BEARING BEHAVIOR OF 3D WOVEN COMPOSITES

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1 Introduction

3D weaving is a manufacturing process capable of producing near net, highly shaped textile preforms with interlocking fibers between layers. A Jacquard loom enables the complicated fiber architectures during 3D weaving, as each warp end in a preform is controlled independently. The preform cross-sectional shape is generated by using either a shuttle or rapier to insert multiple weft fibers (those fibers perpendicular to the warp) to build up thickness. The complete cross section may take several dozen insertions to complete, depending upon the desired structural performance, fiber volume, etc. At the completion of each set of passes, the preform take-up advances and the process is repeated. In effect, the preform consists of a series of parallel planes of fiber connected by small lengths of warp fiber. The interlocking fibers provide increased damage tolerance when compared to 2D laminated composite structures. These types of preforms are now being used, or considered for use, in a wide variety of aerospace engine and airframe applications.

In some of these applications, mechanical fasteners are the primary method for joining structure. Typically, for bearing response, quasi-isotropic laminate designs are found when 2D laminates are employed. However, the off-axis fibers present in a 2D quasi-isotropic laminate are difficult to cost effectively incorporate into a 3D woven structure. Consequently, there is interest in understanding whether the presence of reinforcement in the z-direction of the 3D woven composite compensates for the lack of off axis fibers in bearing applications.

To better characterize 3D composites for use in such applications, Albany Engineered Composites (AEC) investigated the response of 3D woven composites to loads introduced via mechanical fasteners. Tests were conducted on specimens fabricated from 3D woven preforms using a Resin Transfer Molding (RTM) process.

Specifically, AEC examined the bearing response of 3D woven composites in double shear [1] and the pull through strength [2] as a function of weft tow size and preform architecture. Warp tow size was held constant for this study.

2 Materials and Methods

2.1 Fiber

This investigation explored the effect of the tow size in the weft direction for IM 7, which is an intermediate modulus carbon fiber manufactured by Hexcel Corporation [3]. The tow sizes for this study were limited to 12k and 24k. The warp fibers were held constant as 12k IM7. The 12k tow was procured and used as is from Hexcel. Additional processing (twisting) was necessary to make the 24k tow.

Availability, cost and demonstrated application of these fiber types in certified composite structures prompted the selection of this particular fiber type and tow sizes.

2.2 Resin

This research utilized a toughened epoxy resin system, ST-15, which is manufactured by Hexcel Corporation. The resin is formulated for use in the RTM process.

Availability, cost, and the use of ST-15 on aerospace composite structures currently in certification were primary drivers in selecting this resin system for this study.

2.3 Preform Architectures

Two types of preform architectures were examined, orthogonal and ply to ply angle interlock. In an orthogonal design, the warps go from the upper surface of the preform to lower in a single weft column. For a ply to ply angle interlock design, the transition of the warp from surface to surface occurs over numerous weft columns. A weft column refers to the number of wefts inserted into a preform prior to the take-up advancement.

Figure 1 illustrates typical designs for orthogonal and ply to ply angle interlock. It should be noted that the interlocking fiber in the ply to ply design only goes down a few layers. The interlocked layers are tied together by alternating the location of the interlocks along the warp direction of the preform.

Because of the various possible combinations available when designing 3D woven preforms, it was necessary to further limit the design space.

The warp to weft ratio was restricted to 50:50 and 60:40 for each of the architectures. In addition, the selected designs had a fiber volume fraction of 51 ± 3% at the molded thickness. AEC selected the warp/weft ratio based upon previous experience. The availability of an existing molding tool drove the selection of the fiber volume.

2.4 Fabrication Methods

2.4.1 Weaving

All of the preforms were woven on the same jacquard loom using a captured shuttle from the same warp. In this instant, warp refers to the all the fiber set up behind the loom that is pulled through the loom during the manufacturing process. A single warp set-up was chosen to save cost and reduce variability from different fiber lots as it limited the draw-in to a single event. Draw-in is the step in the weaving process where the warp fibers are inserted into the heddles of the jacquard loom.

