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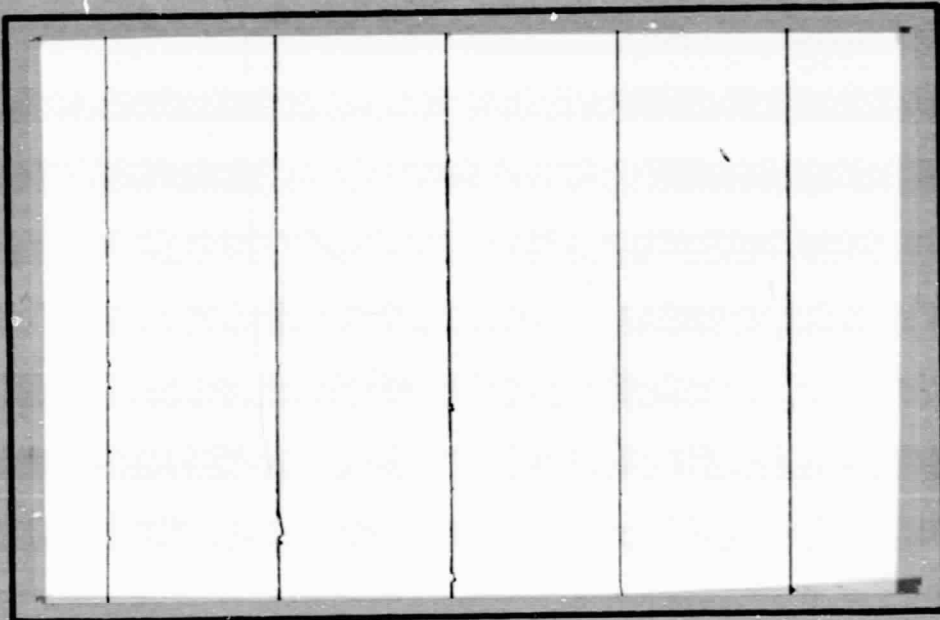
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February 1977

A COMPARISON OF SIMPLE SHEAR CHARACTERIZATION
METHODS FOR COMPOSITE LAMINATES

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ABSTRACT

Various methods for the shear stress-strain characterization of composite laminates are examined and their advantages and limitations are briefly discussed. Experimental results and the necessary accompanying analysis are then presented and compared for three simple shear characterization procedures. These are the off-axis tensile test method, the $[\pm 45^\circ]_s$ tensile test method and the $[0^\circ/90^\circ]_s$ symmetric rail shear test method. It is shown that the first technique indicates the shear properties of the G/E laminates investigated are fundamentally brittle in nature while the latter two methods tend to indicate that the G/E laminates are fundamentally ductile in nature. Finally, predictions of incrementally determined tensile stress-strain curves utilizing the various different shear behavior methods as input information are presented and discussed.

INTRODUCTION

Accurate stress-strain characterization is a necessary requisite if composite laminates are to be safely used as structural components. Probably the most popular and successful analytical tool for both characterization purposes and stress analysis is laminated plate theory. With this procedure multi-directional laminate properties can be calculated provided the properties of an individual ply or lamina are known. If the process is used incrementally and in conjunction with any one of a number of failure theories, the stress-strain behavior of an arbitrary laminate can be predicted from initial loading to complete failure or separation. In other words, initial moduli or stiffnesses can be predicted, instantaneous moduli or stiffnesses at any intermediate load can be predicted, and the final failure stresses or strain can be predicted.

As indicated, fundamental to laminated plate (lamination) theory are the properties of a single ply. Usually, individual lamina are assumed to be homogeneous, orthotropic and in a state of plane stress. As such, only four material properties are required, i.e., the stress-strain response in the fiber direction for a load in the same direction, the stress-strain response normal to the fiber direction for a load in the same direction, the strain response normal to the fibers for a load in the direction of the fibers or vice versa, and the in-plane shear response of the lamina. The first three properties can be obtained relatively easily by performing uniaxial tension tests of

unidirectional laminates. The last property, the in-plane shear behavior, is difficult to obtain and subject to considerable controversy primarily due to the problems encountered in achieving a state of pure shear.

A variety of shear determination techniques have been proposed.^[1-2] The short beam shear test has been used but shear stress variations through the thickness and different properties in tension and compression has limited its utility.^[3] The torsion testing of a thin tube^[4] and the picture frame test^[5] represent a better approach, but material and equipment expense as well as other difficulties make them generally unattractive. The standard rail shear test^[6] also often yields reasonable results. Again, however, material cost as well as the unsymmetric nature of the load (relative to the laminate) represent undesirable features. The symmetric rail shear test^[7] avoids the latter difficulty but does not alleviate material requirements and costs.

Use of judiciously chosen tensile tests seems to represent a rational alternative to the above shear testing techniques. The off-axis tensile testing of unidirectional laminates can be used to obtain shear behavior.^[8,9] Also, the tensile testing of $[\pm 45^\circ]_S$ laminates can be used for shear predictions and has been shown to give good results.^[10-11]

After carefully reviewing the literature, it seemed reasonable that a testing program to investigate the relative utility of several different shear investigative procedures would be worthwhile. Further,

it seemed that such a comparison should not only investigate the relative merits of different tests for the purpose of shear modulus determination, but should also compare the complete stress-strain response in shear together with the failure modes and the fracture stresses and strains encountered. To this end and because of their relative simplicity, the off-axis tensile test, the $[\pm 45^\circ]_5$ tensile test and the symmetric rail shear test were selected. In addition, it was thought desirable to compare the effect of using the shear properties determined by the chosen techniques in an incremental lamination analysis prediction of the tensile stress-strain response of several laminates.

ANALYSIS

In the following, the usual assumptions associated with laminated plate theory will be made.^[1] Further, as depicted in Figure 1, the x-y axes will be referred to as the global coordinates in which specimen geometry and loads are specified and the 1-2 axes will be referred to as the local or material coordinates in which local material properties are specified.

Off-Axis Tests

The shear modulus of a ply or lamina needed in laminated plate theory can be determined using the results of three tension tests. From a tensile test of a unidirectional laminate with the load in the fiber direction, the modulus E_{11} and Poisson's ratio, ν_{12} , can be determined. From a similar test with the load normal to the fibers, the modulus E_{22} can be determined. Using the preceding information

and the results of a third tension test with the load at an angle to the fiber direction (off-axis tensile test), the shear modulus, G_{12} , can be calculated from the following orthotropic transformation equation,

$$\frac{1}{E_x} = \frac{1}{E_{11}} \cos^4 \theta + \left[\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_{11}} \right] \sin^2 \theta \cos^2 \theta + \frac{1}{E_{22}} \sin^4 \theta \quad (1)$$

in which θ is the fiber direction and E_x is the modulus in the load direction.

While the above procedure is quite adequate for modulus, it does not provide a means for the determination of the total stress-strain response as equation (1) is only valid for stiffnesses. Actually, another simple procedure using measurements from an off-axis tensile specimen will yield the entire shear stress-strain curve for a lamina. All that is required is to measure the strains in three directions on such a specimen, e.g., in the longitudinal, transverse and 45° directions which is easily accomplished with an electrical strain gage rosette. By transforming both the measured strains and the applied stress (ϵ_x , ϵ_y , ϵ_{45° and σ_x), the strains and stresses in the local coordinates can be found (ϵ_1 , ϵ_2 , γ_{12} , σ_1 , σ_2 and τ_{12}). A plot of τ_{12} vs. γ_{12} yields the required shear behavior. Daniel^[8] and Chamis^[9] have suggested use of a 10° off-axis specimen for this purpose and have obtained good results with the technique

Often only rectangular rosettes are used in tensile testing to obtain longitudinal and transverse strains only. Thus, for such cases the procedure just outlined cannot be used. However, by assuming that

equation (1) is valid for tangent values of moduli or stiffnesses, it is possible to calculate complete shear stress-strain response using standard lamination theory in an incremental fashion. In other words, the global stiffness matrix A_{ij} can be calculated incrementally using incremental values of E_{11} , E_{22} , ν_{12} and G_{12} where the latter is obtained from equation (1) for a particular off-axis test. Knowing the A_{ij} 's and the load, N_x the global strains, ϵ_x , ϵ_y , γ_{xy} can be obtained. Finally the local stresses and strains can be found by transformation of global values. Hence, the shear, τ_{12} vs. γ_{12} , can be determined. It should be noted that the fundamental reason for this procedure for the case where a rectangular rosette is used is to be able to obtain a value of γ_{xy} . In other words, for the off-axis tension test, the principal axis of stress and strain do not coincide and only an axial stress, σ_x , produces not only an axial strain, ϵ_x , but a shear strain, γ_{xy} , as well.

