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NONLINEAR RESPONSE OF BORON/ALUMINUM ANGLEPLIED LAMINATES UNDER CYCLIC TENSILE LOADING: CONTRIBUTING MECHANISMS AND THEIR EFFECTS

by C. C. Chamis and T. L. Sullivan
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Symposium on Fatigue of Composite Materials
sponsored by American Society for Testing and Materials
Bal Harbour, Florida, December 3-4, 1973

NONLINEAR RESPONSE OF BORON/ALUMINUM ANGLEPLIED LAMINATES UNDER CYCLIC TENSILE LOADING: CONTRIBUTING MECHANISMS AND THEIR EFFECTS

C. C. Chamis* and T. L. Sullivan*
NASA-Lewis Research Center
Cleveland, Ohio

ABSTRACT

The nonlinear response of boron/aluminum angleplied laminates subjected to cyclic loads was investigated. A procedure is outlined and criteria are proposed which can be used to assess the nonlinear response. The procedure consists of testing strategically selected laminate configurations and analyzing the results using composite mechanics. Results from the investigation show the contributions to nonlinear behavior are from: premature random fiber breaks where the ply orientation angle is small relative to the load direction, ply relative rotation at intermediate values of the ply orientation angle, and nonlinear aluminum matrix behavior at large values of the orientation angle. Premature fiber breaks result in progressively more compliant material; large ply relative rotations result in progressively stiffer material; and pronounced matrix nonlinear behavior results in no significant change in the stiffness of the initial load portion.

KEY WORDS: Boron/aluminum, angleplied laminates, nonlinear response, cyclic loading, premature-fiber-fractures, ply relative rotation, experimental, stress analysis

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*Aerospace Engineer, Composites and Structures Branch

INTRODUCTION

Boron/aluminum angleplied laminates exhibit nonlinear stress-strain relationships at relatively low loads(1)[1] as compared with their fracture load. The primary factors that may contribute to this nonlinearity are: early aluminum matrix nonlinear response, premature random fiber fractures, and relative ply rotations. The amount each factor contributes depends on the ply orientation. This paper assesses the effects of the aforementioned factors on the nonlinear response of boron/aluminum angleplied laminates under monotonic and cyclic tensile load.

The procedure followed for the assessment consisted of both experimental and approximate theoretical investigations. The experimental investigation consisted of testing selected boron/aluminum (50% 4 mil boron fiber/6061-0 aluminum alloy) angleplied laminates in cyclic tension. The laminates selected had low, intermediate, and high ply orientation angles relative to the load direction. Specimens with some low ply orientation angles were selected to assess the invluence of premature fiber fractures on nonlinear response. Those of intermediate angles were selected to assess the ply relative rotation (scissoring effect), and those of high angles for the influence of the matrix. Since the focus of the investigation was on nonlinear response, the specimens were loaded well into the nonlinear stress-strain regime and therefore failed in a few cycles.

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[1]The numbers in parentheses refer to list of references appended to this paper.

In the theoretical investigation, well known strain transformations were used in conjunction with the strain-magnification-factor (SMF) concept to determine the strains in the plies, the maximum strains in the matrix, and the changes in the fiber direction. The emphasis of this investigation is on how an assessment can be obtained of the factors contributing to composite nonlinear response using measured strains from a few strategically selected test specimens and available, approximate, theoretical methods. In this sense, the approach can be used as a procedure for obtaining such an assessment. A more detailed stress analysis may be obtained by using nonlinear finite element methods.

In this paper, the term "yield" is used to denote the onset of nonlinear stress-strain behavior in the matrix rather than its classical plasticity meaning.

EXPERIMENTAL INVESTIGATION

Material, Test Apparatus, and Procedure

The composite material for this investigation was 4 mil boron fiber and 6061-0 aluminum foil which was fabricated into 12-inch square plates by a supplier using a conventional diffusion bonding process. Fiber volume was approximately 50 percent. The laminate configurations were of the form $(0^{\circ}_{2}, \pm\theta^{\circ})_{s}$ where θ was 15°, 30°, 45° and 90°, and are identified as plates C, D, E and F respectively. See reference 1. Coupons were cut at specified angles from the plates by shearing. The background for specimen selection is given in the theoretical investigation. The sheared edges of the specimens were ground with a diamond wheel to produce a coupon with smooth edges and a .500-inch width. The specimen configuration, notation, ply orientation and specimen length are depicted in figure 1. The fiber directions relative to the load direction are shown schematically in figure 2. Photomicrographs of specimen cross-sections are shown in figure 3. Each coupon was instrumented with strain gage rosettes. The coupons were clamped in serated, bolted grips (fig. 4) and cyclicly loaded to failure in a hydraulic universal testing machine. The maximum load of each successive cycle was increased to insure failure in relatively few cycles. Loading was halted at intervals for acquiring strain gage data on a digital strain recorder.

The strain gage data were reduced using a computer program (2). This program calculates the strains along the load direction and normal to it. It also provides instantaneous tangent modulus of elasticity, Poisson's ratio, the extension/shear coupling ratio and the angular change of the principal strain axes.

THEORETICAL INVESTIGATION

Theoretical Background

In order to identify and assess the factors contributing to composite nonlinear response the strain states in the composite, plies, and matrix are required as a minimum. In this investigation, the strain state in the composite was measured using delta rosette strain gages. When the composite strain state is known, the other strain states can be determined using available theoretical methods. The underlying theoretical concepts and the equations to be used in the computations are briefly described herein.

Since the strains are kinematic quantities and since three strains are known at a point from the strain gage readings, strains along any ply orientation are determined by well known transformations. The implicit assumption in this transformation is that the strain is constant through the specimen thickness. This assumption is valid so long as no delamination takes place. No delamination was observed in the specimens tested in this program.

