MECHANICAL AND FAILURE CHARACTERIZATION OF TEXTILE COMPOSITES

Isaac M. Daniel, Jyi-Jiin Luo, Patrick M. Schubel
[Isaac M. Daniel]: imdaniel@northwestern.edu
Northwestern University

Keywords: *Textile composites;test methods;failure theories.*

Abstract

Test methods were developed/adapted for complete mechanical characterization of textile composites in three dimensions [1-7]. Through-thickness tensile and compressive properties were obtained by testing short waisted blocks bonded to metal end blocks. The through-thickness shear behavior was determined using a short beam with V-notches under shear. Multiaxial states of stress were investigated by testing in-plane and through-thickness specimens under off-axis tension and compression at various orientations with the in-plane directions. Three types of failure criteria in three dimensions were investigated, limit criteria (maximum stress), fully interactive criteria (Tsai-Hill, Tsai-Wu)), and failure mode based and partially interactive criteria (Hashin-Rotem, Sun, NU). The latter, a new interlaminar failure theory developed by the authors [8,9], was found to be in excellent agreement with experimental results in the through-thickness direction, especially those involving interlaminar shear and compression.

1 Introduction

Fabric reinforced or textile composites are increasingly used in aerospace, automotive, naval and other applications. They are convenient material forms providing adequate stiffness and strength in many structures. In such applications they are subjected to three-dimensional states of stress coupled with hygrothermal effects. The microstructure of composite laminates reinforced with woven, braided, or stitched networks is significantly different from that of tape based laminates. Furthermore, the relative magnitudes of in-plane and through-thickness elastic and strength properties are different from those of tape based composites.

The failure mechanisms of textile reinforced composites depend on the textile type (woven, braided, stitched) and the weave style (plain, twill, satin) in addition to the fiber and matrix properties. One general characteristic of fabric composites is their non-linear stress-strain behavior under normal stress. In the case of in-plane tensile loading along principal axes (warp or fill directions) the nonlinearity is due to matrix microcracking preceding ultimate failure. In a conservative approach, the proportional limit associated with the initial tangent modulus can be defined as a strength parameter. In a less conservative approach, more suitable for satin weave carbon fabric composites, the ultimate strength associated with the secant modulus can be used in failure criteria.

On a macroscopic scale the fabric composite can be considered as a quasi-homogeneous orthotropic material with the warp, fill and the normal through-thickness directions as the principal material axes (Fig. 1). In general, the constitutive behavior is characterized by nine elastic constants. The failure behavior is characterized by nine characteristic strengths, tensile and compressive strengths along the warp (1) and fill (2) directions, $F_{1t}, F_{1c}, F_{2t}, F_{2c}$, tensile end compressive strengths in the through-thickness direction, F_{3t}, F_{3c}, and shear strengths in the in-plane and through-thickness directions (F_{12} or F_6, F_{23} or F_4, and F_{13} or F_5).

The through-thickness characterization of composites is essential for accurate analysis of composite sections where a three-dimensional state of stress exists, such as in right angle brackets and flanges, as well as in composites with 3D reinforcement like stitching and pinning.

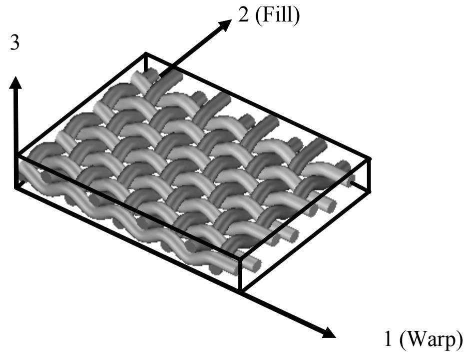

Fig.1. Material coordinates for a fabric composite element.

In the present investigation, in-plane and through-thickness tests were conducted on a carbon fabric/epoxy material to determine its constitutive and failure behavior. The applicability of various failure theories was investigated and a new interlaminar failure theory was proposed.

2 Material Characterization

The material investigated was a carbon-fabric/epoxy composite obtained in prepreg form (AGP 370-5H/3501-6). The fabric reinforcement was a five-harness satin weave of AS4 carbon fibers with the same fiber count in both the warp and fill directions. A unidirectional carbon/epoxy composite (AS4/3501-6) having the same type of fiber and matrix was also tested for comparison.

