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Three-dimensional characterization of textile composites

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Abstract

The mechanical and failure behavior of a carbon-fabric/epoxy composite was characterized and appropriate failure criteria in three dimensions were proposed. The material investigated was reinforced with a five-harness satin carbon fiber weave. Test methods were developed/adapted for complete mechanical characterization of textile composites in three dimensions. 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 proposed, 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 newly developed interlaminar failure theory, was found to be in excellent agreement with experimental results in the through-thickness direction, especially those involving interlaminar shear and compression.

Keywords: A. Fabrics/textiles; Polymer-matrix composites; B. Mechanical properties; D. Mechanical testing

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 and compressive strengths in the through-thickness direction (F_{3t}, F_{3c}), and in-plane and through-thickness shear strengths (F_{12} or F_6, F_{23} or F_4, and F_{13} or F_5).

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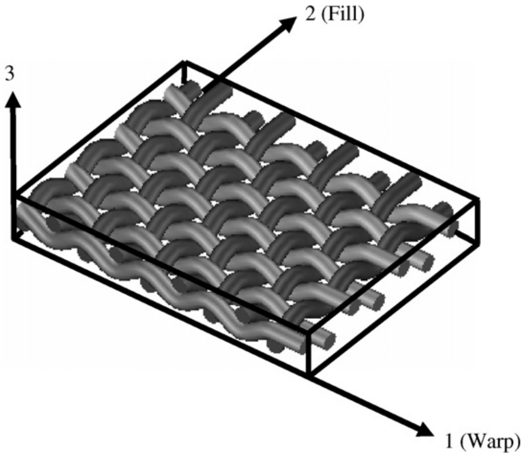

Fig. 1. Material coordinates for a fabric composite element.

The through-thickness characterization of composites is essential for the reliable and robust design of thick structural components. Through-thickness properties are also required 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.

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

2.1. Material

The material investigated was a carbon-fabric/epoxy composite obtained in prepreg form (AGP 370-5H/3501-6S). 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 and also tested for comparison.

2.2. In-plane properties

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, Jacobsen et al. [1], Abot et al. [2], Luo and Daniel [3]. Typical tensile and compressive stress–strain curves for the selected woven carbon/epoxy material loaded along the warp and fill directions and corresponding stress–strain curves for a unidirectional lamina with the same fiber type and matrix are shown in Fig. 2. It is 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.

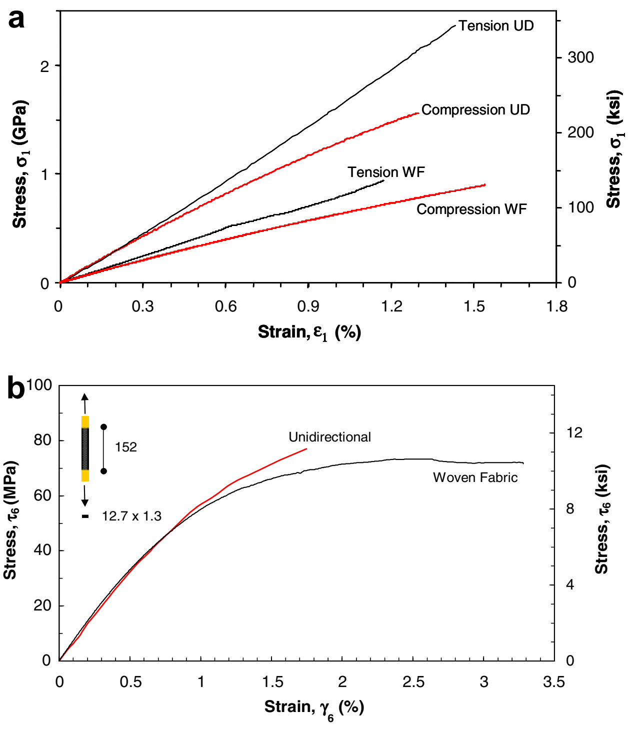

Fig. 2. Stress–strain curves to failure of five harness satin-weave and unidirectional carbon/epoxy composites under: (a) in-plane tensile and compressive loading; (b) in-plane shear (AS4/3501-6 and AGP370-5H/3501-6S).

