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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

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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.

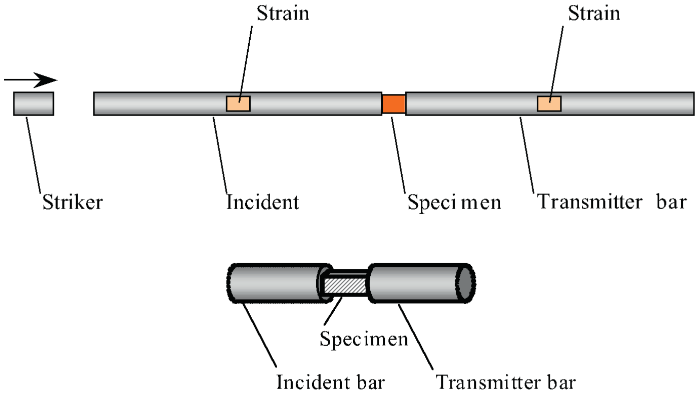

Fig. 1. High Rate Testing of Composite Specimens in Hopkinson Bar

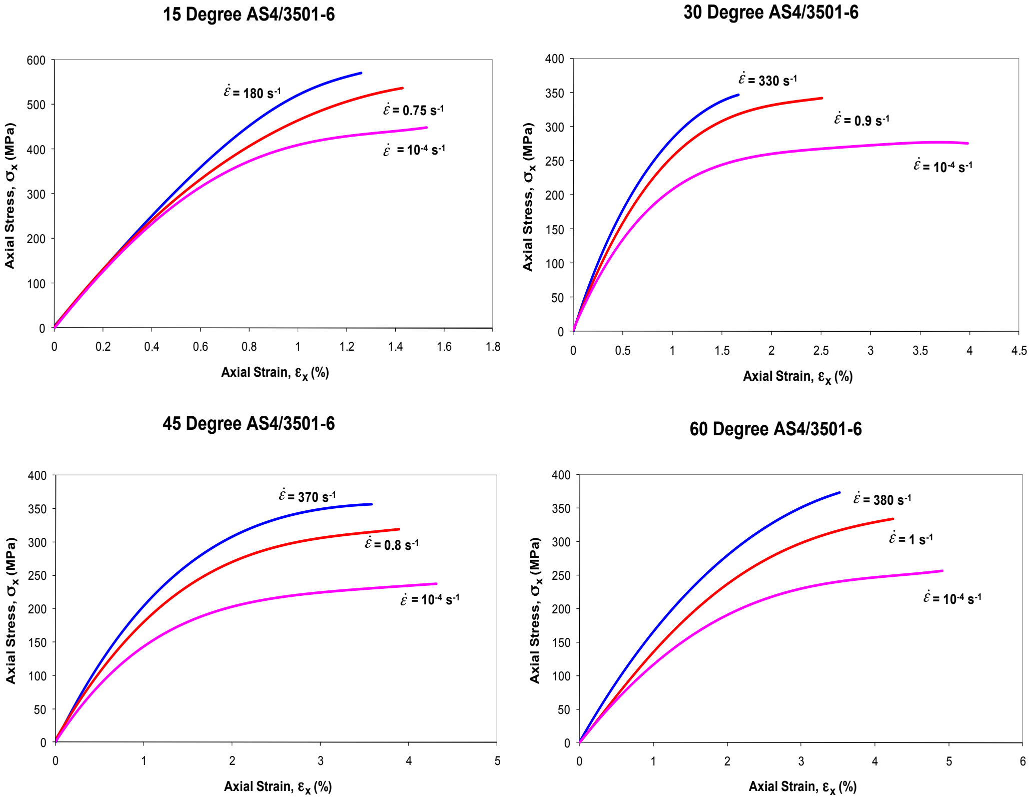

Fig.2. Stress-Strain Curves for Various States of Stress at Three Strain Rates

3. 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 Shùrmann theory is based on the concept of internal friction and a modified Coulomb-Mohr criterion [6]. Only stresses acting on the failure plane determine failure. The internal friction under transverse compression increases the apparent shear strength. The orientation of the failure plane under compression is measured by separate testing and is considered as a material constant. 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.