Specimens for in-plane testing were prepared from laminates consisting of four prepreg plies stacked in the warp direction back to back so that the laminate was symmetric and balanced and without warpage [1-3]. It was observed that the modulus and strength of the fabric composite are roughly half those of the corresponding unidirectional lamina. This is due to the fact that the five-harness satin weave reinforced composite behaves approximately like a $[0/90]_S$ crossply laminate made of unidirectional laminae. In-plane shear properties were obtained by tensile testing of 10° and 45° off-axis specimens [2]. Shear stress-strain curves for the woven carbon/epoxy and corresponding unidirectional carbon/epoxy showed that the two stress-strain curves nearly coincide in the initial quasi-linear region.

Through-thickness properties are required to study the behavior of the material under three-dimensional states of stress. Test methods for textile composites were described by the authors [4-7].

In the present case tensile specimens for through-thickness properties were machined from a laminate of 27 mm thickness with a reduced 4.5 x 4.5 mm square cross section at the center and bonded into specially machined wells in aluminum shanks used for load introduction (Fig. 2). The adhesive worked under both tension and shear to insure failure in the specimen gage section. The specimen was instrumented with strain gages on all four sides. A through-thickness tensile stress-strain curve for the fabric composite studied is shown in Fig. 2. The stress-strain behavior is linear to failure. The strength is comparable to the in-plane transverse tensile strength of the unidirectional composite. The specimens for through-thickness compressive testing were prismatic blocks bonded to steel end blocks. A typical compressive stress-strain curve to failure is shown in Fig. 3.

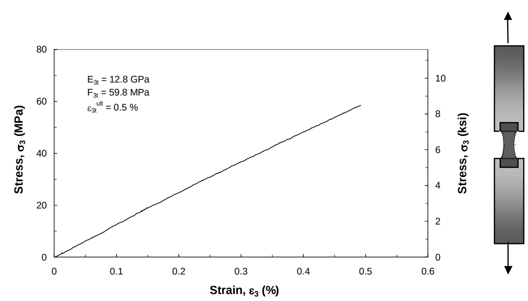

Fig. 2. Stress-strain curve of carbon fabric/epoxy under through-thickness tension

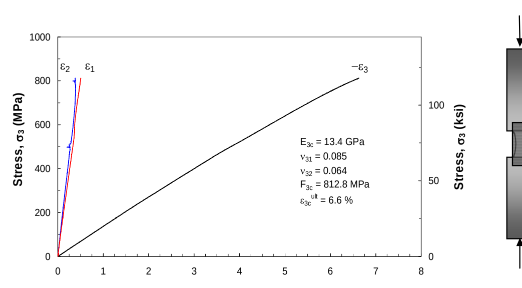

Fig. 3. Stress-strain curves of carbon fabric/epoxy under through-thickness compression

Through-thickness shear properties were obtained by using a modified compact Iosipescu type V-notch specimen under shear. A typical through-thickness shear stress-strain curve is shown in Fig. 4.

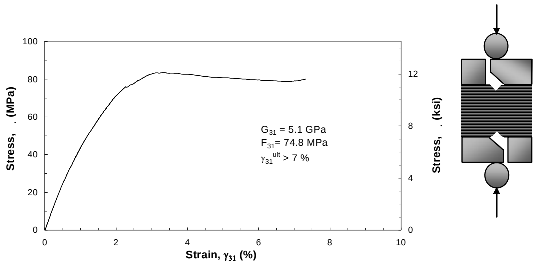

Fig. 4. Shear stress-strain curve of carbon fabric/epoxy under through-thickness shear

3. Failure Analysis

In order to evaluate failure criteria, it was necessary to obtain results under multiaxial states of stress. Such states of stress were produced by testing in-plane and through-thickness specimens at various orientations with the principal material axes. The variation of the in-plane off-axis tensile strength with load orientation was in agreement with predictions of the Tsai-Hill failure theory. Through-thickness off-axis tensile and compressive tests were conducted to produce biaxial states of stress on the 1-3 or 2-3 planes.

Stress-strain curves for various orientations of the tensile load with the 3-axis are shown in Fig. 5. It is seen that the strengths are relatively low and do not vary much with load orientation Stress-strain curves for various orientations of the compressive load with the 3-axis are shown in Fig. 6. Failure patterns are shown in Fig. 7.

