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Failure of Composite Materials under Multi-axial Static and Dynamic Loading

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Abstract

To facilitate and accelerate the process of introducing and evaluating new materials, it is important to develop/establish comprehensive and effective methods and procedures of characterization, modeling and failure prediction of structural laminates based on the properties of the constituent materials and especially the basic building block of the composite, the single ply or lamina. The plethora of available composite failure theories coupled with a dearth of reliable experimental data provides no definitive answer as to the best general approach to failure prediction. A new failure theory developed at Northwestern University has been proven very successful in predicting failure of a composite lamina under multi-axial states of stress and varying strain rates in cases where the biggest discrepancies were observed in predictions by other theories.

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Keywords: Mechanical characterization; dynsamic testing; failure criteria; failure envelopes; strain rate effects

1. Introduction

Composite materials in service are exposed to severe loading and environmental conditions which pose new challenges to the designer. In many structural applications composite materials are exposed to high energy, high velocity dynamic loadings producing multi-axial dynamic states of stress. Under these conditions composites exhibit nonlinear and rate-dependent behavior. Therefore, it is important to characterize experimentally the nonlinear dynamic behavior of composites under multi-axial states of stress and describe their behavior by appropriate constitutive models and failure theories.

Failure of composite materials has been investigated extensively from the physical and phenomenological points of view, on microscopic and macroscopic scales. On the micromechanical scale, failure initiation and failure

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mechanisms vary widely with type of loading and are intimately related to the mechanical, physical and geometric properties of the constituent phases, i.e., matrix, reinforcement, interface/interphase and reinforcement architecture (e. g., fiber packing and lamination stacking sequence) Micromechanics can yield predictions of local failure at critical points. However, such predictions are only approximate as they do not relate easily to global failure of a lamina and failure progression to ultimate failure of a multi-directional laminate and composite structure.

On the macromechanical lamina scale, numerous failure theories have been proposed for analysis of composites and reviewed in the literature [1-12]. The plethora of theories is accompanied by a dearth of suitable and reliable experimental data.

A recent development is a new failure theory developed at Northwestern University (NU-Daniel theory) which has been proven very successful in predicting yielding and failure of a composite lamina under multi-axial states of stress and varying strain rates [13, 14]. This theory addresses a class of problems where other theories differ the most from each other. The challenge now is to adapt and extend this new theory to the analysis of progressive failure of multi-directional structural laminates under multi-axial static and dynamic loadings and offer easily implemented engineering design tools.

2. Characterization of Composite Lamina

Two unidirectional material systems were investigated, AS4/3501-6 and IM7/8552 carbon/epoxy composites. The first one displays quasi-brittle behavior, has been studied more extensively and there is a large body of data available for it. The second system has a higher strength carbon fiber and displays a higher degree of nonlinearity and ductility. Multi-axial experiments were performed by testing unidirectional carbon/epoxy specimens at various loading directions with respect to the principal fiber reinforcement. These experiments produced primarily stress states combining transverse normal and in-plane shear stresses.

Experiments were conducted at three strain rates. Quasi-static tests were conducted in a servohydraulic testing machine at a strain rate of 10^{-4} s^{-1}. Intermediate rate tests were also conducted in the servohydraulic machine at an average strain rate of 1 s^{-1}. High strain rate tests were conducted by means of a split Hopkinson (Kolsky) pressure bar at strain rates ranging from 180 to 400 s^{-1} using prismatic off-axis specimens (Fig. 1). Stress-strain curves were obtained for various off-axis loadings corresponding to different biaxial stress states at various strain rates (Fig.2). The ultimate values provide failure data for various biaxial states of stress.

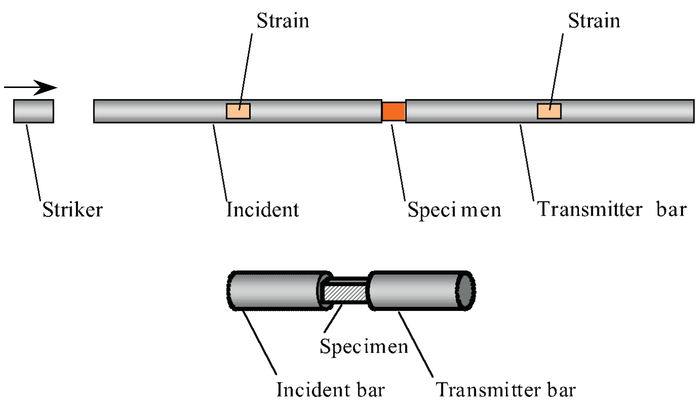

Fig. 1. High Rate Testing of Composite Specimens in Hopkinson Bar