The program code for each design was generated using AEC proprietary software, Techniweaver™. It was then loaded into the loom control system and executed by the weaving technician.

2.4.2 Molding

All of the composite panels were manufactured using Resin Transfer Molding (RTM). A two sided closed mold was utilized to compact the preform to the desired fiber volume fraction. The average panel thickness for this study was 4.08 mm ±0.1mm. For this effort, a single mold injection method was used – one part produced per each injection.

While a press is often used in RTM, these particular composite panels were fabricated in an oven as the tool was designed for oven processing. Strong backs, which are external stiffeners, were employed to minimize the variability between molded parts. In addition, the same oven was used to manufacture the parts to reduce variability.

As the tool was reaching the prescribed temperature, the cavity was evacuated to a predetermined level and a leak check was performed. Upon successful completion of the leak check, a pre-heated resin was then injected into the mold under slight pressure using a Radius 10,000 cc injector. [4]

This particular injector allows process to be controlled by either pressure or flow. Flow control was utilized for these injections. The same injector was used to manufacture all the panels.

The actual RTM process parameters, while proprietary to AEC, were within the recommended parameters provided by the manufacturer.

2.5 Test Methods

AEC utilized an independent test laboratory to perform mechanical testing of the composite panels. Specifically, the testing investigated the bearing response in double shear using reference [1], procedure B and the fastener pull through according to reference [2]. Fiber volume was also determined using method I, procedure B of reference [5] so that the results could be normalized and compared.

For the bearing response in double shear, AEC tested the 3D woven composite panels at three distinct orientations – 0 degrees, which coincides with the warp fiber path, 45 degrees, and 90 degrees, which aligns the load path with the weft fiber direction of the specimen.

This approach resulted in a total of 144 data points for the bearing response of 3D woven composites (eight preform architectures with six specimens per orientation). Figure 2 shows a typical test set-up for the bearing test. Specifically, this set up shows a specimen cut from the molded panel at a 45 degree orientation.

For the bearing test, Hi-Lok® aerospace grade fasteners with a diameter of 6.35 mm were used. The bolt part number was HL18PB8 – 10 and the collar part number was HL70 – 8. The collars were selected as their strength was not important for this test set-up and they provided a cost savings over other material choices.

The fastener pull-through assessment utilized the standard test configuration found in reference [2]. This set-up was not dependent upon the orientation of the specimen. Consequently, many fewer test specimen (48 total – eight preform architectures with six specimen per panel) were required. Figure 4 shows the pull-through test set-up.

The fasteners used in the pull through testing were Hi-Lok® aerospace grade with a diameter of 6.35 mm. In this case though, the head diameter was increased to accommodate tensile loading. The bolt part number was a HL20PB8 – 5, while the collar's part number was a HL75 – 8A.

Both testing procedures used a loading rate of 1.27 mm/min. The load cell for the test machine was 97.9 kN.

All mechanical testing was completed at room temperature ambient conditions. Physical testing was completed in accordance with reference [5], test method I, procedure B.

2.6 Results

The results have been normalized to 60% fiber volume (FV) using equation 1.

$$Normalized\ Value = Test\ Value * \frac{FVnormalizing}{FVtest\ value} \qquad (1)$$

Normalizing the data permits comparison of the results while reducing the influence of manufacturing variability. The 60% FV value was selected as it is typically the number associated with structural prepreg laminates.

The use of a typical cured ply thickness was not used in the normalization as 3D woven composites do not have plies. The variance between the specimen thicknesses was less than one percent and did not influence the results to any degree.

2.6.1 Bearing Testing

The primary failure type found in this testing was predominately bearing with the onset of shearout. Figure 5 displays an idealized failure mode for bearing failure. Figure 6 shows the idealized failure mode for shearout failure. Both figures are found in reference [2]. The reference also provides a detailed breakdown of other possible failure modes. These modes, however, were not observed in any of the testing.

Figure 7 shows a typical bearing testing specimen failure for a 3D composite sample. The primary failure mode in this case was bearing while a slight amount of shearout is visible in the picture along the edge of the coupon that is directly to the right of the hole location.