In-plane shear properties were obtained by tensile testing of 10° and 45° off-axis specimens [2]. The in-plane shear strain was measured with a two-page rosette with its elements oriented at 45° and −45° with the warp direction [4]. Typical 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 (Fig. 2). Beyond a certain strain level the woven fabric composite shows much higher ductility with an ultimate strain exceeding 3%.

2.3. Through-thickness properties

Through-thickness properties are required to study the behavior of the material under three-dimensional states of stress. Through-thickness testing is more problematic than in-plane testing because it is difficult to fabricate material of uniform quality in sufficiently thick sections. It is also difficult to introduce the loading without the deleterious influence of end effects and stress concentrations [5–7]. An overview of through-thickness test methods was given recently by Lodeiro et al. [5]. Test methods were further adapted and applied to textile composites by Abot and Daniel [8].

Various configurations of short tensile specimens have been proposed and used [9,10]. In the present case tensile specimens for through-thickness properties were machined from a laminate of 27 mm thickness with a reduced 4.5 × 4.5 mm square cross section at the center and bonded into specially machined wells in aluminum shanks used for load introduction (Fig. 3). 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. 3. 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

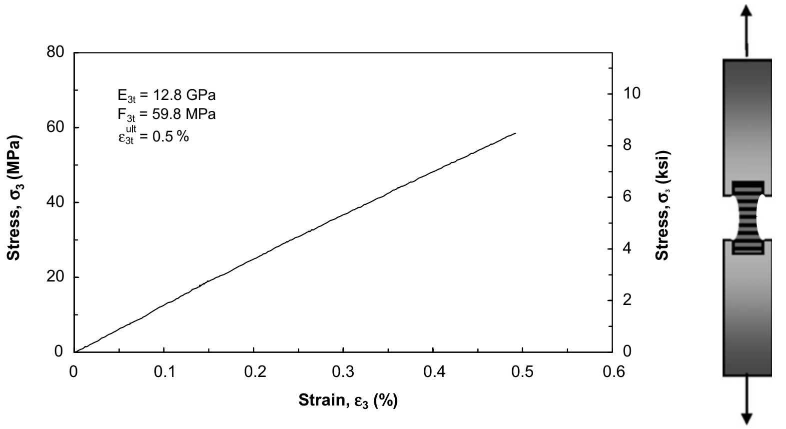

Fig. 3. Stress–strain curve of carbon fabric/epoxy under through-thickness tension.

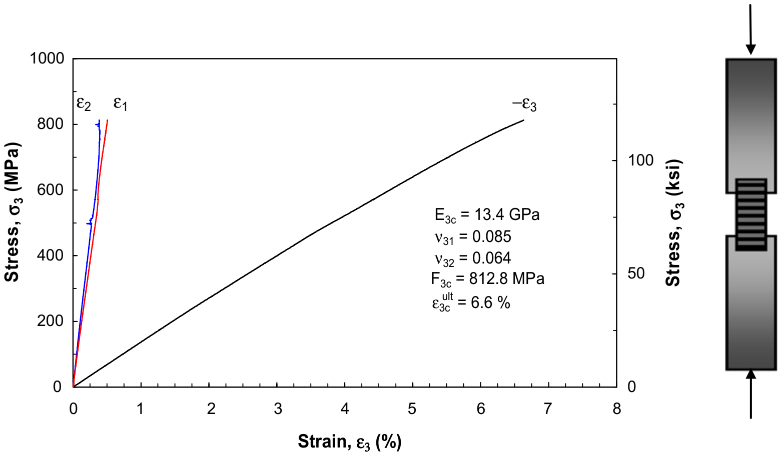

Fig. 4. Stress–strain curves of carbon fabric/epoxy under through-thickness compression.

