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Yield and failure criteria for composite materials under static and dynamic loading

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ABSTRACT

To facilitate and accelerate the process of introducing, evaluating and adopting new material systems, it is important to develop/establish comprehensive and effective procedures of characterization, modeling and failure prediction of structural laminates based on the properties of the constituent materials, e. g., fibers, matrix, and the single ply or lamina. A new failure theory, the Northwestern (NU-Daniel) theory, has been proposed for predicting lamina yielding and failure under multi-axial states of stress including strain rate effects. It is primarily applicable to matrix-dominated interfiber/interlaminar failures. It is based on micromechanical failure mechanisms but is expressed in terms of easily measured macroscopic lamina stiffness and strength properties. It is presented in the form of a master failure envelope incorporating strain rate effects. The theory was further adapted and extended to the prediction of in situ first ply yielding and failure (FPY and FPF) and progressive failure of multi-directional laminates under static and dynamic loadings. The significance of this theory is that it allows for rapid screening of new composite materials without extensive testing and offers easily implemented design tools.

Contents

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. The process of fabrication, testing and modeling of these composites is costly and time consuming and impedes the introduction of new materials. To facilitate and accelerate the process of introducing and evaluating new composite materials, it is important to develop/establish comprehensive and effective methods and procedures of constitutive characterization and modeling of structural laminates based on the properties of the constituent materials, e. g., fibers, polymers and the basic building block of the composite structure, the single ply or lamina.

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 mechanisms vary widely with

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type of loading and are intimately related to the mechanical, physical and geometric properties of the constituent phases.

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 [10–13]. 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 and intermediate rate tests were conducted in a servohydraulic testing machine at strain rates of 10^{-4} s^{-1} and 1 s^{-1}, respectively. 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.

3. Strain-rate-dependent failure criteria

Most failure theories assume linear elastic behavior and are expressed in terms of macroscopic lamina stresses and strength parameters along the principal material axes. These theories in general can be divided into three categories: (1) *Limit or non-interactive theories*, such as the maximum stress and maximum strain theories, (2) *Fully interactive theories* such as the Tsai-Hill and the Tsai-Wu criteria, and (3) *Partially interactive or failure mode based theories*, such as the Hashin–Rotem, Puck, and NU-Daniel theories. The popular fully interactive Tsai-Wu criterion is expressed in the form of a failure polynomial involving all the stress components [1]. The Hashin–Rotem criteria are based on the premise that failure on any plane is only a function of the stress components acting on that plane. Furthermore, separate fiber and interfiber failure modes are considered. The Puck and Shűrmann theory is based on the concept of internal friction and a modified Coulomb–Mohr criterion [6]. Sun et al. proposed an empirical modification of the Hashin–Rotem criterion for matrix compressive failure to account for the apparent increase in shear strength due to the transverse compressive stress [2]. Predictions of the various theories, even for a simple unidirectional lamina, can differ a great deal from each other. Failure theories deviate the most from each other for states of stress involving transverse compression and interfiber shear.

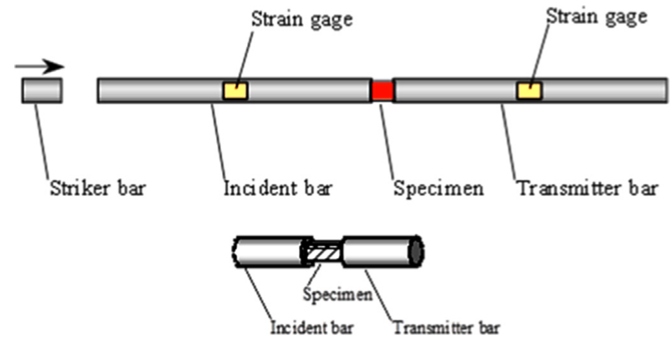

Fig. 1. High rate testing of composite specimens in Hopkinson bar.

The Northwestern (NU-Daniel) interfiber/interlaminar failure theory is based on micromechanical matrix failure mechanisms but is expressed in terms of easily measured macromechanical properties. Three dominant failure mechanisms or modes are identified in a composite element consisting of fibers and interfiber matrix, compression, shear and tension dominated modes [10]. In the compression dominated case, the composite element is loaded primarily in transverse compression with a non-dominant shear component. Failure is assumed to be governed by the maximum (critical) elastic shear strain in the interfiber matrix while the strain along the fiber is constrained to be zero. In the shear dominated case, the composite element is loaded primarily in in-plane shear with a non-dominant compression component. Failure is assumed to be governed by the maximum (critical) elastic tensile strain in the interfiber matrix while constraining the strain component along the fibers. In the tension dominated case, the composite element is loaded primarily in tension with a non-dominant shear component. Failure is assumed to be governed by the maximum (critical) elastic tensile strain in the interfiber matrix while constraining the strain component along the fibers. These failure modes are expressed by the following failure criteria:

Compression dominated failure:

$$\left(\frac{\sigma_2}{F_{2c}}\right)^2 + \alpha^2\left(\frac{\tau_6}{F_{2c}}\right)^2 = 1 \tag{1}$$

Shear dominated failure:

$$\left(\frac{\tau_6}{F_6}\right)^2 + \frac{2}{\alpha}\frac{\sigma_2}{F_6} = 1 \tag{2}$$

Tension dominated failure:

$$\frac{\sigma_2}{F_{2t}} + \left(\frac{\alpha}{2}\right)^2\left(\frac{\tau_6}{F_{2t}}\right)^2 = 1 \tag{3}$$

where σ_2 and τ_6 are the transverse (to the fibers) normal stress and in-plane shear stress; F_{2t}, F_{2c} and F_6 are the transverse normal tensile and compressive strengths and in-plane shear strength, respectively; $\alpha = E_2/G_{12}$ is the ratio of the transverse Young's to the in-plane shear modulus.

Fig. 3 shows failure envelopes for a carbon/epoxy composite (AS4/3501-6) under matrix dominated states of stress (transverse compression, transverse tension and in-plane shear). It is shown how the NU-Daniel theory is in very good agreement with experimental results. Similar results were obtained for IM7/8552 carbon/epoxy, which has a much more ductile matrix [12,13]. The agreement with experimental results is very good. This attests to the robustness of the NU-Daniel theory which is governed by ultimate elastic strains irrespective of the nonlinear elastic and plastic behavior.

Stress–strain curves to failure of 90-° and off-axis specimens of the carbon/epoxy composite were obtained as discussed before at