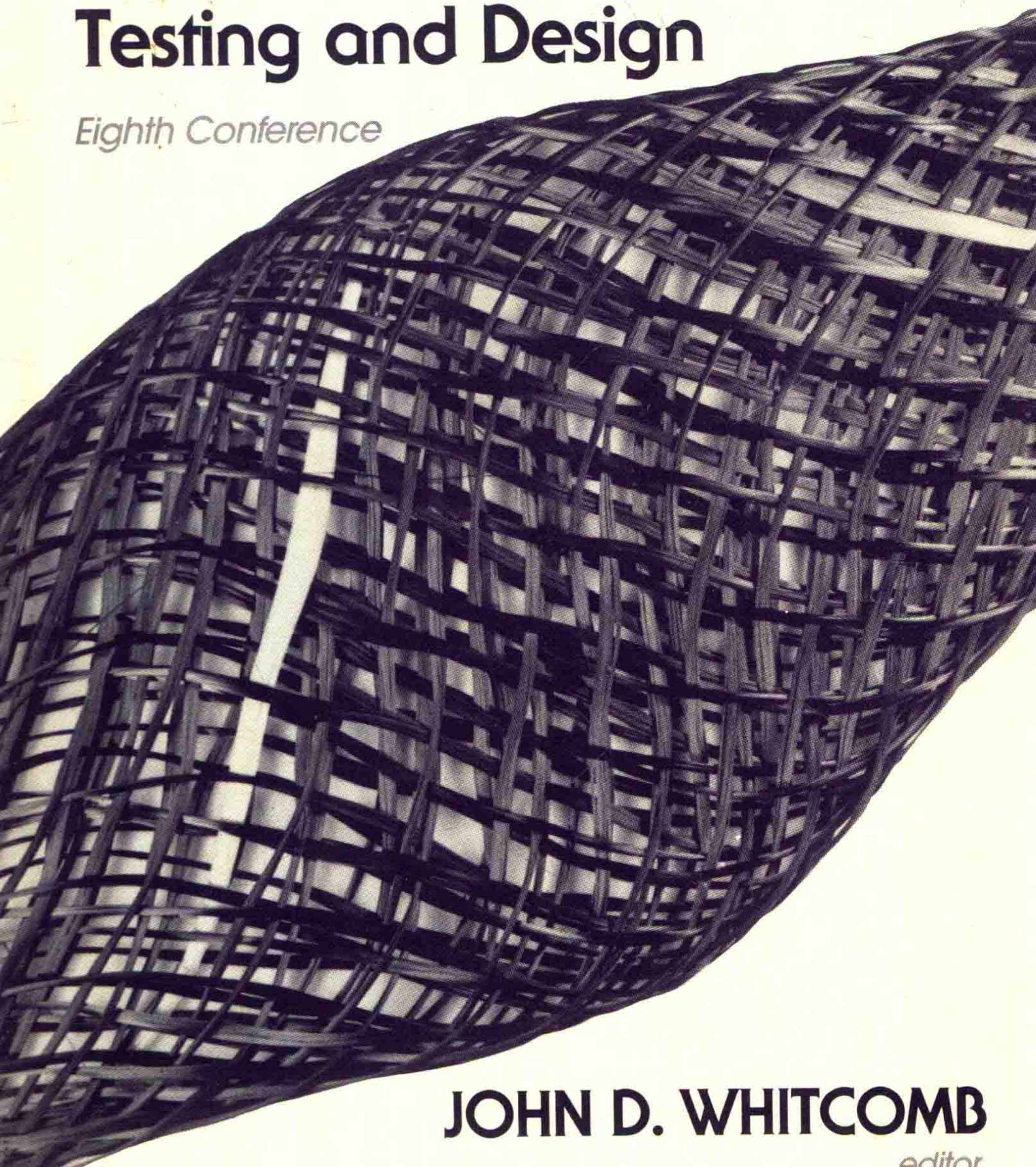
COMPOSITE MATERIALS
Testing and Design

Eighth Conference



JOHN D. WHITCOMB
editor

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John D. Whitcomb, editor

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Foreword

The Eighth Conference on Composite Materials: Testing and Design was held 29 April–1 May 1986 in Charleston, South Carolina. ASTM Committee D-30 on High Modulus Fibers and Their Composites sponsored the conference. John D. Whitcomb, NASA Langley Research Center, served as conference chairman and editor of this publication. Most of the papers presented are included in this volume, which complements the first, second, third, fourth, fifth, sixth, and seventh conference publications—*ASTM STP 460, ASTM STP 497, ASTM STP 546, ASTM STP 617, ASTM STP 674, ASTM STP 787, and ASTM STP 893, Composite Materials: Testing and Design.*

