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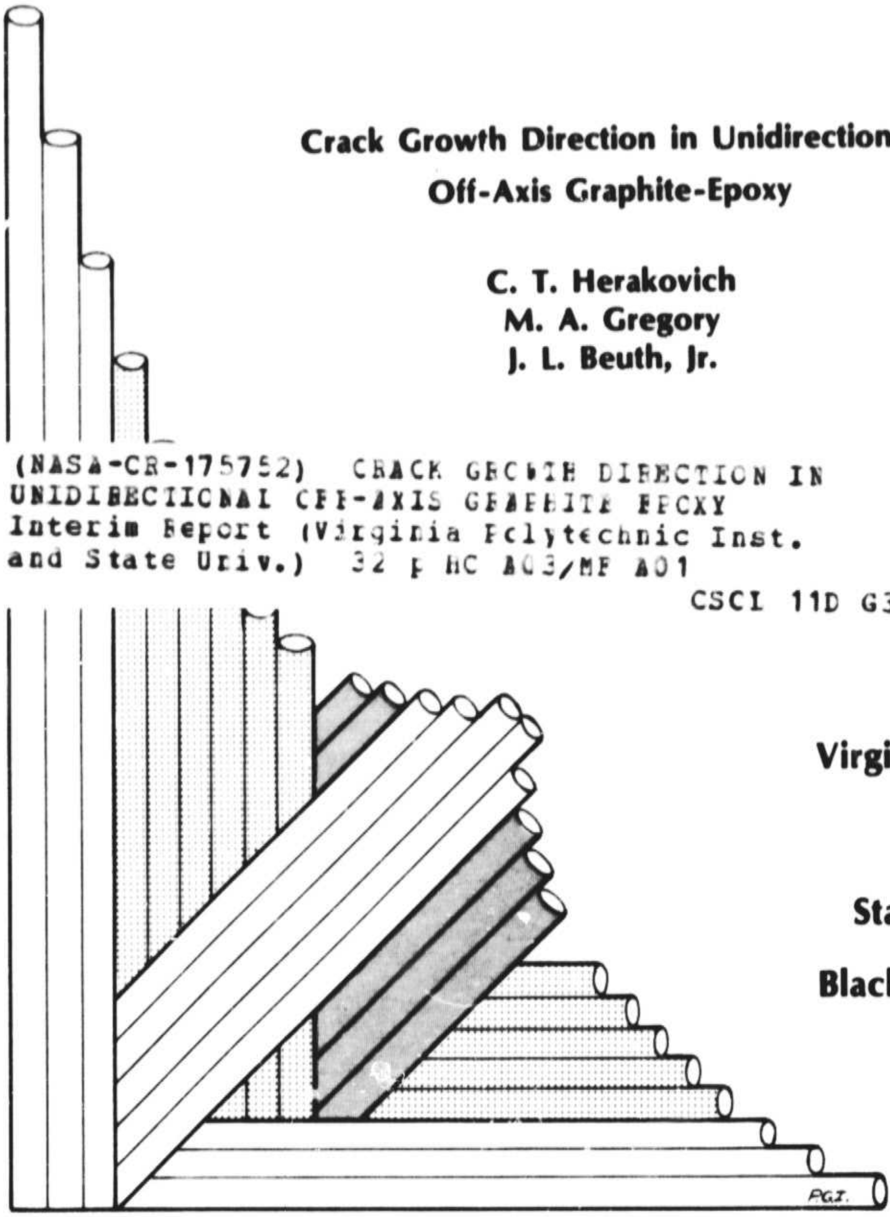

Crack Growth Direction in Unidirectional Off-Axis Graphite-Epoxy

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ABSTRACT

An anisotropic elasticity crack tip stress analysis is implemented using three crack extension direction criteria (the normal stress ratio, the tensor polynomial and the strain energy density) to predict the direction of crack extension in unidirectional off-axis graphite-epoxy. The theoretical predictions of crack extension direction are then compared with experimental results for 15° off-axis tensile coupons with center cracks. Specimens of various aspect ratios and crack orientations are analyzed. It is shown that only the normal stress ratio criterion predicts the correct direction of crack growth.

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INTRODUCTION

A fundamental problem in predicting the failure of laminated composite materials is prediction of the direction of crack growth in the individual laminae, and the laminate. The influence of the direction of crack growth on the failure response of the laminate is shown in Fig. 1 [1]. The clustered $[\theta_2/-\theta_2]_s$ graphite-epoxy laminates fail in a pure matrix mode (delamination and either intralaminar matrix cracking or fiber matrix debonding). In contrast, the alternating $[(+\theta/-\theta)_2]_s$ laminates exhibit fiber breakage in half of the plies, and either matrix cracking or fiber matrix debonding in the others; there is no delamination. The mode of failure has a significant effect on the strength of the laminate. The strength of 10° and 30° alternating laminates is, for example, 30 and 50 percent greater, respectively, than the strength of clustered 10° and 30° laminates [1]. Hence, understanding the parameters that affect laminate failure, particularly those influencing the direction of crack growth in the lamina and between laminae, is of critical importance in predicting the fracture response of laminates.

Predicting the direction of crack extension in laminates is a very complex three-dimensional problem. Since the lamina is the basic building block of the laminate, its behavior must be fully understood as a stepping stone toward understanding the behavior of the laminate. This study was undertaken to assess more critically the applicability of three criteria which have been presented in the literature for predicting the direction of crack growth in unidirectional fibrous composites [2-4].

CRACK EXTENSION DIRECTION CRITERIA

Three phenomenological criteria for predicting the direction of crack extension in homogeneous, anisotropic materials are the normal stress ratio criterion [2], the tensor polynomial criterion [3] and the strain energy density criterion [4]. These criteria can be used to predict the load at failure and the direction of crack extension. The crack tip coordinate system used in this analysis is shown in Fig. 2.

Normal Stress Ratio Criterion

Buczek and Herakovich [2] have hypothesized the normal stress ratio criterion as a crack growth direction criterion. The model assumes that the direction of crack extension corresponds to the direction of the maximum value of the normal stress ratio $R(r_o,\phi)$ where

$$R(r_o,\phi) = \frac{\sigma_{\phi\phi}}{T_{\phi\phi}} \tag{1}$$

In the expression for $R(r_o,\phi)$, $\sigma_{\phi\phi}$ corresponds to the normal stress acting on the radial plane defined by ϕ, and at a given distance, r_o, from the crack tip. $T_{\phi\phi}$ is the tensile strength on the ϕ plane.

Since the tensile strength on an arbitrary plane is difficult, if not impossible, to measure, $T_{\phi\phi}$ is defined in a manner consistent with the tests that can be performed. To meet this requirement, a mathematical definition of $T_{\phi\phi}$ must satisfy the following conditions:

(1) for an isotropic material, $T_{\phi\phi}$ must be independent of ϕ.

(2) for crack growth parallel to the fibers, $T_{\phi\phi}$ must equal the transverse tensile strength Y_T.

(3) for crack growth perpendicular to the fibers, $T_{\phi\phi}$ must equal the longitudinal tensile strength X_T.

A definition satisfying these conditions is:

$$T_{\phi\phi} = X_T \sin^2\beta + Y_T \cos^2\beta \qquad (2)$$

where β is the angle from the plane of interest to the fiber direction.