Once the ply strains are known the maximum strains in the matrix are obtained as follows:

$$\varepsilon_{m11} = \varepsilon_{\ell 11} \tag{1}$$

$$\varepsilon_{m22max} = SMF_{22}\varepsilon_{\ell 22} \tag{2}$$

$$\varepsilon_{m12max} = SMF_{12}\varepsilon_{\ell 12} \tag{3}$$

where ε_{ℓ} is the strain in the ply, ε_{m} is the strain in the matrix. The subscript 1 denotes a measurement along the fiber direction and 2, normal to it. SMF denotes the strain magnification factor (3,4).

The SMF's used are given by the following approximate equations:

$$SMF_{22} = \frac{1}{1 - p\left(1 - \frac{E_m}{E_f}\right)} \tag{4}$$

$$SMF_{12} = \frac{1}{1 - p\left(1 - \frac{G_m}{G_f}\right)} \tag{5}$$

$$p = \left(\frac{4k_f}{\pi}\right)^{1/2} \tag{6}$$

$E_m \to 0$ as the matrix becomes nonlinear

The undefined notation in equations (4), (5) and (6) is as follows: E is the modulus of elasticity, G is the shear modulus; the subscripts f and m denote fiber and matrix, respectively, and k_f is the fiber volume ratio.

The values for the moduli used in this calculation were: $E_f = 60 \times 10^6$ psi, $E_m = 10 \times 10^6$ psi if $\varepsilon_{m22} < .001$ and $E_m = 0$ if $\varepsilon_{m22} \geq .001$, the ratio of $(G_m/G_f) = 1/6$ if $\varepsilon_{m12} \leq .002$ and $(G_m/G_f) = 0$ if $\varepsilon_{m12} >$ .002. The strain limits of 0.001 and 0.002 were determined from normal and shear stress-strain curves respectively.

The ply strains were computed from the measured strains by the following well known transformation equation:

$$\begin{Bmatrix} \varepsilon_{\ell 11} \\ \varepsilon_{\ell 22} \\ \varepsilon_{\ell 12} \end{Bmatrix} = \begin{bmatrix} \cos^2\theta_\ell & \sin^2\theta_\ell & -\frac{1}{2}\sin 2\theta_\ell \\ \sin^2\theta_\ell & \cos^2\theta_\ell & \frac{1}{2}\sin 2\theta_\ell \\ -\sin 2\theta_\ell & \sin 2\theta_\ell & \cos 2\theta_\ell \end{bmatrix} \begin{Bmatrix} \varepsilon_{\ell xx} \\ \varepsilon_{cyy} \\ \varepsilon_{cxy} \end{Bmatrix} \tag{7}$$

where θ_ℓ is the angle between the load and the direction of the fibers in the ply under consideration and is given by $\theta_\ell = \theta_{L/O} + \theta$ (see figure 1). ε_{cxx} is the measured strain in the laminate along the load direction, ε_{cyy} is the measured strain normal to the load direction and ε_{cxy} is the corresponding shear strain.

The change in the fiber direction can be determined from the last equation of (7). See reference (4) or (5).

The instantaneous change of the principal-strain axes as a function of load is another measure of nonlinear response especially for nonsymmetrically loaded specimens. By definition, the principal-strain axes is a set of axes on which the shear strains are equal to zero. The equation for the principal strain-axes is given by

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{\varepsilon_{cxy}}{\varepsilon_{cxx} - \varepsilon_{cyy}}\right) \tag{8}$$

where θ is the angle between the load direction and the ε_{11} axis of the principal strain axes. The composite strains (ε_c) have been already defined. Equation (8) is derived from the last of equations (7) by letting $\theta_\ell = \theta$ and requiring $\varepsilon_{\ell 12}$ to equal zero.

In addition to the above mentioned calculations, the equivalent modified-total-strain (or equivalent strain for convenience) in the matrix was calculated. The general equation for calculating this strain is given by (from ref. 6)

$$\varepsilon_e = \frac{\sqrt{2}}{3}\left[(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2 + 6(\varepsilon_{xy}^2 + \varepsilon_{yx}^2 + \varepsilon_{zx}^2)\right]^{1/2} \quad (9)$$

where ε_x, etc. are the normal strains along a mutually orthogonal coordinate axes and ε_{xy}, etc. are the shear strains associated with these normal strains. For the present case the strains ε_z, ε_{xz} and ε_{yz} represent strains in the matrix through the specimen thickness and were assumed to be negligible compared to the other strains. With this assumption and using the previous notation, equation (9) reduces to

$$\varepsilon_{me} = \frac{\sqrt{2}}{3}\left[2\left(\varepsilon_{m11}^2 + \varepsilon_{m22}^2 - \varepsilon_{m11}\varepsilon_{m22}\right) + 6\varepsilon_{m12}^2\right]^{1/2} \quad (10)$$

where ε_{me} is the equivalent strain in the matrix and the other strains have been defined previously.

The equivalent strain concept is useful in performing stress analysis problems in the presence of material nonlinearities. Our interest herein is to obtain some indication as to whether this approach may be applicable to the present problem.

The above approach for determining the maximum strains in the matrix has several advantages over more refined analyses. Some of the advantages are: simplicity, amenable to quick hand computations, does not require detailed knowledge of the nonlinear material properties, does not require calculation of the stresses in the ply. Its main disadvantage is that it only yields a good approximation of the maximum strains in the matrix. It provides no direct means for determining the strain variation in the matrix or the stresses in the plies. However, this approach can be used in conjunction with an incremental nonlinear analysis to facilitate estimation of material properties for the current increment.

It should be noted that the measured strains do not include residual strains. In the discussion that follows the influence of the residual stress is not considered separately. Its presence produces nonlinear behavior in the matrix at relatively low loads (1) which is picked up by the strain gage as a mechanical load effect.

