CHARACTERIZATION OF FAILURE BEHAVIOR OF ADVANCED COMPOSITES USING OFF-AXIS FLEXURAL STRENGTH TESTS

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ABSTRACT

This paper discusses failure behavior of graphite/epoxy and Kevlar/epoxy advanced composites. Flexural strengths of unidirectional and cross-ply composites were measured by taking off-axis flexural specimens at regular intervals. The specimens were tested in the four point flexural test. Results are compared with several failure criteria existing in the literature.

KEYWORDS

Advanced composites; failure; off-axis flexural strength; graphite-epoxy; Kevlar-epoxy.

INTRODUCTION

Composite materials are finding ever-increasing use in the structural applications. It is essential to establish a general failure criterion to act as a guide for the design engineer. An essential requirement of a failure criterion is that it should be general but it should be simple to use. There are two alternate approaches: a criterion based on the micromechanics of composites describing failure behavior at the micro level; another approach is to examine failure behavior of composites at the macro level. The first suggested approach is very general but it is cumbersome, and unwieldy to use in design calculations. In the second approach, a phenomenological criterion describing a three dimensional stress state is assumed. A convenient representation of such a criterion is in terms of polynominals. It is then essential to establish coefficients of the polynomial experimentally. The coefficients of a polynomial should be represented in terms of basic material properties, i.e., tensile and compressive strengths in the three directions or in terms of similar parameters.

Tsai (1965) has used a failure criterion, given by Hill (1948) for orthotropic materials, to describe failure behavior of unidirectional composites. This criterion assumes equal tensile and compressive strengths in a particular direction. A modification of Hill's (1948) criterion has been given by Hoffman (1967) and Tsai and Wu (1971) and several other criteria have been proposed. A comprehensive review is given by Owen and Griffiths (1978) where it has been reported that differences in these failure criteria are small and subtle. However, evaluation of polynomial constants is very cumbersome and tedius. Hashin (1980) has recognized this problem recently and has proposed four piece-wise failure criteria to describe four distinct failure modes. The four distinct failure modes - tensile and compressive fiber and matrix modes - are modeled separately.

Flexural strengths of unidirectional graphite/epoxy and Kevlar/epoxy composites have been measured as a function of orientation angle starting from the fiber direction. The measured off-axis flexural strengths are compared with the predicted values calculated using maximum stress theory and the failure criteria suggested by Hashin (1980) and Tsai-Hill (Tsai, 1965, 1968; Hill, 1948). Experimental results could not be compared with Tsai-Wu (1971) failure criterion due to difficulty encountered in the evaluation of an interaction term used in the failure criterion (Hashin, 1980). Pipes and Cole (1973) have shown in their failure study of boron/epoxy composites that the influence of an interaction term on predicted strength values is, only, of second order.

In this study, off-axis flexural strength tests are used because of simplicity in testing procedure; and unlike tension tests, flexural strength tests do not possess end constraints. However, lift-off of the ends of unidirectional composite specimen occurs in the three point flexural test (Halpin and Pagano, 1969; Whitney and Dauksys, 1970). The end lift-off phenomenon gives erroneous values of mechanical properties obtained using flexural test. However, Agarwal and Broutman (1980) have suggested that lift-off of ends is suppressed if a four point flexural test is used in the measurement of off-axis flexural properties. Also, Ishai and Lavengood (1969) have shown experimentally that tensile and flexural off-axis properties of glass-epoxy unidirectional composites are identical if slender specimens having length-to-width ratio greater than six and span-to-depth ratio greater than 20 are used (Hoggatt, 1969).

THEORY

In this section three failure criteria, maximum stress theory (Jones, 1975), Tsai-Hill (Tsai, 1965, 1968; Hill, 1948; Jones, 1975) theory and Hashin's (1980) piece-wise failure criterion, will be discussed to describe failure behavior of unidirectional composites.

Maximum Stress Theory

This theory predicts that failure will occur as soon as a principal stress in a material exceeds the material strength in that direction. This theory is two dimensional, and it can be applied to analyze effects of two dimensional stresses.

If the tensile strengths along x and y are represented by X and Y, respectively, S is shear strength in the x-y plane. If a specimen shown in Fig. 1 is machined at an angle, θ, from the fiber direction of a unidirectional composite laminate and the specimen is loaded in plane tension or flexure, the stress is denoted by σ_θ.

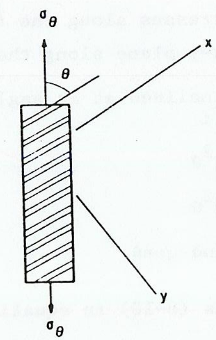

Fig. 1. Off-axis specimen and coordinate system.

