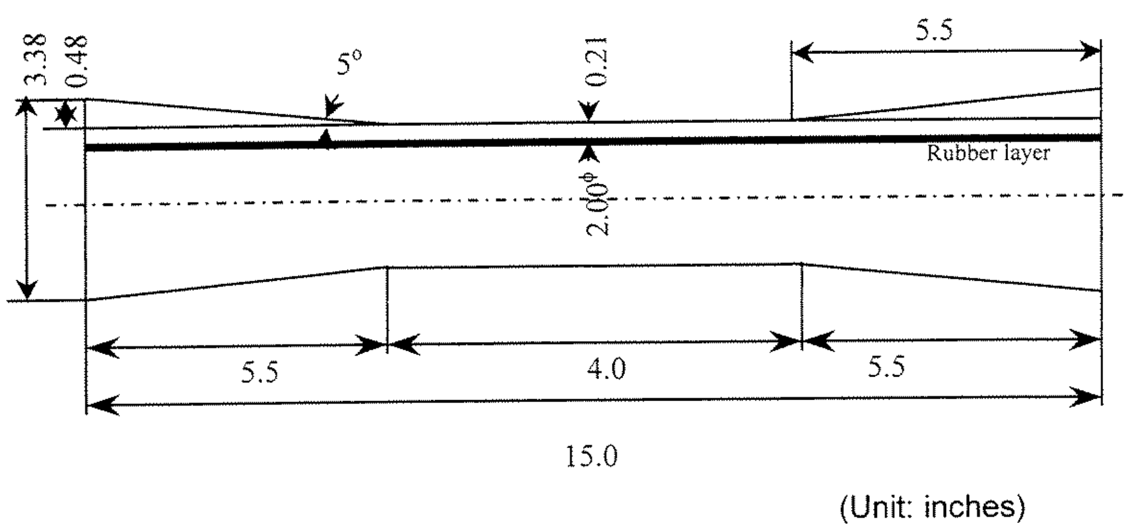


Figure 1. Kevlar/Epoxy Composite Test Specimen Geometry

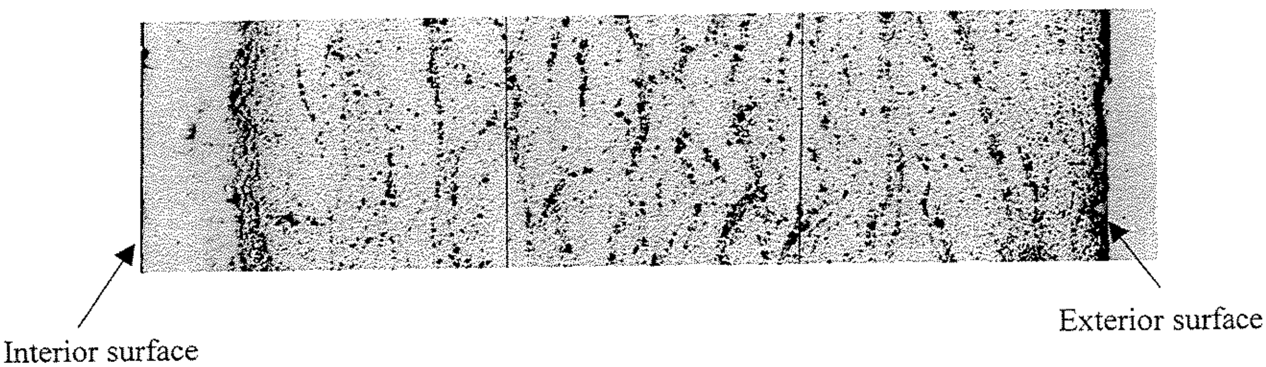


Figure 2. Microstructure of the Kevlar/Epoxy Composite