$[\pm 45^\circ]_s$ Tests

Petit suggested the use of a uniaxial tensile test on a $[\pm 45^\circ]_s$ laminate for the purposes of obtaining the shear stress-strain response of a lamina.^[10] He showed that such properties could be obtained from measurements of the tensile load and axial and transverse strains coupled with an incremental lamination theory analysis of the $[\pm 45^\circ]_s$ laminate. His results were expressed as

$$G_{12} = \frac{2U_1 E_x}{8U_1 - E_x} \quad (2)$$

where

$$U_1 = \frac{[E_{11} + E_{22} + 2\nu_{21} E_{11}]}{8(1 - \nu_{12} \nu_{21})}$$

and

$$\nu_{21} = \frac{\nu_{12} E_{22}}{E_{11}}$$

E_{11} , E_{22} , etc., are the properties as previously defined and E_x is the axial modulus of the $[\pm 45^\circ]_S$ laminate. The shearing strain was expressed as

$$\gamma_{12} = (1 + \nu_{xy}) \epsilon_x \quad (3)$$

in which

$$\nu_{xy} = - \frac{\epsilon_y}{\epsilon_x}$$

and where ϵ_x was the axial strain and ϵ_y was the transverse strain of the $[\pm 45^\circ]_S$ laminate. An incremental procedure was used in order to account for the non-linear shear stress-strain response. The tangent modulus at different strain levels of the $[\pm 45^\circ]_S$ tensile response curve was found and used with equations (2) and (3) to obtain incremental shear stresses, $\Delta\tau_{12}$, at the various strain increments, $\Delta\gamma_{12}$, from the following expression

$$\Delta\tau_{12} = G_{12} \Delta\gamma_{12} \quad (4)$$

where G_{12} was taken from the previous strain level. Thus, using equations (2) to (4), the complete shear stress-strain response was predicted.

Later, Rosen^[11] simplified Petit's analysis by noting that the shearing stress is half of the applied stress for a tensile test in general and for a $[\pm 45^\circ]_s$ laminate in particular and by further defining the shearing strain to be the same as equation (3). Rosen's results were expressed as

$$G_{12} = \frac{\sigma_x}{2(\epsilon_x - \epsilon_y)} \quad (5)$$

Good agreement was found between Rosen's and Petit's results.

Rail Shear Tests

A symmetric rail shear test fixture proposed by Sims^[7] for use with $[0^\circ/90^\circ]_s$ laminates is shown in Figure 2. Since the specimen used was symmetric with respect to the applied load, P , the shearing stress, τ_{12} , was expressed as

$$\tau_{12} = \frac{P}{2A} \quad (6)$$

and the shearing strain as

$$\gamma_{12} = 2\epsilon_{45^\circ} \quad (7)$$

where A was the cross-sectional area parallel to the load and the strain was measured at an angle of 45° to the applied load. While Sims did not present a more detailed analysis, laminated plate theory can be used to show that this method does correspond to intralamina shear stress-strain response. As a $[0^\circ/90^\circ]_s$ laminate can be considered to be orthotropic, its constitutive relation can be expressed as

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} \quad (8)$$

where N_x , N_y and N_{xy} are the applied loads and ϵ_x , ϵ_y and γ_{xy} are the laminate strains with respect to the global axes. The $[S_{ij}]$ matrix is the compliance for the $[0^\circ/90^\circ]_s$ laminate. When only a shear load, N_{xy} , is applied, equation (8) reduces to

$$\gamma_{xy} = S_{66} N_{xy} = \frac{\tau_{xy}}{G_{12}} \quad (9)$$

as N_{xy} has a dimension of force per unit length and

$$S_{66} = \frac{1}{G_{12} t} \quad (10)$$

for a $[0^\circ/90^\circ]_s$ laminate. For this laminate, the principal stress and strain axes do coincide. Thus, equation (9) can be expressed as

$$G_{12} = \frac{\tau_{12}}{\gamma_{12}} \quad (11)$$

or it can be expressed in terms of the experimental quantities of Sims by substituting equations (6) and (7) into (11). The resulting equation can be written as

$$G_{12} = \frac{P}{4A\epsilon_{45}} \quad (12)$$

EXPERIMENTAL PROCEDURES

The T300-934 graphite/epoxy 16 ply flat laminates tested were supplied by Lockheed Sunneyvale. All specimens were machined from

these panels using a diamond impregnated saw. Three replicates of each geometry were manufactured and each contained fiberglass end tabs such that the ratio of the distance between tabs to width was 12 for tensile specimens and 10 for rail shear specimens. These ratios were selected in accordance with the analysis of Pagano and Halpin^[12] for tensile specimens and Whitney, et al^[6] for rail shear specimens. Errors due to the influence of the clamped end constraints were estimated to be of the order of a fraction of a percent and were thus neglected.

Specimens were stored in a desiccator after machining. Specimens were allowed to soak at room environmental conditions of approximately 70°F (25°C) and a 60% R.H. for one hour prior to testing. All tests were performed with an Instron testing machine at a head rate of 0.05 in/min (1.27 mm/min). The laminates tested for this shear stress-strain response investigation are listed in Table 1. Electrical strain gage rosettes were used in all cases. Further, loads and strains were monitored throughout a test and were recorded digitally on either paper or magnetic tape. Data taken in this way was processed by an IBM 370 computer using a linear regression subroutine. The results of the three replicates were fitted by the linear regression analysis and averaged in a least squares sense to give the best polynomial fitted to the data. The program gave a listing of coefficients of the appropriate n^{th} order polynomial together with discrete values of stress and strain for the fitted curve. Incremental values of moduli, Poisson's ratios, stresses and strains for all subsequently discussed calculations were taken from the fitted curve. Also, all values of

initial moduli to be discussed subsequently were taken from the computer generated stress-strain data. Because of the enormous amount of calculations required to incorporate data into composite analytical programs, such computer numerical procedures are not only convenient but are fast becoming the standard approach to composite design. Partially, the reason for the current investigation was to develop, use and study the effect of computer assisted numerical procedures for the collection, conditioning and interpretation of data as well as to compare the different shear generative procedures and the effect of both on composite response predictions.

EXPERIMENTAL RESULTS

Tensile Behavior

Uniaxial tensile tests were performed on 0.5 in (12.7 mm) strips taken from each of the laminates identified in the preceding section. For the unidirectional laminates, tensile tests were performed such that the load was at a variety of angles with respect to fiber direction as illustrated schematically in Figure 1. The resulting stress-strain curves for the angles 0° , 15° , and 90° as well as the axial strain vs. transverse strain for the 0° laminate are shown in Figures 3 and 4. All the curves shown were computer conditioned and plotted as mentioned briefly in the preceding section. The bilinear behavior of the $[0^\circ]_{8S}$ laminate observed is apparent and occurred at about 75 ksi. It might be noted that the raw data for each specimen showed the same trends. In fact, for the $[0^\circ]_{8S}$ and $[15^\circ]_{8S}$ almost no dispersion occurred and the computer generated curves shown are nearly identical

to the response obtained in each test.

Figure 5 shows the results for the initial moduli and ultimate strengths of all the tensile tests for the $[0^\circ]_{8S}$ laminates with the load at various angles to the fiber directions. As may be observed these data follow the expected trends of decreasing values for increasing fiber angle. Equation (1) is shown superimposed on the moduli results in Figure 7 with the various properties evaluated from the 0° , 15° , and 90° tests. This orthotropic transformation equation fits the data extremely well when the G_{12} value obtained from the 15° data is used and tends to validate the use of an orthotropy assumption for unidirectional materials. An analogous equation for ultimate strengths was fitted to the data using 0° , 30° , and 90° results. Use of other angles than 30° fitted the data even more poorly. Obviously, equation (1) as modified for strengths does not properly represent actual data.^[2] The amount of data scatter was relatively low for modulus but more pronounced for strengths. In both cases the amount of scatter was not systematic and probably depended only on the chance or random selection of specimens.

Other laminates were tested to determine their stress-strain response in different directions. However, only the resulting initial moduli, Poisson's ratios, fracture stresses and fracture strains are recorded in Table 1. Relatively high values of Poisson's ratios were found for $[0^\circ/\pm\theta/0^\circ]_{2S}$ and $[\pm 45^\circ]_{4S}$ laminates whereas relatively low values were found for the $[90^\circ/\pm\theta/90^\circ]_{2S}$ laminates. Such results are undoubtedly due to the "scissoring" effect (or lack of in the latter cases) of the fibers in the angle plies.

Shear Behavior

In addition to the off-axis testing discussed in the previous section, three tensile tests were performed on the $[0^\circ]_{8S}$ material with the load at a 10° angle to the fiber direction. Strain data was taken at 0° , 45° and 90° to the load direction and both stresses and strains were transformed to the fiber coordinates as suggested by Daniel and Chamis.^[8,9] The computer conditioned shear stress-strain plot for the fiber coordinates 10° is shown plotted in Figure 6.

Other tensile tests were performed on $[\pm 45^\circ]_{4S}$ laminates to determine the intralamina or lamina shear stress-strain response of the T300/934 G/E material investigated. The results of these tests were also computer conditioned and plotted using the analysis of both Petit and Rosen each of which was previously described. The shear stress-strain curves so generated are shown in Figure 6.

