SIMPLIFYING CERTIFICATION OF DISCONTINUOUS COMPOSITE MATERIAL FORMS FOR PRIMARY AIRCRAFT STRUCTURES

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ABSTRACT

Discontinuous Fiber Composite (DFC) parts produced using compression molding are being implemented in complex structural geometries in new generation commercial aircraft. However, structural analysis of DFC parts is a challenge since DFC materials do not behave like traditional composites nor like isotropic materials. This paper presents some initial results related to the behavior of HexMC®, a proprietary DFC system produced by the Hexcel Corporation. Flat HexMC test panels were produced using compression molding and used to study the effects of material flow on material behavior. The results of optical microscopy inspections and tensile testing are described and discussed.

1. INTRODUCTION

Discontinuous Fiber Composite (DFC) components are now being used in commercial airplanes. The increasing use of DFC materials is driven by the fact that (relative to continuous fiber composites) these materials allow compression molding of complex parts at relatively low cost. In addition, DFCs provide high delamination resistance, near quasi-isotropic in-plane stiffness, high out-of-plane strength and stiffness, and low notch sensitivity.

Structural analysis of DFC parts is a challenge, since DFC materials do not behave like traditional composites nor like isotropic materials. Further, there are no standards for generating material allowables, design, or analysis methods. As a result, certification of DFC parts is currently achieved by testing a large number of parts (i.e. “Point Design”). This is a time consuming and costly process for the parts manufacturer, the aircraft manufacturer, and the FAA, and may lead to over-conservative part designs. In order to transition to a more desirable certification process based on analysis supported by test evidence, fundamental material behavior must be understood, and material allowables and related analysis methods must be developed to reliably predict the performance of structural details.

A multi-year study with an ultimate goal of simplifying certification of DFC parts has been undertaken by members of AMTAS (Advanced Materials for Transport Aircraft Structures), which is one of two university groups that together form the Joint Advanced Materials & Structures (JAMS) Center of Excellence. JAMS is supported by the FAA and several industrial partners [1]. The present study is focused on HexMC®, a DFC produced by the Hexcel Corporation. HexMC consists of randomly-distributed carbon-epoxy ‘chips’, which are themselves produced from unidirectional AS4/8552 pre-preg (see Figure 1). The chips have nominal in-plane dimensions of 8 mm x 50 mm (0.3 x 2 in). Industrial grade HexMC is

Figure 1: Sample of HexMC random chipped fiber distribution

commercially available in pre-preg form, whereas proprietary aerospace grade HexMC is provided exclusively by Hexcel in the form of manufactured and finished parts [2].

The multi-year AMTAS study involves tests and analyses at both the coupon level and at the component level. At the coupon level, Hexcel is developing an allowables database for aerospace grade HexMC in-house, which will be made available to AMTAS participants involved in the study when completed. This effort involves performing literally hundreds of coupon tests, including unnotched, open-hole, and filled-hole tensile and compressive tests, bearing and bearing-by-pass tests using mechanically-fastened joints with varying hole diameter/specimen width ratios, and buckling/crippling tests, to name but a few. Coupon-level tests intended to supplement the Hexcel allowables testing program are also being conducted at the University of Washington (UW). Some of these will be described in this paper.

At the component level, an aircraft component called an intercostal has been selected for consideration during the AMTAS study. The intercostal is manufactured by Hexcel and is used by Boeing to provide additional load carrying capability between selected circumferential frames of a transport aircraft fuselage. Various tests of intercostals will be performed, and based on both theses tests and the allowables database semi-empirical analysis methods will be developed to match the experimental results.

Tests and analyses of the intercostal components will not be further discussed herein. Rather, the present paper is devoted to some of the coupon-level tests performed at the UW. Specifically, tests of specialized test panels, called ‘high-flow’ panels, will be described. As will be seen, these panels are produced using non-standard manufacturing processes intended to exaggerate the impact(s) of material flow on fiber/chip structure and tensile properties. The AMTAS team plans to present additional papers describing the intercostal tests and analyses during future SAMPE conferences.