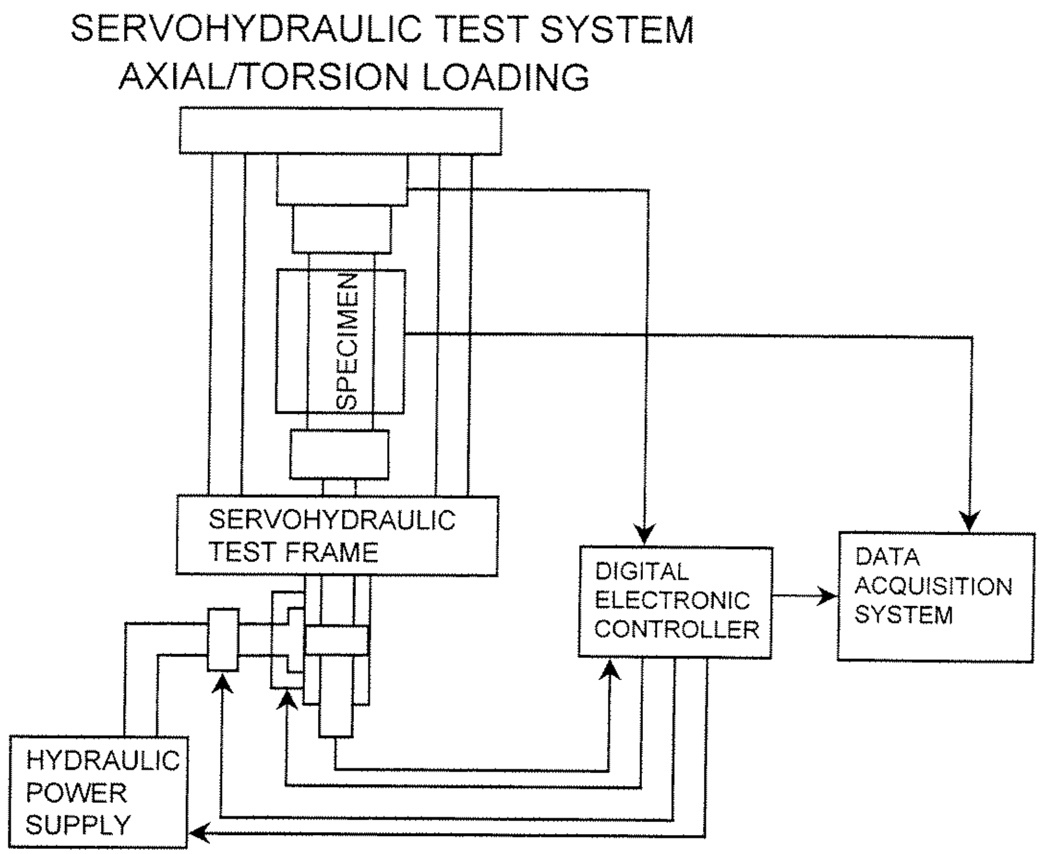


Figure 3. Servo-Hydraulic Multiaxial Material Test System

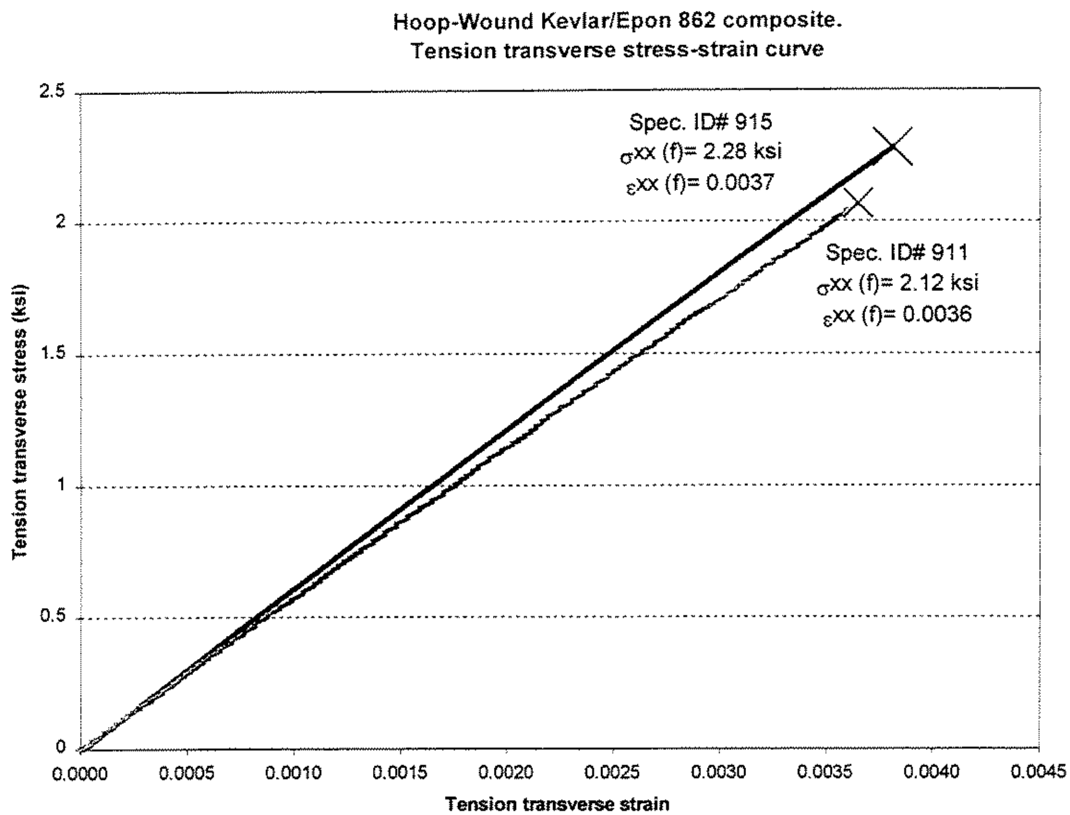


Figure 4. Tensile Transverse Stress-Strain