Specimen Selection Background

Some remarks with regard to the anticipated results will help set the stage for the discussion that follows. As was mentioned previously, the ply orientations (fiber directions) in the specimens selected are shown in figure 2. These configurations were selected because when the specimens are loaded, as noted in figure 2, one of the factors mentioned earlier contributes a significant part to nonlinear response with some interaction from the other factors. For example, the matrix will contribute the major portion to the nonlinear response in specimens C-80° and D-80°. Premature fiber fracture will contribute to the nonlinear response of specimens D-22.5° and E-37.5°. Ply relative rotation will contribute to the nonlinear response of specimen F-37.5°.

Specimens D-22.5° and E-27.5° are loaded unsymmetrically. These specimens will exhibit considerable change in the principal-strain-axes direction during each loading cycle and from loading cycle to loading cycle. The other specimens will exhibit only small changes in the principal-strain-axes direction. Specimens D-22.5° and E-37.5° will exhibit some ply relative rotation.

The above remarks lead to specific criteria for identifying and assessing factors contriuting to the nonlinear response of boron/aluminum angleplied laminates as will be described in the next section.

Criteria for Assessing
Factors Contributing to Nonlinear Response

Two criteria will be used for identifying and assessing the importance of the factors contributing to the nonlinear response. The primary criterion is the change of the specimen instantaneous (tangent) modulus during the <u>initial portion</u> of the <u>loading</u> with successive cycles. Specifically:

a. Negligible changes in modulus with successive loading cycles indicate that the matrix is the major contributor.

b. Decreases in modulus with successive loading cycles indicate that premature fiber fracture is the major contributor.

c. Increases in modulus with successive loading cycles indicate that ply relative rotation is the major contributor.

The secondary criterion to be used is the shape of the load versus strain curve. Specifically:

a. When the matrix is the major contributor, the curve will be analogous to that of a material showing strain hardening, that is linear unloading response and little or no hysteresis.

b. When premature fiber fracture is a significant contributor, the unloading portion of the curve will be linear initially, with a smaller slope than the corresponding loading part, followed by a nonlinear portion anologous to Bauschinger effect. The reason for this is that fiber fractures cause excessive localized matrix nonlinearities. Upon unloading, these local nonlinearities go into compression and "yield" in compression long before the specimen is completely unloaded. The curve for this case will show considerable hysteresis.

   Also, during unloading, it is possible for the matrix to go into nonlinear compression without premature fiber fractures. This will be the case when the longitudinal tensile strain in some plies is greater than the "yield" strain of the matrix. However, for this case the modulus of elasticity of the initial portion of both unloading and next-cycle-loading curves will be approximately equal to the corresponding portion of the previous cycle.

c. When ply relative rotation is a significant contributor, the unloading curve will be linear with no or little hysteresis, so long as no severe matrix shear "yielding" takes place (7). The curve will show a higher strain hardening rate than the curve for case (a). The reason for this is that the ply relative rotation is caused by fiber direction changes which tend to decrease the angle between fiber and load directions for the tensile load case. This results in a stiffer material and therefore a steeper strain hardening slope.

RESULTS AND DISCUSSION

Nonlinear Response of the Specimens Tested and Assessment of Contributing Factors

In view of the secondary criterion, a convenient way for assessing factors contributing to nonlinear response is to plot tensile load in the specimen versus composite strain along the load direction (axial strain). This is a stiffness curve and reflects the effects of any cross-section changes.

Tensile cyclic load versus axial strain plots were made for all the specimens tested. The results are shown in figures 5 through 9. Applying the secondary criterion to these curves leads to the following observations:

a. The matrix was the major contributor to the nonlinear response of specimens C-80° (fig. 5) and D-80° (fig. 6).

b. Premature fiber fracture was a significant contributor to the nonlinear response of specimens D-22.5° (fig. 7) and E-37.5° (fig. 8). Note, the nonlinear portion of the unloading curve and the relatively large hysterysis loop in figure 7.

c. The ply relative rotation was a significant contributor to the nonlinear response of specimen F-37.5° (fig. 9). Note, the unloading curve is linear in its entirety and the lack of hysterysis.

All of the above observations are consistent with the anticipated results from the Specimen Selection Background section. An important conclusion from the above observations is that the secondary criterion may be a sufficient condition for assessing the contribution to the composite nonlinear response of the three major factors.

The changes in the tangent modulus with successive loading cycles may be illustrated by plotting the tangent modulus versus relative axial strain. By relative strain it is meant that the residual strain from previous cycles has been subtracted. Tangent mdoulus versus relative axial strain was plotted for some of the specimens tested. The results are shown in figures 10, 11 and 12. Applying the primary criterion and restricting our attention to the initial portion of the loading curve it is observed that:

a. The matrix was the major contributor to the nonlinear response of specimen C-80° (fig. 10) with some contribution from ply relative rotation.

b. Premature fiber fracture was the predominant contributor to the nonlinear response of specimen D-22.5° (fig. 11).

c. Ply relative rotation was the predominant contributor to the nonlinear response of specimen F-37.5 (fig. 12).

These observations are in agreement with those made using the secondary criterion and are consistent with the anticipated results discussed previously.

An additional observation from the results in figure 12 is: The matrix strain-hardening effect on the "yield" strain is maximum on the second load cycle and decreases rapidly with additional cycles.

The results discussed thus far show that the significant contribution to the nonlinear response of B/Al angleplied laminates when subjected to a few cycles of tensile load was from: premature random fiber breaks when the ply orientation angle is small (less than 10°) relative to the load direction, ply relative rotation at intermediate values (35° to 55°) of the ply orientation angle, and aluminum matrix nonlinear behavior at large values (greater than 70°) of the ply orientation angle.

Principal-Strains Axes Change

The change of the principal-strains axis (θ) is a good measure of obtaining a combined measure of nonlinear response. A graphical representation of this change may be obtained by plotting θ versus initial-area stress or relative axial strain.