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.

Figure 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-deg and off-axis specimens of the carbon/epoxy composite were obtained discussed before at three different strain rates, quasi-static, intermediate and high (Fig. 2). The basic strength parameters at different strain rates were used in the failure criteria of Eqs. (1-3). Failure envelopes were plotted in Fig. 4 at three strain rates. The comparison between these failure envelopes predicted by the NU-Daniel theory and experimental results is very satisfactory.

The basic matrix dominated properties of the composite, including the initial transverse and in-plane shear moduli, E_2 and G_{12}, the transverse tensile and compressive strengths, F_{2t} and F_{2c}, and the in-plane shear strength, F_6, were obtained from the tests at different strain rates. The strengths, normalized by their quasi-static values, were found to vary linearly with the logarithm of strain rate (Fig. 5). It appears that, for the range of strain rates considered, the variation with strain rate of the matrix dominated strengths can be described as

$$F(\dot{\varepsilon}) = F(\dot{\varepsilon}_o)\left(m \log_{10}\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o} + 1\right) \tag{4}$$

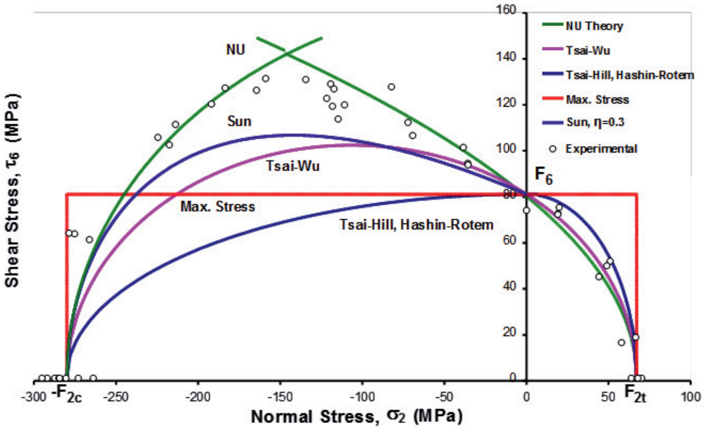

Fig. 3. Failure Envelopes and Experimental Results for AS4/3501-6 Unidirectional Carbon/Epoxy Composite under In-Plane Shear and Transverse Normal Loading [10].

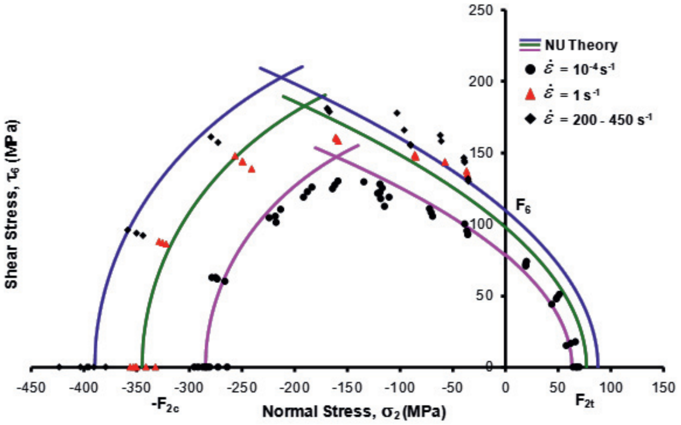

Fig. 4. Experimental Results and Failure Envelopes for AS4/3501-6 Carbon/Epoxy Composite at Three Strain Rates [12].