Behavior of Hoop-Wound Kevlar/Epoxy Composite

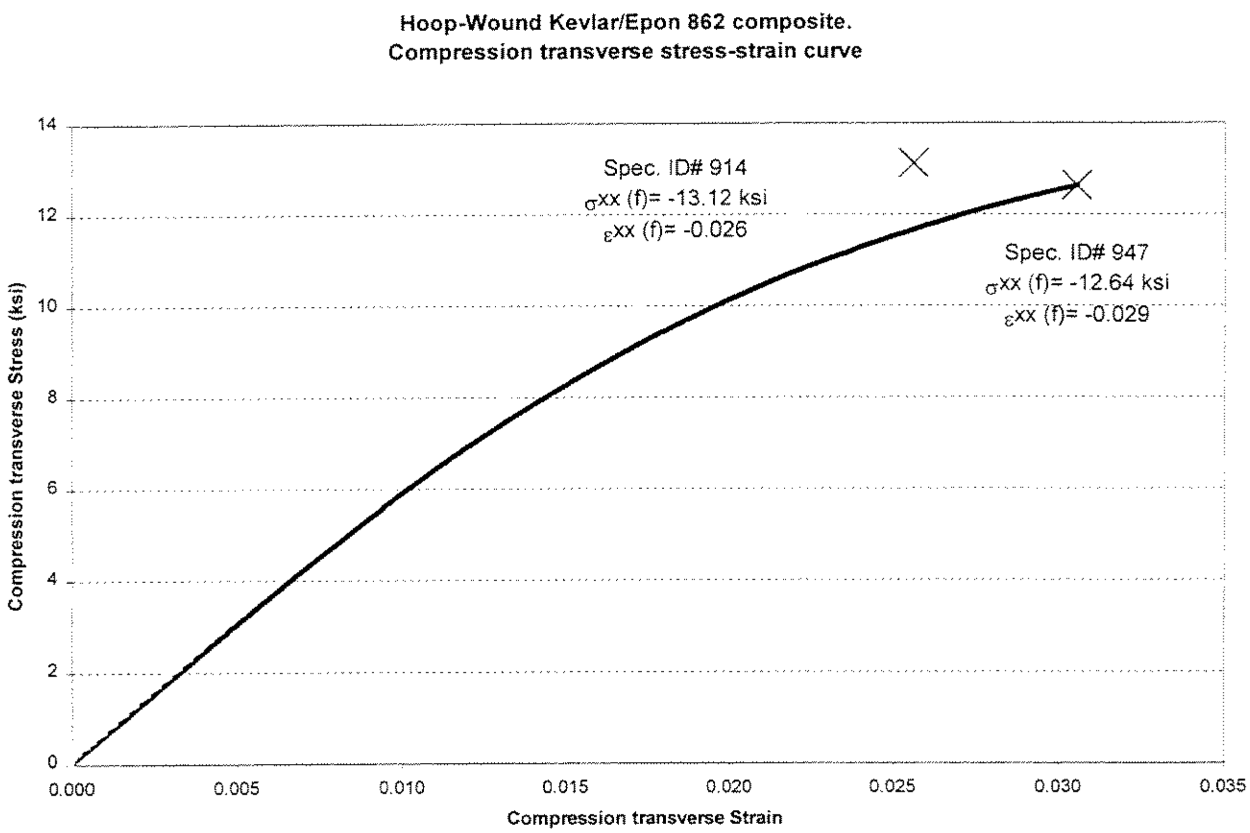


Figure 5. Transverse Compressive Stress-Strain Behavior of Hoop-Wound Kevlar/Epoxy Composite