Contents

Overview

The Eighth ASTM Conference on Composite Materials Testing and Design was held 29 April–1 May 1986 in Charleston, South Carolina. Since the First Materials Testing and Design Conference in 1969, this series of conferences has maintained a tradition of documenting progress in a variety of areas of interest to the composites community. The particular areas considered in this latest conference were:

1. Analysis
2. Impact and Compression
3. Materials Characterization
4. Failure Mechanisms
5. Nondestructive Evaluation
6. Filament Wound and Woven Composites

Each of these six areas could have been easily expanded into a single topic conference. Obviously, this Conference did not pretend to present an exhaustive state-of-the-art review of the six areas covered. Instead, there was a sampling of the technology. The papers in the Analysis session ranged from a continuum mechanics treatment of distributed damage to automated design procedures. The Impact and Compression session included such diverse, but related topics as modified materials for improved impact resistance, delamination growth under compression, and postbuckling of a composite panel with a cut out. The session on Materials Characterization included papers on determining interlaminar fracture toughness and fiber properties. There was also a paper on shear fatigue testing. Analytical and experimental studies of delamination growth were presented in the Failure Mechanisms session. In-plane, transverse shear, and bending loads were considered. The session also included one paper on the failure of thick laminates with notches. The papers in the Nondestructive Evaluation session described the use of acoustic emission to detect damage. Two acoustic emission techniques were described. One involved monitoring acoustic waves initiated by damage events. The other technique involved injecting a stress wave into a damaged specimen and then monitoring the interaction of the stress wave with the damage. The final session was on Filament Wound and Woven Composites. The papers ranged from modeling of the incremental nature of filament winding to measuring the strength of woven composites with molded-in holes.

This volume includes most of the papers presented at the Eighth Composite Materials Testing and Design Conference. It should be of interest to anyone involved in composite research or design of advanced composite structures.

John D. Whitcomb

NASA Langley Research Center, Hampton, VA 23665-5225; symposium chairman and editor.

Analysis

Zafer Gürdal[1] *and Raphael T. Haftka*[1]

Automated Design of Composite Plates for Improved Damage Tolerance

REFERENCE: Gürdal, Z. and Haftka, R. T., **"Automated Design of Composite Plates for Improved Damage Tolerance,"** *Composite Materials: Testing and Design (Eighth Conference), ASTM STP 972*, J. D. Whitcomb, Ed., American Society for Testing and Materials, Philadelphia, 1988, pp. 5–22.

ABSTRACT: This paper is a first step toward automating the design for local damage tolerance of composite plates under compressive loadings simulating the local damage condition by a central through-the-thickness crack-like notch. Based on recent experimental investigations, the failure mode is assumed to be shear crippling, believed to be the result of kinking failure of the principal load-carrying fibers at a point of stress concentration in a laminate. The paper utilizes a micromechanical failure model for the fiber kink formation in the load-carrying layers accounting for the combined effects of compressive and shearing stresses around the notch.

A previously developed code for cracked plates under tensile loading is used for the design purpose. The design code combines a finite-element analysis program with an optimization program and an automated mesh generation interface program. Minimum weight designs are achieved for stiffened and unstiffened plates subject to a constraint that a crack will not grow by fiber kinking failures. Design variables are ply thicknesses in different regions of the plates. Stiffened plates with four stiffeners that are assumed to be perfectly bonded to the plate section are considered. For stiffened plates, minimum weight configurations are obtained where the crack is isolated in low stiffness plate regions.

KEY WORDS: composite plates, optimization, damage tolerance, cracks, compressive loading, fiber kinking

Laminated composite materials are recognized as an attractive replacement for metallic materials for aeronautical applications because of their high strength-to-weight and stiffness-to-weight ratios. If composite materials are to be used in aircraft structural components, they must be designed to satisfy several structural requirements. For example, fuselage and skin panels must be designed to include geometric discontinuities in the form of cutouts (cabin windows, doors, access holes, etc.), and provisions must be made for sufficient damage tolerance [*1,2*].