The rail shear test described previously was used on both $[0^\circ]_{8S}$ and $[0^\circ/90^\circ]_{4S}$ laminates to obtain the shear stress-strain response of a lamina. In the latter case the analysis of Sims was used in conjunction with the previously described computational procedures and the results are shown in Figure 6. The results for the former are not shown due to the large amount of scatter encountered. The $[0^\circ]_{8S}$ laminate was quite weak in shear and could easily have been damaged prior to testing due to the clamping process.

DISCUSSION

In addition to determining the shear stress-strain response of a lamina, by the various test methods, the incremental computational

procedure described in the analysis section was used. That is, the 0° , 15° , and 90° data shown in Figures 3 and 4 were used together with equation (1) and lamination theory in an incremental fashion to obtain the lamina shear behavior. The reasons for performing this calculation were several-fold. The incremental computational procedure using only longitudinal and transverse gages for 0° , 15° , and 90° tensile tests depends heavily on the validity of the orthotropic assumption or equation (1) for unidirectional composites not only for initial modulus values but for tangent modulus values as well. On the other hand, the 10° off-axis test using three gage rosettes, while simple in nature, tacitly assumes that shear properties are not affected by biaxial stress states. Because of the biaxiality, it is our feeling that the former method is likely to be as good as the latter. Further, the former requires less gage and instrumentation expense and biaxial effects are thought to be minimized. (Note the 10° test could have been used in the incremental computation procedures but the 15° results were used to avoid confusion.)

The results from both the 10° off-axis tests and the incremental procedure using the 15° tests are shown in Figure 6 together with the results from the rail shear and $[\pm 45^\circ]_{4S}$ laminate tests. Considerable differences between the various shear results are apparent. The two off-axis shear curves agree with each other quite well but defer drastically from the other methods. The fracture stress for the off-axis test depends heavily on the fiber angle as indicated by Figure 5. Obviously a 10° angle is better in this regard than the

15° angle. Otherwise, the general shapes of the 10° and the 15° curves are quite similar.

The symmetric rail shear tests gave a much higher value of fracture strain but a lower value of initial modulus. The $[\pm 45^\circ]_S$ shear test method gave results intermediate to the off-axis and rail shear tests. In other words, the shear results from laminates, $[\pm 45^\circ]_{4S}$ or $[0^\circ/90^\circ]_{4S}$, tended to be much more ductile in nature than the off-axis test. This is reasonable inasmuch as laminates obviously contain interlamina as well as intralamina shear response. In fact post examination of the off-axis specimens revealed a predominately brittle failure between fibers. Similar examination of the $[\pm 45^\circ]_{4S}$ tensile and $[0^\circ/90^\circ]_{4S}$ rail shear specimens indicated extensive delamination and interply failures prior to separation. In fact in some rail shear tests, complete separation never occurred.

A comparison of the initial shear modulus obtained using the various techniques is given in Table 2. The shear modulus of a lamina as predicted by either the $[\pm 45^\circ]_{4S}$ tension tests or the $[0^\circ/90^\circ]_{4S}$ rail shear tests are in reasonable agreement with each other. Also, the modulus obtained from the off-axis tests as well as the $[0^\circ]_{8S}$ rail shear tests are in reasonable agreement. However, the $[0^\circ]_{8S}$ results defer drastically from the $[\pm 45^\circ]_{4S}$ and $[0^\circ/90^\circ]_{4S}$ results. It might be noted that the value of $G_{12} = 1.22 \times 10^3$ ksi (8.44×10^3 MPA) reported for the 15° off-axis test is thought to be a little high. However, when this value was used in equation (1), excellent correlation between computed and measured values of E_x for unidirectional laminates was obtained as is evident from examination of Figure 5. When the

$G_{12} = 0.753 \times 10^3$ ksi (5.19×10^3 MPA) obtained from Rosen's analysis of the $[\pm 45^\circ]_{4s}$ tensile data was used in equation (1), poor correlation was obtained between computed and experimental data. Therefore, it appears that such a high value of G_{12} is justified and in fact needed for the orthotropic transformation equation to be a valid representation of our experimental data.

The real purpose in obtaining the shear stress-strain response of a lamina using any procedure is to be able to provide correct input to a lamination stress analysis in order to predict laminate response characteristics under arbitrary boundary loads. Thus, in the present case it was decided to use the shear results obtained from the 15° off-axis tests (incremental procedure) and the shear results used from the $[\pm 45^\circ]_{4s}$ tension tests as represented by Rosen's analysis to predict the responses of several laminates under a remote tensile load. These two methods were used in an attempt to get a comparison between making such predictions using essentially brittle shear response as opposed to using essentially ductile response. The 15° incrementally determined shear behavior further created favorable comparisons between equation (1), upon which lamination theory depends, and experimental data for initial modulus values. In addition, as the initial modulus values were quite different, use of these two shear properties established bounds on predicted response and indicate the relative importance of G_{12} values in our lamination analysis.

Standard lamination analysis as outlined by Jones was used together with the Tsia-Hill failure criterion.^[1] That is, an incremental procedure was used to account for non-linear tensile and

shear properties and failure of a ply was assumed to occur when that ply reached a stress state equivalent to that predicted by the failure criterion. A failed ply was physically eliminated from carrying further load in a particular direction by assigning it zero stiffness if the strain exceeded the ultimate value in that direction. The results of these computations are shown in Figures 7-11 and in Table 1. As may be observed the 15° off-axis shear behavior gave reasonable predictions for the tensile response of all laminates except $[\pm 45^\circ]_{4S}$ and $[0^\circ/\pm 30^\circ/0^\circ]_{2S}$. In general, the shear response obtained from the $[\pm 45^\circ]_{4S}$ tensile tests gave predictions which did not correlate well with measurements. The 15° off-axis shear data gave a non-conservative prediction of the $[\pm 45^\circ]_{4S}$ tensile response whereas the shear response obtained from the very same $[\pm 45^\circ]_{4S}$ tests data gave a conservative prediction of tensile response. It is interesting to note that in several cases, i.e., $[0^\circ/90^\circ]_{4S}$, $[0^\circ/\pm 45^\circ/0^\circ]_{2S}$, $[90^\circ/\pm 45^\circ/90^\circ]_{2S}$ and $[90^\circ/\pm 60^\circ/90^\circ]_{2S}$, little difference between the two predictions were obtained. Apparently in these cases, the intralamina shear response did not play as an important role as in other cases and other parameters were more dominant.

The $G_{12} = 1.22 \times 10^3$ ksi (8.44×10^3 MPA) value was used in association with lamination theory to predict the shear modulus of a $[0^\circ/\pm 45^\circ/0^\circ]_{2S}$ laminate with the results given in Table 2. Further a symmetric rail shear test was performed on the same laminate to determine its initial shear modulus using a three gage strain rosette. The shear stress, τ_{xy} , was calculated as noted in the analysis section and the shear strain, γ_{xy} , was calculated using standard procedures. As

may be observed excellent agreement between theory and experiment was obtained.

SUMMARY AND CONCLUSIONS

Several methods to obtain the shear stress-strain response of a lamina have been presented. Two procedures using off-axis tensile data have been described. For one, only experimental results from an off-axis test (in our case 10°) were needed whereas the other used off-axis data (in our case 15°) in combination with lamination theory. Two other procedures utilizing $[\pm 45^\circ]_{4S}$ tension tests and $[0^\circ/90^\circ]_{4S}$ rail shear tests have been presented. From a comparison of the shear response obtained by the various methods and the predictions of tensile behavior of several laminates using two of these methods, a number of conclusions have already been presented and can be summarized as,

- The two off-axis methods were in reasonable agreement with each other. Thus, an off-axis test together with incremental lamination theory calculations is a reasonable approach to shear property determination.
- The $[\pm 45^\circ]_{4S}$ tensile and $[0^\circ/90^\circ]_{4S}$ rail shear results were in reasonable agreement.
- The response as obtained from $[0^\circ]_{8S}$ laminates was considerably different from the response as obtained from $[\pm 45^\circ]_{4S}$ and $[0^\circ/90^\circ]_{4S}$ laminates. The former tended toward brittle characteristics. The latter tended toward ductile characteristics which were probably due to interply effects.

- Predictions of laminate response were reasonable using off-axis data except for the case of a $[\pm 45^\circ]_{4s}$ laminate in tension. Predictions of laminate response using $[\pm 45^\circ]_{4s}$ shear data was poor in all cases except the ones in which the shear modulus did not appear to play an important role.

It should be noted, of course, that the latter conclusion is drawn on the basis of the computational techniques used, i.e., linear regression analysis, polynomial least square fitting, lamination theory, failure theory used, etc. No doubt refinement of all these procedures, particularly use of a different failure theory, could result in substantial improvement of predictions. Nevertheless, it is our feelings that the computations used are valid to show the effect of using variously determined shear properties in a lamination analysis.