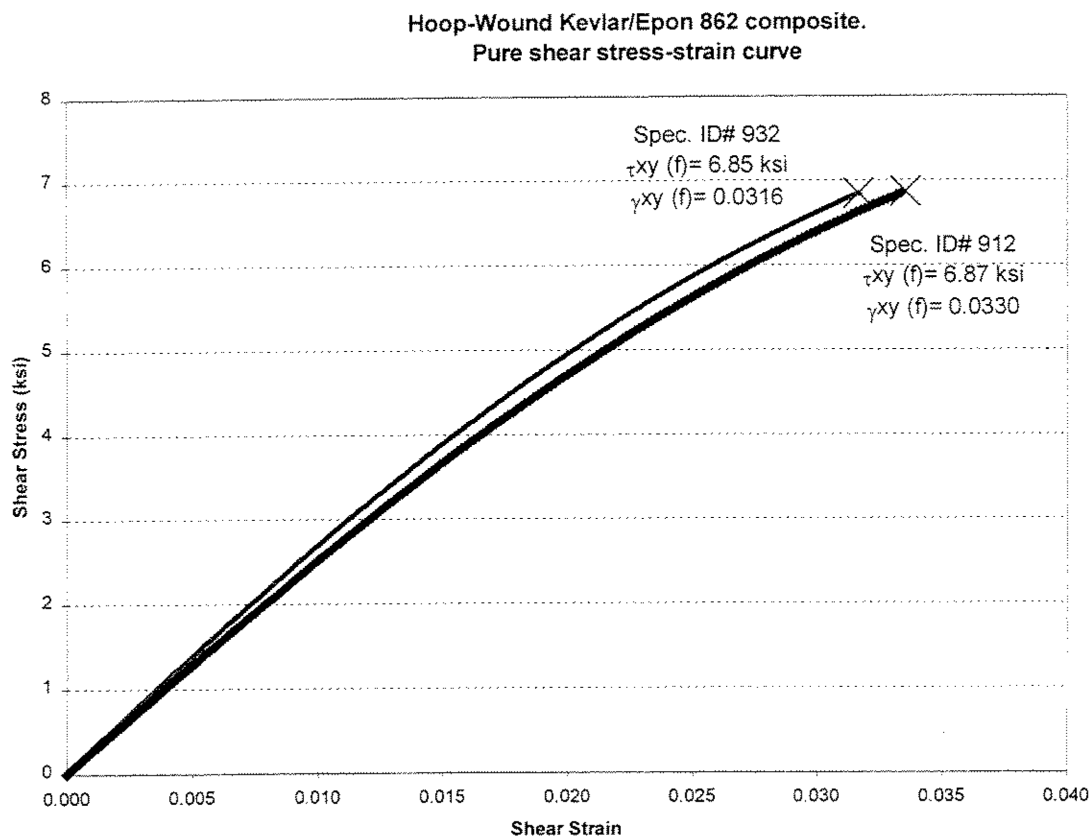


Figure 6. Pure shear stress-strain behavior of hoop-wound Kevlar/epoxy composite