Damage tolerance is one of the most important performance constraints that must be considered in the design of modern aircraft. Airworthiness regulations requires that catastrophic structural failure due to damage must be avoided throughout the operational life of an airplane. One form of damage which is a serious threat for survivability of metallic aircraft structures is cracks. Cracks often initiate from material defects or existing holes and cutouts under cyclic loadings. Advanced fibrous composite materials, which are prime candidates for aircraft applications, exhibit good fatigue properties and have been shown to be resistant to fatigue crack growth. However, they present other problems that are not common to conventional materials. Experimental studies have shown that holes and cutouts can cause a severe reduction in tensile strength of composites. The lack of ductile behavior of composites at the points of high strain

[1]Assistant professor, Department of Engineering Science and Mechanics, and professor, Aerospace and Ocean Engineering Department, respectively, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061.

concentrations around cutouts results in localized failures. Unlike metals, composites have also been shown to be notch sensitive under compressive loadings. Manufacturing defects and accidental damage during maintenance are also problem areas that can degrade the performance of the structure. Low-velocity impacts such as tool drops or runway debris have been shown to result in serious damage in composites [*3,4*] and to degrade both compressive and tensile strength of a composite plate. In contrast, in homogeneous metallic plates, no strength reduction occur due to such effects.

A damage-tolerant, minimum-weight design approach was previously developed by the authors for composite plates under tensile loadings [*5*]. In Ref *5*, the local damage condition is assumed to be a central through-the-thickness crack, and failure is characterized by the propagation of the crack with fiber tension failures. That is, local damage tolerance implies structural integrity of the plate under the design loads in the presence of local failures such as cracks that may develop during the service life of the component. The present paper is concerned with design for local damage tolerance of composite plates under compressive loadings.

While the state of the art in predicting the strength and damage development of composites has progressed rapidly during the past decade, there are still some unresolved problems. One such problem is the analytical prediction of the compressive strength of reinforced composites and, even more so, the compressive strength of composite plates with damage. The number of possible modes of local failure leading to damage development is large, and they are usually micromechanically governed and complex [*6*]. The complexity of the problem also offers a variety of possible solutions. For example, damage tolerance concepts that can be pursued against impact damage are categorized under two main approaches [*7*]. The first approach, called the materials approach, is aimed at understanding the damage mechanism and improving the material response to achieve damage tolerance. For example, using graphite fabric material instead of unidirectional tape material improved the impact damage behavior through mechanical linking of the cross-plies and reduced delamination. Similarly, transverse reinforcement in the form of through-the-thickness stitching suppresses delaminations and causes the plate to fail in a higher-energy failure model. Impact-damage tolerance can also be improved by material modifications that result in a higher fracture energy matrix material.

The second approach, widely used for metallic plate designs and adapted in the present work, is to achieve efficient structural configurations which are capable of arresting or limiting the growth of local damage and which tend to redistribute the applied loads. Several structural configurations were considered in Ref *7*. One of the promising structural concepts is to isolate the portions of the plate to high and low axial stiffness regions (Fig. 1). Preliminary experimental investigations cited in Ref *7* indicated that the low-stiffness regions of the plates are tolerant to impact damages. It has also been shown that in some cases, low-stiffness regions are capable of arresting the damage propagation due to impact inflicted on the high-stiffness region. Simi-

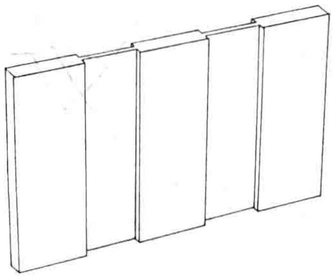


FIG. 1—*Damage-tolerant discrete stiffness design.*

lar geometries obtained by using buffer strips have also been shown to arrest and increase the residual strength of plates with cracks under tensile loadings [*8*].

The nature of most of the design approaches mentioned above is experimental. A more rational approach to design under compressive loads requires a simple and sound analysis technique that can be incorporated in an automated procedure. Following Ref *5*, the present study assumes the local damage condition to be a central through-the-thickness crack. Failure is characterized by the propagation of the crack with compressive fiber failures. This simplification makes the analysis of the plate with the damage condition analytically tractable. Furthermore, cracks are often used to estimate the residual strength of structures with other types of damage such as impact damage and delaminations.