2. HIGH-FLOW TEST PANELS

Special ‘high-flow’ test panels were produced to evaluate the effects of material flow on fiber orientation, through-thickness fiber/chip structure, and various mechanical properties. The panels were produced as summarized in Figure 2. A stack of HexMC pre-preg was placed in the center of a simple rectangular mold cavity (Figure 2a). The pre-preg stack had an initial width of 152 mm (6 in) and length of 330 mm (13 in). Application of heat and pressure caused the pre-preg to flow throughout the rectangular cavity (Figure 2b), and the panel was removed from the mold following cure (Figure 2c). Final in-plane plate dimensions were 330 mm x 457 mm (13 in x 18 in). Hence, material flow resulted in a X3 increase in width. Plates with three different target thicknesses were produced: 2.3 mm, 3.6 mm, and 5.8 mm (0.09 in, 0.140 in, and 0.230 in). Plate thickness was increased by increasing the number of HexMC plies in the initial ply stack.

The center region of the panels experienced relatively low levels of chip flow during the molding process, whereas the left and right regions of the panel experienced very high flow levels. The effects of material flow could therefore be explored by studying specimens machined from different regions of the panels.

Tensile specimens were machined from these panels as shown in Figure 3. A numbering system was adopted that reflected symmetrical specimen locations with respect to the panel centerline. Specimen width and length was 38 mm (1.5 in) and 330 mm (13 in), respectively.

2.1 Optical Microscopy

High resolution optical micrographs were obtained at several points within the panels. Results obtained using specimens machined from a 3.6 mm thick panel will be used to illustrate typical results. Micrographs obtained from specimen 1R, near the center of the panel, are shown in Figure 4. Figures 4a,b show that chips remain approximately planar in low-flow regions. The absolute value of the orientation angle of fibers within a given chip can be inferred from the aspect ratio of the polished fiber ends (Fig 4c) and is given by:

$$q = \cos\left[\frac{y}{x}\right] \qquad [1]$$

By convention the angles returned by Eq 1 were interpreted to be within the first quadrant, i.e., 0° £ $|q|$ £ 90°.

In contrast, a micrograph obtained from specimen 6R, near the edge of the panel in the high-flow region, is shown in Figure 5. It is apparent that substantial fiber and chip distortions can occur in high-flow regions, particularly near the edge of the mould. In these areas the chip structure is no longer even approximately planar.

Having used Eq 1 to determine the fiber orientation of individual chips through the thickness of the panel, the weighted average fiber orientation can be calculated as:

$$q_{avg} = \frac{\sum_{i=1}^{n} q_i t_i}{t_{tot}} \qquad [2]$$

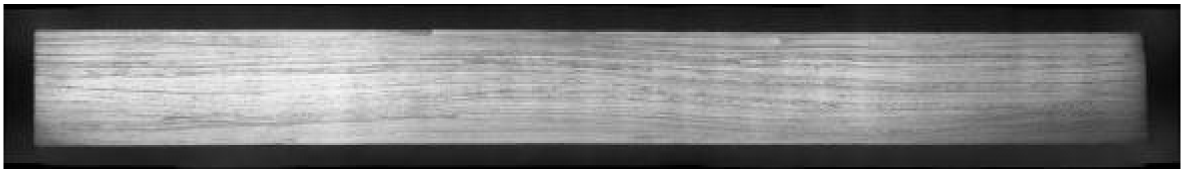
(a) HexMC prepreg stack placed in mold cavity

(b) Heat and pressure applied; material flows to fill mold cavity

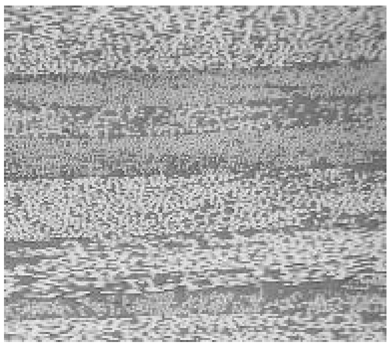
(c) Finished test panel

Figure 2: Producing a high-flow test panel

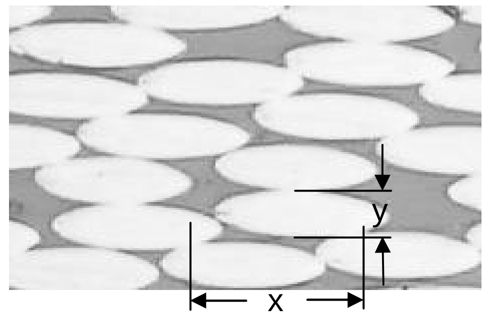
Figure 3: Tensile specimens machined from a high-flow test panel