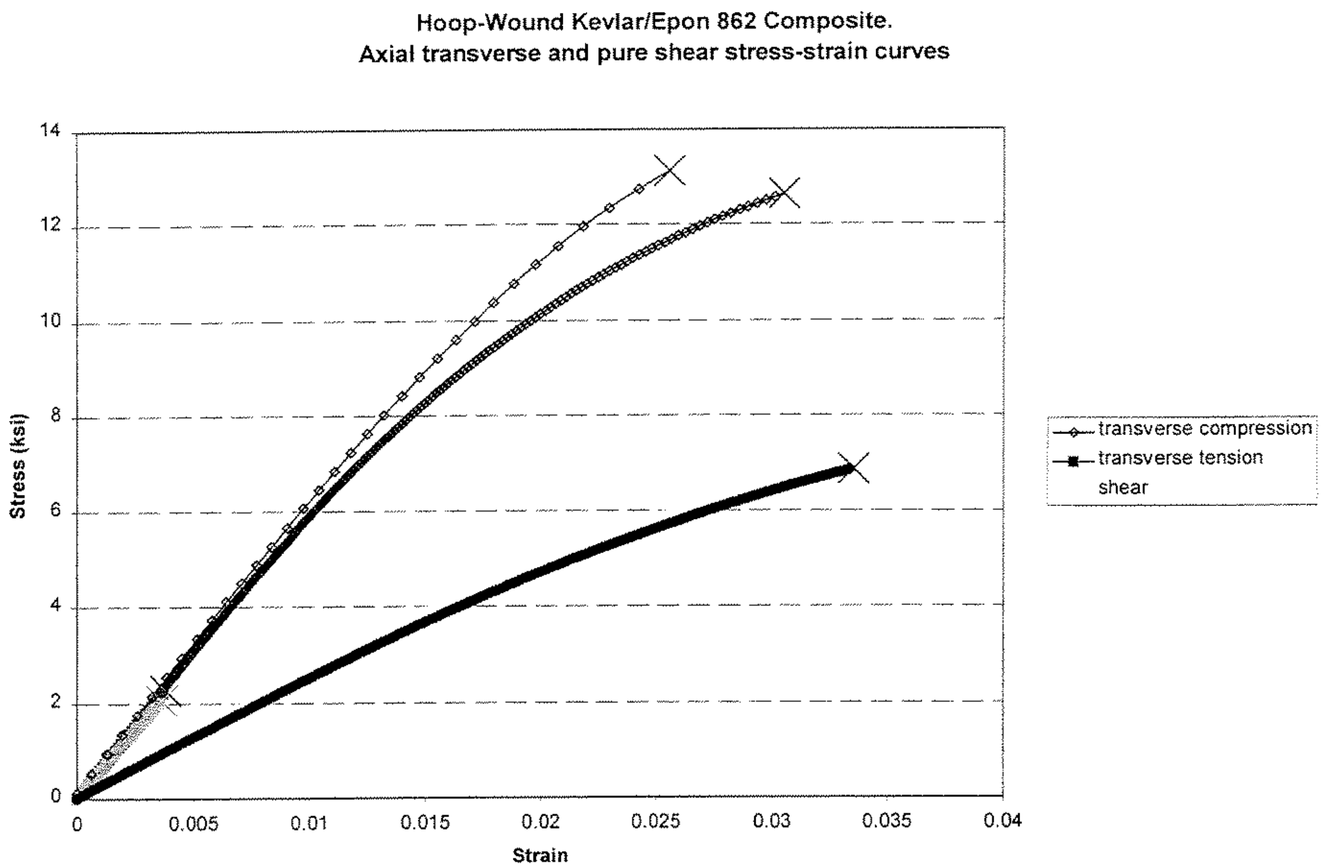


Figure 7. Transverse Axial and Pure Shear Stress-Strain Behavior of Hoop-Wound Kevlar/Epoxy Composite