Using orthogonal transformation, relationships between external stress and the material constants are as follows:

$$X = \sigma_\theta \cos^2\theta \tag{1}$$

$$Y = \sigma_\theta \sin^2\theta \tag{2}$$

$$S = \sigma_\theta \sin\theta \cos\theta \tag{3}$$

Thus, the above equations relate tensile strength of a unidirectional composite at an angle, θ, in terms of the strengths of the material in the fiber and transverse to fiber directions and strengths at an angle, θ, are given:

$$\sigma_\theta = X/\cos^2\theta \tag{4}$$

$$\sigma_\theta = Y/\sin^2\theta \tag{5}$$

$$\sigma_\theta = S/\sin\theta \cos\theta \tag{6}$$

As soon as one of the above conditions is met, failure occurs. It can be seen that the above equations are uncoupled, i.e., there is no interaction between the stresses.

Tsai-Hill Theory

Tsai (1968) used Hill's (1948) criterion, suggested for anisotropic metals, to describe failure behavior of composite materials. For plane stress in the x-y plane, Hill's (1948) criterion reduces to:

$$\left(\frac{\sigma_x}{X}\right)^2 + \left(\frac{\sigma_y}{Y}\right)^2 - \frac{\sigma_x\sigma_y}{X^2} + \left(\frac{\tau_{x,y}}{S}\right)^2 = 1 \tag{7}$$

where:

σ_x and σ_y are stresses along the fiber and transverse to it and $\tau_{x,y}$ is shear stress in the x-y plane along the x axis.

Stresses on a plane inclined at an angle, θ, to the x axis are given as follows (Jones, 1975):

$$\sigma_x = \sigma_\theta \cos^2\theta \tag{8}$$

$$\sigma_y = \sigma_\theta \sin^2\theta \tag{9}$$

$$\tau_{xy} = \sigma_\theta \sin\theta \cos\theta \tag{10}$$

Substituting equations (8-10) in equation (7),

$$\frac{\cos^4\theta}{X^2} + \left(\frac{1}{S^2} - \frac{1}{X^2}\right) \cos^2\theta \sin^2\theta + \frac{\sin^4\theta}{Y^2} = \frac{1}{\sigma_\theta^{\,2}} \tag{11}$$

By knowing material constants, X, Y and S, the strength, σ_θ, of a unidirectional composite at an angle, θ, from the fiber direction can be calculated from equation (11).

Hashin's Piece-wise Failure Criterion

For the tensile failure mode, Hashin's criteria are given as follows:

Tensile fiber failure mode:

$$\sigma_{f,\theta}^{\;2} = \frac{1}{\cos^2\theta\left[\frac{\cos^2\theta}{X^2} + \frac{\sin^2\theta}{S^2}\right]} \tag{12}$$

Tensile matrix failure mode:

$$\sigma_{m,\theta}^{\;2} = \frac{1}{\sin^2\left[\frac{\sin^2}{Y^2} + \frac{\cos^2}{S^2}\right]} \tag{13}$$

where:

σ_f,θ and σ_m,θ are failure strengths of a composite specimen machined at an angle, θ, from the fiber direction and failed in either fiber or matrix mode, respectively. X and Y are tensile strengths in the fiber (x) and transverse to fiber (y) directions, respectively. S is the shear strength of a composite in the x-y plane.

It is interesting to note that equations (12) and (13) can be approximated from equation (11) by imposing the following restrictions:

When θ is small, $\sin^4\theta$ is very small, and it can be neglected. This condition approximates equation (12) when θ is large, $\cos^4\theta$ is small, and it can be neglected. This condition gives equation (13). Figure 2 compares Hashin's (1980) piece-wise failure theory and Hill's (1948) quadratic failure criterion for boron/epoxy and glass/epoxy unidirectional composites. The normalized

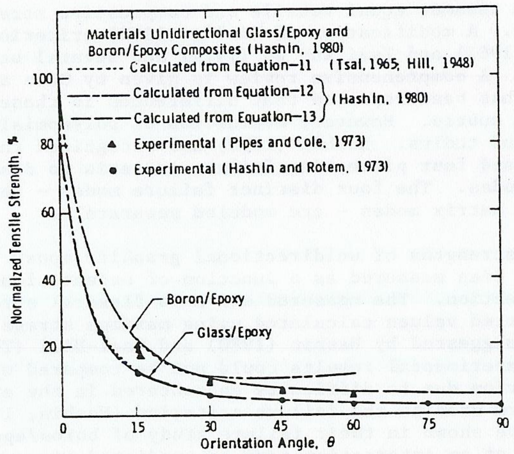

Fig. 2. Comparison of failure theories of Tsai-Hill and Hashin.

tensile off-axis strengths are calculated according to the failure theories of Hill (1948) and Hashin (1980) using published experimental information (Pipes and Cole, 1973; Hashin and Ratem, 1973). It can be seen that the results obtained from the two theories overlap. Hashin's (1980) theory under plane stress conditions is a special case of Hill's (1948) generalized criterion. Similar conclusions can be drawn when predicting failure behavior of unidirectional composites under plane stress compressive loads.