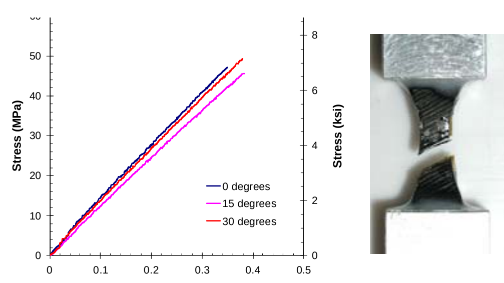

Fig. 5. Stress-strain curves of carbon fabric/epoxy under through-thickness tension at various angles

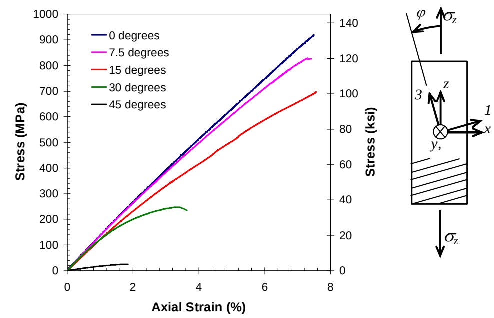

Fig. 6. Stress-strain curves of carbon fabric/epoxy under through-thickness compression at various angles

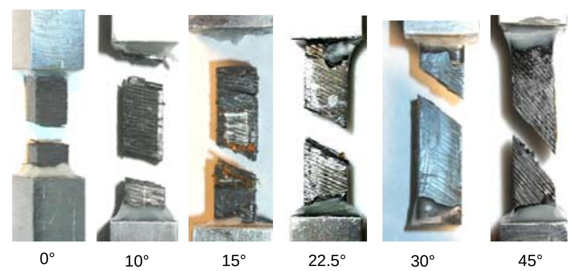

Fig. 7. Failure patterns of woven carbon/epoxy specimens under through-thickness compression at various angles

The results obtained were evaluated based on three types of failure criteria, noninteractive or limit criteria (maximum stress), fully interactive criteria (Tsai-Hill, Tsai-Wu), and failure mode based and partially interactive theories (Hashin-Rotem, Sun, NU). The latter is a recently developed at Northwestern University (NU) interlaminar failure theory based on maximum strain criteria [8]. For orthotropic textile composites the failure criteria can be expressed in general in terms of nine strength parameters $(F_{1t}, F_{1c}, F_{2t}, F_{2c}, F_{3t}, F_{3c}, F_4, F_5, F_6)$.

According to the maximum stress theory, failure occurs when any of the following sub-criteria are met

$$\sigma_1 = \begin{cases} F_{1t} & \text{when} \quad \sigma_1 > 0 \\ -F_{1c} & \text{when} \quad \sigma_1 < 0 \end{cases} \tag{1}$$

$$\sigma_2 = \begin{cases} F_{2t} & \text{when} \quad \sigma_2 > 0 \\ -F_{2c} & \text{when} \quad \sigma_2 < 0 \end{cases} \tag{2}$$

$$\sigma_3 = \begin{cases} F_{3t} & \text{when} \quad \sigma_3 > 0 \\ -F_{3c} & \text{when} \quad \sigma_3 < 0 \end{cases} \qquad (3)$$

$$|\tau_4| = F_4 \; , \; |\tau_5| = F_5 \; , \; |\tau_6| = F_6 \qquad (4)$$

For many textile composites

$$F_{1t} \cong F_{2t}, \quad F_{1c} \cong F_{2c}, \quad F_4 \cong F_5$$

Thus, the number of strength parameters can be reduced from 9 to 6.

The Tsai-Hill criterion for the above conditions takes the form

$$\frac{1}{F_1^2}\left(\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2 - \sigma_2\sigma_3 - \sigma_3\sigma_1\right) + \left(\frac{\sigma_3}{F_3}\right)^2 + \frac{\tau_4^2 + \tau_5^2}{F_4^2} + \left(\frac{\tau_6}{F_6}\right)^2 = 1 \qquad (5)$$

The Tsai-Wu criterion in three dimensions takes the form

$$f_1\sigma_1 + f_2\sigma_2 + f_3\sigma_3 + f_{11}\sigma_1^2 + f_{22}\sigma_2^2 + f_{33}\sigma_3^2 + f_{44}\tau_4^2 + f_{55}\tau_5^2 + f_{66}\tau_6^2 + 2f_{12}\sigma_1\sigma_2 + 2f_{23}\sigma_2\sigma_3 + 2f_{31}\sigma_3\sigma_1 = 1 \qquad (6)$$

where

$$f_i = \frac{1}{F_{it}} - \frac{1}{F_{ic}} \qquad (i = 1, 2, 3)$$

$$f_{ii} = \frac{1}{F_{it}F_{ic}}$$

$$f_{44} = \frac{1}{F_4^2}, \quad f_{55} = \frac{1}{F_5^2}, \quad f_{66} = \frac{1}{F_6^2}$$

$$f_{ij} \cong -\frac{1}{2}\sqrt{f_{ii}f_{jj}}$$

(ij = 12, 23, 31, no summation implied)