Table 1 contains the average of the 2% offset bearing strength for each design normalized to 60%. At each orientation of the studied architectures – 0º (parallel with warp direction), 45º, and 90º (weft aligned with the load) – 3D woven composites have comparable 2% Offset Yield Stress and Ultimate Strength in bearing when compared against similar architectures.

For similar preform construction (i.e. same size weft tows), ply to ply architectures tend to have greater strength in the 0 and 45 degree directions while the bearing strengths in the 90 degree direction appear to be comparable for either architecture with no apparent trends.

Figure 8 shows a typical stress strain curve for 3D woven composites at 0, 45 and 90 degree orientations. While this illustration is for a ply to ply design, the response of the orthogonal architecture was similar.

The significant amount of area under the curve suggests 3D woven composites can carry substantial load after the initial onset of damage.

The bearing strength was not influenced by fill tow sizes (12k vs 24k) for either architecture.

2.6.2 Pull-Through Testing

This testing utilized procedure A of reference [2] to examine the pull through strength of the 3D woven composites. Figure 4 shows the conventional test set-up for procedure A. Since this particular test examines a characteristic normal to the fiber plane, it was not necessary to characterize the specimen at any prescribed orientations.

There were two types of failure – pull through and flexure, when tested in accordance with reference [2]. Figure 9 shows a typical flexure failure while figure 10 demonstrates a typical pull through failure.

For the pull through testing, 3D woven composites exhibit little variation (3%) in the initial critical loads among the considered fiber architectures. They do display a long elongation to fracture (~9 mm) and a damage that is localized near the hole.

2.7 Conclusions

Initial results indicate that 3D woven composites can provide adequate bearing strength without the use of bias fibers. The weft tow size, as well as the selected warp to weft ratios, does not appear to influence the bearing response. The ply to ply architecture provides slight improvement in bearing response for applied loads along the warp direction and those applied at 45 degree angle to the warp direction. For loads applied at 90 degrees to the warp direction, the architecture had no apparent effect on bearing response.

Bearing failure modes, specifically bearing and shearout, were consistent with modes observed in 2D laminates. This result suggests that current analytical methods may be used to rough size holes for bearing in 3D composites. However, to fully exploit the capabilities of 3D composite, new micromechanical and analytical models are needed, as 3D woven composites hold significantly more load to significantly higher strains beyond the initial knee in the bearing stress strain curve than conventional 2D laminates. Further work is necessary to fully characterize the bearing response of 3D composites.

2.8 Future Work

Near-term work shall investigate the bearing response of prepreg laminates at the orientations used in this study. The laminates shall be a quasi-isotropic lay-up with similar thickness to the panels used in this investigation. Furthermore, the prepreg laminates will consist of 12k IM-7 fiber in a toughened matrix manufactured by Hexcel.

Additional near term work will investigate the response of intermittent angles between the three (0, 45, and 90) examined in this effort. Specifically, the effort will characterize the bearing response for ply to ply angle interlock panel at every 15 degrees from 0 to 90 degrees, inclusive.

The last part of the near term work will confirm the linearity of 3D woven composites assumed in using normalization. One of the ply to ply architectures will be selected and manufactured with varying levels of fiber volume.

Far-term work will characterize additional resin systems, the fatigue response of promising architecture designs, and conduct some testing at elevated temperature. Additional efforts will utilize the data generated to develop analytical models to predict the stress state within 3D composites structures used in bolted joints.

References

[1] ASTM D 5961, Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates

[2] ASTM D 7332, Standard Test Method for Measuring the Fastener Pull-Through Resistance of a Fiber-Reinforced Polymer Matrix Composite

[3] http://www.hexcel.com/resources/datasheets/carbon-fiber-data-sheets/im7.pdf

[4] http://www.radiuseng.com/10000.pdf

[5] ASTM D3171, Standard Test Methods for Constituent Content of Composite Materials