Tensor Polynomial Criterion

Tsai and Wu [5] first presented the tensor polynomial criterion as an anisotropic failure criterion. This criterion is based on the existence of a failure surface in stress space of the form:

$$f(\sigma_i) = F_i\sigma_i + F_{ij}\sigma_i\sigma_j \qquad (3)$$

where F_i and F_{ij} are strength tensors of second and fourth order, and σ_i is the contracted form of the stress tensor. Expressions for F_i and F_{ij} are given in Table 1.

In application of the tensor polynomial to fracture problems [3], the assumed direction of crack extension is the radial direction of maximum $f(\sigma_i)$. The stress components σ_i are those determined by a continuum mechanics-based stress analysis, and must be evaluated at a finite distance, r_o, from the crack tip.

Strain Energy Density Criterion

The strain energy density criterion is based on variations in the energy stored along the periphery of a core region surrounding the crack. Sih presents the criterion for isotropic fracture in [6] and a modified form for application to anisotropic fracture in [4].

The strain energy density factor, S, is defined as:

$$\frac{\partial W}{\partial V} = \frac{S}{r} \tag{4}$$

where $\frac{\partial W}{\partial V}$ is the strain energy density function and r is the distance from the crack tip. Since the strain energy density function can be expressed in terms of the crack tip stresses and strains for plane stress as:

$$\frac{\partial W}{\partial V} = \frac{1}{2}\left(\sigma_x \varepsilon_x + \sigma_y \varepsilon_y + \tau_{xy} \gamma_{xy}\right) \tag{5}$$

an expression for the strain energy density factor, S. can be obtained by substitution. The resulting expression is:

$$S = \frac{r}{2}\left(\sigma_x \varepsilon_x + \sigma_y \varepsilon_y + \tau_{xy} \gamma_{xy}\right) \tag{6}$$

The fundamental hypothesis of Sih [4] for unstable crack growth is that crack initiation takes place in the radial direction corresponding to a minimum value of the strain energy density factor, i.e.,

$$\frac{\partial S}{\partial \phi} = 0 \quad \text{and} \quad \frac{\partial^2 S}{\partial \phi^2} > 0 \qquad \text{at } \phi = \phi_c \tag{7}$$

Sih cautions that for small values of r, a continuum mechanics-based crack tip stress analysis is invalid. Hence, the strain energy factor should be evaluated at a finite distance, r_o, from the crack tip, where r_o is of the same order of magnitude as the crack tip curvature.

ANISOTROPIC ELASTICITY ANALYSIS OF CRACK TIP STRESS FIELDS

The stress analysis of an infinite homogeneous anisotropic plate containing a center crack can be directly related to a homogeneous anisotropic plate with an elliptic hole. By reducing the minor axis dimension to zero and evaluating the stress potential functions in the neighborhood of the crack tip, Lekhnitskii's complex variable solution [7] for an elliptic hole in an anisotropic plate can be adapted to solve anisotropic fracture problems. Wu presents a detailed description of this procedure in [8], along with equations describing the crack tip stresses for an infinite homogeneous anisotropic center-cracked plate. The problem under consideration is shown in Fig. 3.

The governing partial differential equation for this problem in terms of the Airy's stress function U is:

$$\frac{\partial^4 U}{\partial x^4} - \frac{2A_{26}}{A_{22}}\frac{\partial^4 U}{\partial x^3 \partial y} + \frac{(2A_{12} + A_{66})}{A_{22}}\frac{\partial^4 U}{\partial x^2 \partial y^2} - \frac{2A_{16}}{A_{22}}\frac{\partial^4 U}{\partial x \partial y^3} + \frac{A_{11}}{A_{22}}\frac{\partial^4 U}{\partial y^4} = 0 \quad (8)$$

where A_{ij} are components of the compliance tensor for plane stress or plane strain, depending on the analysis desired.

Assuming $U = e^{x+sy}$, the characteristic equation for (8) takes the form:

$$A_{11}S^4 - 2A_{16}S^3 + (2A_{12} + A_{66})S^2 - 2A_{26}S + A_{22} = 0 \quad (9)$$

The roots of the characteristic equation, S_1 and S_2, (and their conjugates) are complex, and are functions of the material properties and the orientation of the crack relative to the principal material direction.

Assuming $S_1 \neq S_2$, evaluation of the complex potential functions near the crack tip yields expressions for the stress and displacement distributions of the form:

$$\sigma_x = \frac{\sigma^\infty \sqrt{a}}{\sqrt{2r}} \operatorname{Re} \left\{\frac{S_1 S_2}{(S_1 - S_2)} \left[\frac{S_2}{\psi_2^{1/2}} - \frac{S_1}{\psi_1^{1/2}}\right]\right\} + \frac{\tau^\infty \sqrt{a}}{\sqrt{2r}} \operatorname{Re}\left\{\frac{1}{(S_1 - S_2)} \left[\frac{S_2^2}{\psi_2^{1/2}} - \frac{S_1^2}{\psi_1^{1/2}}\right]\right\}$$

$$\sigma_y = \frac{\sigma^\infty \sqrt{a}}{\sqrt{2r}} \operatorname{Re} \left\{\frac{1}{(S_1 - S_2)} \left[\frac{S_1}{\psi_2^{1/2}} - \frac{S_2}{\psi_1^{1/2}}\right]\right\} + \frac{\tau^\infty \sqrt{a}}{\sqrt{2r}} \operatorname{Re} \left\{\frac{1}{(S_1 - S_2)} \left[\frac{1}{\psi_2^{1/2}} - \frac{1}{\psi_1^{1/2}}\right]\right\}$$

$$\tau_{xy} = \frac{\sigma^\infty \sqrt{a}}{\sqrt{2r}} \operatorname{Re} \left\{\frac{S_1 S_2}{(S_1 - S_2)} \left[\frac{1}{\psi_1^{1/2}} - \frac{1}{\psi_2^{1/2}}\right]\right\} + \frac{\tau^\infty \sqrt{a}}{\sqrt{2r}} \operatorname{Re} \left\{\frac{1}{(S_1 - S_2)} \left[\frac{S_1}{\psi_1^{1/2}} - \frac{S_2}{\psi_2^{1/2}}\right]\right\}$$

$$u = \sigma^\infty \sqrt{2ar} \operatorname{Re} \left\{\frac{1}{(S_1 - S_2)}\left[S_1 p_2 \psi_2^{1/2} - S_2 p_1 \psi_1^{1/2}\right]\right\} + \tau^\infty \sqrt{2ar} \operatorname{Re} \left\{\frac{1}{(S_1 - S_2)}\left[p_2 \psi_2^{1/2} - p_1 \psi_1^{1/2}\right]\right\} \tag{10}$$

$$v = \sigma^\infty \sqrt{2ar} \operatorname{Re} \left\{\frac{1}{(S_1 - S_2)}\left[S_1 q_2 \psi_2^{1/2} - S_2 q_1 \psi_1^{1/2}\right]\right\} + \tau^\infty \sqrt{2ar} \operatorname{Re} \left\{\frac{1}{(S_1 - S_2)}\left[q_2 \psi_2^{1/2} - q_1 \psi_1^{1/2}\right]\right\}$$

where

$$\psi_1 = \cos\phi + S_1 \sin\phi \qquad \psi_2 = \cos\phi + S_2 \sin\phi$$

$$p_1 = A_{11} S_1^2 + A_{12} - A_{16} S_1 \qquad p_2 = A_{11} S_2^2 + A_{12} - A_{16} S_2$$

$$q_1 = \frac{A_{12} S_1^2 + A_{22} - A_{26} S_1}{S_1} \qquad q_2 = \frac{A_{12} S_2^2 + A_{22} - A_{26} S_2}{S_2}$$