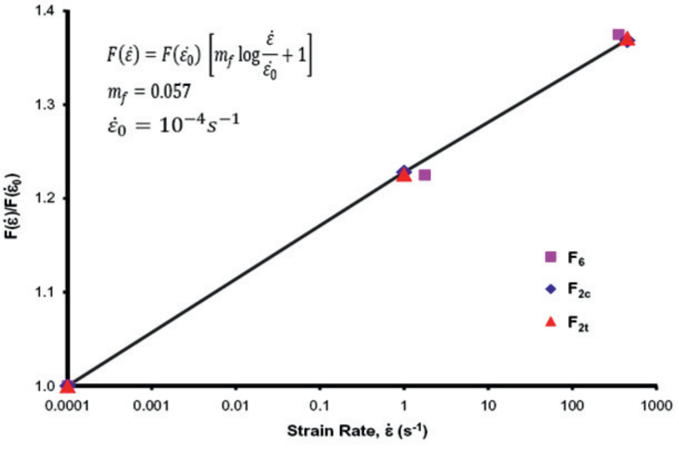

Fig. 5. Variation of Transverse and Shear Strengths with Strain Rate

where F = strength (F_{2t}, F_{2c}, F_6)
$m = 0.057$

$\dot{\varepsilon}_o$ = reference strain rate = ($\dot{\varepsilon}_o = 10^{-4}\,s^{-1}$ for quasi-static loading)

In view of the results of Fig. 5 and Eq. (4), the failure criteria of Eqs, (1-3) are recast in a normalized form incorporating the strain rate effects as follows [11]:

Compression dominated failure:

$$\left(\frac{\sigma_2^*}{F_{2c}}\right)^2 + \alpha^2\left(\frac{\tau_6^*}{F_{2c}}\right)^2 = 1 \tag{5}$$

Shear dominated failure:

$$\left(\frac{\tau_6^*}{F_6}\right)^2 + \frac{2}{\alpha}\frac{\sigma_2^*}{F_6} = 1 \tag{6}$$

Tension dominated failure:

$$\frac{\sigma_2^*}{F_{2t}} + \left(\frac{\alpha}{2}\right)^2\left(\frac{\tau_6^*}{F_{2t}}\right)^2 = 1 \tag{7}$$

where, $$\sigma_i^* = \sigma_i\left(m\,\log\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o} + 1\right)^{-1}, \qquad \sigma_i = \sigma_2, \tau_6 \tag{8}$$

and $\alpha = E_2 / G_{12}$ (independent of strain rate)

Based on the above generalized criteria, the failure envelopes of Fig. 4 collapse into the normalized master envelope shown in Fig. 6.

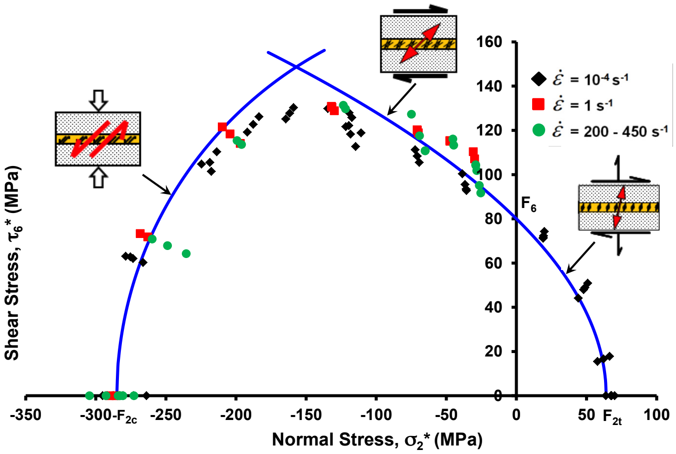

Fig. 6. Master Failure Envelope for AS4/3501-6 Carbon/Epoxy Composite for Strain Rates in the Range of 10^{-4} to 450 s^{-1} [11]

4. Multi-Directional Laminates

For a given loading condition, the first stage of failure in a multi-directional laminate is the so-called first-ply-failure (FPF), i.e., the loading at which the first ply or group of plies begins to fail [8]. Prediction and characterization of FPF is a challenging task and defines the capability of a given theory to predict ultimate failure. First-ply-failure is determined by conducting a stress analysis of the laminate under the given loading conditions, determining the state of stress in each individual layer, and assessing the strength of each layer by applying a selected failure criterion. This assumes that a layer or lamina within the laminate exhibits the same properties and behavior as an isolated unidirectional lamina. This is questionable, however, because the in-situ properties of an embedded layer may be different from those of an isolated layer. A layer within the laminate is constrained by adjacent plies and is under a state of fabrication residual stresses. Predictions of first-ply-failure can vary a great deal depending on the failure crirerion used.