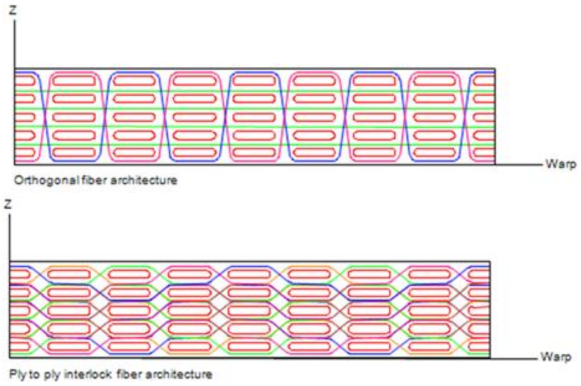

Fig. 1. Preform architecture examples – orthogonal (top) and ply to ply angle interlock (bottom)

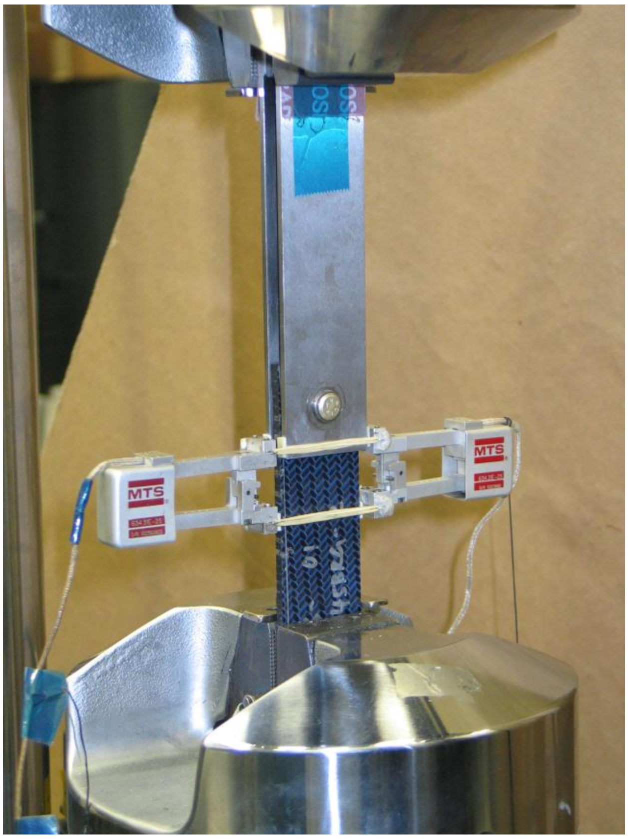

Fig. 2. Double shear test set-up, 45 degree specimen

Fig. 3. Double shear bolt and collar

Fig. 4. Pull-through test set-up

2% Offset Average Bearing Strength, MPa (Normalized)				
Architecture	**Fill Tow Size**	**0 Deg**	**45 Deg**	**90 Deg**
Orthogonal, 50/50	12k	656 ±45	590 ±7	638 ±55
Orthogonal, 60/40	12k	636 ±25	592 ±25	568 ±35
Orthogonal, 50/50	24k	670 ±23	585 ±18	557 ±61
Orthogonal, 60/40	24k	626 ±10	567 ±16	573 ±28
Ply to Ply, 50/50	12k	702 ±31	626 ±31	632 ±18
Ply to Ply, 60/40	12k	693 ±46	613 ±24	572 ±21
Ply to Ply, 50/50	24k	670 ±20	642 ±17	578 ±21
Ply to Ply, 60/40	24k	729 ±35	642 ±25	566 ±23

Table 1. Average bearing stress normalized to 60% FV

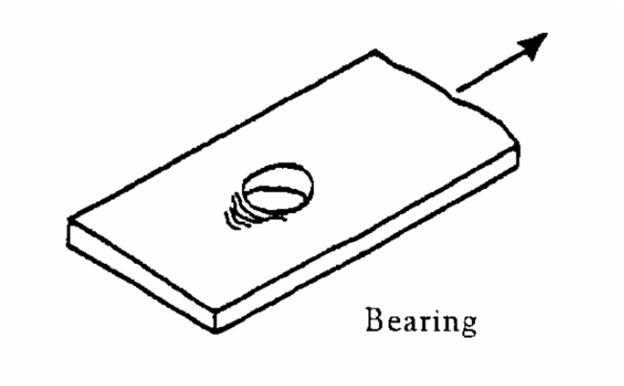

Fig 5. Specimen failure in bearing, B1I, idealized [1]

