Compressive response and failure of braided textile composites: Part 1—experiments

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Abstract

Experimental results obtained by examining the planar biaxial compression/tension response of carbon 2D triaxial braided composites (2DTBC) are reported in this paper. These experiments were motivated by a need to examine the failure of 2DTBC in a state of stress that would be similar to what is experienced by the walls of a tubular member under compressive crush loads. Results obtained from a series of biaxial tests that were conducted with different proportional displacement loading ratio combinations of compression and tension are reported. In all cases, the dominant failure mechanism under such a stress state is the buckling of the bias and axial tows within the composite. Full field surface displacement data is acquired concurrently during all biaxial and some uniaxial tests using the technique of digital speckle photography. Digital images of the specimen surface that is illuminated with a He–Ne laser are acquired at discrete time intervals during the loading history using a high-resolution digital camera. These images are stored and analyzed to obtain the incremental inplane surface displacement fields, $\Delta u(x, y)$ and $\Delta v(x, y)$. From these, the incremental inplane surface strains $\varepsilon_{xx}$, $\varepsilon_{yy}$ and $\gamma_{xy}$ are obtained by numerical differentiation. The present paper, which is the first in a two part series, is devoted to the biaxial experimental results pertaining to 2DTBC failure.

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1. Introduction

Although organic matrix composites are superior to metals in specific stiffness and specific strength, significant weight savings in applications are only possible with either thin or moderately thick walls for the composite body. In a crash or impact situation of a moderately thick-walled composite body, typical structural members will be subjected to membrane, bending and through the thickness (interlaminar shear and normal stresses) stresses. Thus, the state of stress in a typical member will, in general, be strictly three-dimensional (3D) with the magnitude of the out-of-plane stresses largely controlled by the relative thickness and the number of plies making the thickness. On the other hand, for thin-walled structural members, the stress state can be approximated to be two-dimensional (2D) dominated by the in-plane stresses developed during deformation. The deformation response and subsequent failure of composite structures under planar multiaxial load situations are areas of research that have seen significant growth in the recent past. Much of this activity is related to the increased engineering applications of composite structures. In such cases, design engineers resort to finite element stress and
failure analysis of composite structures. One aspect of such analyses requires the choice of a suitable failure criterion and its implementation in a multi-axial stress setting.

In this, the first in a two-part paper, we report experimental results pertaining to the failure mechanisms of 2D triaxial braided composites (2DTBC) in a biaxial planar setting, so that a mechanism-based failure predictive methodology could be developed to analyze and design safe 2DTBC structures. The biaxial setting is representative of what is encountered in the wall of a structural member, such as that in a tube subjected to crushing under axial compression with an initiator plug, where the tube wall material is in a state of biaxial stress [1–3]. Towards reaching this goal, a number of planar biaxial tests with cruciform-shaped specimens (Fig. 1) were conducted. Strains in the center of the specimen were measured via strain gages placed on the surface in a rosette configuration on the backside together with the use of DSP [4] on the other side of the specimen (Fig. 2). In DSP, the incremental displacement field from a reference state to the current state is measured. Thus, if the load at the reference state and the current state are recorded, then using DSP, it is possible to measure the full field incremental displacement field (and thus the strains) corresponding to an incremental load.
In a biaxial test, the global stress field (on the remote boundaries) and the local strain fields are measured as in Khamesh and Waas’s [5,6] work. Thus, the biaxial test data offers a means to assess the validity of constitutive equations and numerical schemes that have been proposed to handle strain “softening” in 2DTBC. In addition, the effect of the biaxial stress or strain fields on the nature of damage evolution in composites with triaxially flat braided architectures, must be characterized quantitatively (i.e. via measurement) in order to understand the different mechanisms of failure that are operative in a biaxial stress state of compression/tension. This would ultimately help to develop micromechanics based models that are reflective of the failure mechanism present. Since the cruciform configuration provides a means to contain damaged material in a well-defined region, it allows one to obtain local strain field information that will be reported in the following sections.

