Experimental Observations of Damage States in Unnotched and Notched 3D Orthogonal Woven Coupons Loaded in Tension

Wade C. Jackson¹, Andrew C. Bergan², Cheryl A. Rose³
NASA Langley Research Center, Hampton, VA, 23681, U.S.A.

Kenneth N. Segal⁴
Goddard Space Flight Center, Greenbelt, MD, 20771, U.S.A.

Nathaniel W. Gardner⁵
Analytical Services and Materials, Hampton, VA, 23681, U.S.A.

Nalinda W. Waas⁶
National Institute for Aviation Research (NIAR), Wichita State University, Wichita, KS, 67260, U.S.A.

This paper describes a series of unnotched and notched tensile tests on two 3D orthogonal woven architectures. Dog bone specimens were used for the unnotched tests, and open-hole specimens were used for the notched tests. For each architecture and test type, two specimens were loaded under monotonic displacement control to failure and two specimens were incrementally loaded to failure in five steps. X-ray computed tomography (CT) was used to characterize the woven architecture and defects on each specimen prior to testing. Digital image correlation (DIC) images were obtained from both sides of the specimen throughout the loading and unloading. Acoustic emission (AE) data were also continuously acquired throughout the loading. For the incremental tests, X-ray CT was used to document the damage progression after each load increment. The damage progression was analyzed based on the results from these three techniques. The results for both architectures and test specimens followed a pattern where matrix cracks formed at the surface perpendicular to the tensile load direction. New surface cracks formed continuously throughout the loading and cracks extended in depth and width. In general, fiber failure was not detected until specimen failure.

I. Introduction

Three-dimensional (3D) orthogonal woven composites offer reinforcement in all three directions. Some of the advantages of this class of materials include reduced notch sensitivity, near net-shape preforming, and improved through-thickness load carrying capability. The through-thickness reinforcement essentially eliminates delamination between the in-plane layers. Structures with complex shapes or with significant out-of-plane loads may gain performance advantages by using 3D woven composites. A more complete discussion of the current state-of-the-art in 3D orthogonal woven composites is available in recent review articles [1, 2]. In application of 3D orthogonal woven composites, the weave architecture becomes an additional design variable. As a result of the numerous permutations of weave architectures and loading conditions that arise, numerical simulation tools that can evaluate the performance of different architectures under relevant loading conditions are sought to reduce the empirical burden.

1 Senior Research Aerospace Engineer, Durability, Damage Tolerance, and Reliability Branch, MS 188E.
2 Research Aerospace Engineer, Durability, Damage Tolerance, and Reliability Branch, MS 188E, Senior Member.
3 Senior Research Aerospace Engineer, Durability, Damage Tolerance, and Reliability Branch, MS 188E.
4 Aerospace Engineer, Mechanical Systems Analysis and Simulation Branch, Member.
6 Research Associate, Composites and Structures.
Numerous modeling approaches have been proposed for predicting the stiffness, strength, and damage tolerance of 3D woven materials, e.g., [2, 3, 4, 5, 6, 7, 8]. However, the maturity of these models remains low for several reasons that include the complexity of the tow architecture and associated difficulties with development of representative models, variations and defects that are unavoidable during the manufacturing process, and a lack of experimental understanding of the damage process during loading. Researchers have contributed to the third issue by conducting test campaigns with post-mortem or incremental inspections. Warren et al. conducted quasi-static tension, compression, and in-plane shear tests on 3D orthogonal woven specimens fabricated with IM7 fibers and epoxy resin [9]. Post-mortem inspections showed debonding of the matrix from the tows was a common failure mechanism. Bogdanovich et al. used acoustic emission, digital image correlation (DIC), X-ray, and microscopy to determine damage initiation strain in the range of 0.4–0.6% [10]. Pankow et al. compared the response of orthogonal and layer-to-layer 3D woven S2 glass/SC-resin composite specimens loaded under quasi-static tension [11]. The DIC data revealed architecture dependent strain fields. Post-test visual inspection aided by dye penetrant showed matrix cracks developed following the tow boundaries and correlated spatially with the strain concentrations observed in the DIC data. Castaneda et al. also found good agreement between strain localizations observed in DIC and matrix cracks with locations and sizes correlated to the weave pattern [12]. Muñoz et al. reported the damage mechanisms in the warp and weft directions of 3D woven coupons with a hybridized architecture consisting of glass and carbon tows subjected to tensile loading [13]. The damage was imaged at various subcritical load levels with X-ray computed tomography (CT) and an X-ray opaque liquid to assist visualization. They found matrix cracking and tow debonding started at relatively low strains. These damage modes were arrested by fibers oriented across the crack plane and therefore had minimal effect on the stiffness.