The following section is devoted to discussion of failure criteria that can be used in an automated procedure for designing minimum-weight composite plates subject to a local damage constraint under compressive loadings. An analytical failure criterion which is formulated in Ref *9* and demonstrated for plates with a circular hole in Ref *10* is used for cracked plates under compression. The design procedure previously developed in Ref *5* is used in conjunction with the failure model of Ref *9* to demonstrate the design capabilities. Various examples are presented for compression-loaded unstiffened and stiffened plates for the purpose of gaining insight into the process of designing with damage-tolerance constraints.

Compressive Strength of Notched Composites

Seeking a failure criterion for the prediction of compressive strength of cracked plates presents difficulty due to the paucity of both experimental and analytical information. Early work on unnotched compressive strength of fiber-reinforced composite materials has considered microbuckling of stiff fibers in a relatively flexible matrix [*11,12*]. For the microbuckling criterion, the critical fiber stress is obtained to be a function of the matrix shear modulus and fiber volume fraction. Another approach, called macroscopic shear instability formulation [*13,14*], also relates the compressive strength to the shear modulus of the material. Experimental results, however, do not correlate well with the predictions of the two models for practical composites. Broad reviews of early analytical and experimental work on microbuckling of composites and further references can be obtained in Refs *15–18*.

Some of the failure criteria developed for strength prediction of plates with holes and notches under tensile loadings have been used for predicting compressive fracture strengths [*19,21*]. Rhodes et al. [*19*] and Haftka and Starnes [*21*] have used the point-stress criterion due to Whitney and Nuismer [*22*] for flat plates with holes. Nuismer [*20*] used the average-stress criterion. However, the point-stress (average-stress) criterion does not provide insight into the local material behavior and does not relate the local behavior to the failure process. Also, the stress state close to a notch or other types of cutouts is usually multidirectional. The point-stress and average-stress criteria in Refs *19–21*, like the previous microbuckling criteria [*11,12*], consider failure as a result of only the unidirectional compressive stresses and, therefore, may not be suitable for the failure of compressively loaded notched plates.

More recent investigations [*23–27*] suggest another type of compressive failure mechanism, called fiber kinking failure, which is characterized by a band of buckled, fractured fibers that has undergone both shearing and compressional deformations as seen in Fig. 2. Experimental investigations have shown that localized fiber rotations due to microbuckling are associated with the kinking process [*24*]. Fiber fracture strength is viewed as a primary property governing the kink formation [*24–27*]. Weaver [*25*] concluded that the kinking process is initiated by the transverse fracture of buckled fibers in the composite laminate. Kink formation is assumed to nucleate at a material defect point such as a region with poor fiber alignment [*23*] or at a notch that acts as a stress concentrator [*28*]. The propagation of kinking through the composite is preceded by a process of successive buckling and fracture of adjacent fibers to form the kink band. The nature of this process is essentially the same as the crack propagation from a notch