For textile composites with

$$F_{1t} \cong F_{2t}, \quad F_{1c} \cong F_{2c}, \text{ and } \quad F_4 \cong F_5,$$

$$f_1 \cong f_2, \quad f_{11} \cong f_{22}, \quad f_{44} \cong f_{55}, \quad f_{23} \cong f_{31}$$

For loading on the 1-3 plane, as was the case in the experiments reported, Eq. (6) is reduced to

$$f_1\sigma_1 + f_3\sigma_3 + f_{11}\sigma_1^2 + f_{33}\sigma_3^2 + f_{55}\tau_5^2 + 2f_{13}\sigma_1\sigma_3 = 1 \qquad (7)$$

The Hashin-Rotem criteria for the textile composite considered here are expressed as

$$\frac{|\sigma_1|}{F_1} = 1, \quad \frac{|\sigma_2|}{F_2} = 1 \qquad (8)$$

(fiber failure modes)

$$\left(\frac{\tau_5}{F_5}\right)^2 + \left(\frac{\tau_6}{F_6}\right)^2 = 1 \qquad (9)$$

(Interfiber failure mode on plane 1)

$$\left(\frac{\tau_4}{F_4}\right)^2 + \left(\frac{\tau_6}{F_6}\right)^2 = 1 \qquad (10)$$

(Interfiber failure mode on plane 2)

$$\left(\frac{\sigma_3}{F_{3t}}\right)^2 + \left(\frac{\tau_4}{F_4}\right)^2 + \left(\frac{\tau_5}{F_5}\right)^2 = 1 \qquad (11)$$

(Interfiber failure mode on plane 3 for $\sigma_3 > 0$)

When $\sigma_3 < 0$, the last criterion above is not appropriate and should be replaced with a fully interactive one, such as the Tsai-Hill of Tsai-Wu criterion.

The experimental results from the through-thickness tests were compared with predictions of the above theories. Results for through-thickness tensile behavior are shown in Fig. 8. All theoretical predictions and the experimental results are in relatively good agreement in the range of load orientation between 0º and 45º.

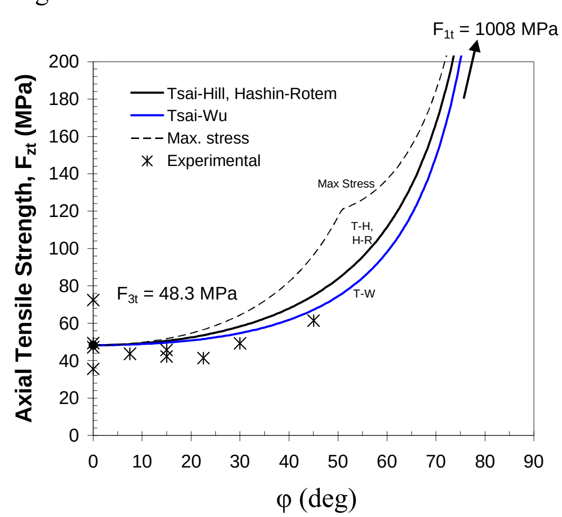

Fig. 8. Comparison of experimental results and predictions of through-thickness tensile strength of woven-carbon/epoxy composite

Theoretical predictions and experimental results differ the most from each other for states of stress involving transverse (to the fibers) normal stress and shear stress. i. e., $\sigma_2 < 0, \tau_6$ or $\sigma_3 < 0, \tau_5$.

C. T. Sun described the fact that the apparent shear strength increases when combined with a normal compressive stress, by modifying the relevant Hashin-Rotem criterion as follows (for the 1-3 plane)

$$\left(\frac{\sigma_3}{F_{3c}}\right)^2 + \left(\frac{\tau_5}{F_5 - \eta\sigma_3}\right)^2 = 1 \qquad (12)$$

where η is a friction type coefficient that must be estimated with the help of additional testing [10].