The major conclusion to draw seems to be that the off-axis test represents the better method of those investigated for the determination of the shear response of a ply or lamina. On the other hand, the $[\pm 45^\circ]_s$ tensile and $[0^\circ/90^\circ]_s$ rail shear methods seem to include interply effects. Thus, it appears that the appropriate test method would depend primarily upon what was sought. For example, if the effect of a variable, say environment (temperature and humidity), on shear properties within a ply (intralamina) were to be determined, the off-axis test would be appropriate. If, on the other hand, the effect of the same variable on laminate shear response, including both intralamina and interlaminae effects, were to be determined, $[\pm 45^\circ]_s$ tension, $[0^\circ/90^\circ]_s$ or other laminate tests would be in order.

In the final analysis, the shear response measured appears to be not only a function of the loading but a function of the laminate geometry as well. An easy, simple, good shear test valid for all types of laminates and their shear responses analogous to the torsion test for isotropic materials probably does not exist.

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Table i. Tensile Properties of T300-934 Graphite-Epoxy Composite Laminates.

Laminate Orientation	Axial Modulus (x 10 ⁶ psi)	Poisson's Ratio ν_{xy}	Fracture Stress (ksi)	Fracture Strain (%)
[0°] _{8s}	19.89	0.352	207.77	0.947
[15°] _{8s}	10.56	0.250	34.72	0.434
[30°] _{8s}	4.88	0.234	14.87	0.491
[60°] _{8s}	2.48	0.146	7.90	0.462
[75°] _{8s}	2.30	0.052	7.28	0.450
[90°] _{8s}	2.17	0.024	5.77	0.429
[0°/±30°/0°] _{2s}	14.76	0.877	146.84	1.008
[90°/±60°/90°] _{2s}	2.70	0.108	10.68	1.746
[0°/±45°/0°] _{2s}	12.05	0.645	105.86	0.935
[90°/±45°/90°] _{2s}	4.38	0.191	21.50	0.786
[0°/±45°/90°] _{2s}	8.08	0.264	81.09	1.118
[45°/0°/90°/-45°] _{2s}	8.04	0.321	69.81	1.021
[0°/90°] _{4s}	11.10	0.100	115.09	1.031
[±45°] _{4s}	4.19	0.759	24.41	1.913

Table 2. Comparison of Initial Intralaminar Shear Moduli.

Laminate Orientation	Test Method	Analysis Method	Intralaminar Shear Modulus (x 10 ⁶ psi)
[0°] _{8s}	Sym. Rail Shear	-	1.0*
[10°] _{8s}	Tension	-	1.13
[15°] _{8s}	Tension	Equation (1)	1.22
[±45°] _{4s}	Tension	Rosen	0.75
[±45°] _{4s}	Tension	Petit	0.67
[0°/90°] _{4s}	Sym. Rail Shear	Sims	0.59
[0°/±45°/0°] _{2s}	Sym. Rail Shear	-	3.15*
[0°/±45°/0°] _{2s}	-	Laminated Plate	3.22**

*Measured using strain gages and Sym. Rail Shear Test.

**Calculated from Laminated Plate theory using $G_{12} = 1.22$.

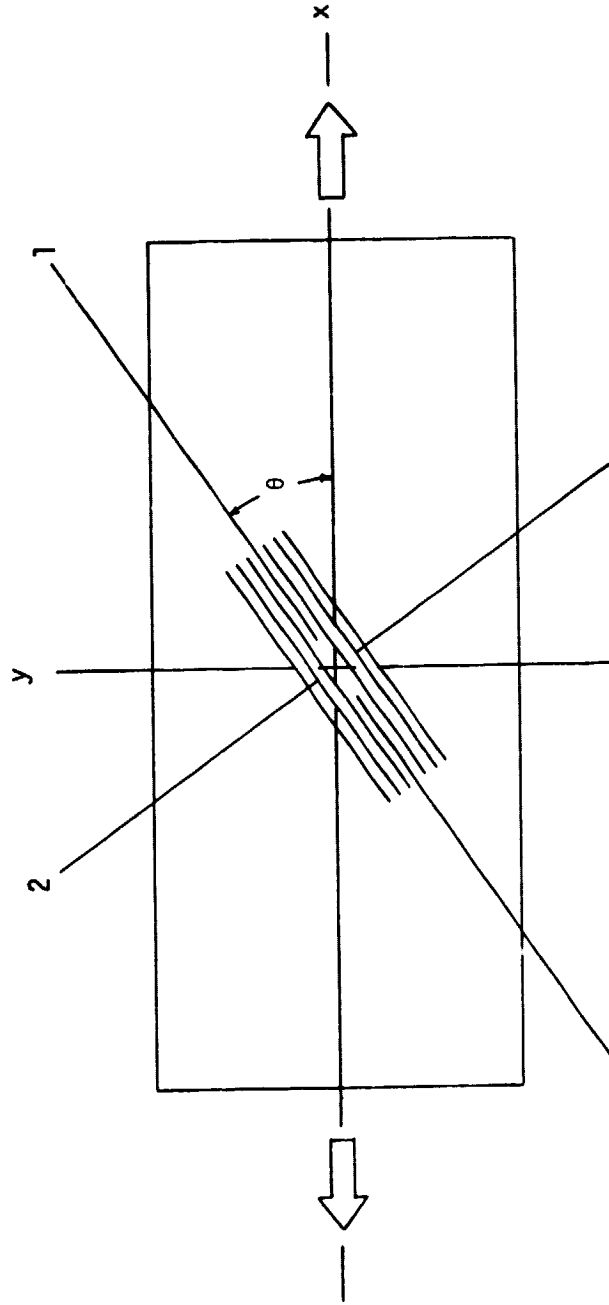


Figure 1. Coordinate System Used for General Lamina or Ply and for Off-Axis Tests.

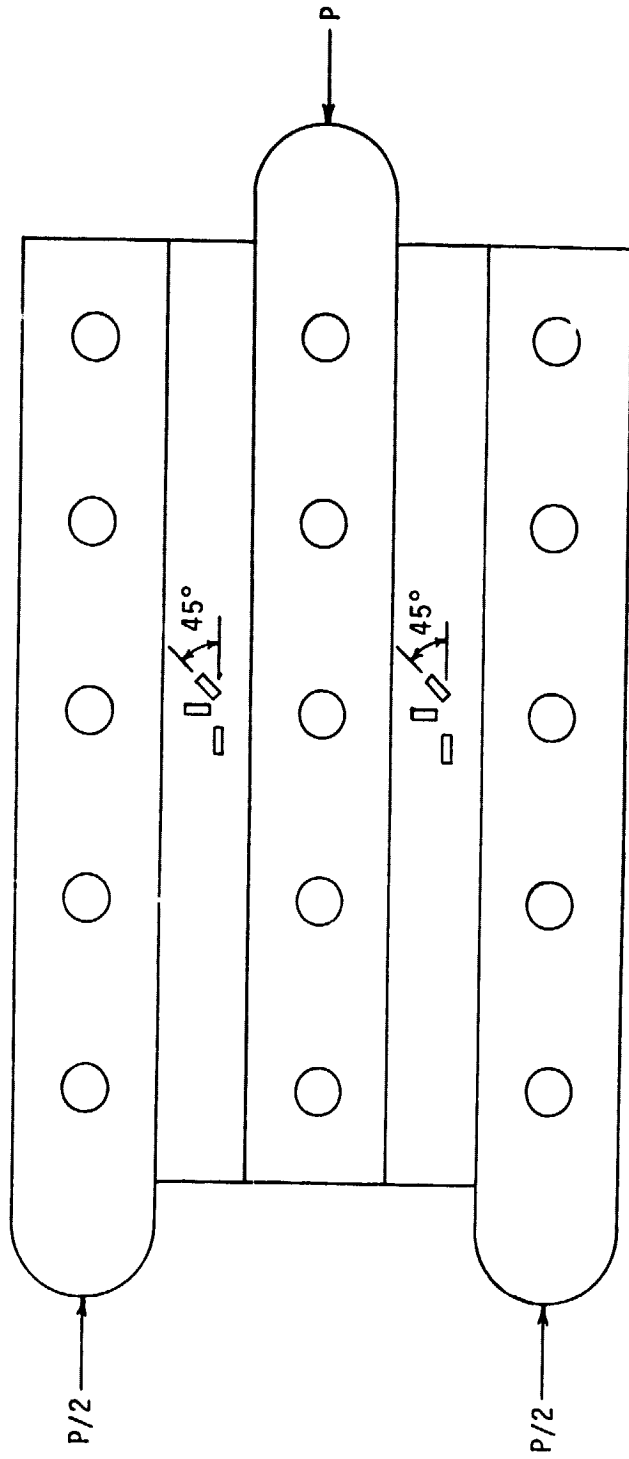


Figure 2. Symmetric Rail Shear Test Fixture Showing Strain Gage Orientations.