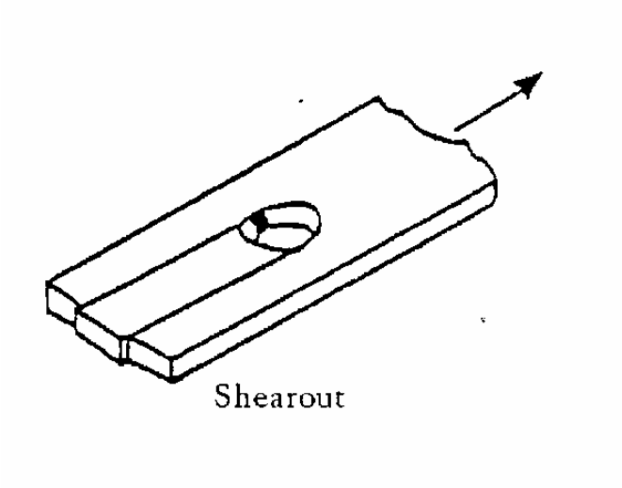

Fig 6. Specimen failure due to shearout, idealized [1]

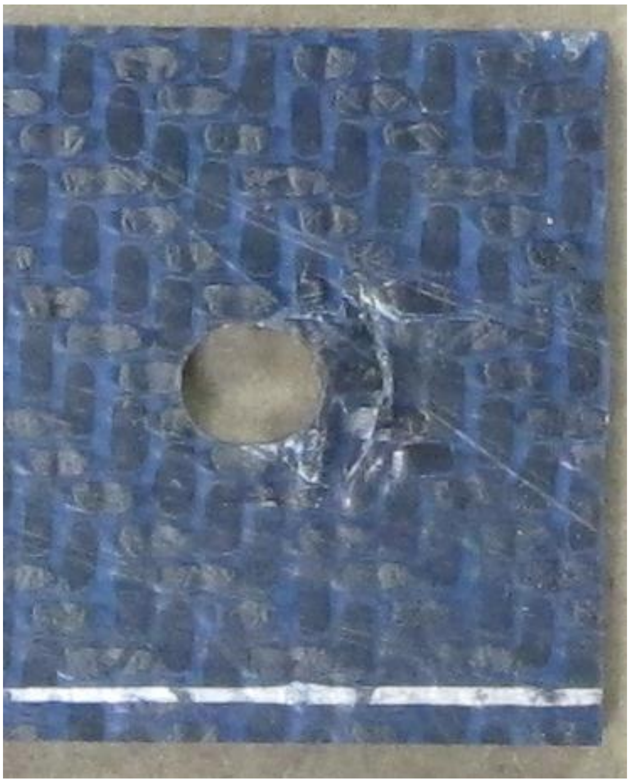

Fig 7. Typical bearing specimen failure for B1I/S1I result, 0 deg specimen shown

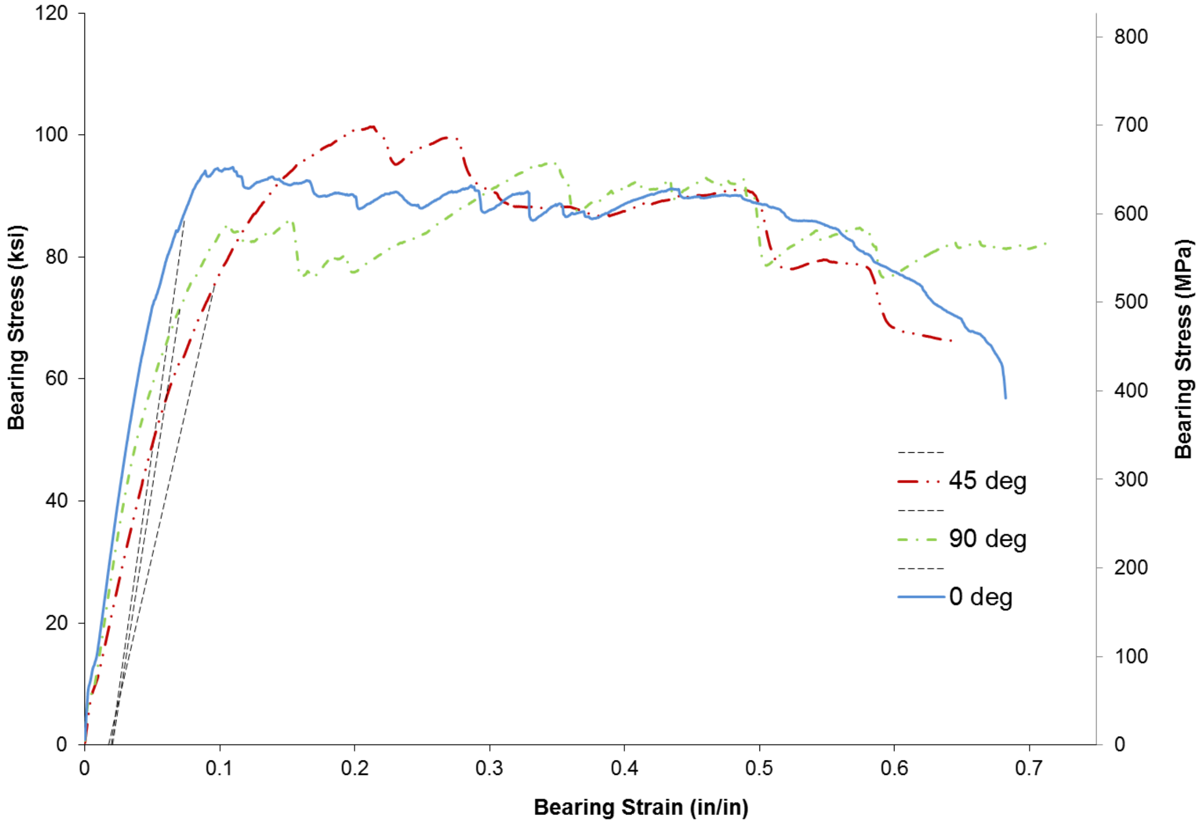

Fig 8. Typical bearing stress-strain
curves for 3D woven architectures

Architecture	Fill Tow Size	Average Maximum Pull-through Load (Normalized)
Orthogonal, 50/50	12k	11.43kN ±580N
Orthogonal, 60/40	12k	11.24kN ±162N