As in the isotropic case, the crack tip stresses exhibit a singularity of $1/\sqrt{r}$. However, the magnitude of the stresses is not simply a function of the stress intensity factors. The quantities S_1 and S_2 also affect the magnitude of the stresses. This is an important difference between anisotropic and isotropic fracture. In anisotropic fracture, the magnitude of the crack tip stresses is a function of not only the applied load, specimen geometry and crack length, but also the material properties and the orientation of the crack relative to the principal material direction. Application of this solution to the analysis of unidirectional composites with crack orientations other than parallel to the X-axis is presented in Gregory and Herakovich [9].

EXPERIMENTAL PROGRAM

In order to test the ability of the theoretical models to predict the direction of crack extension, tests were performed on center-cracked specimens of 16 ply unidirectional AS4/3501-6 graphite/epoxy. Material properties for AS4/3501-6 graphite/epoxy are given in Table 2. The experimental investigation consisted of a series of 15° off-axis tensile tests with rigid end constraints. Coupons of various aspect ratios with pre-machined cracks oriented perpendicular to the loading direction or perpendicular to the fibers were tested. The specimen configurations are illustrated in Fig. 4; two coupons were tested for each configuration.

The test specimens were 1.00 inch (25.4 mm) wide and contained center cracks of 0.20 inches (5.08 mm). The aspect ratios (gauge length to width) of the specimens were 8, 4, and 1. Since off-axis specimens with rigid end constraints experience increased shear loading as the aspect ratio is reduced [10], specimens of various aspect ratios were tested to vary the biaxial stress state in the region of the crack.

Strain gauge rosettes were attached to each specimen at a point far from the crack. During each test, the direction of crack extension, the load at crack initiation, and the load at failure were observed and measured. To facilitate visual observation of crack growth, load was incrementally applied at a crosshead speed of 40 microstrain per second.

CORRELATION OF THEORETICAL MODELS WITH EXPERIMENTAL RESULTS

In all the experiments performed, crack extension occurred parallel to the fibers, with no observable fiber breakage. A broken specimen for each combination of crack orientation and aspect ratio is shown in Fig. 5.

The anisotropic elasticity solution was used to model the experimental procedures. To better approximate the far field stresses acting on the crack, the Pagano and Halpin solution [10] for the state of stress in an off-axis tensile coupon with rigid end constraints was incorporated. Though the Pagano and Halpin solution does not account for the presence of a crack, it does account for the high stress gradients and shear stress generated by the fixed ends. The far field stresses used as input for the anisotropic elasticity solution are the stresses generated by the Pagano and Halpin solution at a point corresponding to the crack tip location. The far field stresses, predicted direction of crack growth and the experimentally observed direction of crack extension are given in Table 3.

From Table 3, it is apparent that only the normal stress ratio criterion predicts the correct direction of crack extension. The other crack extension direction criteria show no correlation with the experimental results. Distributions in the crack extension criteria as a function of ϕ, for test case A (crack perpendicular to the loading axis), with aspect ratio 1 are shown in Figs. 6-8. Distributions in the normal stress ratio as a function of ϕ, for aspect ratios 1, 4, and 8 of test case B, are shown in Fig. 9-11.

Analysis of Figs. 6, 9, 10 and 11 and Table 3 yields an interesting characteristic of the normal stress ratio criterion. The theoretical predictions of crack extension direction differ slightly from the experimentally observed values. There is, however, a strong peak in the distribution of the normal stress ratio as a function of ϕ in the actual direction of crack growth. This fact is very important. The normal stress ratio may not have the accuracy to predict correctly the direction of crack extension to within one degree. When observed graphically, however, the normal stress ratio represents the direction of crack extension exceptionally well.

The normal stress ratio criterion predicted the correct direction of crack extension for every test analyzed, except for test case B (crack perpendicular to the fibers) with aspect ratio 1. For this problem, the normal stress ratio correctly predicts crack extension parallel to the fibers, however the predicted direction of extension is 180° out of phase with the observed direction. Analysis of Figs. 9-11 reveals that for test case B, there are two peaks in the normal stress ratio. The first peak, near $\phi = -90^{\circ}$, predicts crack extension parallel to the fibers, toward the center of the coupon. The second peak, near $\phi = +90^{o}$, implies crack extension parallel to the fibers, toward the free edge. For aspect ratios 4 and 8, the second peak is the maximum value. This is not true for aspect ratio 1, which has a maximum value at the first peak.

The discrepancy in the normal stress ratio criterion for test case B with aspect ratio 1 does not necessarily compromise the validity of the criterion. The stress gradients in a rigidly constrained tensile test of aspect ratio 1 are very high. One can also question the adequacy of the crack tip stress analysis; i.e., using Pagano and Halpin tensile coupon stresses as far field stresses in the anisotropic elasticity solution. The discrepancy is noted and further research is required.

CONCLUSIONS

This study was concerned with the development of a model to predict the direction of crack extension in unidirectional composite materials. An anisotropic elasticity solution, in conjunction with Pagano and Halpin's solution for stresses in a fixed end tensile test, was used to calculate the crack tip stress field in a center-cracked off-axis tensile coupon. Three crack extension direction criteria, the normal stress ratio criterion, the tensor polynomial criterion and the strain energy density criterion, were then incorporated into the model to predict the direction of crack extension.

Comparison of the predicted direction of crack extension with experimentally observed crack growth, indicates that only the normal stress ratio criterion consistently predicts the correct direction of crack extension.

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Table 1

Relationships for Strength Tensors in Terms of Measured Strengths

$F_1 = (1/X_T + 1/X_c)$
$F_2 = (1/Y_T + 1/Y_c)$
$F_6 = 0.0$
$F_{11} = -1/(X_T X_c)$
$F_{22} = -1/(Y_T Y_c)$
$F_{66} = 1/(S^2)$

Table 2

Lamina Properties of AS4/3501-6 Graphite/Epoxy

$E_1 = 21.6$ MSI	(148.9 GPa)
$E_2 = 1.96$ MSI	(13.5 GPa)
$G_{12} = 0.83$ MSI	(5.7 GPa)
$\nu_{12} = 0.28$	
$X_T = 282$ KSI	(1.94 GPa)
$X_c = -282$ KSI	(-1.94 GPa)
$Y_T = 10$ KSI	(68.9 MPa)
$Y_c = -10$ KSI	(-68.9 MPa)
$S = 14.2$ KSI	(97.9 MPa)

Table 3

Comparison of Theoretical and Experimental Results

Aspect Ratio	Test Case	s_{yy} (KSI)	t_{xy} (KSI)	Predicted Direction of Crack Extension: Normal Stress Ratio	Tensor Polynomial	Strain Energy Density
1	A	13.7	2.86	72°	347°	0°
4	A	10.2	1.01	73°	85°	315°
8	A	8.98	0.33	74°	87°	305°
1	B	13.7	-2.86	275°	10°	330°
4	B	10.2	-1.01	87°	110°	325°
8	B	8.98	-0.33	88°	103°	315°

Notes:

(i) Specimens from test case A have center cracks perpendicular to loading axis.