EXPERIMENTAL

Graphite/epoxy (Hercules AS4/3501-6) and Kevlar/epoxy (Fiberite HY-E1734A) unidirectional composite prepregs were received. Prepregs were cut to 12" x 12" size and the plies were stacked unidirectionally in a steel mold to give a 12" x 12" x 0.2" thick unidirectional laminate. Laminates were cured at 350°F in a hydraulic press following the cure cycle (approximately 50 psi pressure and 350°F for 1 hour) recommended by the prepreg manufacturers. It was observed earlier that the unidirectional Kevlar/epoxy laminate is very weak in the transverse direction and testing of the laminate in the transverse direction is very difficult. Thus, it was decided to stack one 90° ply each on top and bottom of both the Kevlar/epoxy and graphite/epoxy laminate, respectively, to overcome this problem. These laminates henceforth, will be referred to as cross-ply laminates.

Specimens (5" x 1/2" x 0.2") were machined from unidirectional and cross-ply laminates at a desired angular orientation. Fifteen degree interval for cross-ply laminates and 30° interval for unidirectional laminates was maintained. Three specimens were tested for each orientation angle in four point flexural test (ASTM D790-71). Average values of flexural strengths are plotted in figures of the following section.

RESULTS AND DISCUSSION

Figures 3 and 4 give off-axis normalized values of flexural strengths for unidirectional graphite/epoxy and Kevlar/epoxy composite laminates, respectively, as a function of off-axis angle or orientation angle, θ, from the fiber direction. Theoretically calculated values using maximum stress theory, Tsai-Hill (Tsai, 1965, 1968; Hill, 1948; Jones, 1975) and Hashin's (1980) piece-wise theories are superimposed. Based upon rather limited experimental information, it can be seen from Figs. 3 and 4 that the calculated values using Equations 8 and 9 predict significantly higher values than the measured values except for higher angles (>60°) in Fig. 3. The predicted values, assuming shear failure mode (Equation 10), for Kevlar/epoxy composite (Fig. 4) are in agreement with the experimental values. However, this is not true for graphite/epoxy composite (Fig. 3) where predicted values (Equation 10) are higher than the experimental values. Thus, in general, maximum stress theory predicts higher strength values for unidirectional graphite/epoxy and Kevlar/epoxy composites.

Comparison of plots in Figs. 3 and 4, obtained from Equations 11-13, shows that the Tsai-Hill (Tsai, 1965, 1968; Hill, 1948; Jones, 1975) and Hashin (1980) piece wise failure theories are identical in the different domains. For smaller off-axis angle, θ, values predicted by Equations 11 and 12 are close together. For higher off-axis angle, θ, Equations 11 and 13 give similar values. The Tsai-Hill (Tsai, 1965, 1968; Hill, 1948; Jones, 1975) theory, unlike the maximum stress theory, and the Hashin's (1980) piece-wise theory, is continuous and does not possess cusps. The Tsai-Hill (Tsai, 1965,

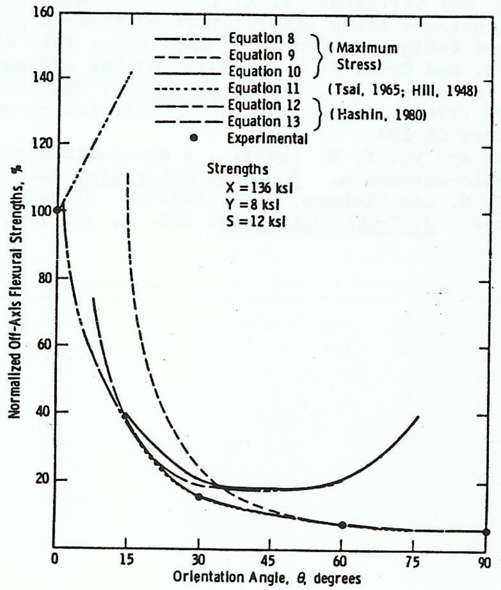

Fig. 3. Normalized off-axis flexural strength versus orientation angle for unidirectional graphite/epoxy composite.