This paper builds on the existing body of work by reporting the damage onset and evolution behavior of 3D orthogonal woven carbon/epoxy coupons subjected to tension loads. A series of unnotched and notched tensile tests were conducted on two different 3D orthogonal woven architectures. Understanding of the failure mechanisms was gained through the use of X-ray computed tomography (CT) inspection, high-resolution digital image correlation (DIC), and acoustic emission (AE). The results of the experimental investigation provide an understanding of the complex failure mechanisms that are required to enable safe and efficient application of this class of materials, as well as a detailed record of damage development and progression throughout the loading history. Characterization of the damage and its progression is necessary to support the development of progressive damage analysis methods that can predict this damage behavior and therefore the strength and damage tolerance of 3D woven structures.

II. Three-Dimensional Orthogonal Weave Architecture

Two 3D orthogonal weave architectures were selected for testing. The test specimens were woven with IM7 fiber tows and infused with RTM6 in a resin transfer molding process. The weaving was performed by Bally Ribbon Mills. The tests described herein were conducted on specimens from two panels, designated CTE-1Z and CTE-3Z. These two panels were woven with 6K tows and the weave patterns are shown in Figure 1.

Fig. 1. The primary difference between the two weave patterns is panel CTE-3Z has three Z-tows per dent and CTE-1Z has one Z-tow per dent. The design values for weaves are summarized in Table 1. The panels were infused with resin and cured by North Coast Composites.
Fig. 1 Weave patterns used for the two panels: (a) CTE-1Z and (b) CTE-3Z. The tow sizes and aspect ratios are arbitrary in this figure.

Table 1 As-designed flat panel weave information.

<table>
<thead>
<tr>
<th>Panel</th>
<th>Unit cell dimensions (inches)</th>
<th>Fiber content (%)</th>
<th>% fiber volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warp</td>
<td>Weft</td>
<td>Z</td>
</tr>
<tr>
<td>CTE-1Z</td>
<td>0.378</td>
<td>0.125</td>
<td>0.125</td>
</tr>
<tr>
<td>CTE-3Z</td>
<td>0.324</td>
<td>0.189</td>
<td>0.125</td>
</tr>
</tbody>
</table>

III. Test Specimens and Techniques

A dog-bone specimen and an open-hole specimen were selected for the unnotched and notched configurations, respectively. Four tension dog-bone (TDB) specimens were cut from each of the two panels with the length of the specimen aligned in the warp direction. These specimens were named, beginning with the panel number, CTE-3Z-TDB-X (where X corresponds to the letters D through H) and CTE-1Z-TDB-X (where X corresponds to the letters H through M). Similarly, four open-hole tension (OHT) specimens were cut from each panel with the length of the specimen aligned in the warp direction. These specimens were named CTE-1Z-OHT-X (X corresponds to T through W) and CTE-3Z-OHT-X (X corresponds to D through G). The letter designation identifies the individual replicates.

The nominal specimen configurations are shown in Fig. 2. In all the OHT specimens, the specimen width to hole diameter ratio, \( w/d \), is equal to 6, and the gage length to hole diameter ratio, \( l/d \), is 20. The OHT dimensions are provided below:

- Hole diameter \( (d) = 0.25 \) in.
- Gauge Section Length \( (l) = 5 \) in.
- Width \( (w) = 1.5 \) in.
- Thickness = 0.125 in.
All tests were performed under ambient conditions using a servo-hydraulic test stand with hydraulic wedge grips. Test data/instrumentation included test stand cross-head displacement, force, displacement transducers attached to the specimens, high-resolution digital image correlation (DIC) systems on front and back surfaces, and real-time acoustic emission (AE). The OHT specimens also had four strain gages, front to back on either end near the grips. Prior to testing, a high-resolution X-ray computed tomography (CT) scan was obtained on each specimen to document the woven architecture within the specimen and to identify defects (primarily cracks) from manufacturing and machining.

AE sensors were bonded onto all specimens and were monitored in real time during testing. The AE sensors were used as an aid to guide test interruptions (unloading points). The AE systems provided feedback that was useful for identifying damage onset, progression, and times when large acoustic events occurred. The TDB specimens had one sensor at each end along the centerline and near the grips. The OHT specimens had two sensors at each end, which were spread out near the edges. In addition to providing information on when damage events occurred during loading, the sensors were used to triangulate the source of the acoustic events. Since there were only two sensors on the TDB specimens, the AE source locations were limited to a one-dimensional plot. However, for the OHT specimens, AE sources could be located on a 2D map of the specimen. After testing, the AE data was correlated with the DIC data to identify specific crack formations that resulted in acoustic events.

For each test series, two specimens were loaded monotonically to failure, and two specimens were loaded incrementally to failure. The tests were performed incrementally so that X-ray CT scans could be performed between test runs to investigate the damage formation and progression. Test interruptions on the incremental testing focused on damage initiation and damage formation near failure. Both real-time AE and real-time DIC were used to guide the test interruptions.

IV. Results

The baseline X-ray CT scans revealed extensive cracking from the cure cycle. Typical defects are shown in an X-ray CT scan in Figure 3. The majority of cracking was around and within the Z-direction or binder tows. There was
also a significant amount of voids and splitting within the weft tows. Cracks were also present in the resin areas between the warp tows. For the incremental test series, the initial cracks were noted and monitored for growth.