(ii) The experimentally observed direction of crack extension for all specimens of test case A is 75°.

(iii) Specimens from test case B have center cracks perpendicular to the fiber direction.

(iv) The experimentally observed direction of crack extension for all specimens of test case B is 90°.

(v) The far field loads correspond to the crack tip loading at 1% strain.

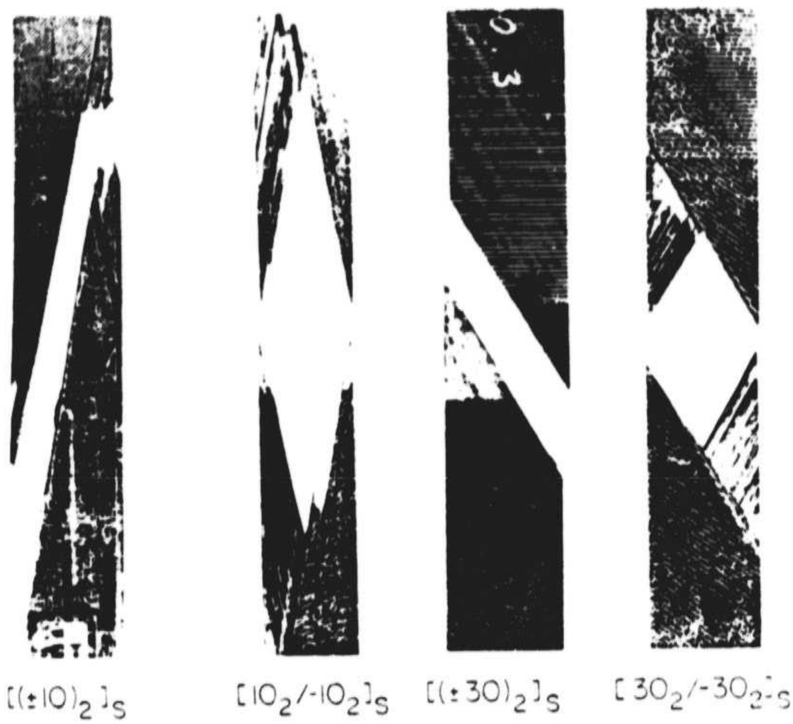


FIG. 1 FAILURE MODES IN ANGLE-PLY LAMINATES

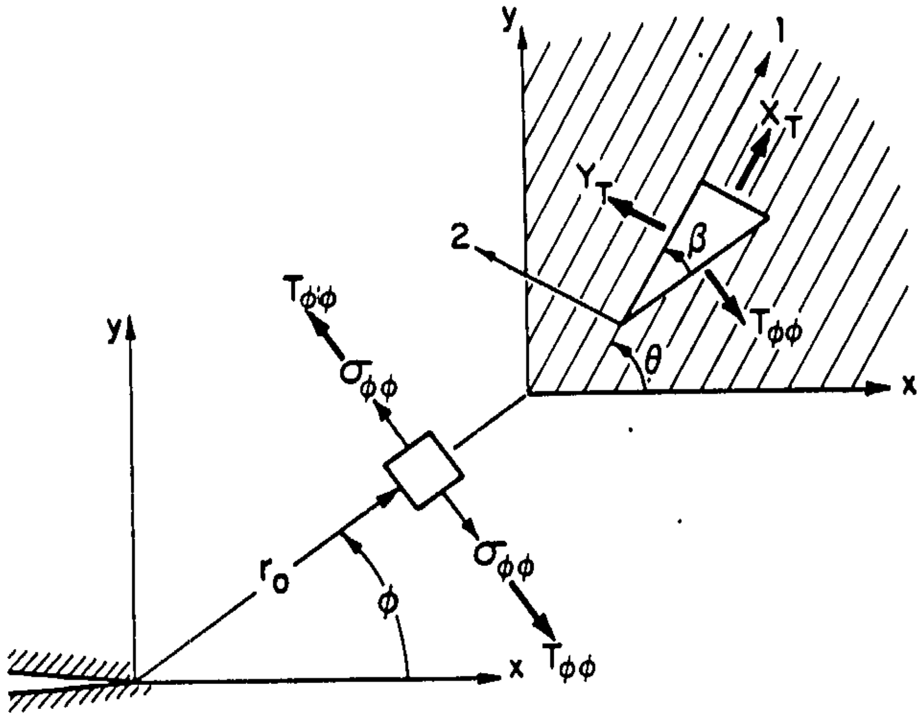


FIG. 2 COORDINATE SYSTEM & NORMAL STRESS RATIO PARAMETERS

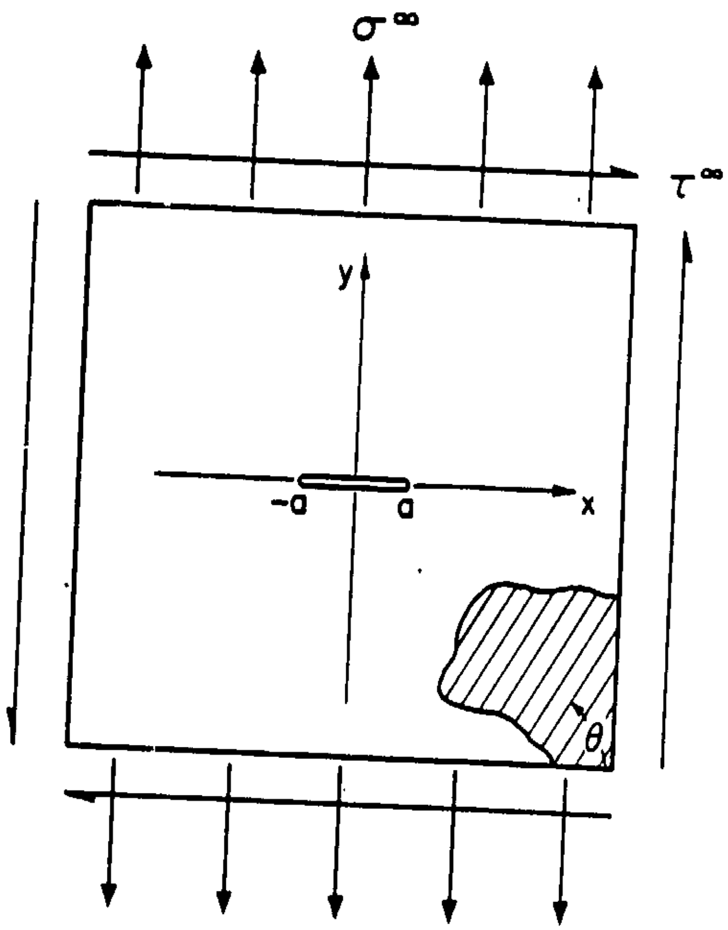
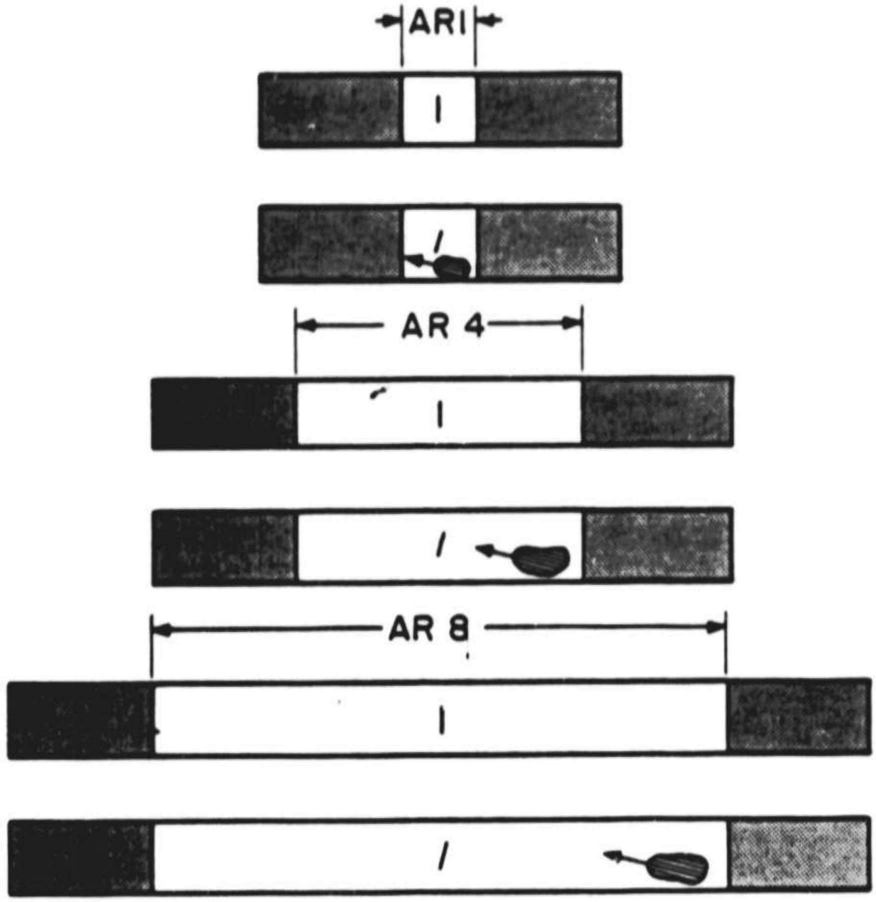