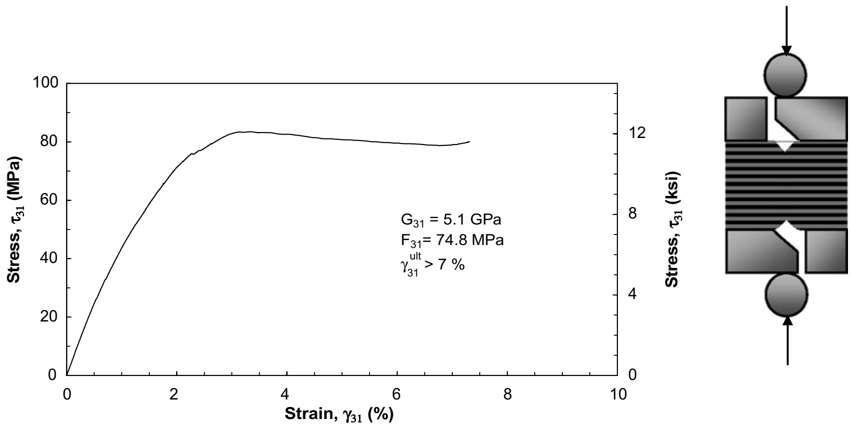

Fig. 5. Shear stress–strain curve of carbon fabric/epoxy under through-thickness shear.

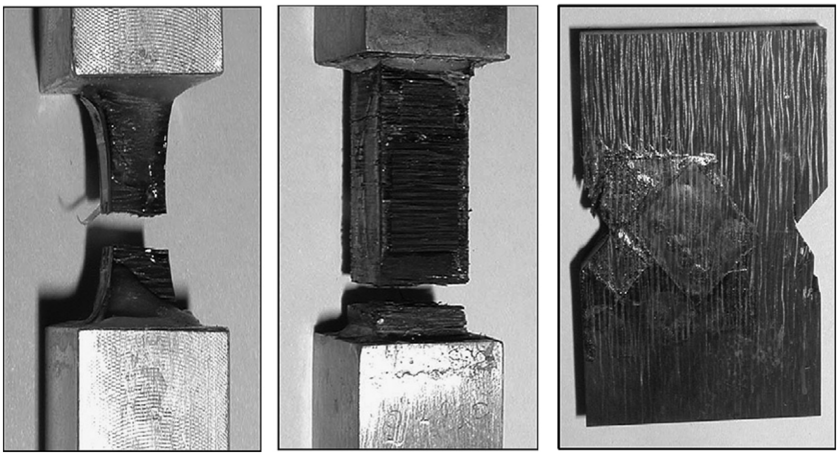

Fig. 6. Failure modes of carbon fabric/epoxy composite under through-thickness tension, compression, and shear.

for through-thickness compressive testing were prismatic blocks bonded to steel end blocks. A typical stress–strain curve to failure is shown in Fig. 4. 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. 5. Failure patterns of the woven-carbon/epoxy specimens tested are shown in Fig. 6.

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 is shown in Fig. 7 where it is compared with predictions of the Tsai–Hill failure theory. Through-thickness off-axis tensile tests were conducted to produce biaxial states of stress on the 1–3 or 2–3 planes.

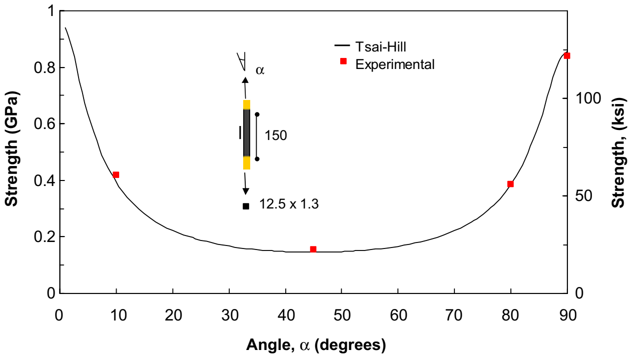

Fig. 7. Off-axis tensile strength as a function of load orientation for woven carbon/epoxy (AGP370-5H/3501-6S).