2. Test specimens, biaxial loading frame, data acquisition and test procedure

2.1. Test specimens

Achieving failure within the gage section of the cruciform specimen is a difficulty that several papers have addressed before, see for example, Makinde et al. [7,8], Demmerle and Boehler [9], Khamesh and Waas [10] and Welsh et al. [11]. In order to select a desirable design of the specimen, a complete finite element model of the specimen with the loading end tabs was created to investigate the stress state involved for a compression/tension type of biaxial test. Unlike Demmerle and Boehler’s [9] work, where they studied the optimal design of a tension/tension type biaxial cruciform shaped specimen, it is not possible to reduce the thickness of the specimen gage section (the test region) because that would alter the microarchitecture of the braided composite. Further, with a thinned out specimen, out of plane buckling of the thinned out section is likely to occur and this would detract from the main goal of achieving failure within the gage section under a planar stress state. As such, specimen configurations of several radii, $R$ (Fig. 1a) was investigated using the finite element package SDRC-IDEAS as the pre-processor and the ABAQUS finite element analysis (FEA) software package, for the stress analysis. Stress analyses were performed where displacement boundary loading was applied at the boundary (Fig. 1b). Plate material and steel loading tabs were modeled using eight-noded parabolic plane stress elements. Material architecture descriptions and macroscopic orthotropic elastic properties are shown in Tables 1 and 2, respectively. With the guidance of previous work by Khamesh and Waas [10], a final specimen geometry was achieved with dimensions given in Fig. 1. The “working area” of the specimen measures $50.80 \text{ mm} \times 50.80 \text{ mm} (2 \text{ in} \times 2 \text{ in})$ as shown in the braided portion of Fig. 1a.

2.2. Biaxial loading apparatus

The biaxial tests were carried out in a special custom designed load frame capable of exerting tension/compression loads of $222 \text{kN (50,000 lbf)}$ along two perpendicular planar axes. Each actuator of the frame (four of them) can be independently programmed either in load or displacement control via a feedback loop from load cells or linear variable differential transformer (LVDT) as shown in Fig. 3. There are 2 load cells indicated as A and B in Fig. 3 mated to 2 of the 4 actuators. Each load cell is rated for a magnitude of $222 \text{kN (50,000 lbf)}$ in tension and compression. A typical test would use proportional loading, whereby the loads (or displacements) increase in the same proportion along the two axes.

2.3. Data acquisition

The objective of the biaxial tests was to measure the response of the material as it progressively fails. For this purpose, the applied load resultants, the strain state at the center of the specimen (via strain gages) and the entire biaxial strain field ($\epsilon_x, \epsilon_y$ and $\gamma_{xy}$) within the area of the specimen surface that is illuminated, via DSP, were measured during the entire loading process (from inception to final catastrophic failure). The DSP leads to large amounts of image data, typically 500 MB to 1 GB amount of data per test. In early stages (linear response) of loading, these image data shed no new light on the specimen response, when compared to the data from strain gages. But consequently, as the testing progressed, data from selected images corresponding to stages of damage initiation, localization and damage
Table 1
Material descriptions of carbon braided composites

| Braided $-45^\circ/0^\circ/+45^\circ$ Carbon fiber composite (8.6 mm thick) |
|-----------------|-----------------|-----------------|-----------------|
| Fiber           | Resin           | No. of plies    | Thickness       |
| Fortafib Fibers | Epoxy           | 8              | 0.339 in        |
| (axial tow)     | vinyl ester     |                | 55%             |
| Tensile modulus | (Ashland       |                |                 |
| 231 GPa         | Hetron 922)     |                |                 |
| $X$-sectional area (3.3 x 10^5 mm$^2$) | 3.72 GPa |

Grafil 12 K (Bias tow)
Tensile modulus 234 GPa
Tensile strength 4.5 GPa
$X$-sectional area (3.7 x 10^5 mm$^2$)

propagation provided much more information, since at this stage the strain gages have exceeded their capacity and are rendered inaccurate.

Strain gages are placed in a rosette pattern as shown in Fig. 2. The 3-gage rosette pattern is used in the back surface of the specimen and a single gage is placed on the specimen front surface in the direction of the compressive load. In this manner, the front surface of the specimen can be used to obtain full field strain data via the DSP procedure. The back-to-back gages, in the compressive loading direction, provide the average compressive axial strains and bending strains. In this case, bending strains are expected to be near zero, which is the case during the tests, as will be evident later. With the 3-gage rosette pattern, all strain components are determined through the small strain transformation relationships below.

$$
\varepsilon_1(\theta_1) = m^2(\theta_1)\varepsilon_x + n^2(\theta_1)\varepsilon_y + m(\theta_1)n(\theta_1)\gamma_{xy}/2,
$$

$$
\varepsilon_2(\theta_2) = m^2(\theta_2)\varepsilon_x + n^2(\theta_2)\varepsilon_y + m(\theta_2)n(\theta_2)\gamma_{xy}/2,
$$

$$
\varepsilon_3(\theta_3) = m^2(\theta_3)\varepsilon_x + n^2(\theta_3)\varepsilon_y + m(\theta_3)n(\theta_3)\gamma_{xy}/2,
$$

(1)

where, $m(\theta_i) = \cos \theta_i$ and $n(\theta_i) = \sin \theta_i$.