FIG. 3 INFINITE CENTER CRACKED PLATE UNDER BIAXIAL LOAD



AR = Aspect Ratio

FIG. 4 CENTER CRACKED SPECIMEN CONFIGURATIONS

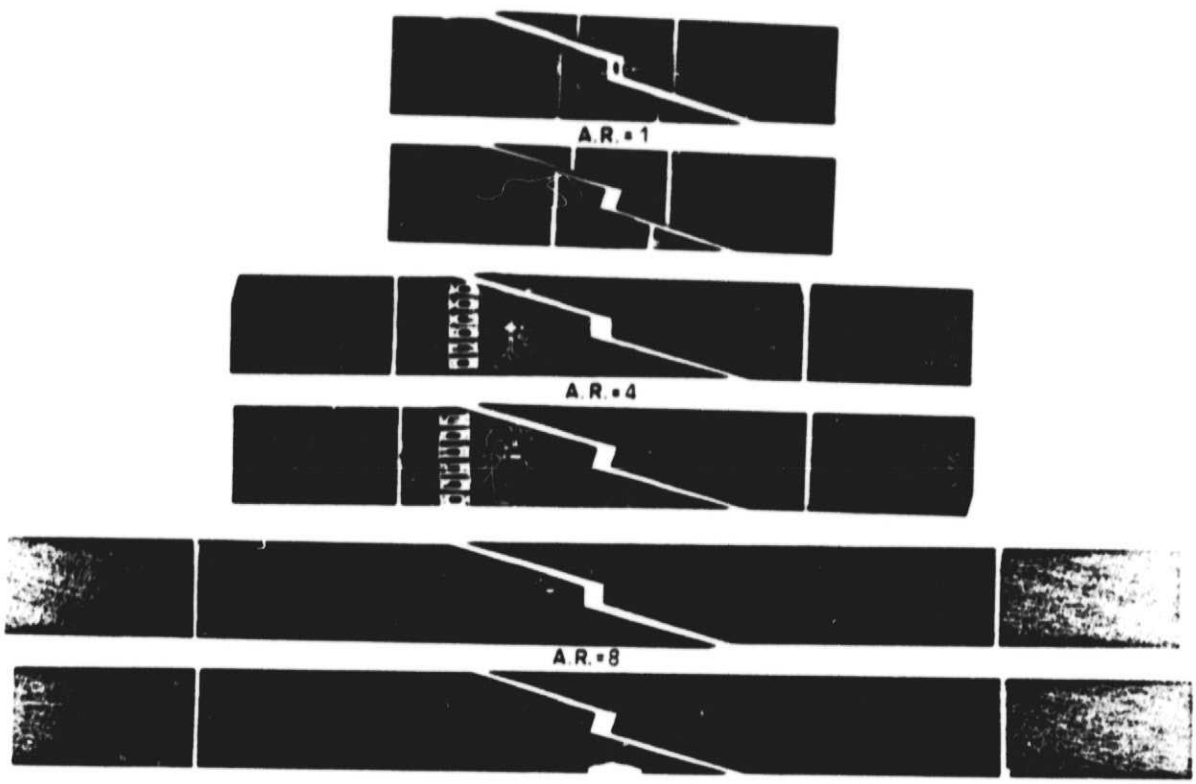


FIG. 5 FAILED CENTER CRACKED SPECIMENS

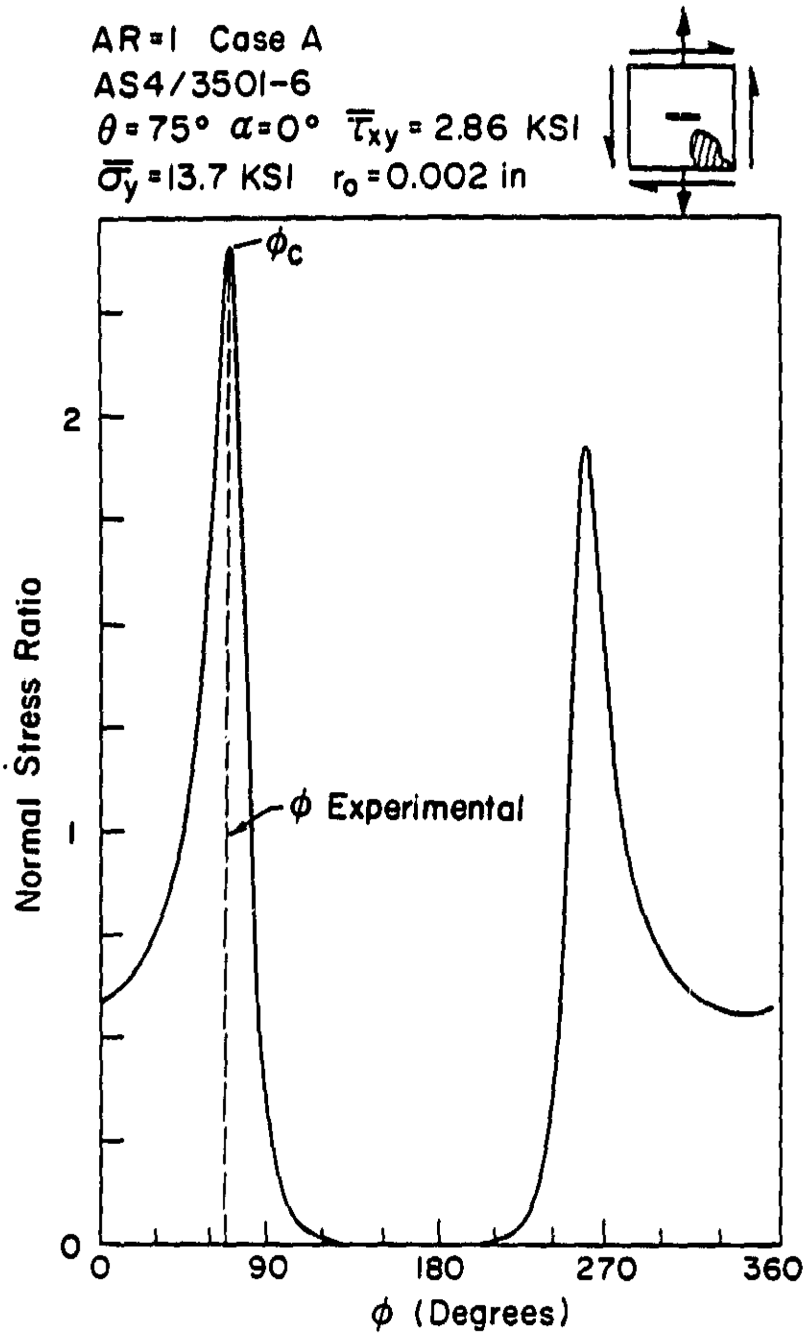


FIG. 6 NORMAL STRESS RATIO NEAR A CRACK TIP, AR=1, CASE A

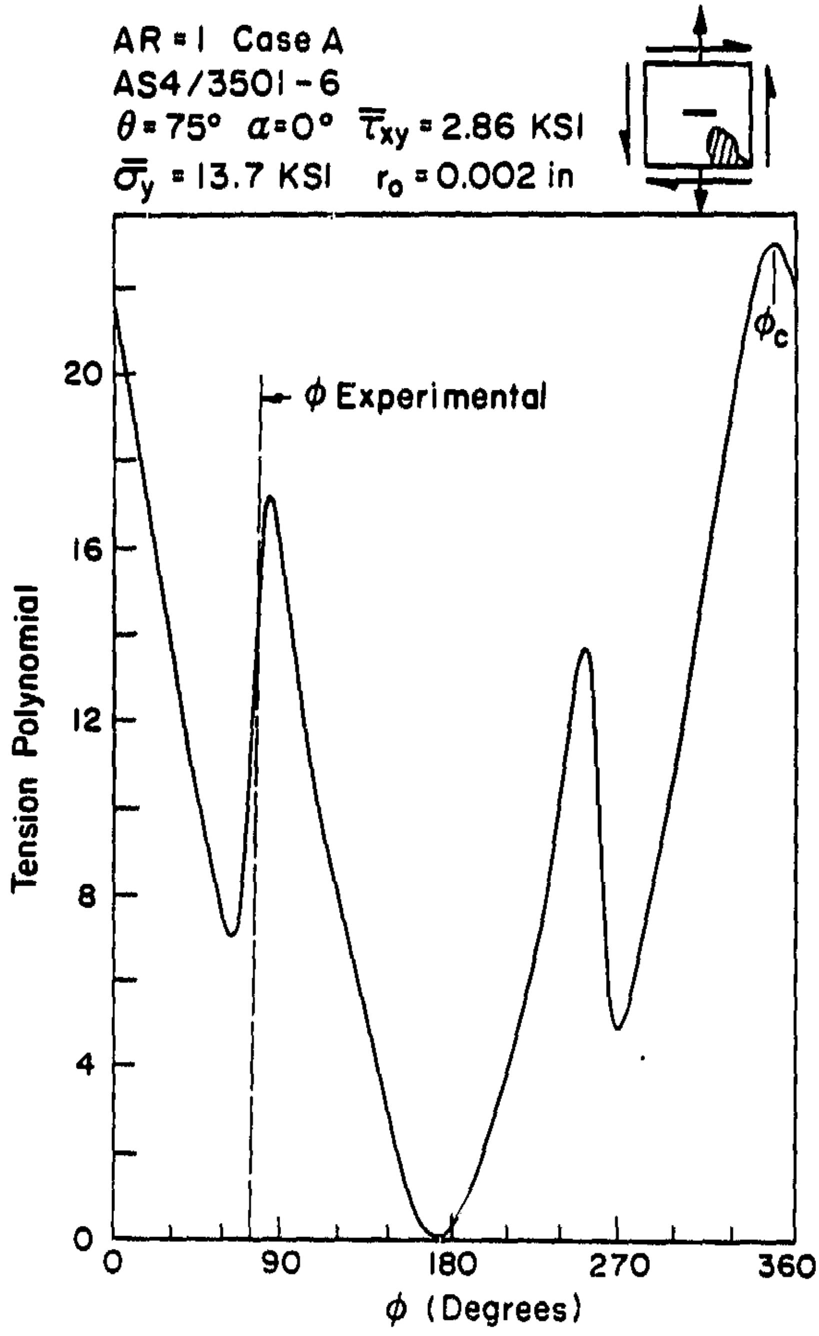


FIG. 7 TENSOR POLYNOMIAL NEAR A CRACK TIP, AR=1, CASE A