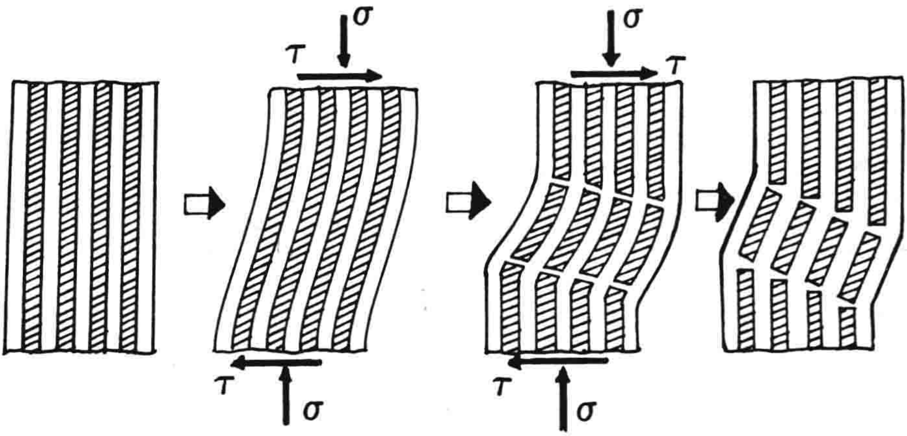


FIG. 2—*Kinking mode of compressive failure.*

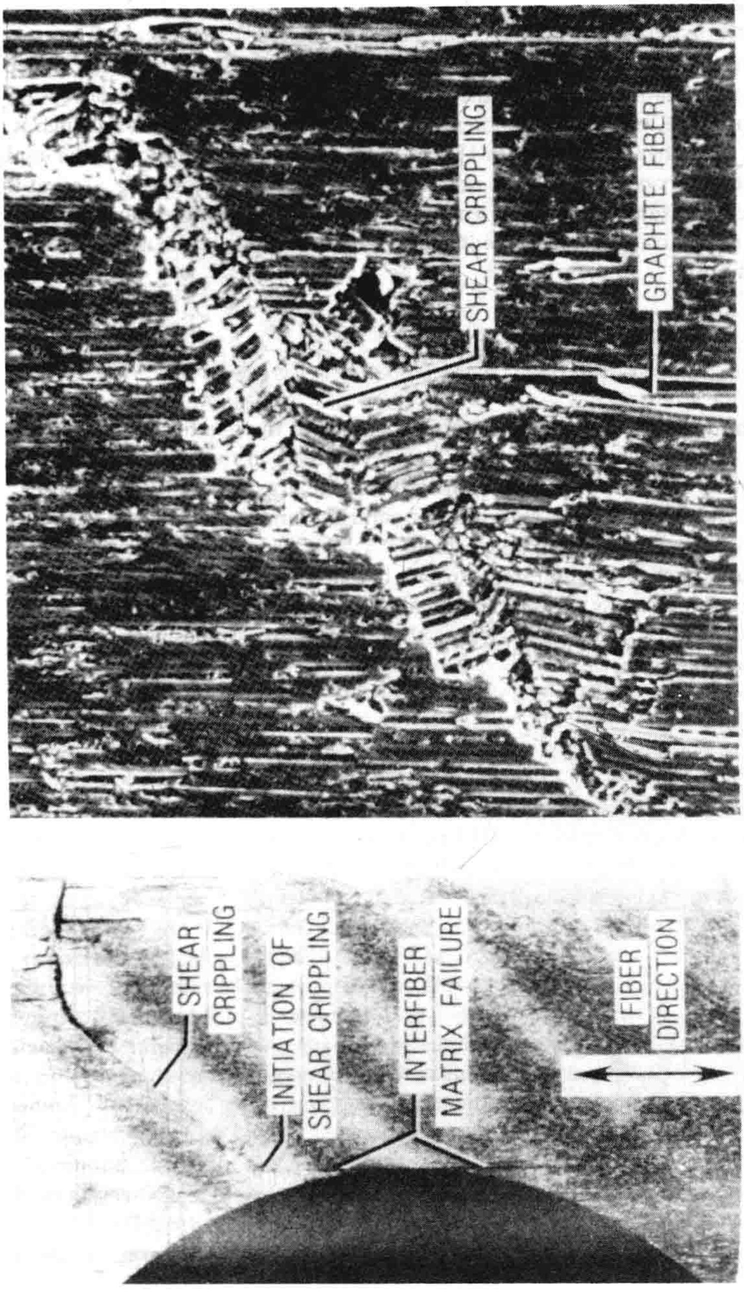
under tensile loading that causes fibers to break successively. Indeed, Chaplin [*28*] postulated that the prediction of compression failure of composites is a classical fracture-mechanics problem that requires the determination of the extent of the degradation in compressive load-carrying capacity due to a given defect.

Based on these observations it is possible that the strength failure of composite plates with a crack is governed by fiber kinking. Compressive fatigue tests by Berg and Salama [*29*] and static tests by Parry and Wronski [*30*] of notched specimens indicate that microbuckling in the form of kink band formation at the tip of the notches is the principal mechanism of compressive notch extension and failure. Also, the shear crippling failure observed by Rhodes et al. [*19*] in compressive specimens with a hole (Fig. 3) is believed to be initiated by local microbuckling of 0-deg plies followed by fiber kinking. In addition to high compressive stress concentrations, which may be the main cause of microbuckling of the fibers, significant in-plane shearing stress concentrations exist near the tips of a crack even for a quasi-isotropic plate under uniaxial loadings. Transverse shear deformations were shown analytically to have a detrimental effect on the compressive strength of composites [*31*]. Also, Shuart and Williams [*32*] suggested that failure of plates with central holes is affected by the presence of such shearing stresses around the edges of the hole.