In these tests, $\theta_1 = 0^\circ$, $\theta_2 = 45^\circ$, $\theta_3 = 90^\circ$. Angles are measured with respect to the horizontal axis and
these angles indicate that the 1–2 coordinate system corresponds to the x–y coordinate system, as indicated in Fig. 2.

Dog-bone type uniaxial test specimens were used to obtain the orthotropic moduli, and the major Poisson’s ratio. The values so obtained that are reported here are reflective of at least three tests per each type of moduli reported. Both, strain gage readings and DSP were used to measure the average gage section strains in all of the uniaxial tests.

2.4. Test procedure

In a typical biaxial test, the specimen is placed within the wedge grips and all strain gages are balanced and initialized to zero prior to commencement of loading. The digital camera that is positioned to acquire images is pre-programmed to capture images of the specimen front surface (an area of 10 mm × 10 mm) at a frequency of 1 frame/s, throughout the loading history. The schematic drawing of the test setup and experimental setup is shown in Fig. 4. The setup to use DSP in the experiments is shown in Fig. 5. The strain gage readings and the load cell readings are acquired at 4 Hz, while the actuator movement rate (the displacement control loading) is carried out at 0.0005 in/s for the uniaxial tests and for a 1:1.5 compression-tension test, the compression direction actuator moves at 0.0005 in/s while the tension direction actuator moves at 0.00075 in/s.

3. Results and discussion of failure mechanisms for uniaxial and biaxial tests of carbon (−45°/0°/ + 45°) 2DTBCs

Fig. 6 shows the incremental (snap shot) shear strain, $\gamma_{xy}$, contour plots for a typical 2DTBC specimen undergoing a displacement-control loading ratio of 1:1.5 (see Fig. 7 for loading ratios). All notations, as in 1:1.5, indicate that the first number of the ratio refers to compression and the second number refers to tension. Sample DSP calculation in Fig. 6 is done with reference time at ‘t1’ as indicated in Fig. 8. This figure shows or locates the reference times, t1–t8 corresponding to each image from frame 76 to frame 83 (F76–F83), respectively. These master plots (Figs. 7–9) show the actuator displacements, loads and strains gage readings, respectively, as functions of time. Fig. 6 also shows the planar area that is in view in each contour plot, outlined in the upper left corner image. For example, the incremental strain contour plot for $\Delta_8$ for this test of loading ratio 1:1.5 in Fig. 11, are the incremental strains at time t2 with respect to the deformation state at time t1. The current time t2 and the reference time t1 are indicated at the top of each contour plot and the corresponding frame number F76–F77 is indicated at the bottom. These reference times in turn can be used for locating the corresponding load cell and strain gage data from the other graphs or master plots. A series of speckle images corresponding to the times indicated in Fig. 8 are shown in Fig. 10. In this manner, a sequence of incremental strain plots for $\Delta_8$, $\Delta_9$, and $\Delta_7$ as indicated in Figs. 11–13 are obtained. No incremental strain plots were made between times t7 and t8 because the material has completely ruptured at this point and thus no correlation can be found in the DSP method. These plots provide non-linear (with respect to load) pointwise values of strains in the regions of damaging material. In this particular specimen, distributed matrix cracking (DMC) that start at very low tensile loads progressively accumulate leading to fiber tows locally loosing their support, which in the case of local compression leads to tow buckling/tow kinking. This type of damage is as shown in Fig. 14. The distributed matrix cracks are caused by the large tensile stresses that develop in the matrix situated between fiber tows. Within a tow, individual fibers undergo different deformation and rotation; consequently the matrix layers in between are subjected to shear. This shear generates substantial tensile stresses at large values (a shear can be decomposed into diagonal tension/compression). The large incremental shear strains just prior to failure are clearly visible in the speckle strain maps shown in Fig. 13. Notice that the maximum $\Delta_7$, within the imaged area is indicated on top of each specklegram, and as seen in Fig. 13, the total accumulated $\Delta_7$, is on the order of 1.41E – 2. Similarly, the maximum accumulated tensile strains and compressive strains are on the order of 9.00E – 3 and 9.65E – 3, respectively. Furthermore, notice in Fig. 13 (compared to the last specklegram in Fig. 10, which shows the failed bias tow) that the maximum incremental shear strains are occurring parallel to the bias tows.
Fig. 4. A schematic of the biaxial test set-up.
indicative of the large deformation preceding the buckling event.