A plot of θ versus relative axial strain is shown in figure 13 for all the specimens tested. As can be readily observed in figure 13, the instantaneous values of θ increase with increasing relative strain. The maximum values of θ are less than 4° for specimens C-22.5°, D-80°, and F-37.5°; about 10° for specimen D-22.5°; and about 20° for specimen E-37.5°. As can be seen from the schematics in figure 13, or figure 2, low values of θ correspond with specimens whose axis of symmetry is nearly coincident with the load direction. The converse is true for the larger θ values.

Two points need be made in connection with the above discussion: (a) upon unloading, the major portion of the θ value remains as residual angle; and (b) fiber direction shifts are possible with large or progressively larger values of θ.

Maximum Matrix Strains

The maximum strains in the matrix were computed using equations (1) through (6) discussed previously. The variation of the maximum transverse matrix strain with composite stress is shown in figure 14 for all the specimens tested. Note that the transverse strain increases very rapidly at about the same value of composite stress in specimens (C-80° and D-80°) where the matrix carried the major portion of the load. In the specimens where the fibers carried the major portion of the load (D-22.5° and E-37.5°), the maximum transverse strain in the matrix appears to go along for the ride.

The above discussion leads to the following conclusion. The maximum transverse tensile strain in the matrix may be used as a criterion to identify plies and/or composites in which the matrix carries the major portion of the load. This strain increases very rapidly at some composite stress value indicating onset of pronounced matrix nonlinearity.

The maximum shear strain in the matrix is plotted versus composite initial-area stress in figure 15 for all the specimens tested. The important point to be observed in figure 15 is that the very large shear strain for the specimen F-37.5° as compared with the other specimens. It is this large shear strain which causes ply relative rotation (scissoring effect). The conclusion is, then, that very large shear strains in the matrix may be used as a criterion to identify plies undergoing ply relative rotation. Advantage may be taken of this observation in practical designs where the need for the structural part is to become stiffer with successive loading cycles.

The equivalent strain in the matrix may also be used as a combined index to assess composite nonlinear response. The equivalent strain is plotted versus composite initial-area stress in figure 16 for all the specimens tested. Comparing the curves in figure 16 with the corresponding ones in figure 15, it is seen that the equivalent strains are similar to the maximum shear strains. This is anticipated from equation (1) where is is seen that the shear strain term ε_{m12} has the largest multiplier. We conclude, therefore, that the equivalent strain in the matrix does not provide any more information than the maximum shear strain in the matrix.

As a side note, the equivalent strain in the matrix is used to carry out nonlinear stress analysis of fiber composites based at the constituents level. The equivalent strain approach presupposes isotropic "yielding" or deviations from linearity. In view of the "yielding" directionality forced on the matrix by the restraining fibers, the isotropic "yielding" assumption might be premature.

Changes in Fiber Direction

It was mentioned in the theoretical background section that the change in the fiber direction may be computed from the last equation of equations (7). An assessment on the fiber direction change may be obtained by plotting the fiber direction change versus composite initial-area stress or relative axial strain.

The fiber direction change versus composite initial-area stress is plotted in figure 17 for the specimens tested. Note that the curves in figure 17 are similar to those in figure 15 for maximum shear stress in the matrix. This should be so since they both were computed using the same equation but with different multipliers. The conclusion, therefore, is that excessively large shear strains in the matrix produce corresponding changes in the fiber direction. As is seen in figure 17, the maximum change in fiber direction was in the F-37.5° as was expected.

As a side note, the computed change in angle between the 0° and 90° plies in the F-37.5° laminate was about 3.2° at the end of the third loading cycle. The measured change in angle when the specimen broke was about 23° corresponding to a 20 percent width reduction.

SUMMARY OF RESULTS

The following are the important results obtained from an investigation of 4 mil boron/6061-0 aluminum angleplied laminates, subjected to cyclic tensile loading.

A procedure has been described and criteria have been proposed which can be used to assess the factors contributing to nonlinear response of fiber composite angleplied laminates when subjected to tensile cyclic loading.

The results of the specimens tested and analyzed showed that the significant contribution to the nonlinear response of B/Al angleplied laminates when subjected to a few cycles of tensile load was from: premature random fiber breaks when the ply orientation angle is small (less than 10°) relative to the load direction, ply relative rotation at intermediate values (35° to 55°) of the ply orientation angle, and aluminum matrix nonlinear behavior at large values (greater than 70°) of the ply orientation angle.

Premature fiber breaks result in a progressively compliant material with considerable nonlinearity in the unloading curve and a significant amount of hysteresis.

Ply relative rotation results in a progressively stiffer material with linear unloading and little or no hysteresis.

Pronounced matrix nonlinear behavior results in: no significant changes in stiffness with successive load cycles, linear unloading, and little hysteresis which seems to grow larger with successive cycles. The strain hardening effects on the "yield" strain are significant from the first to the second cycle and appear to diminish thereafter.

Nonsymmetrically loaded B/Al angleplied laminates exhibit significant changes in the direction of the principal strain axes which becomes progressively larger. The major portion of this change remains as residual.

Pronounced matrix nonlinear behavior is the result of large transverse strain in the matrix. This strain increases very rapidly at about the 0.1 percent value of the relative axial strain for the specimens tested.

Ply relative rotation (fiber direction change) is caused by large shear strains in the matrix. The specimen used to test this condition accumulated a ply relative rotation of about 23° when it fractures.