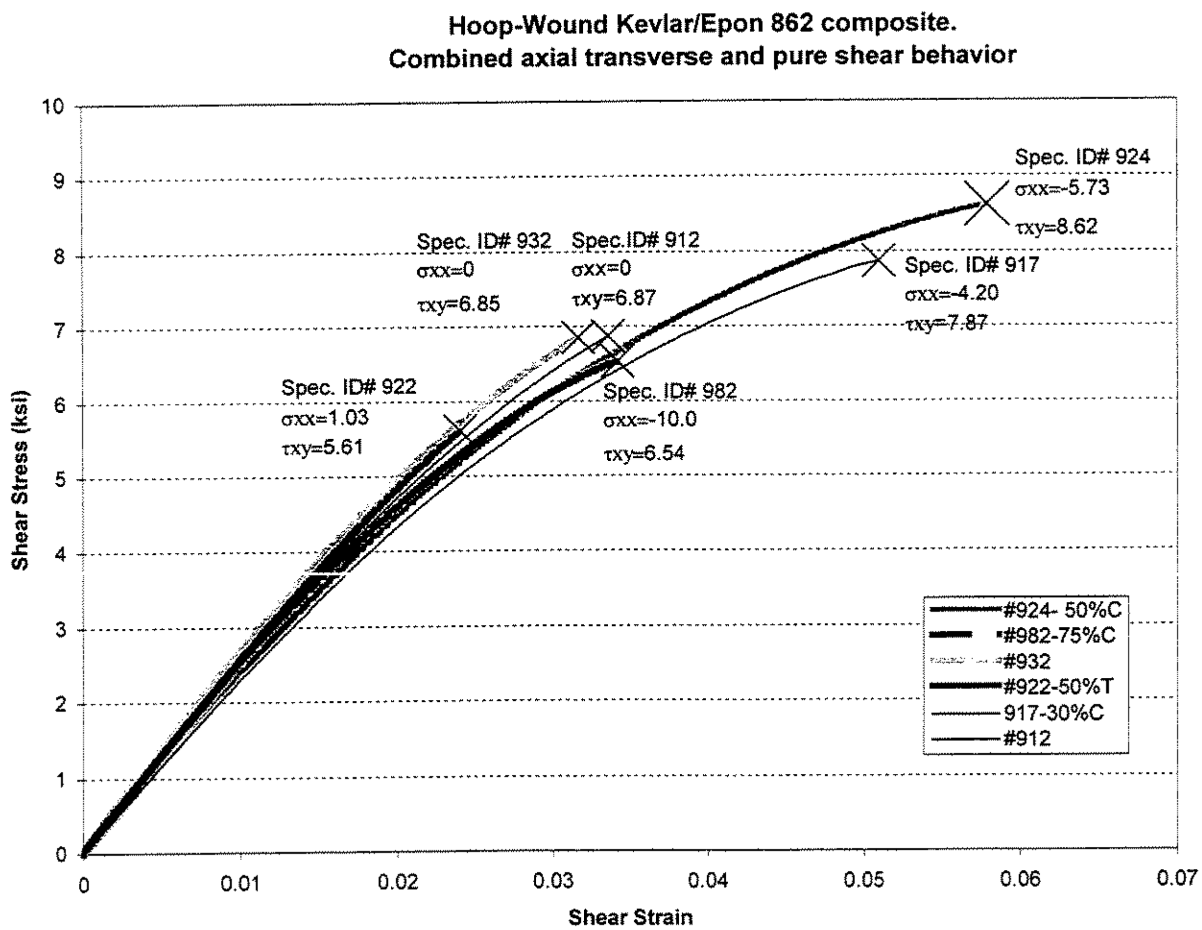


Figure 8. Multiaxial Mechanical Behavior of Kevlar/Epoxy Subject to Combined Transverse Axial and Pure Shear Loading