In the Northwestern (NU) theory, when failure is compression dominated (for large angles between the load and the interlaminar plane), the failure criterion is the maximum shear strain. This strain under a two-dimensional state of stress (σ_3, τ_5) is expressed in terms of applied stresses and macroscopic composite material stiffnesses and compressive strength to obtain the following criterion [8, 9]

$$\left(\frac{\sigma_3}{F_{3c}}\right)^2 + \left(\frac{\tau_5}{F_{3c}}\right)^2 \left(\frac{E_3}{G_{13}}\right)^2 = 1 \qquad (13)$$

When the failure is shear dominated (for small angles between the loading direction and interlaminar plane), the failure criterion is the maximum tensile strain which is expressed in terms of applied stresses, macroscopic material stiffnesses and interlaminar strength. This mode of failure is governed by the following criterion

$$\left(\frac{\tau_5}{F_5}\right)^2 + 2\frac{\sigma_3}{F_5}\frac{G_{13}}{E_3} = 1 \qquad (14)$$

Experimental results of through-thickness compressive strength are compared in Fig. 9 with predictions of various classical theories, including those by Sun [10], Christensen [11], and the Northwestern (NU) theory based on maximum strain criteria [8, 9].

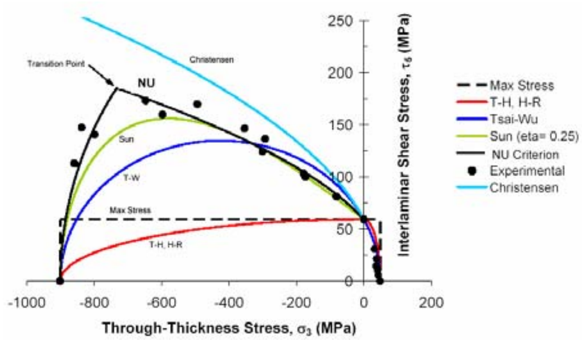

Fig. 9. Comparison of experimental results of interlaminar strength and predictions of various theories including NU theory [8, 9].

Acknowledgements

The work described here was sponsored by the Office of Naval Research (ONR). We are grateful to Dr. Y. D. S. Rajapakse of ONR for his encouragement and cooperation and to Mrs. Yolande Mallian for typing the manuscript.

References

[1]. Jacobsen A. J., Luo J. J. and Daniel I. M. “Characterization of constitutive behavior of satin-weave fabric composite,” *J. Composite Materials*, Vol. 38, No. 7, pp. 555-565, 2004.

[2]. Abot J. L., Yasmin A., Jacobsen A. J. and Daniel I. M. “In-plane mechanical, thermal, and viscoelastic properties of a satin fabric carbon/epoxy composite,” *Composites Science and Technology*, Vol. 64, pp. 263-268, 2004.

[3]. Luo J. J. and. Daniel I. M. “Sublaminate-based lamination theory and symmetry properties of textile composite laminates,” *Composites, Part B*, Vol. 35, No. 6-8, pp. 483-496, 2004.

[4]. Abot J. L. and Daniel I. M. “Through-thickness mechanical characterization of woven fabric composites,” *Journal of Composite Materials*, Vol. 38, No. 7, pp. 543-554, 2004.

[5]. Daniel I. M., Abot J. L., Luo J. J. and Schubel P. M. “Three-dimensional characterization of constitutive behavior and failure of textile composites,” *11th International Conference on Fracture, ICF 11*, Turin, Italy, Mar. 20-25, 2005.

[6]. Daniel I. M., Luo J. J. and Schubel P. M. “Three-dimensional characterization of textile composites,” *Composites, Part B*, in press, 2007

[7]. Schubel P. M., Luo J. J. and Daniel I. M. “Through-thickness characterization of thick composite laminates,” *Proc. of SEM Annual Meeting*, St. Louis, MO, 2006.

[8]. Luo J. J., Daniel I. M. and Schubel P. M. "Interlaminar failure theory for thick textile composites," in preparation.
[9]. Daniel I. M. "Failure of composite materials," *Strain,* Vol. 43, No. 1, pp. 4-12, 2007.
[10]. Sun, C. T. "Strength analysis of unidirectional composites and laminates," in *Comprehensive Composite Materials*, A. Kelly and C. Zweben (Eds.) Elsevier Science Ltd., Oxford, Ch. 1.20, pp. 641-666, 2000.
[11]. Christensen, R. M. and DeTeresa, S. J. , Delamination failure investigation for out-of-plane loading in laminates, J. Comp. Materials 38 (24, 2004, 2231-2238.