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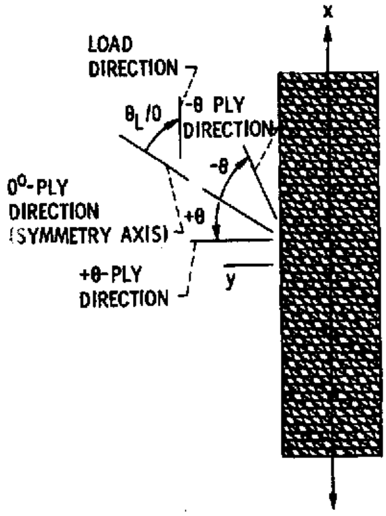

PLY ORIENTATION, LOAD DIRECTION & LENGTH

SPECIMEN, DEG	θ, DEG	$\theta_L/0$, DEG	LENGTH, IN.
C-80	15	-80	10.0
D-22.5	30	-22.5	10.0
D-80	30	-80	10.0
E-37.5	45	-37.5	9.60
F-37.5	90	-37.5	9.60

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Figure 1. - Schematic of specimen geometry 8(0, 0, +θ, -θ, θ, +θ, 0, 0) boron/aluminum angleplied laminate.

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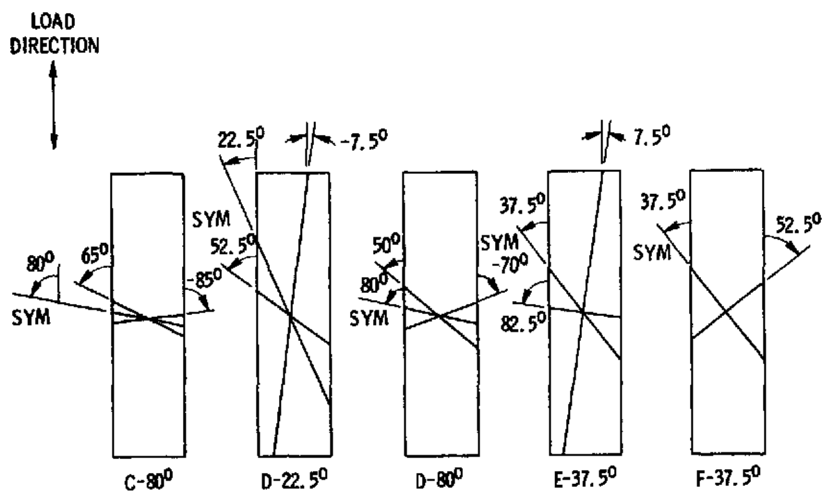

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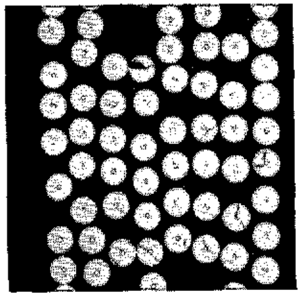
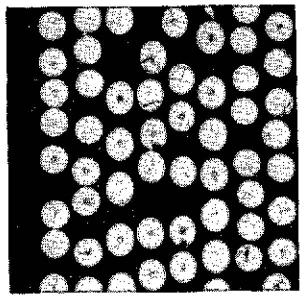
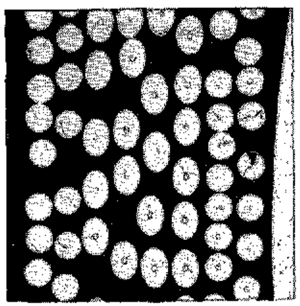
Figure 2. - Schematic depicting the fiber directions in the various specimens.



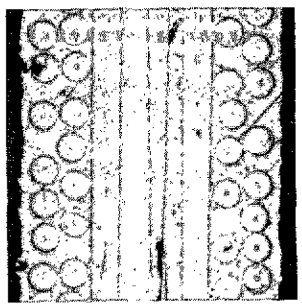
(a) $[0, 0, \pm 15]_S$.



(b) $[0, 0, \pm 30]_S$.

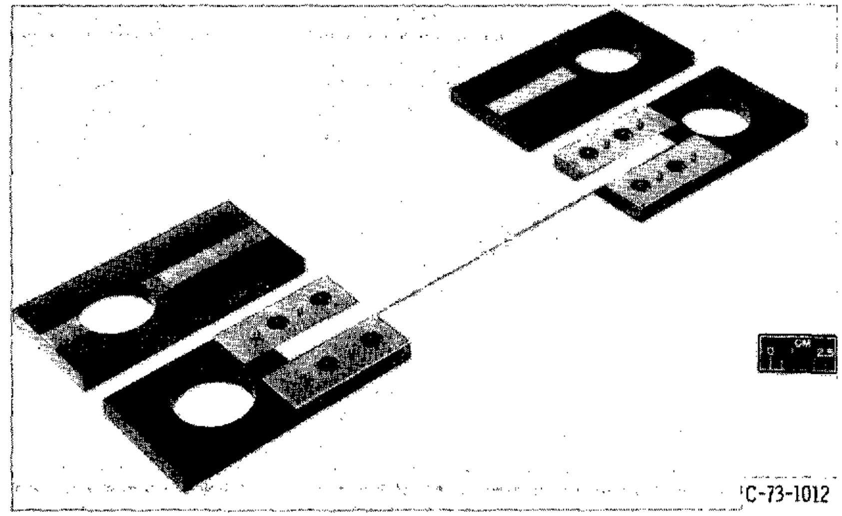


(c) $[0, 0, \pm 45]_S$.

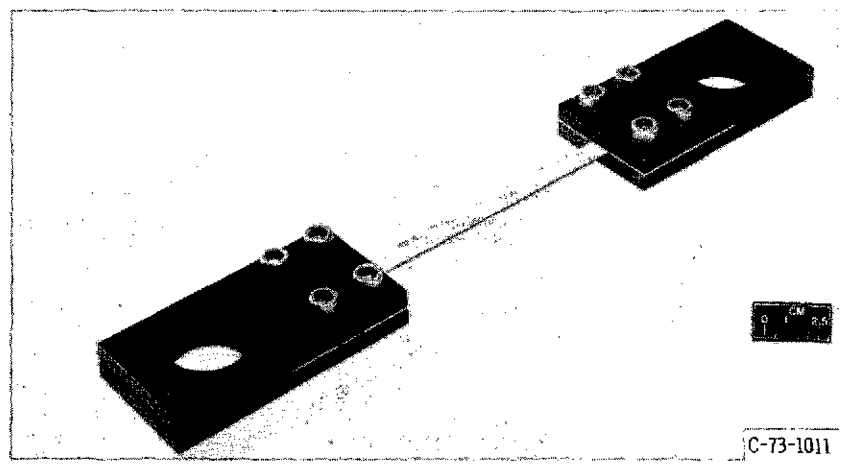


(d) $[0, 0, 90, 90]_S$.

