# THREE-DIMENSIONAL CHARACTERIZATION OF CONSTITUTIVE BEHAVIOR AND FAILURE OF TEXTILE COMPOSITES

Isaac M. Daniel,[1] Jandro L. Abot,[2] Jyi-Jiin Luo[1] and Patrick M. Schubel[1]

[1]Center for Intelligent Processing of Composites, Northwestern University, Evanston, IL 60208, USA
[2]Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221, USA

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. In-plane tensile, compressive, and shear properties along the warp and fill directions were determined for the fabric composite and compared with a corresponding unidirectional composite having the same fiber and matrix constituents. 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. Three types of failure criteria in three dimensions were investigated, a limit criterion (maximum stress) , interactive criteria (Tsai-Hill, Tsai-Wu), and failure mode based or partially interactive criteria (Hashin-Rotem). Results obtained to date are in good agreement with a fully interactive criterion.

## 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

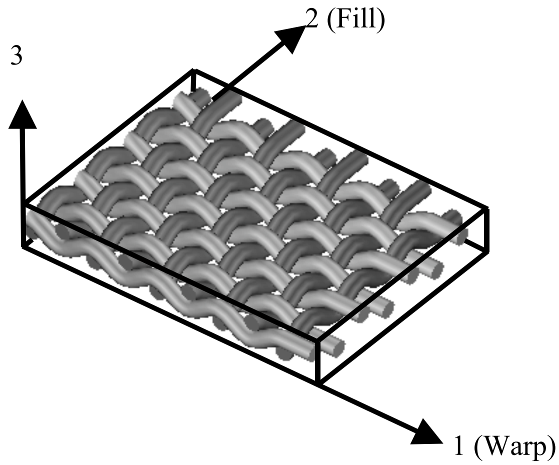



Figure 1: Material coordinates for a fabric composite element.

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 in-plane and through-thickness shear strengths ($F_{12}$ or $F_6$, $F_{23}$ or $F_4$, and $F_{13}$ or $F_5$).

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.

## 2. MATERIAL CHARACTERIZATION

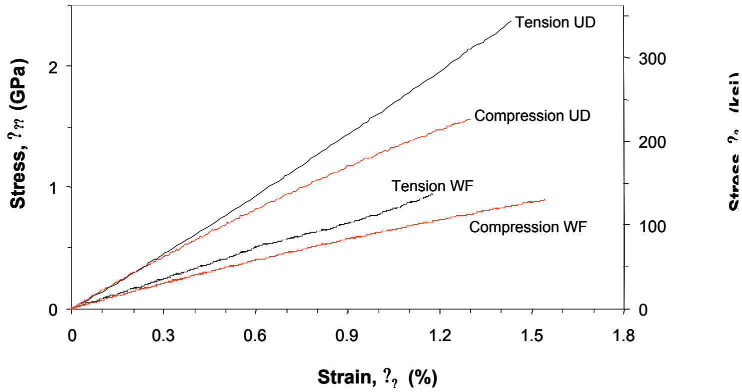
### *2.1 Material*

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 (AS4/3502-6) having the same type of fiber and matrix and also tested for comparison.

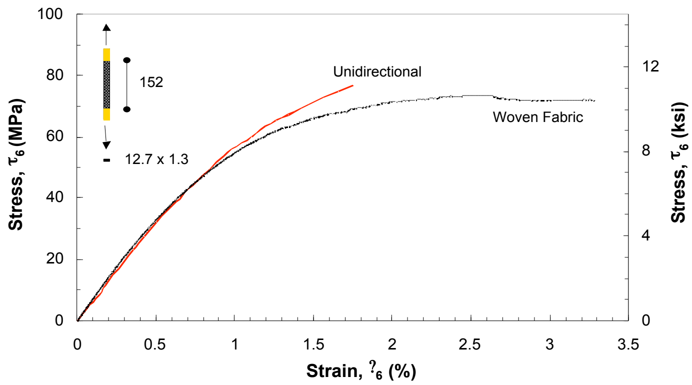
### *2.2 In-Plane Properties*

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 are shown in Fig. 2. The corresponding stress-strain curves for a unidirectional lamina with the same fiber type and matrix are also shown for comparison. 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.