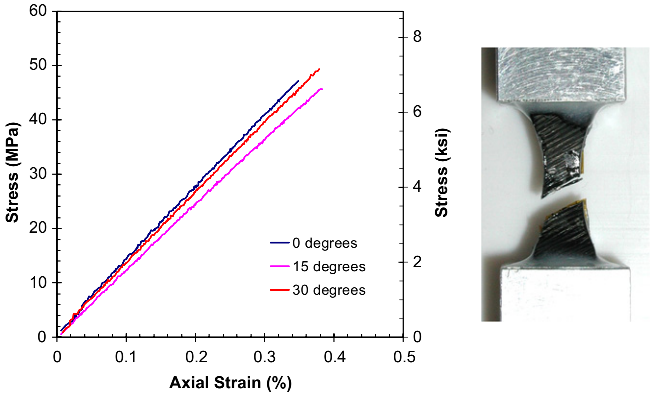

Fig. 8. Stress–strain curves of carbon fabric/epoxy under through-thickness tension at various angles.

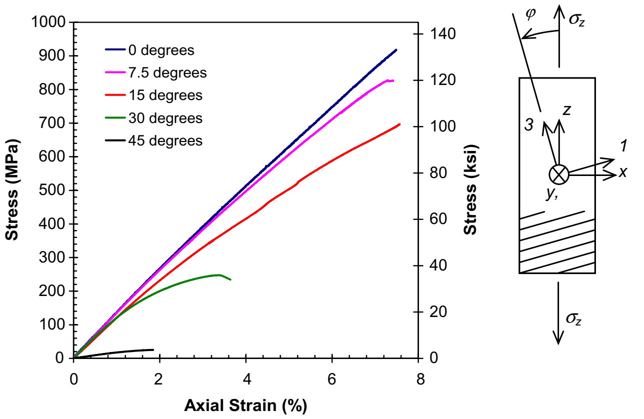

Fig. 9. Stress–strain curves of carbon fabric/epoxy under through-thickness compression at various angles.

Stress–strain curves for various orientations of the tensile load with the 3-axis are shown in Fig. 8. It is seen that the strengths are relatively low and do not vary much with load orientation. Similar tests were conducted in compression at various angles with the 3-direction. The corresponding stress–strain curves show large variations in stiffness and strength with load orientation (Fig. 9). Failure patterns are shown in Fig. 10.

The results obtained were evaluated based on three types of failure criteria, noninteractive or limit criteria

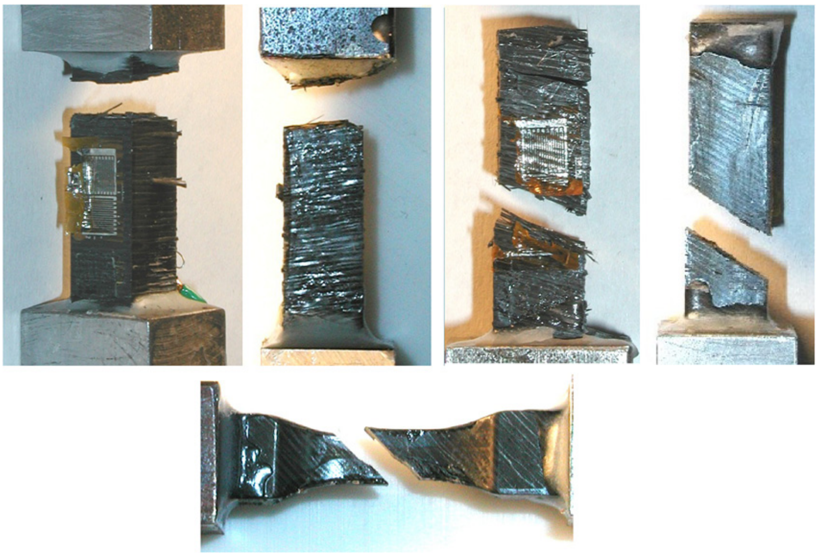

Fig. 10. Failure patterns of woven carbon/epoxy specimens under through-thickness compression at various angles.

(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. 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).