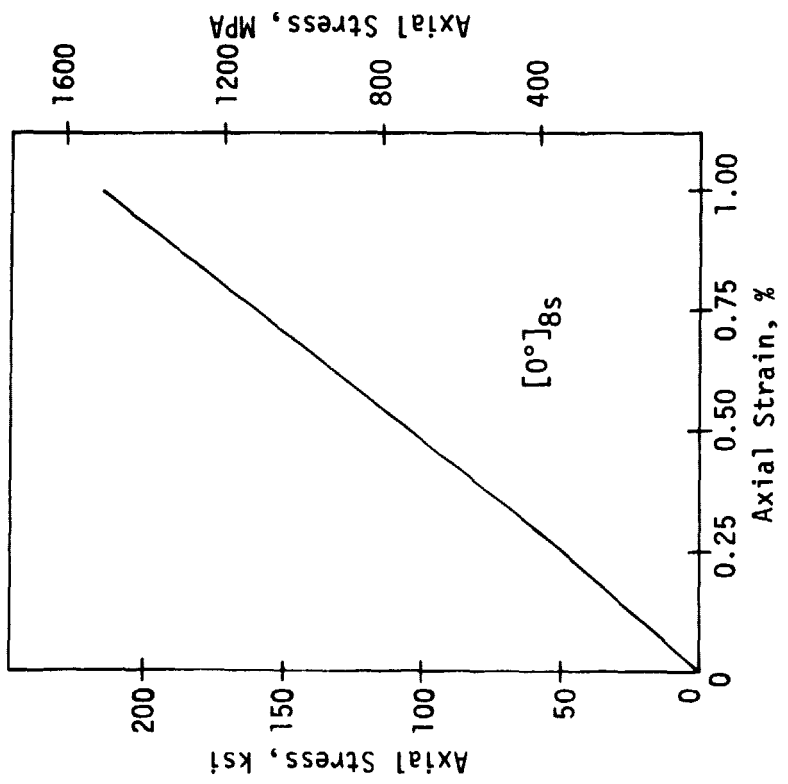
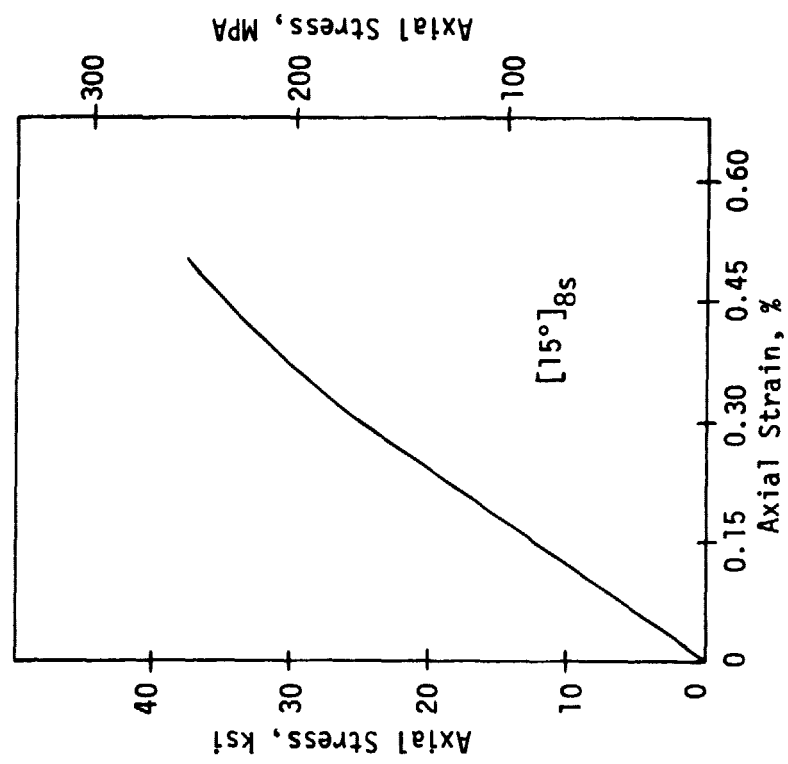


Figure 3. Tensile Behavior of Unidirectional Laminates.

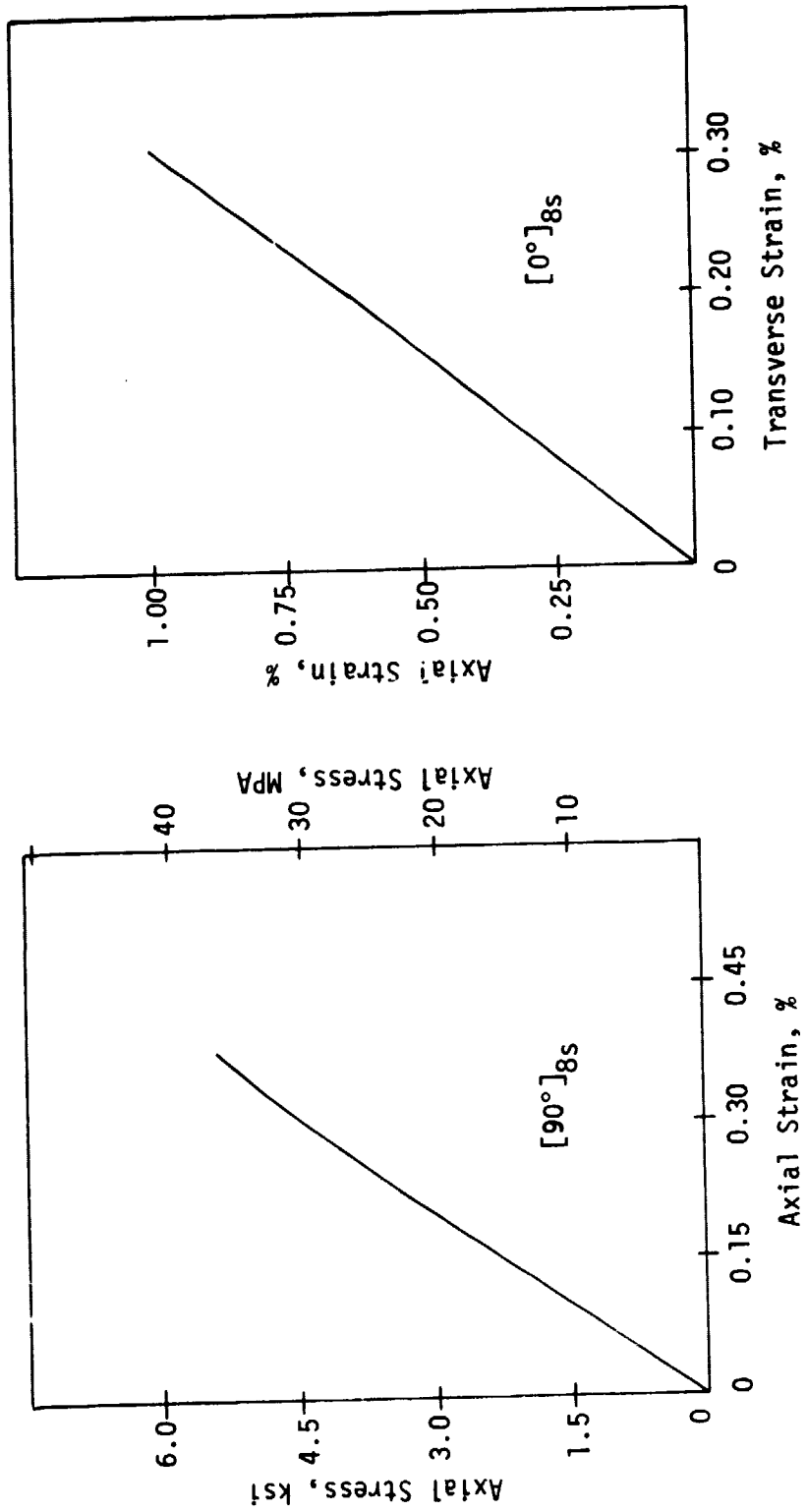


Figure 4. Tensile Behavior of Unidirection Laminates.