In-plane shear properties were obtained by tensile testing of 10° and 45° off-axis specimens (Abot et al. [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 (Daniel and Ishai [4]). Typical shear




(a)




(b)

Figure 2: Stress-strain curves to failure of 5 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)

stress-strain curves for the woven carbon/epoxy and corresponding unidirectional carbon/epoxy are shown in Fig. 2b. It is observed that the two stress-strain curves nearly coincide in the initial quasi-linear region, up to a shear strain of approximately $\gamma_6 \cong 0.8\%$. Beyond this 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. 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 [2].

Various configurations of short tensile specimens have been proposed and used (Ferguson et al.[6], Ishai [7]). In the present case tensile specimens 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. 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 specimens 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.

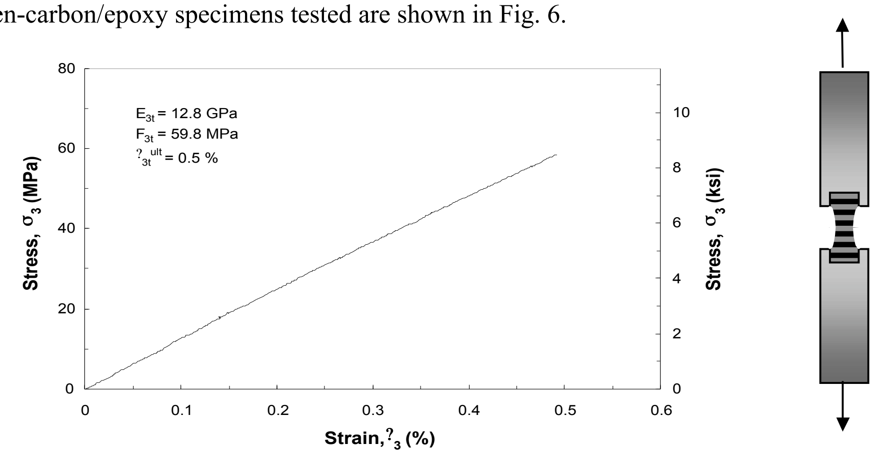



Figure 3: Stress-strain curve of carbon fabric/epoxy under through-thickness tension

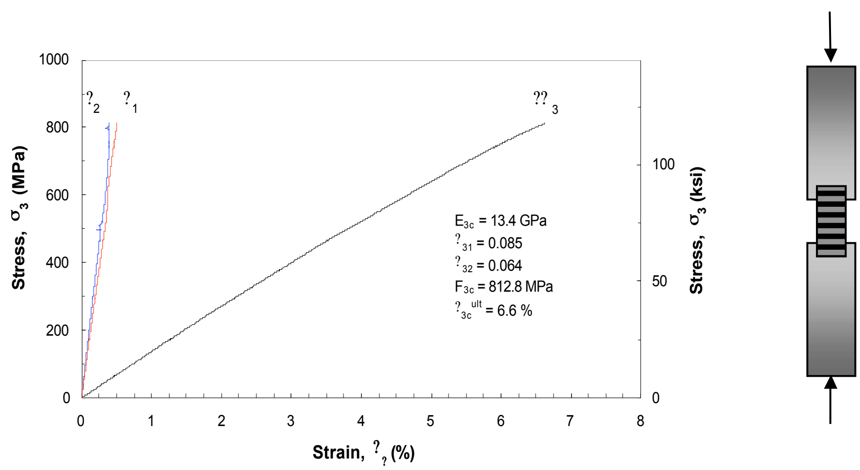



Figure 4: Stress-strain curves of carbon fabric/epoxy under through-thickness compression

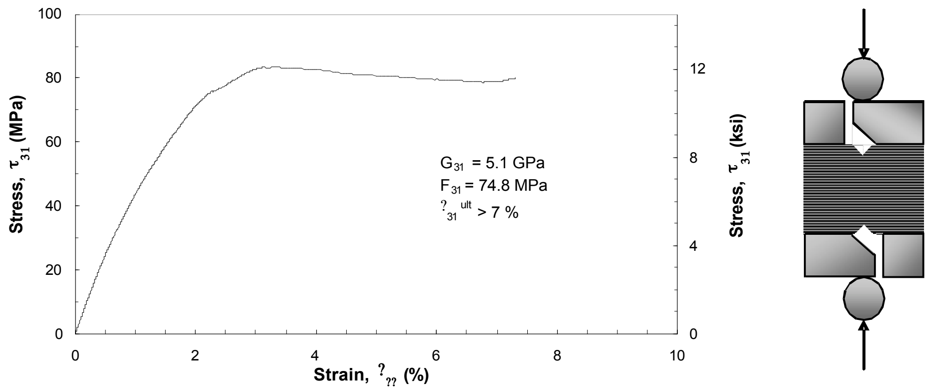



Figure 5: Shear stress-strain curve of carbon fabric/epoxy under through-thickness shear