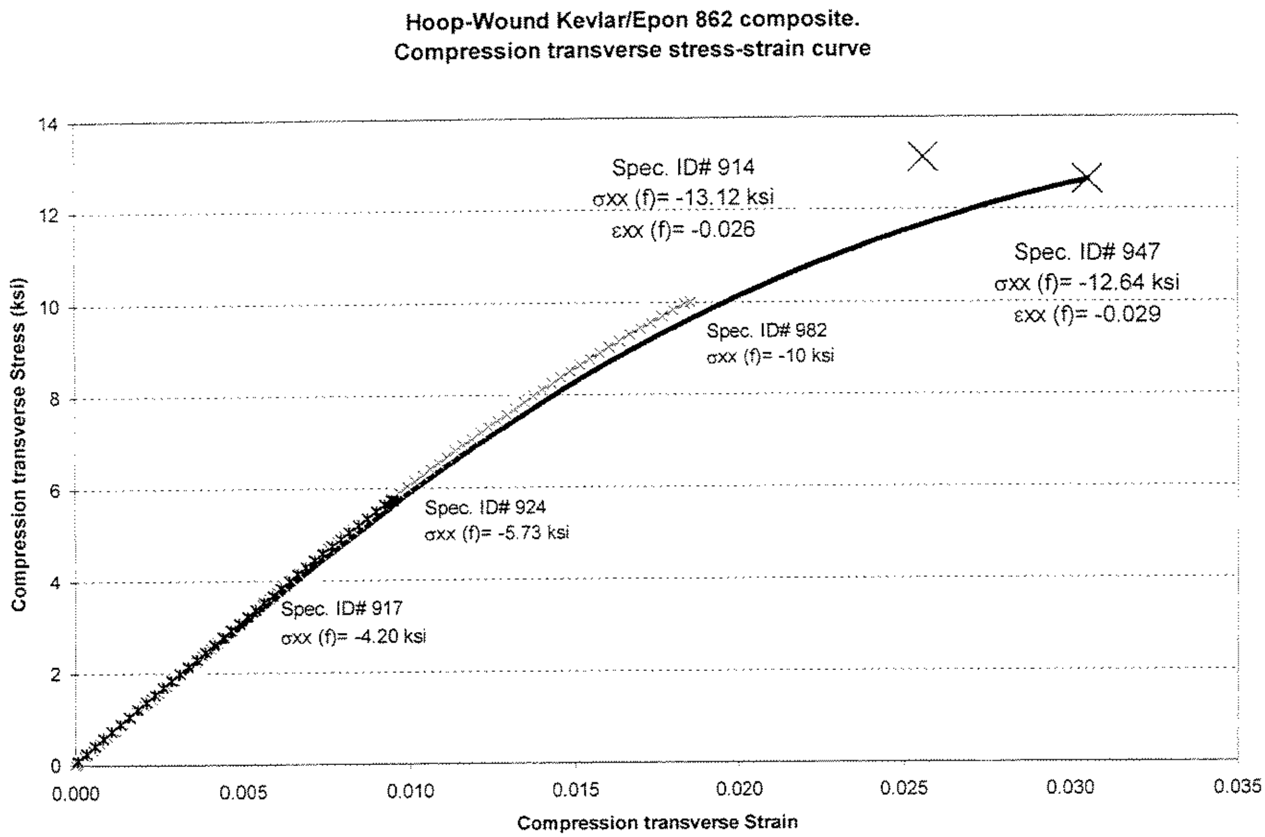


Figure 9. Transverse Compressive Stress-Strain Behavior of Hoop-Wound Kevlar/Epoxy Composite