Fig. 3 Initial defects shown in a X-ray CT image of a dog-bone specimen. Cut-planes are shown to display interior damage.

For each panel and test type, two specimens were loaded to failure, and then the incremental tests followed. Specimens were loaded in displacement control at a ramp rate of 0.01 inches/min. For OHT specimens, the average failure loads (set of four specimens) were 10,673 lbs. and 12,965 lbs. for specimens from panels CTE-1Z and CTE-3Z, respectively. Similarly, for the TDB tests, the average failure loads were 6411 lbs. and 7922 lbs. for specimens from panels CTE-1Z and CTE-3Z, respectively. Figure 4 shows a typical failure for a TDB and for a OHT specimen. Failures on the TDB specimens were located at or near where the curved edges transition into the straight section and were straight across the width. Failures on the OHT specimens also went almost straight across the specimen width and were near the center of the hole.

Fig. 4 Typical failure locations. Gripped region of dogbone specimen is not shown.
Acoustic emission and DIC measurements were used to detect damage development early in the loading. The DIC systems were able to highlight surface crack formation using “sigma” which is a calculated value related to measurement uncertainty in the image correlation [14]. High sigma values are typically associated with damage, and the high-sigma regions from the DIC were later confirmed as surface cracking on the X-ray CT scans. The surface cracks tended to form in the resin pockets at the surface and were normal to the loading direction. On the TDB specimens, surface crack development began at approximately 20% of the failure load. With increasing load, cracks developed over the entire front and back surface with a crack length corresponding to the distance between warp tows. For the OHT specimens, the initial cracks formed at approximately 7% of the maximum load ($F_{\text{max}}$) and were located at the hole edge (Figure 5). At higher loads, these cracks became distributed over the front and back surfaces as shown in Figure 5 for loads of 50% and 99% of the specimen failure load, $F_{\text{max}}$.

![Fig. 5 Surface crack formation as shown in the DIC sigma field for a CTE-1Z OHT specimen. Red regions indicate high values of the correlation coefficient, sigma, corresponding to cracking.](image)

Examples of acoustic event plots are shown in Figure 6 for the first incremental loading of a CTE OHT specimen. The first significant event occurs just after 40 seconds and corresponds to damage development at the hole edge (Figure 6a). After 80 seconds, damage develops almost continuously and includes damage development around the hole and tensile cracks on the surface away from the hole. Points of audible events are also noted on the figure. On Figure 6b, the cumulative absolute acoustic energy from each of the four AE sensors is shown as a function of time along with the applied load. AE sensor 3 has the highest cumulative energy, which should correspond to more damage events near that sensor. Using this information in real time guided test interruptions to identify damage initiation and significant events that was documented using X-ray CT scans.
By using multiple AE sensors on each specimen, sources of acoustic events could be spatially identified. The AE event time and location information were cross referenced with the front and back processed DIC images to correlate crack formation with acoustic events. A correlation of these two data sets is shown for significant acoustic events in Figure 7 using a plot of longitudinal strain obtained from the DIC data. For this CTE-3Z TDB specimen, most of the higher energy events are shown in the upper region where the specimen width transitions from straight to curved. This upper transition region is where the specimen eventually failed.
Fig. 7 Surface crack formation as shown in the DIC $\varepsilon_{yy}$ field for a CTE-3Z TDB specimen.

The principal means of investigating the development and progression of damage mechanisms is through the use of X-ray CT scans in the incremental test series. The primary damage observations were the formation of tensile cracks perpendicular to the load direction. After a certain critical load, these cracks were observed to form nearly continually over most of the front and back surfaces until failure. X-ray CT images showed that the cracks may be present at the surface but can extend completely through the thickness as the specimen approaches failure. An example of this behavior is shown in Figure 8 where cracks are shown to extend between the front and back surfaces and often pass through the weft tows. Although initial scans showed widespread cracking, formation and extension of these transverse tensile matrix cracks were the primary damage mechanisms. No fiber failures were observed in the TDB specimens prior to failure. In the OHT specimens, a limited amount of fiber failures was observed in warp tows (along the loading direction) that intersected the edge of the hole.

(a) Pre-test CT image showing cracking from manufacturing
The damage mechanisms in 3D orthogonal woven specimens were investigated using unnotched (dogbone) and notched (open hole) tensile coupons. The test series was repeated for two different woven architectures and consisted of both monotonically loading specimens straight to failure and incrementally loading to failure. The final version of this paper will include a more detailed analysis of the damage development and growth. In addition, the differences in damage response between the two woven architectures will be further investigated.

Acknowledgments

The authors wish to acknowledge the inputs from Will Johnston and Mike Horne on the test plan, experimental setup, and results interpretation.

References


American Institute of Aeronautics and Astronautics