Figure 3. - Photomicrographs of cross section of boron/aluminum angleplied laminates. X75.



(a) GRIPS DISASSEMBLED.



(b) GRIPS ASSEMBLED.

Figure 4. - Boron/aluminum angleplied laminate test specimen and grips.

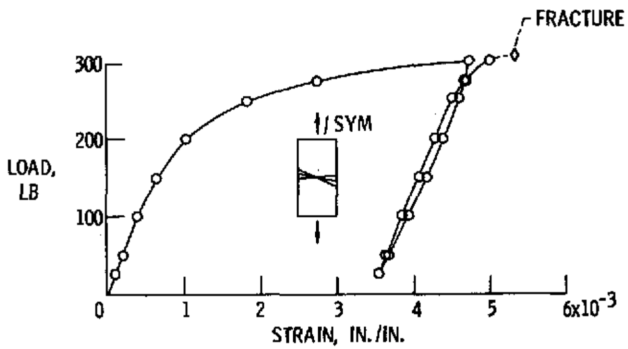


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Figure 5. - Experimental nonlinear cyclic load response of boron/aluminum angleplied laminate C-80^0 8(0, 0, ±15, ∓15, 0, 0) loaded in tension at -80^0 to the 0^0-ply direction. (4 mil dia. fiber; fiber volume ratio ≈ 0.5; 6061-0 aluminum alloy.)

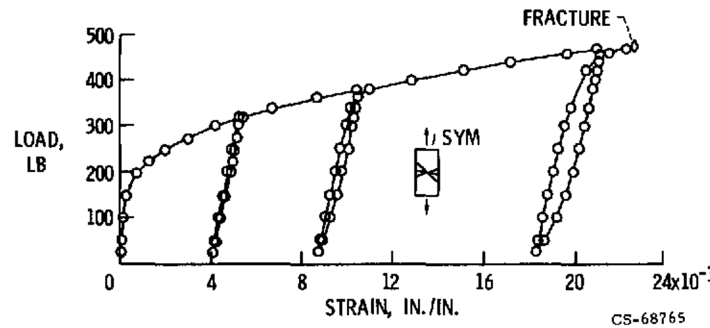

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Figure 6. - Experimental nonlinear cyclic load response of boron/aluminum angleplied D-80^0 8(0, 0, ± 30, ∓30, 0, 0) loaded in tension at -80^0 to the 0^0-ply direction. (4 mil dia. fiber; fiber volume ratio≈0.5; 6061-0 aluminum alloy.)

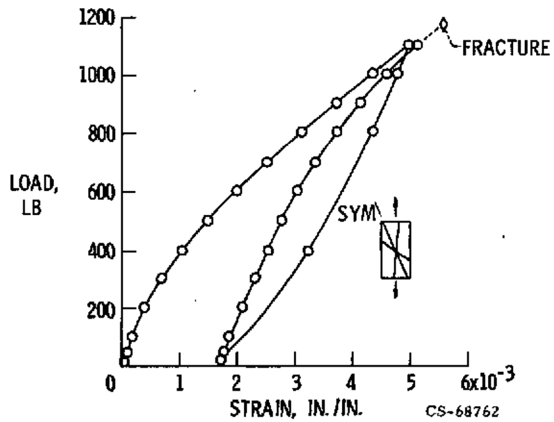

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Figure 7. - Experimental nonlinear cyclic load response of boron/aluminum angleplied laminate D-22.5^0 8(0, 0, ± 30, ∓30, 0, 0) loaded in tension at -22.5^0 to the 0^0-ply direction. (4 mil dia. fiber; fiber volume ratio ≈ 0.5; 6061-0 aluminum alloy.)

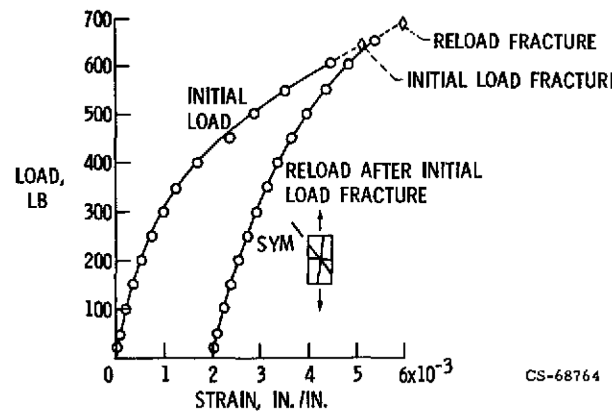

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Figure 8. - Experimental nonlinear cyclic load response of boron/aluminum angleplied laminate E-37.5^0 8(0, 0, ±45, ∓, 0, 0) loaded in tension at -37.5^0 to the 0^0-ply direction. (4 mil dia. fiber; fiber volume ratio, 0.5; 6061-0 aluminum alloy.)