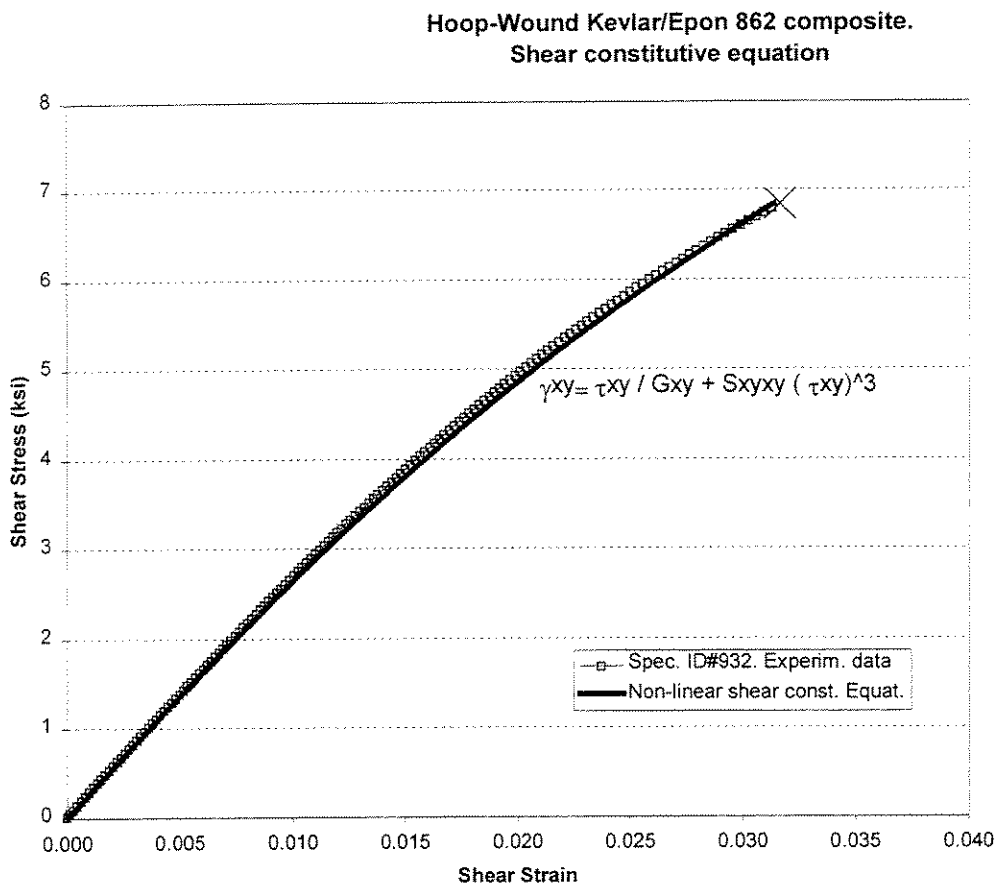


Figure 10. Nonlinear Shear Constitutive Equation for Hoop-Wound Kevlar/Epoxy Composite

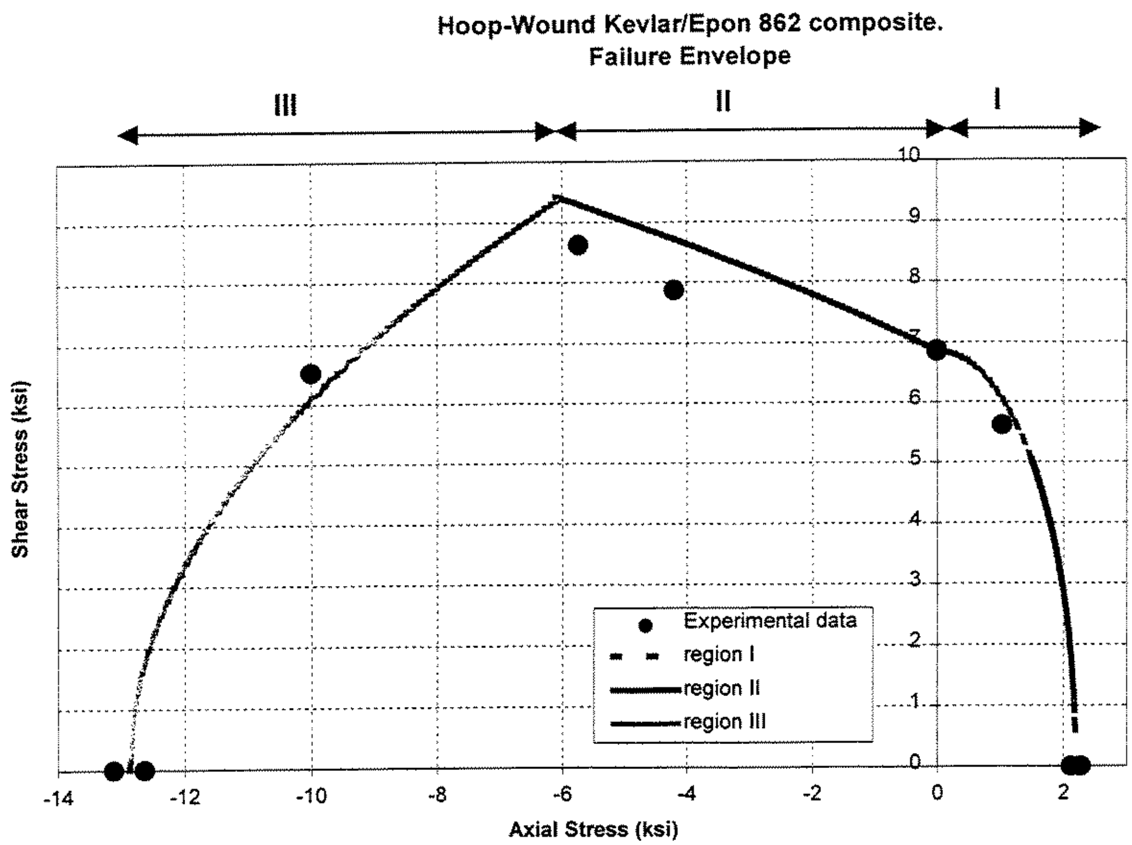


Figure 11. Multiaxial Failure Strength Envelope for Kevlar/Epoxy Composite