A failure model originally developed in Ref *9* based on fiber breaking under the combination of normal and shear stresses around a crack tip is used in this paper. The key aspects of the model and its application to the present problem is discussed in the following paragraphs. Further details of the model are given in Refs *9* and *10*. An important issue in the adoption of a failure criterion for cracked plates is the singularity of the stress field at the crack tip. The model developed must be capable of accounting for this stress singularity. Two equivalent approaches are used in the literature. One approach, used in classical fracture mechanics, is to combine some of the terms that multiply the singularity term and assume that these have an upper value which is a material constant at failure. The second approach is to associate the failure with what is happening at a specified distance from the crack tip. Examples of this latter approach are the point-stress and average-stress criteria, and it is also used in the present work.

Fiber-Beam Model

The approach used here is to modify Rosen's microbuckling model [*11*] to account for the shearing stresses around the crack tip. The assumed mode of fiber deformation within a lamina



a) Typical failure in a laminate.

b) Enlarged view of shear crippling failure.

FIG. 3—*Shear crippling failure of specimen with a hole, from Ref* 19.

at a point around the crack tip is shown in Fig. 4. In contrast to the two deformation shapes considered in Rosen's microbuckling model, namely extension and shear modes, only a single mode similar to the shearing mode of deformation is considered in the present approach. The analytical formulation of the model follows the same set of assumptions that are used in Ref *11*. Individual fibers of length ℓ are considered as beams on elastic foundation. Shearing deformations of the fiber and the extensional deformations of the matrix are neglected. The cross section of the beams is rectangular with a thickness equal to the fiber thickness h and a unit depth. The thickness of the foundation is equal to the distance between fibers, $2c$ (Fig. 5).

An energy approach, including the potential energy due to the side force S_f which is applied at the free end of the beam as shown in Fig. 5, is used for the formulation of the equilibrium equation and boundary conditions. The side force S_f is the result of shearing stress at the point of interest which is assumed to be uniform along the length of the beam and modeled as two equal opposite concentrated forces at two ends. Stability analysis of the model produces a microbuckling load of

$$P_{f.C} = 2cG_m\left(1 + \frac{h}{2c}\right)^2 + \frac{\pi^2}{\ell^2}E_fI_f$$

The corresponding critical value of the stress is similar to the one for the shear mode of the microbuckling model given by Rosen [*11*]. The second term in the equation was neglected by Rosen by assuming the buckling wavelength ℓ to be much larger than the fiber width h. For the wave lengths considered in the present work, the contribution from the second term is comparable to the first one and, hence, will be retained.

The present approach is different from Rosen's in that significant lateral displacements of the fiber end are possible at loads substantially smaller than the microbuckling load even for small local shearing stresses [*9*]. Rosen's model, on the other hand, assumes perfectly straight fibers up to the microbuckling load.

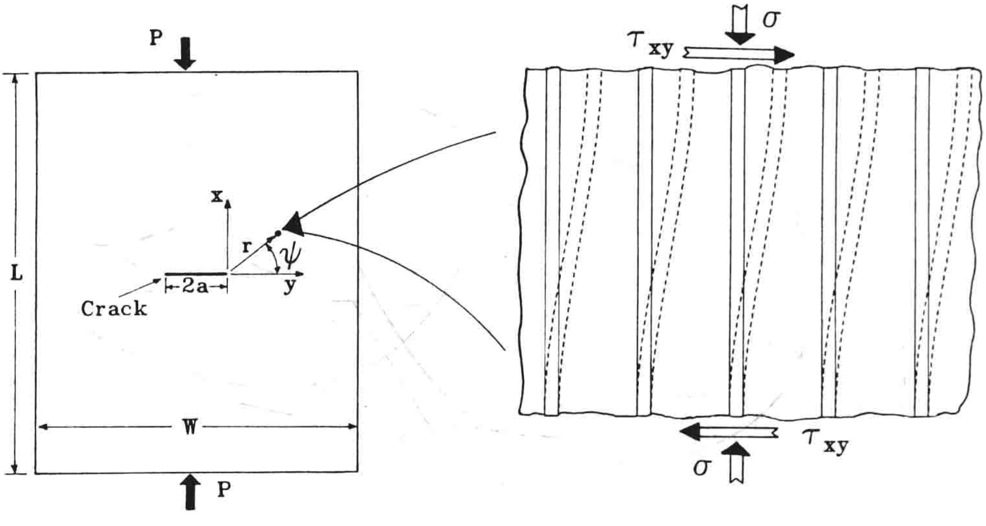


FIG. 4—*Deformation mode of the fibers at a point around the crack tip.*