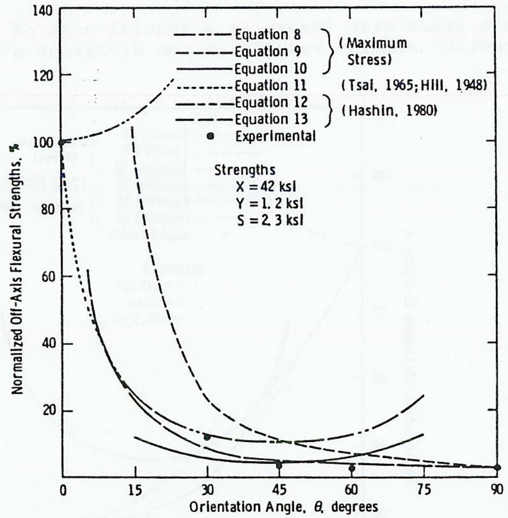

Fig. 4. Normalized off-axis flexural strengths versus orientation angle for unidirectional Kevlar/epoxy composite.

1968; Hill, 1948; Jones, 1975) theory plotted in Figs. 3 and 4 shows close agreement between calculated and experimental off-axis flexural strengths of unidirectional graphite/epoxy and Kevlar/epoxy composites.

Normalized flexural strengths for cross-ply $[(0°)_{20}90°]_S$ graphite/epoxy and Kevlar/epoxy laminates have been plotted in Figs. 5 and 6, respectively, as a function of off-axis angle. The agreement between calculated values using Tsai-Hill (Tsai, 1965, 1968; Hill, 1948; Jones, 1975) theory or Hashin's (1980) piece-wise theory and the off-axis measured values of strengths is very good for graphite/epoxy cross-ply laminates. Discrepancy between the predicted and calculated values is significant for 30° off-axis angle; reasons for this discrepancy are not clear. However, for Kevlar/epoxy cross-ply laminates, the experimental off-axis flexural strength values are lower than the predicted values using three different theories. This discrepancy can be ascribed to the shear failure mode of the cross-ply, i.e., the failure did not occur due to the last ply failure in tension or compression; instead it was observed that the failure was due to shearing of the last ply (90°) from contiguous 0° lamina. Also, it has been reported (Deteresa and co-workers, 1984) that compressive strength of Kevlar fiber is significantly lower than its tensile strength.

CONCLUSIONS

1. The maximum stress theory, in general, predicts higher off-axis flexural strength values for unidirectional and cross-ply graphite/epoxy and Kevlar/epoxy laminates than the experimental values.

2. Using the Tsai-Hill theory, agreement between calculated off-axis strength values for unidirectional graphite/epoxy, Kevlar/epoxy and cross-ply graphite/epoxy laminate and the experimental results is good.

3. Hashin's piece-wise theory is a special case of the Tsai-Hill theory and predicts similar results in the different off-axis directions.

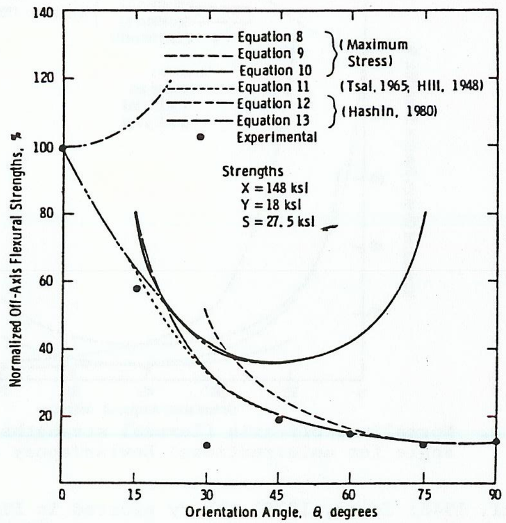

Fig. 5. Off-axis flexural strength versus orientation angle of graphite/epoxy cross-ply $[(0°)_{20}90°]_S$ laminates.

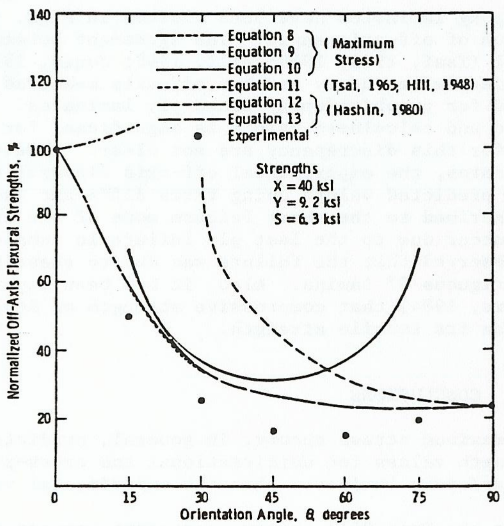

Fig. 6. Normalized off-axis flexural strength versus orientation angle of Kevlar/epoxy $[(0°)_{20}90°]_S$ laminates.

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