In many fabric composites with equal yarn counts in the warp and fill directions $F_{1t} \cong F_{2t}$, $F_{1c} \cong F_{2c}$, $F_4 \cong F_5$. The Tsai Hill interactive failure criterion in three dimensions takes the form

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

For in-plane loading (1–2 plane) it reduces to

$$\frac{1}{F_1^2}(\sigma_1^2+\sigma_2^2-\sigma_1\sigma_2)+\left(\frac{\tau_6}{F_6}\right)=1 \tag{2}$$

As seen in Fig. 7 this theory is in very good agreement with in-plane experimental results.

The Hashin–Rotem failure criteria, adapted to textile composites, take this form [4]

$$\frac{|\sigma_1|}{F_1}=1, \frac{|\sigma_2|}{F_2}=1 \quad \text{(Fiber failure modes)} \tag{3}$$

$$\left(\frac{\tau_5}{F_5}\right)^2+\left(\frac{\tau_6}{F_6}\right)^2=1 \quad \text{(Interfiber failure mode on plane 1)} \tag{4}$$

$$\left(\frac{\tau_4}{F_4}\right)^2+\left(\frac{\tau_6}{F_6}\right)^2=1 \quad \text{(Interfiber failure mode on plane 2)} \tag{5}$$

$$\left(\frac{\sigma_3}{F_3}\right)^2+\left(\frac{\tau_4}{F_4}\right)^2+\left(\frac{\tau_5}{F_5}\right)^2=1 \quad \text{(Interfiber failure mode on plane 3)} \tag{6}$$

The Tsai–Wu interaction criterion in three dimensions is

$$f_1\sigma_1+f_2\sigma_2+f_3\sigma_3+f_{11}\sigma_1^2+f_{22}\sigma_2^2+f_{33}\sigma_3^2+f_{44}\tau_4^2 + f_{55}\tau_5^2+f_{66}\tau_6^2+2f_{12}\sigma_1\sigma_2+2f_{13}\sigma_1\sigma_3+2f_{23}\sigma_2\sigma_3=1 \tag{7}$$

In two dimensions (1–3 plane) it reduces to

$$f_1\sigma_1+f_3\sigma_3+f_{11}\sigma_1^2+f_{33}\sigma_3^2++f_{55}\tau_5^2+2f_{13}\sigma_1\sigma_3=1 \tag{8}$$

where

$$f_1=\frac{1}{F_{1t}}-\frac{1}{F_{1c}} \qquad f_{11}=\frac{1}{F_{1t}F_{1c}}$$

$$f_3=\frac{1}{F_{3t}}-\frac{1}{F_{3c}} \qquad f_{33}=\frac{1}{F_{3t}F_{3c}}$$

$$f_{55}=\frac{1}{F_5^2} \qquad f_{13}\cong-\frac{1}{2}\sqrt{f_{11}f_{33}}$$

Failure theories deviate the most from each other and from experimental results for stress states combining normal compression and shear, such as

$$\sigma_2<0,\ \tau_6 \quad \text{or} \quad \sigma_3<0,\ \tau_5$$

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)

$$\left(\frac{\sigma_3}{F_{3c}}\right)^2+\left(\frac{\tau_5}{F_5-\eta\sigma_3}\right)^2=1 \tag{9}$$

where η is a friction type coefficient that must be estimated with the help of additional testing [11].

In the 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 mode of failure is governed by the following criterion

$$\left(\frac{\sigma_3}{F_{3c}}\right)^2+\left(\frac{\tau_5}{F_{3c}}\right)^2\left(\frac{E_3}{G_{13}}\right)^2=1 \tag{10}$$

When the failure is shear dominated (for small angles between the loading direction and interlaminar plane), the failure criterion is the maximum tensile strain. This mode of failure is governed by the following criterion

$$\left(\frac{\tau_5}{F_5}\right)^2+2\frac{\sigma_3}{F_5}\frac{G_{13}}{E_3}=1 \tag{11}$$

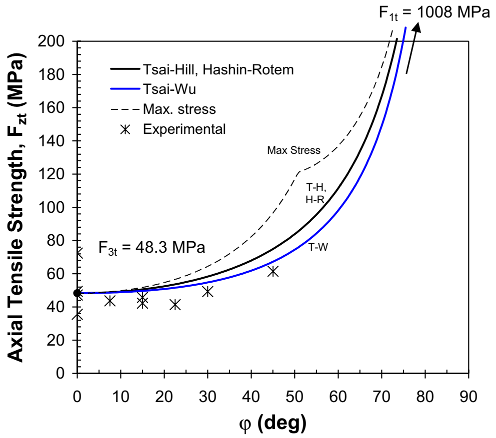

Fig. 11. Comparison of experimental results and predictions of through-thickness tensile strength of woven-carbon/epoxy composite.