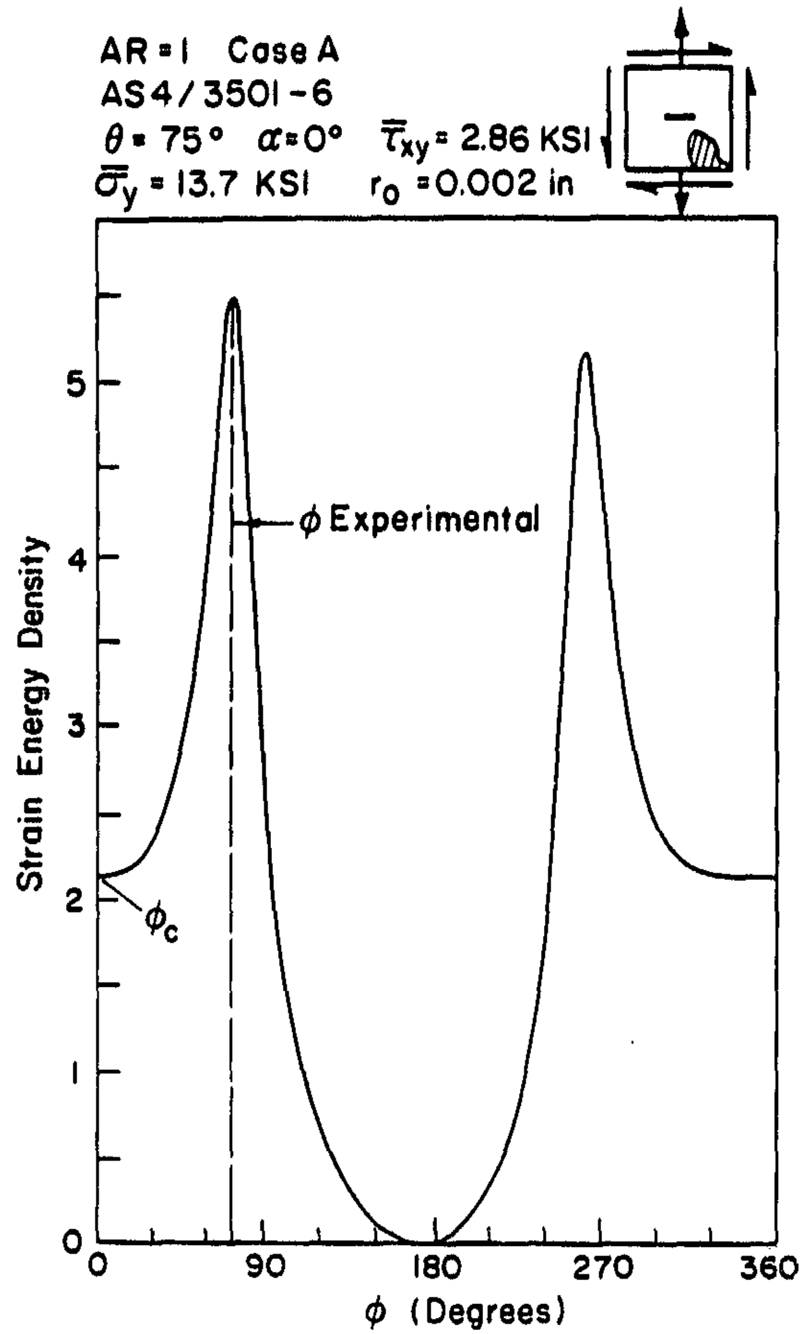


FIG. 8 STRAIN ENERGY DENSITY NEAR A CRACK TIP, AR=1, CASE A

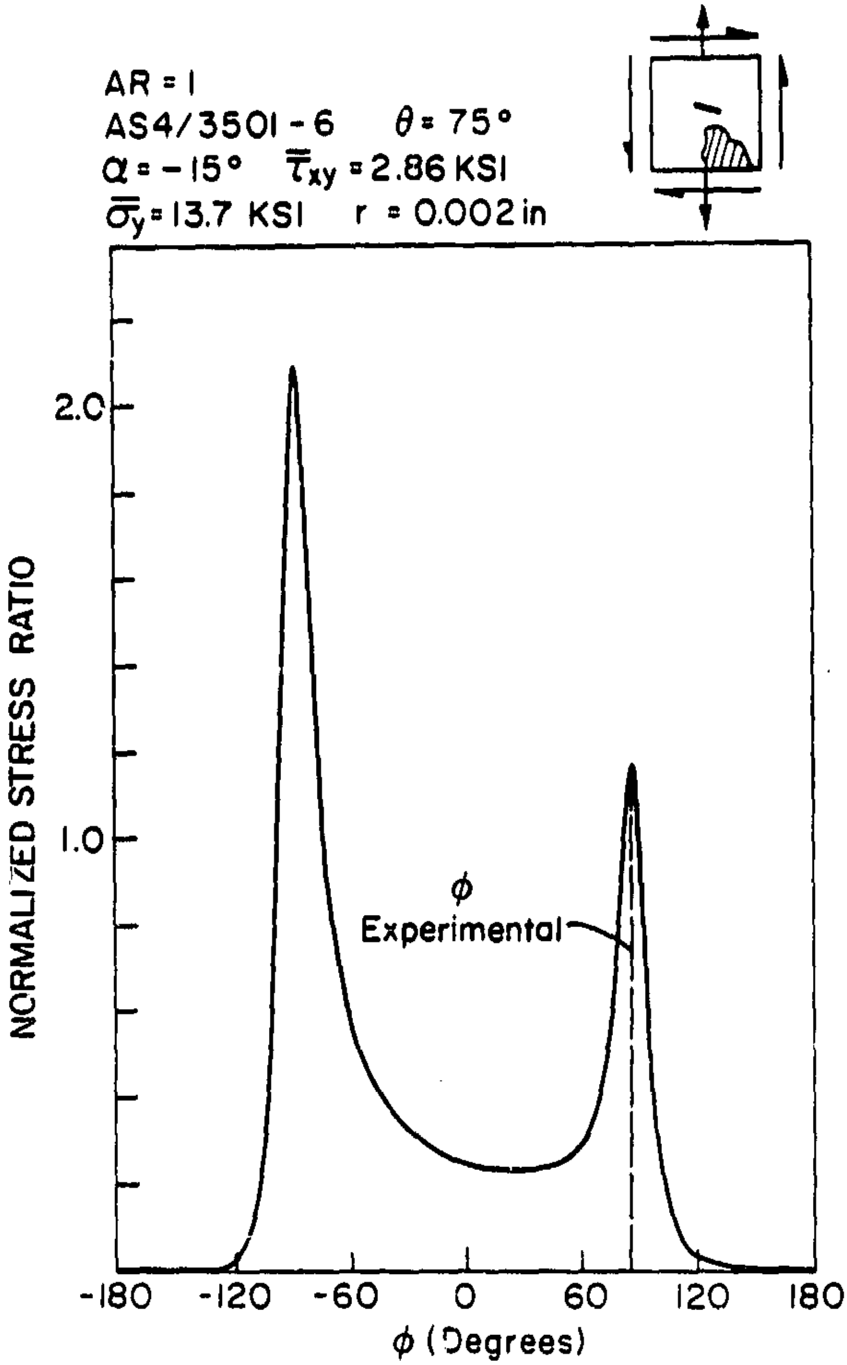


FIG. 9 NORMAL STRESS RATIO NEAR A CRACK TIP, AR=1, CASE B

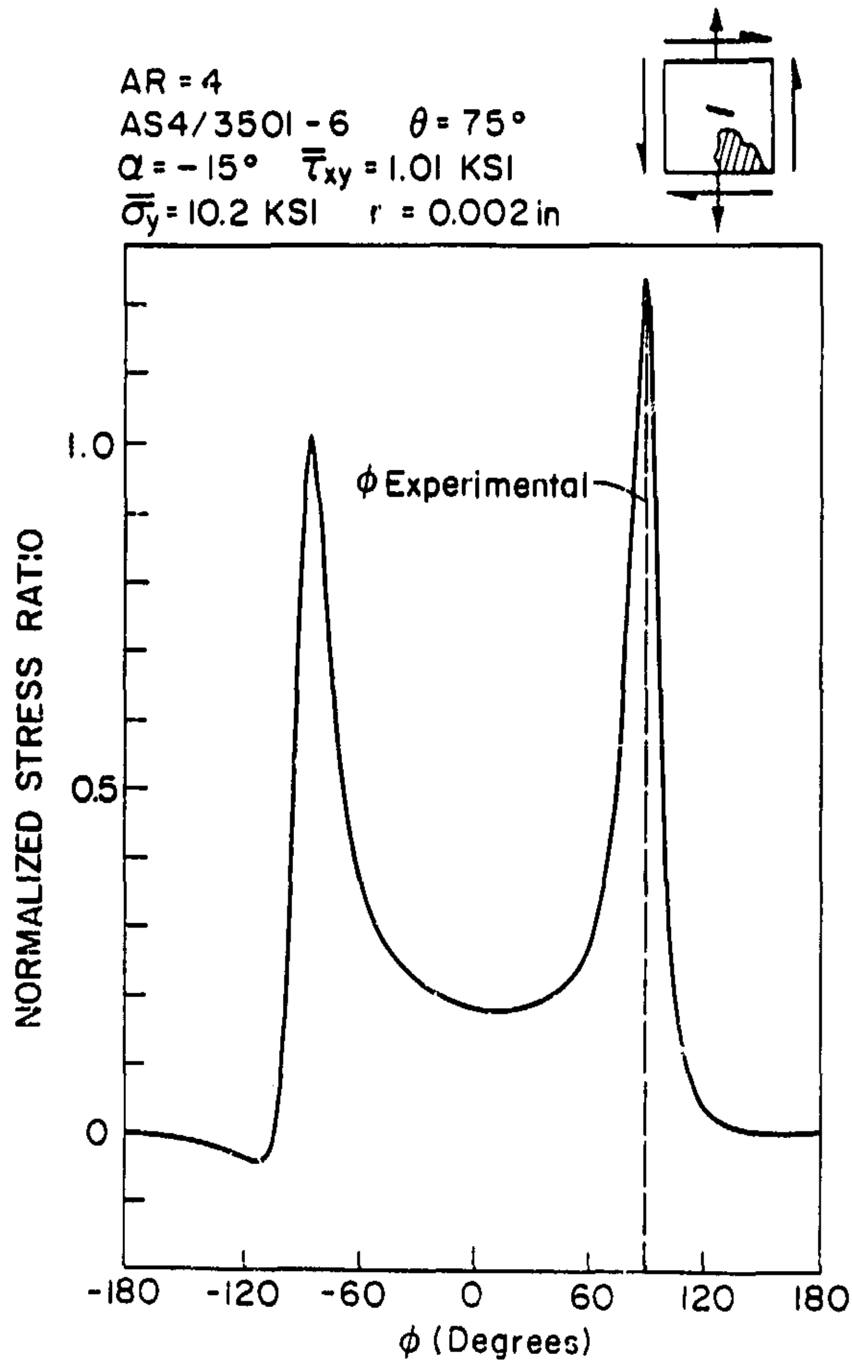


FIG. 10 NORMAL STRESS RATIO NEAR A CRACK TIP, AR=4, CASE B

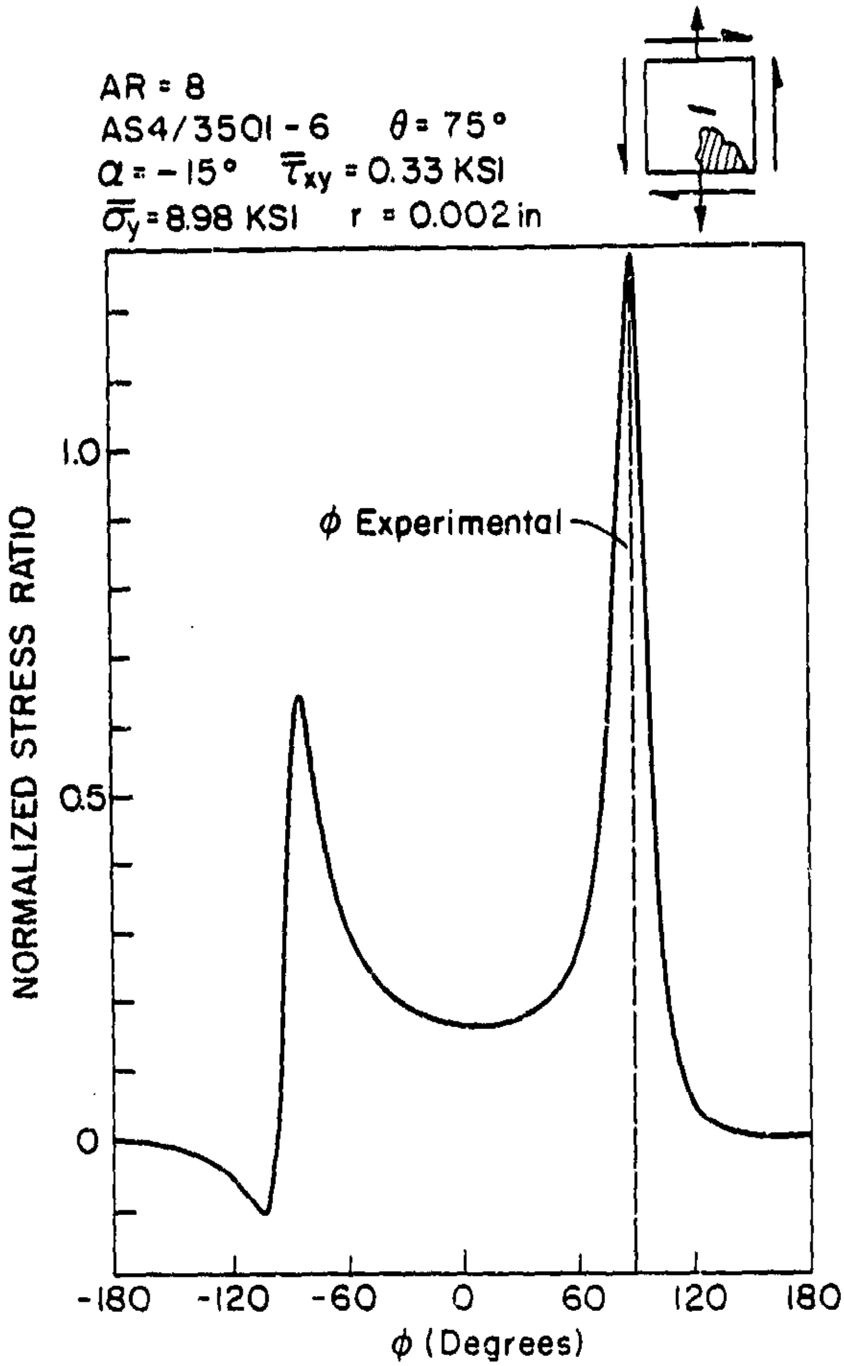


FIG. 11 NORMAL STRESS RATIO NEAR A CRACK TIP, AR=8, CASE B

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15. Supplementary Notes

16. Abstracts

An anisotropic elasticity crack tip stress analysis is implemented using three crack extension direction criteria (the normal stress ratio, the tensor polynominal and the strain energy density) to predict the direction of crack extension in unidirectional off-axis graphite-epoxy. The theoretical predictions of crack extension direction are then compared with experimental results for 15° off-axis tensile coupons with center cracks. Specimens of various aspect ratios and crack orientations are analyzed. It is shown that only the normal stress ratio criterion predicts the correct direction of crack growth.

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17b. Identifiers/Open-Ended Terms

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