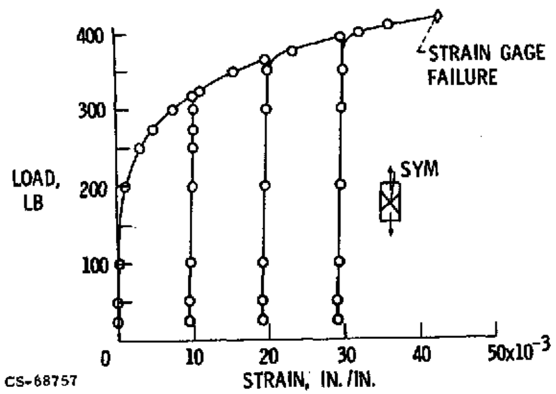

Figure 9. - Experimental nonlinear cyclic load response of boron/aluminum angleplied laminate F-37.5^0 8(0, 0, 4(90), 0, 0) loaded in tension at -37.5^0 to the 0^0-ply direction. (4 mil dia. fiber; fiber volume ratio, 0.5; 6061-0 aluminum alloy.)

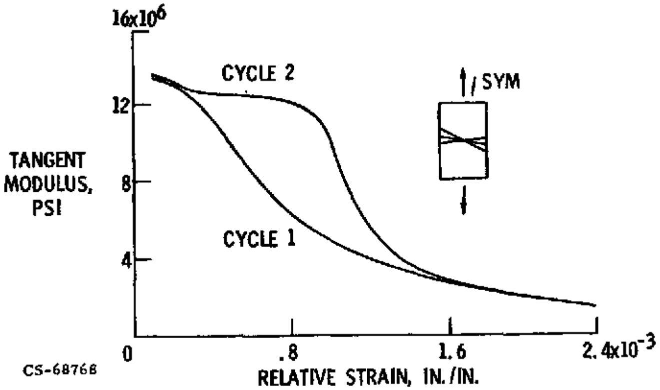

Figure 10. - Nonlinear matrix behavior influence on modulus. Boron/aluminum angleplied laminate C-80^0 8(0, 0, ± 15, ∓15, 0, 0) loaded -80^0 in tension to the 0^0-ply direction. (4 mil dia. fiber; fiber volume ratio ≈ 0.50; 6061-0 aluminum alloy.)

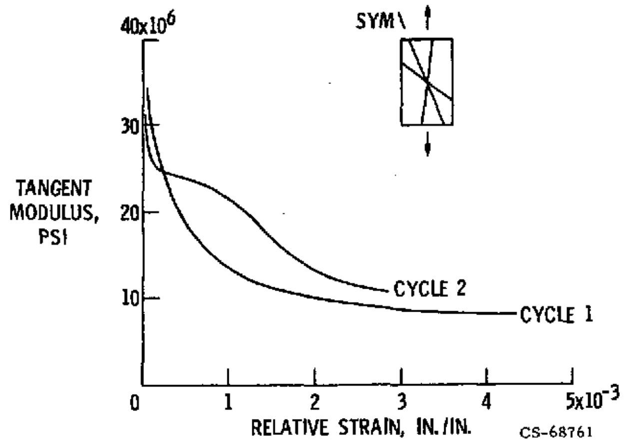

Figure 11. - Premature fiber fracture influence on modulus. Boron/aluminum angleplied laminate D-22.5^0 8(0, 0, ± 30, ∓30, 0, 0) loaded -22.5^0 in tension to the 0^0-ply direction. (4 mil dia. fiber; fiber volume ratio ≈ 0.50; 6061-0 aluminum alloy.)

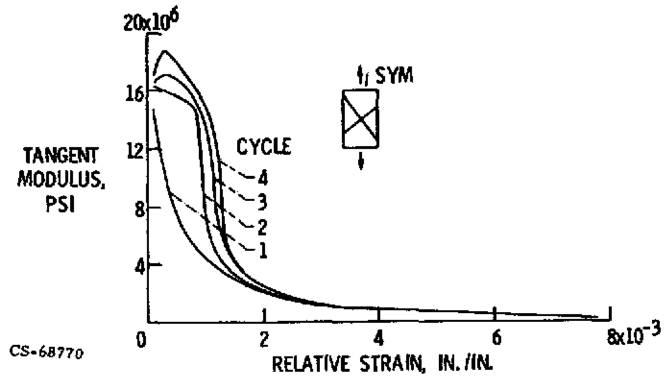

Figure 12. - Ply relative rotation influence on modulus. Boron/aluminum angleplied laminate F-37.5^0 8[2(0), 4(90), 2(0)] loaded at -37.5^0 in tension to the 0^0-ply direction. (4 mil dia. fiber; fiber volume ratio ≈ 0.50; 6061-0 aluminum alloy.)

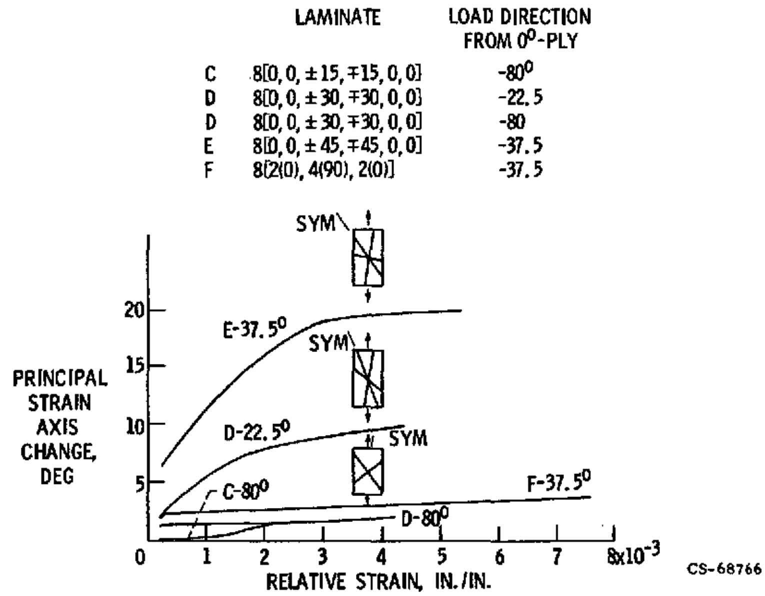

Figure 13. - First cycle principal-strain axis change with strain. Boron/aluminum angleplied laminates loaded in tension as noted in the figure. (4 mil dia. fiber; fiber volume ratio ≈ 0.50; 6061-0 aluminum alloy).