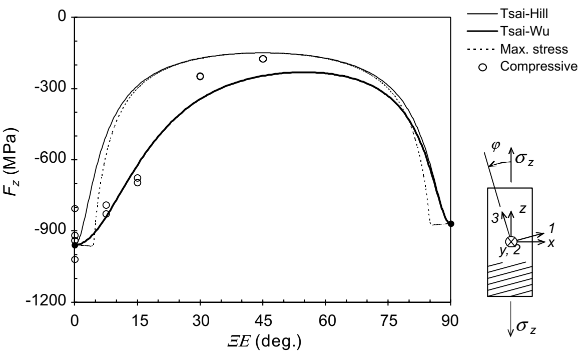

Fig. 12. Comparison of experimental results and predictions of through-thickness compressive strength of woven-carbon/epoxy composite.

The variation of the through-thickness tensile strength as a function of the load orientation with respect to the 3-axis is shown in Fig. 11. Experimental results are compared with predictions of the maximum stress, Tsai–Hill and Tsai–Wu theories. All theoretical predictions and the experimental results are in good agreement in the range of load orientation between 0° and 30°.

The variation of the through-thickness compressive strength as a function of the load orientation with respect to the 3-axis is shown in Fig. 12. Experimental results are in better agreement with predictions of the Tsai–Wu theory in the range of load orientation angle between 0° and 30° and deviate appreciably from the other predictions.

Experimental results of through-thickness compressive strength are compared with prediction of various classical theories including the NU theory in Fig. 13. The agreement of experimental results with the new theory is excellent.

4. Summary and conclusions

Test methods were developed/adapted for complete mechanical characterization of textile composites in three dimensions. Various states of stress were investigated by testing off-axis through-thickness specimens in tension and compression at various orientations with the in-plane directions. Three types of failure criteria in three dimensions were proposed, limit criteria (maximum stress), fully interactive criteria (Tsai–Hill, Tsai–Wu), and failure mode based and partially interactive criteria (Hashin–Rotem, Sun, NU). Experimental results in the through-thickness direction, especially those involving interlaminar shear

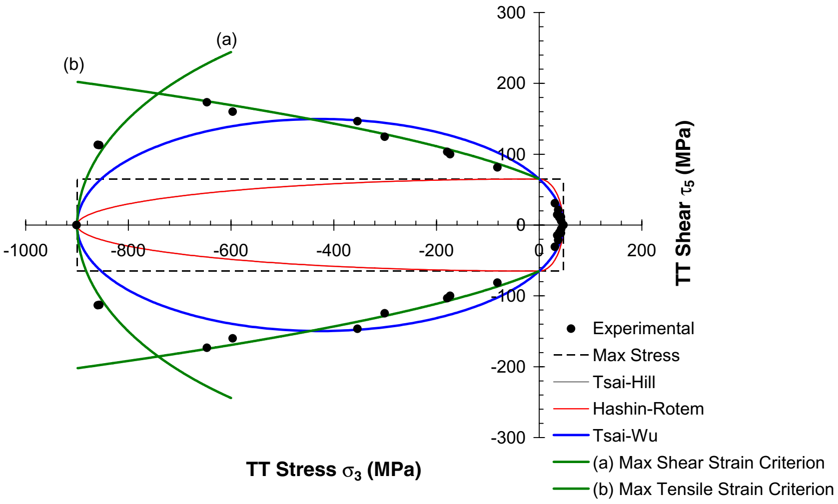

Fig. 13. Comparison of experimental results of through-thickness compressive strength and predictions of various theories including new theory based on maximum strain criteria.

and compression, are in very good agreement with the NU criterion.

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