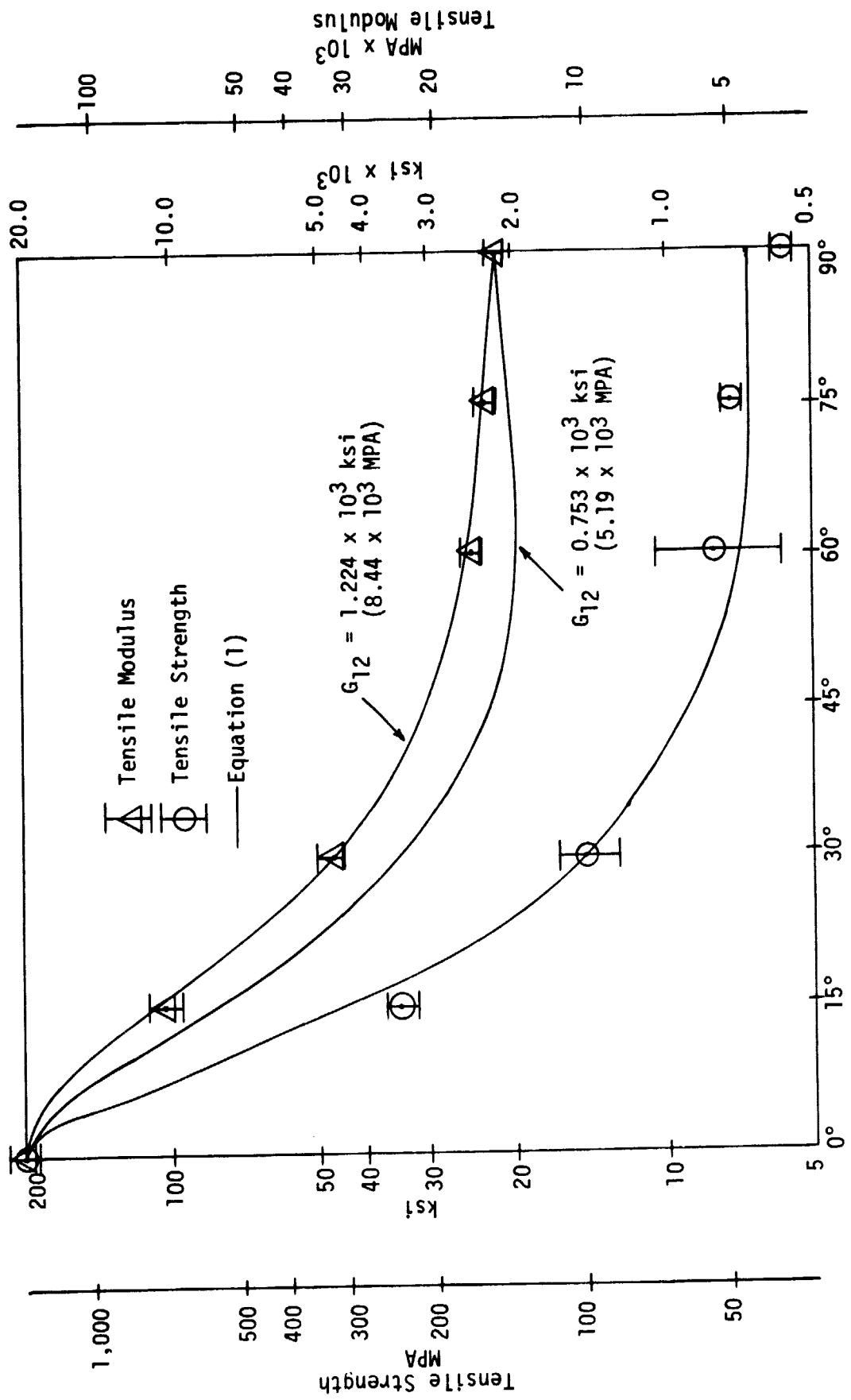


Figure 5. Tensile Properties of T300/934 Graphite/Epoxy Unidirectional Laminates.

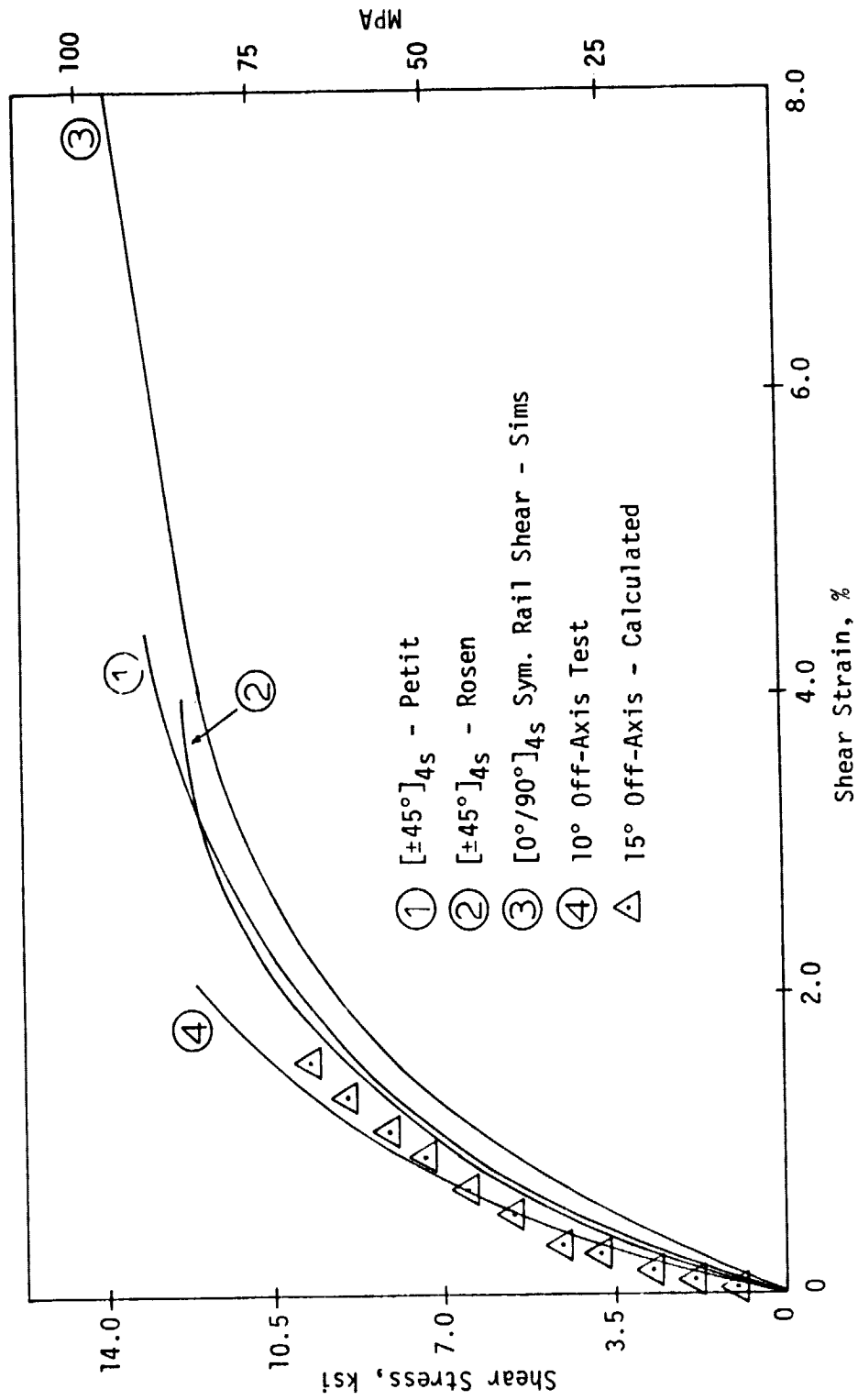


Figure 6. Lamina Shear Stress-Strain Response of T300/934 Graphite/Epoxy Material as Determined by Different Methods.