Notice that the incremental shear strains are relatively large compared to the other strain values and progressing to different areas between the matrix and bias or angle tows. These large strains lead to progressive matrix cracking indicating strain softening induced by the damaging material.

With a view to understanding the effects of different biaxial stress and strain ratios, 10 types of tests were performed on the braided composite, including uniaxial tension tests and uniaxial compression tests. In each test, the specimen was subjected to biaxial tension and compression displacement loading, but each type of test was done with a different loading ratio. The loading ratios used are presented in Fig. 15.

The main mechanisms of failure for all the braided composite samples loaded biaxially is braid (tow)/matrix interfacial failure along the tows and tow buckling. Moreover, there are also many visible distributed cracks perpendicular to the tensioned direction. This distributed cracking occurs prior to the catastrophic failure event and is the mechanism by which the entire specimen undergoes strain softening. The culmination of this event is the growth of damage along the braid/matrix interface, and in the case
Fig. 7. Plot of actuator displacement versus time for a compression/tension ratio of 1:1.5.

Fig. 8. Plot of compressive load and tensile load versus time for a ratio of 1:1.5.
of large compression, tow buckling and tow kinking. In the pure compression case, distributed cracks were not present in the failed specimen. In compression, the damage localizes into a band of about 8–12 mm in width, which is approximately the size of the representative unit cell (RUC) for the braided composite (the RUC is also termed the “repeat unit”). This implies that the failure mechanism, and thus the physics that limit the compressive strength of 2DTBC is tow buckling in the presence of a matrix that is continually
Fig. 11. Compressive strain plots for 1:1.5 loading ratio for load increments (and corresponding time increments) indicated in Fig. 8.

Fig. 12. Tensile strain plots for 1:1.5 loading ratio for load increments (and corresponding time increments) indicated in Fig. 8.
being sheared (between tows) and “plastically” deforming, offering less and less resistance with continued loading. Here, we are collectively referring to all the mechanisms that cause softening of the matrix as “plastically” deforming. During this process some of the angled tows have also “popped” out from the surface. This mechanism persists for the biaxial compression dominated tests as well. However, the band of failed material becomes rotated (with respect to the loading directions) for different loadings ratios as seen in Fig. 15. For the uniaxial tension test, catastrophic failure is associated with matrix cracking and subsequent rupture of the bias tows. The failing material, as in the uniaxial compression case, forms a damage zone that is perpendicular to the direction of applied load.

The complete compression/tension failure envelope, which is the locus of points in stress space corresponding to catastrophic failure (indicated by a large drop in load carrying capacity (see Fig. 8), is given in Fig. 16. These points can be connected by a representative curve, as indicated, that is parabolic, although careful observation reveals that there seems to be a compressive load limit and a tensile load limit. This implies that there exists a small range of
Fig. 15. Displacement ratios used in biaxial test matrix and corresponding failure points in displacement space.

Fig. 16. Failure envelope of biaxial tests for $-45^\circ/0^\circ/+45^\circ$ CTBC in stress space.
compressive/tensile load combinations that are not affected by load biaxiality. Instead, there is an upper bound for the compressive strength controlled by tow buckling and a lower bound for the tensile strength that is limited by the critical matrix tensile cracking strain. Typical failure patterns for different loading ratios are shown in Fig. 17 (images a–e).

4. Concluding remarks

The experimental results that we have presented clearly identify the failure mechanisms and how remote loads influence these mechanisms. In particular, the mode of failure for braided composites (under bi-axial stress states) involve distributed matrix cracking (DMC), and local loss of stability due to tow buckling, which precipitates braid/matrix interfacial failure (BMI). These mechanisms cause the release of internal strain energy. The damage zone is usually localized and causes the specimen to loose structural integrity.

For compression-dominated situations, there is an upper bound on the compressive strength and this can be obtained by a uniaxial compression test. For pure tension loading, the matrix cracking strain limits the tensile strength. DMC leads to gradual softening, which ultimately leads to catastrophic failure. For DMC, the relevant quantities that are important for characterizing the energy released are the matrix tensile cracking strain and the matrix fracture energy, while for BMI, the relevant quantities are local stability of the microstructure and the interfacial fiber/matrix fracture energy. In the case of pure compression, DMC is absent, instead tow buckling and tow kinking along with matrix inelasticity are the dominant modes of failure. When the tows buckle, the tow/interface fails (BMI) and this mechanism releases energy. A micromechanics based finite element model is developed in the second part of this two part paper. This model, which is a mechanism based approach to predicting failure, will be shown to predict the failure initiation envelope quite well.
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