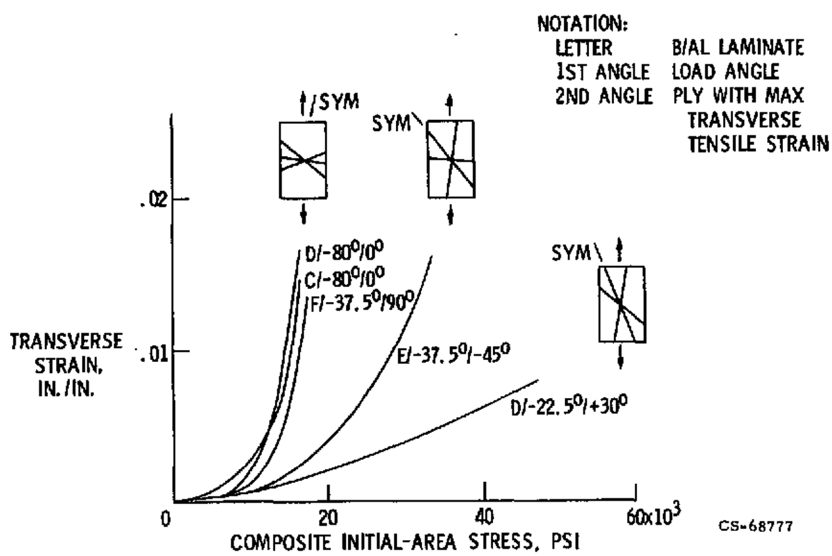

Figure 14. - The effect of composite stress on the maximum transverse matrix strain. Boron/aluminum angleplied laminates loaded in tension at various angles to the 0°-ply direction. (4 mil dia. fiber; fiber volume ratio ≈ 0.50; 6061-0 aluminum alloy.)

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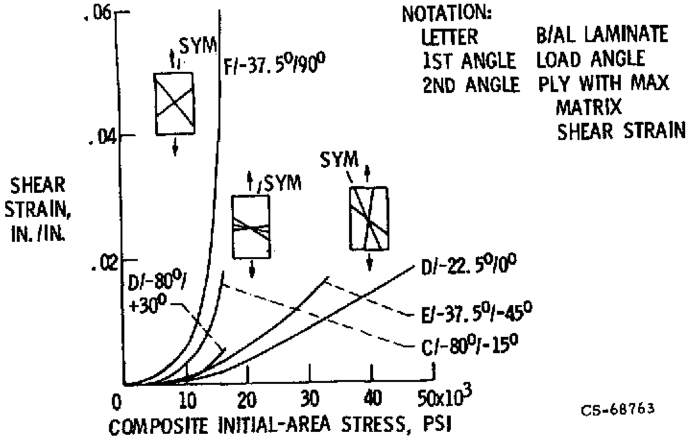

Figure 15. - The effect of composite stress on the maximum shear matrix strain. Boron/aluminum angleplied laminates loaded in tension at various angles to 0°-ply direction. (4 mil dia. fiber; fiber volume ratio ≈ 0.50; 6061-0 aluminum alloy.)

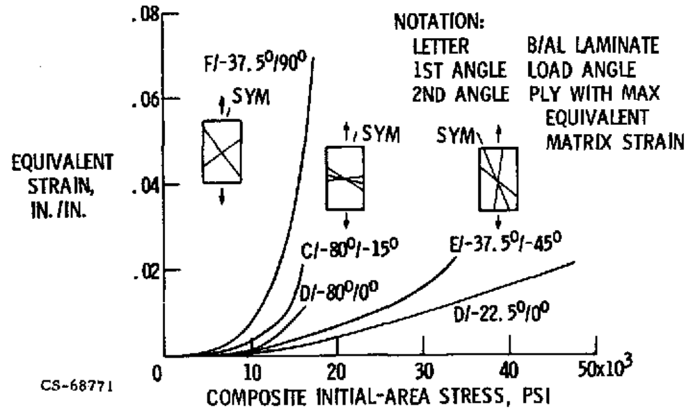

Figure 16. - The effect of composite stress on equivalent matrix strain. Boron/aluminum angleplied laminates loaded in tension at various angles to 0°-ply direction. (4 mil dia. fiber; fiber volume ratio ≈ 0.50; 6061-0 aluminum alloy.)

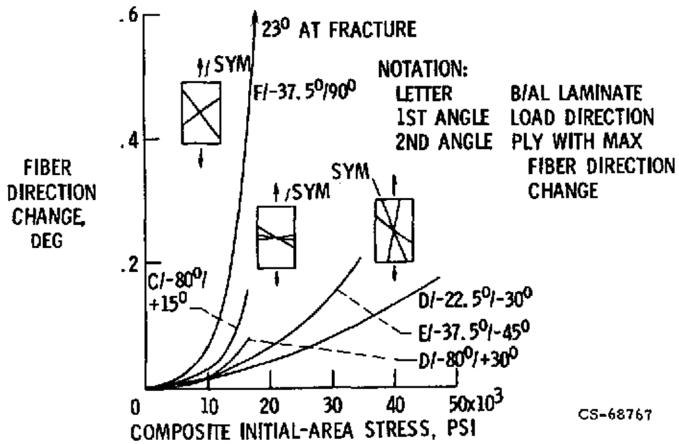

Figure 17. - The effect of composite stress on fiber direction change. Boron/aluminum angleplied laminates loaded in tension at various angles to the 0°-ply direction. (4 mil dia. fiber; fiber volume ratio ≈ 0.50; 6061-0 aluminum alloy.)