Lamina failure within a laminate takes the form of dispersed damage (microcracking) rather than a major localized flaw or crack. This microcracking progresses up to a limiting state, referred to as the characteristic damage state (CDS). The latter is a guide for the ply discounting scheme in subsequent progressive failure analysis of the laminate. The onset of first-ply-failure, damage mode, and damage progression to the limiting damage state of the ply are very much dependent on the strain rate. The failure modes of the failed lamina or laminae are identified as matrix/interfiber or fiber failures. The stiffnesses of the damaged lamina must be discounted depending on the failure mode.

In this study, carbon/epoxy (IM7/8552) angle-ply laminates of $[\pm\theta]_{14s}$ layup, were tested under uniaxial compression at two different strain rates [14]. This produces various levels of biaxial stress within the lamina for different angles, θ. In this case first-ply-failure occurs simultaneously in both layers and manifests itself as a gradual stiffness degradation corresponding to increasing matrix microcracking in the layers up to a limiting or saturation level (CDS). The stress at this characteristic damage state, σ_{cds}, is clearly defined in angle-ply laminates as the point of minimum or terminal modulus. At this point the layer has reached maximum ply damage and, in an angle-ply laminate, it has reached the maximum stiffness reduction. For this reason, the characteristic damage state stress found experimentally for the various angle-ply laminates in compression was used to test the predictive capability of the NU-Daniel theory for laminates.

The characteristic damage state stress for the various laminates was obtained from the stress-strain curves of Fig. 14, by determining the laminate stress at which the terminal modulus is reached as shown in Fig. 15. Using the characteristic damage state stress, the residual stresses, and lamination theory, the lamina stresses at the CDS level are determined and compared with the maximum ply damage envelope obtained by the NU-Daniel theory for the quasi-static and higher strain rates (Fig. 7).

5. Summary and Conclusions

Composite materials were characterized under quasi-static and dynamic multi-axial states of stress. The failure theory developed at Northwestern University (NU-Daniel theory) has been proven very successful in predicting failure of a composite lamina under multi-axial states of stress and varying strain rates. This theory addresses a class of problems where other theories differ the most from each other. One significant result of this theory is that it affords the designer easily implemented design and failure analysis tools. Furthermore, it may facilitate and accelerate the process of screening, evaluating and adopting new candidate materials in the industry. The challenge now is to adapt and extend this 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.

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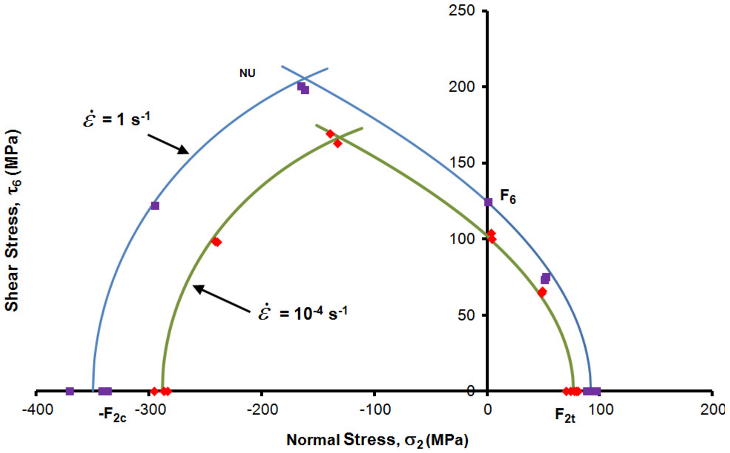

Fig. 7. Predictions by NU-Daniel Theory and Experimental Results for Characteristic Damage State ly of Angle-Ply Laminates at Two Strain Rates [14]

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