Orthogonal, 50/50	24k	11.61kN ±352N
Orthogonal, 60/40	24k	11.77kN ±161N
Ply to Ply, 50/50	12k	10.77kN ±514N
Ply to Ply, 60/40	12k	11.22kN ±456N
Ply to Ply, 50/50	24k	9.97kN ±294N
Ply to Ply, 60/40	24k	10.23kN ±503N

Table 2. Average maximum pull through load normalized to 60% FV

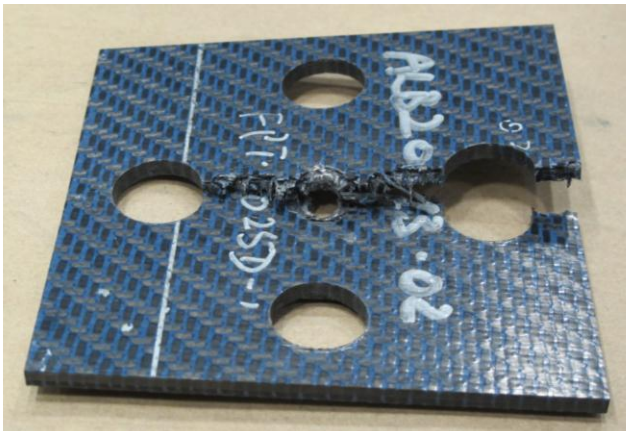

Fig 9. Typical flexural failure mode demonstrated in pull through testing

Fig 10. Typical pull through failure mode demonstrated in pull through testing