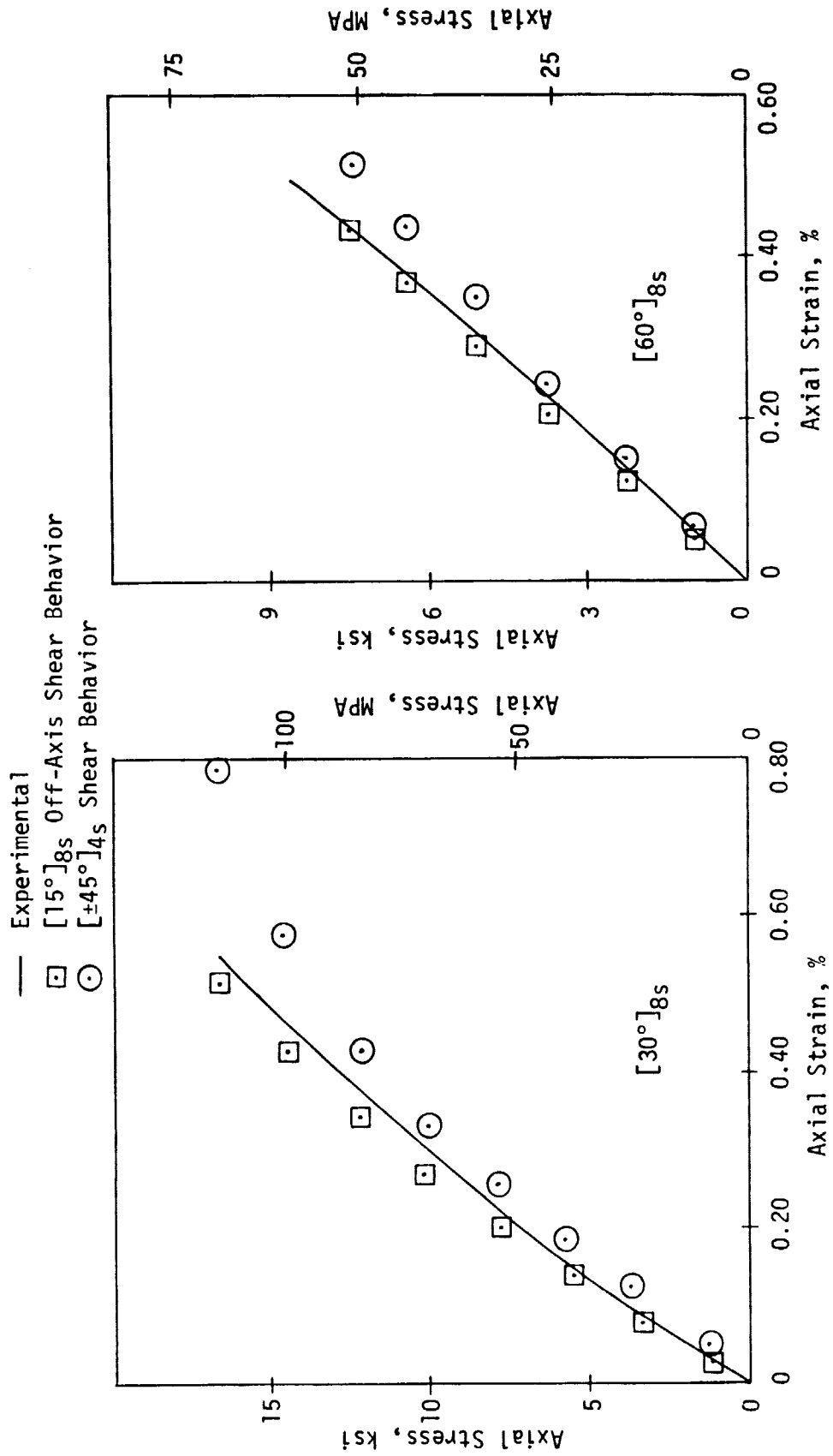


Figure 7. Predicted Unidirectional Laminate Tensile Response Using Indicated Shear Behavior Compared with Experimental Results.

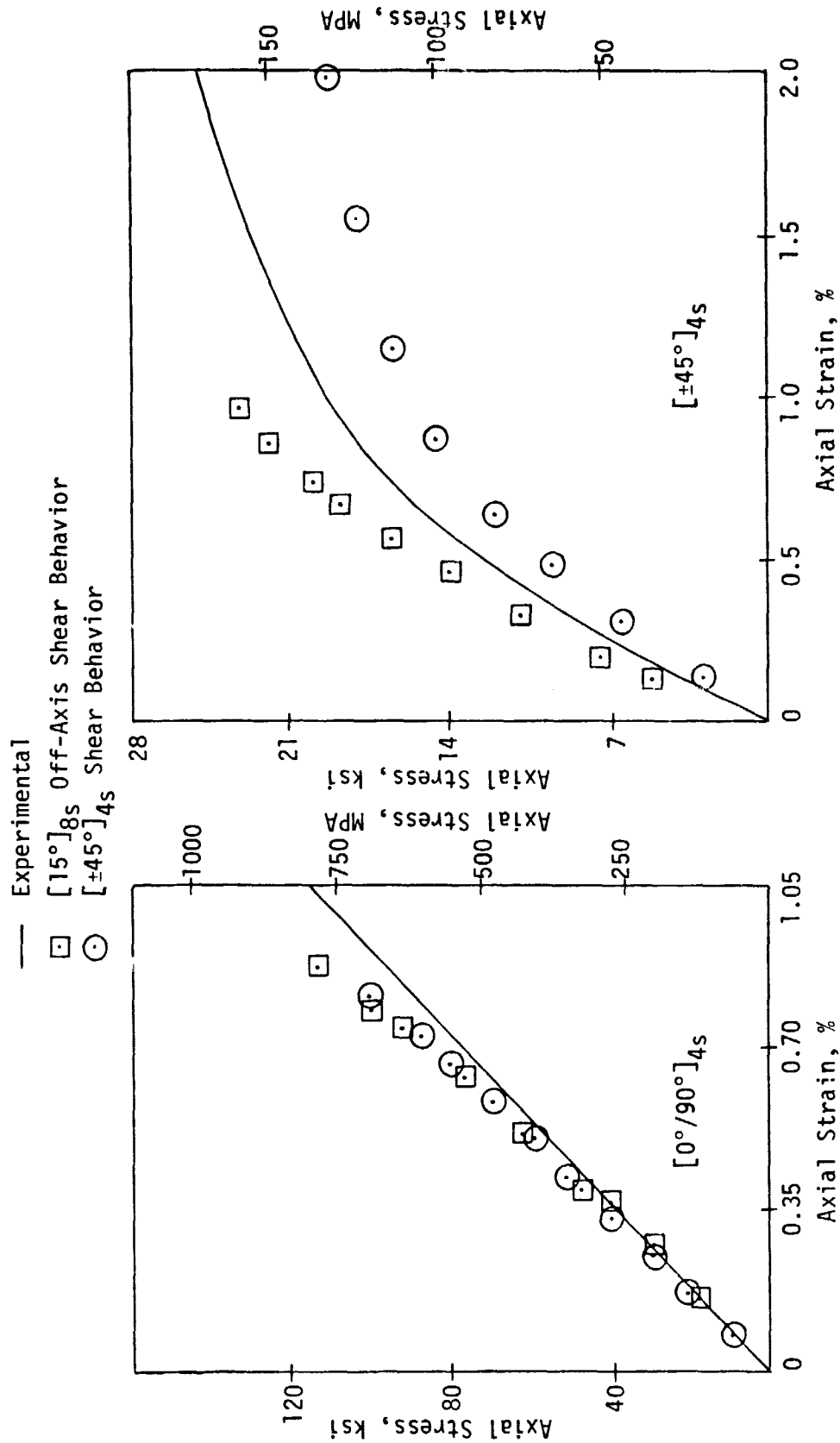


Figure 8. Predicted Laminate Tensile Response Using Indicated Shear Behavior Compared with Experimental Results.

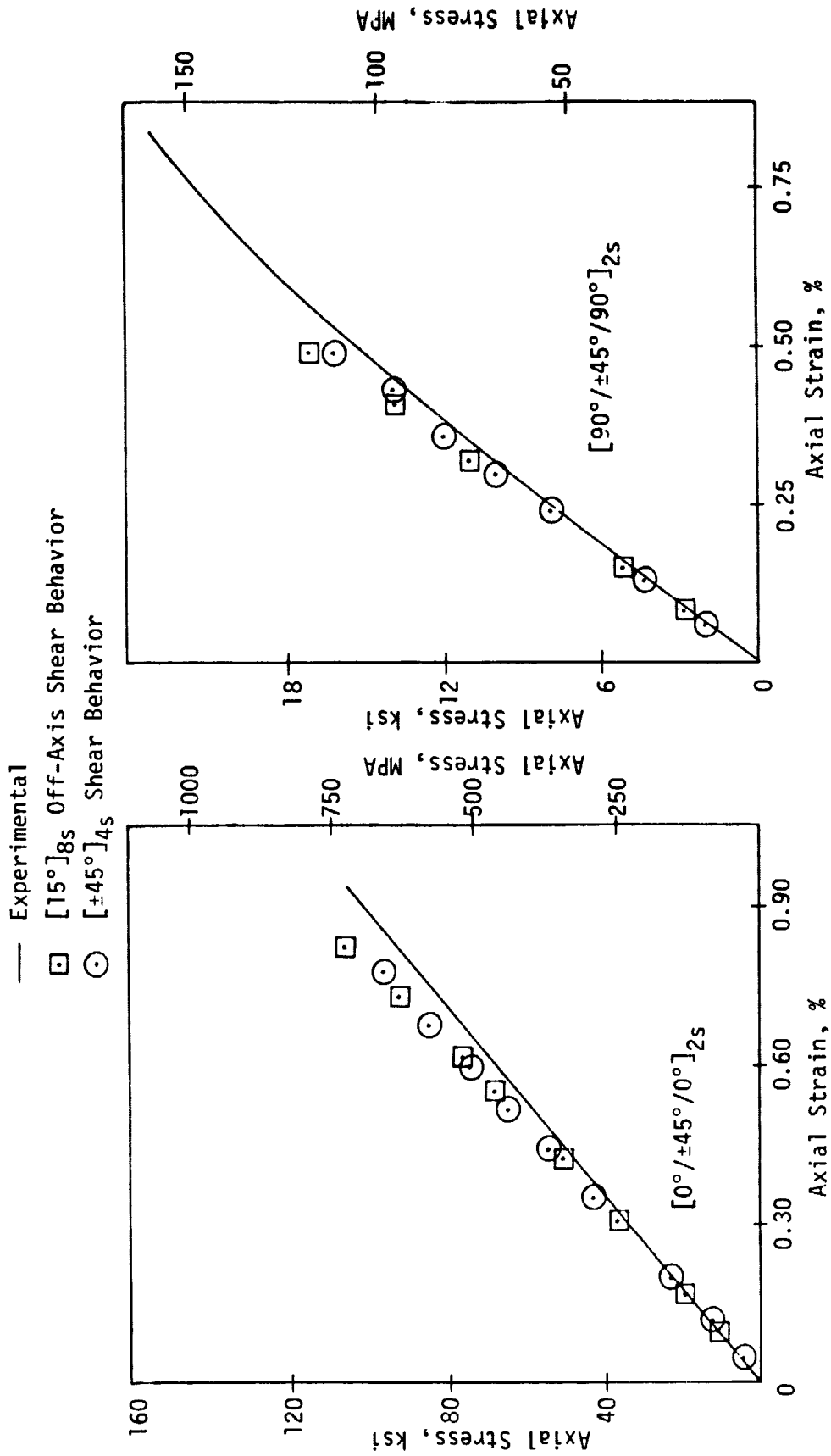


Figure 9. Predicted Laminate Tensile Response Using Indicated Shear Behavior Compared with Experimental Results.