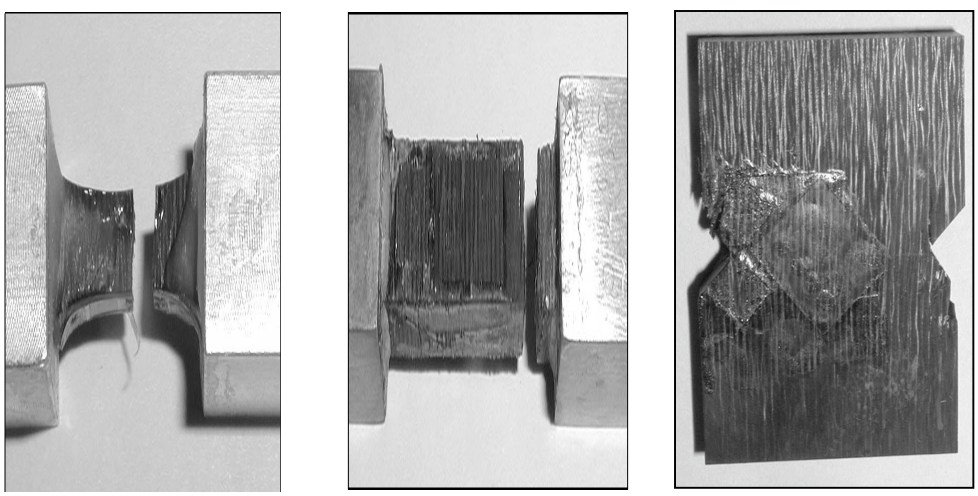


Figure 6: Failure modes of carbon fabric/epoxy composite under through-thickness tension, compression, and shear

## 3. FAILURE ANALYSIS

The results obtained were evaluated based on three types of failure criteria, a noninteractive limit criterion (maximum stress), a failure mode based and partially interactive theory (Hashin-Rotem), and fully interactive criteria (e.g., Tsai-Hill, Tsai-Wu). 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 two dimensions (1-2 plane) takes the form

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

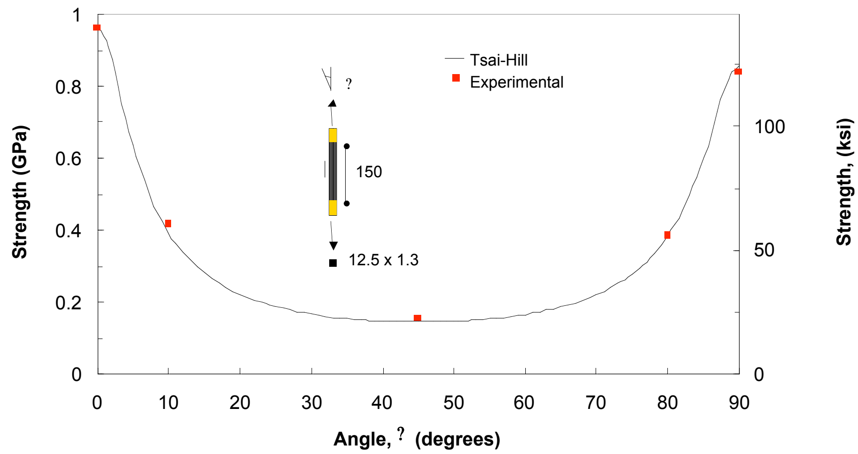



Figure 7: Off-axis tensile strength as a function of load orientation for woven-carbon/epoxy (AGP370-5H/3501-6S)

Theoretical predictions and experimental results are in excellent agreement in this case as shown in Fig. 7. Results under biaxial compression on a different plane (1-3 plane) deviate significantly from predictions of the Tsai-Hill and maximum stress theories, but are in better agreement with predictions of the Tsai-Wu theory.

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