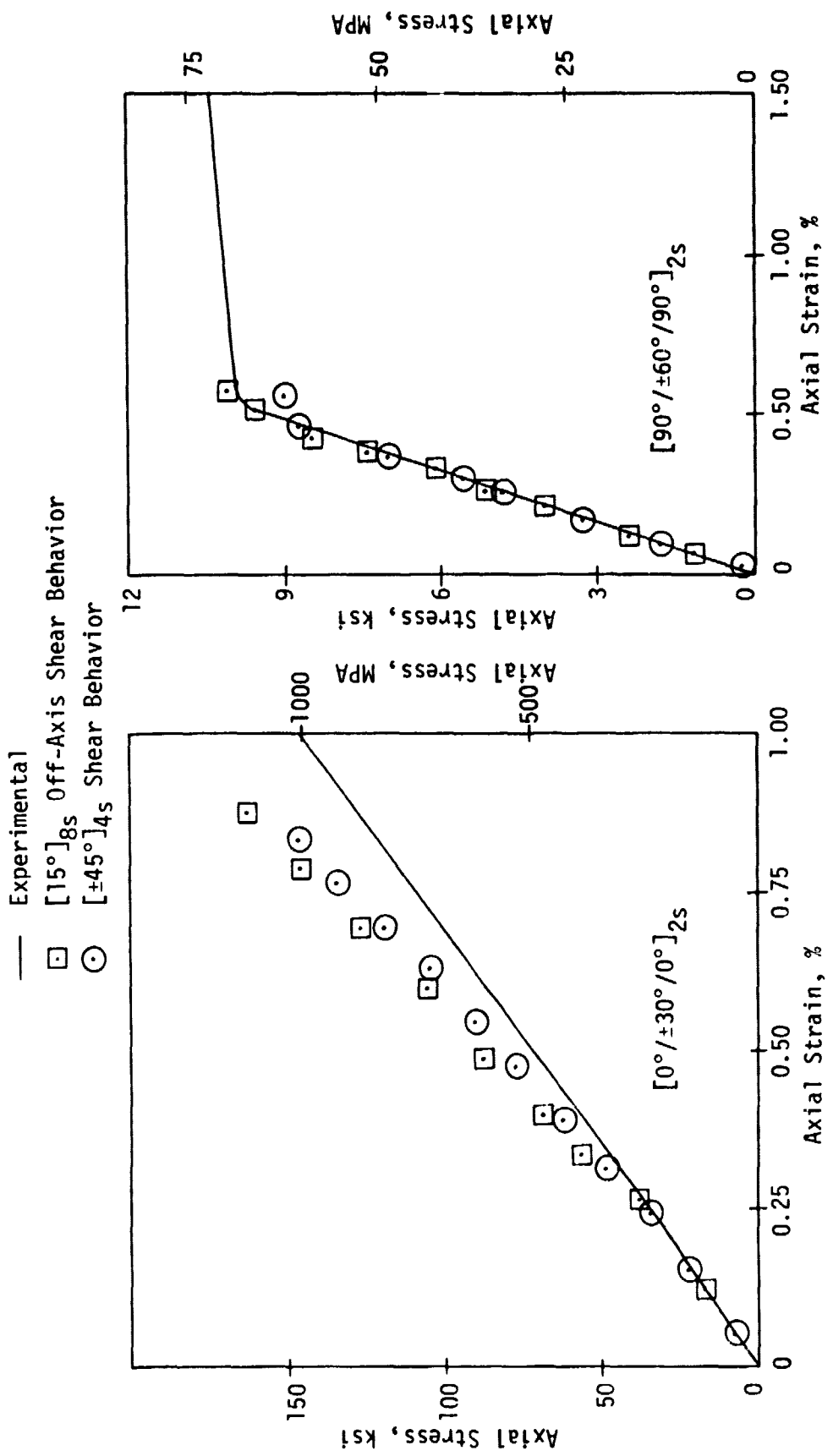


Figure 10. Predicted Laminate Tensile Response Using Indicated Shear Behavior with Experimental Results.

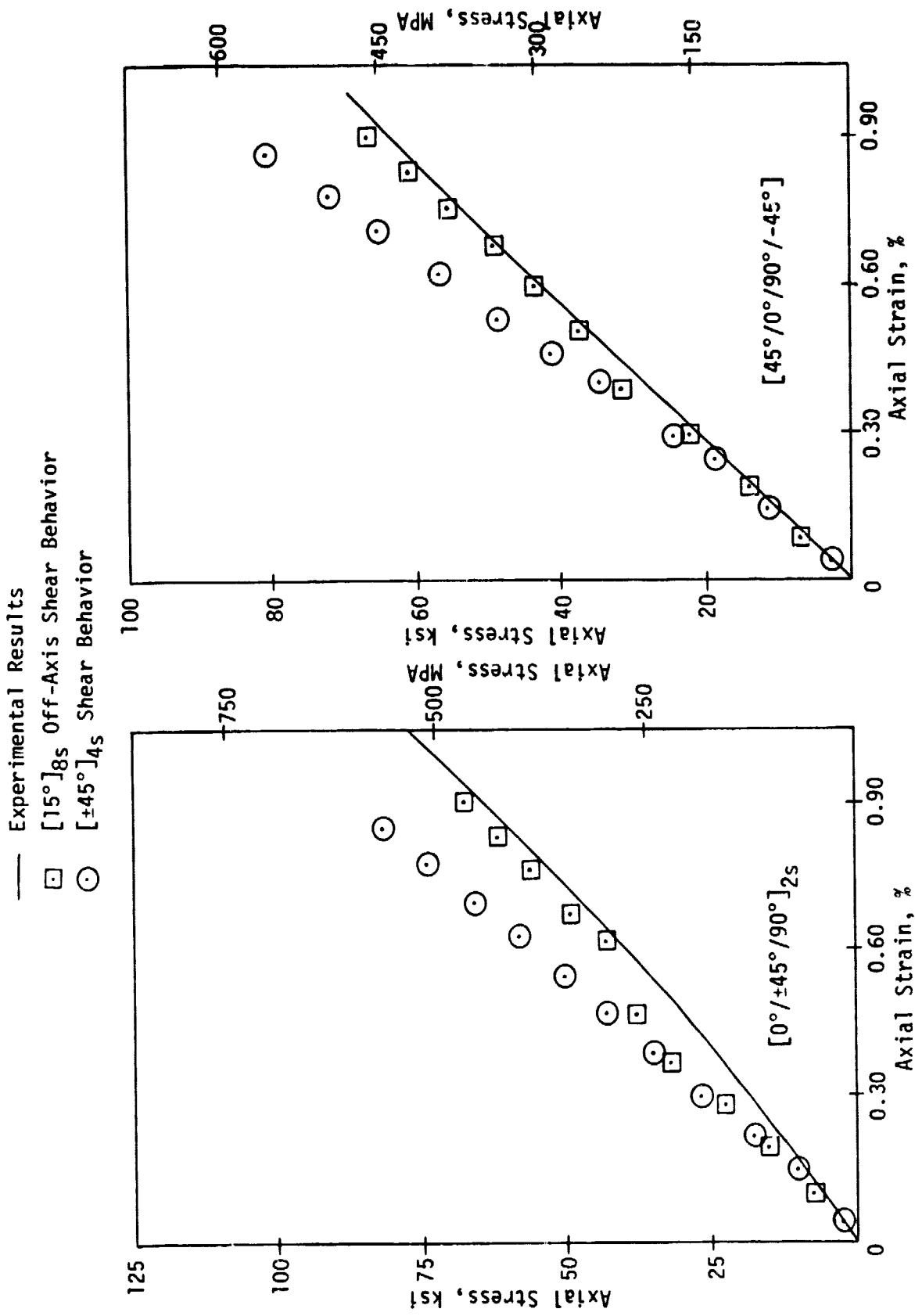


Figure 11. Predicted Laminate Tensile Response Using Indicated Shear Behavior Compared with Experimental Results.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Various methods for the shear stress-strain characterization of composite laminates are examined and their advantages and limitations are briefly discussed. Experimental results and the necessary accompanying analysis are then presented and compared for three simple shear characterization procedures. These are the off-axis tensile test method, the $[±45°]_s$ tensile test method and the $[0°/90°]_s$ symmetric rail shear test method. It is shown that the first technique indicates the shear properties of the G/E laminates investigated are fundamentally brittle in nature while the latter two methods tend to indicate that the G/E laminates		

Item 20 (cont.)

are fundamentally ductile in nature. Finally, predictions of incrementally determined tensile stress-strain curves utilizing the various different shear behavior methods as input information are presented and discussed.