(a) Polished specimen end (x4 magnification)



(b) Micrograph showing 8 distinct chips (x100)



(c) Micrograph used to infer fiber orientation

Figure 4: Optical micrographs obtained from specimen 1R, machined from the low-flow region of a 3.6mm thick panel

Figure 5: Optical micrograph of edge of plate region showing nonplanar chip formation, specimen 6R

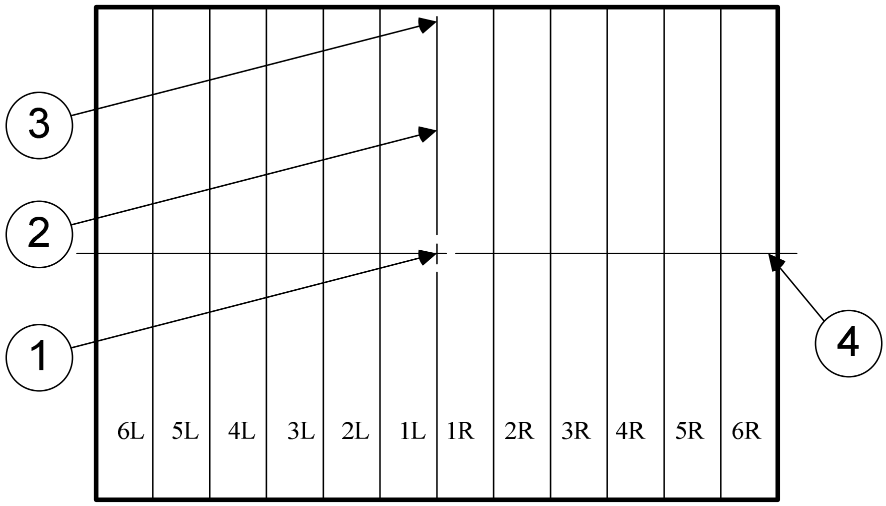


Figure 6: Locations 1-4, where weighted average fiber angles were measured

Table 1: Weighted average fiber angles and fiber volume fractions for a 3.6 mm thick panel, at the locations shown in Figure 6

Location	Number of chips, *n*	Weighted average fiber angle (degs)	Fiber volume fraction (%)
1	38	56.6	54.9
2	34	55.7	54.3
3	26	73.3	N/A
4	24	25.3	54.2

Where t_i is the thickness of an individual chip, n is the number of chips through the thickness of the panel, and t_{tot} is the total thickness of the panel. If fiber orientations were perfectly random, and the number of chips is very large, then the weighted average fiber orientation would converge to 45˚. Measured weighted average fiber angles were obtained at the locations shown in Figure 6. These include the relatively low flow region "1", an intermediate region "2", a region near the low flow edge "3", and a region near the high flow edge "4". Results are tabulated in Table 1. As seen in the table the weighted averages differed significantly from location to location. Reasonably random orientations were measured at the center of the plate and at the intermediate locations (regions 1 and 2, respectively), where the weighted average fiber orientations were found to be ~55º. A preferential orientation was measured near both the low and the high flow edges of the mold, however (locations 3 and 4). In these regions the fibers tend to become aligned parallel to the edge of the mold. As will be seen in a later section, fiber alignment causes a change in tensile modulus near the edge of the panel.

2.2 Fiber Volume Fraction

Fiber volume fractions calculated at sites 1, 2, and 4 for the 3.6 mm thick panel have been included in Table 1. Fiber volume fractions were also determined for the 2.3mm and 5.8 mm thick panels. Volume fractions were calculated using Method 2 described in the ASTM D-3171 standard [3]. This procedure involved calculations of the volume of each specimen as well as weight measurements to determine the composite density. The volume fractions were then derived from the composite density and their constituent densities, i.e. 1.79 g/cc and 1.30 g/cc for the fiber and matrix densities respectively. Very little variation in fiber volume fraction from one point to the next was observed. Volume fractions were also independent of panel thickness. It was concluded that material flow during the molding process had no appreciable impact on fiber volume fraction.

2.3 Tensile Modulus

Each of the three target thickness HexMC panels were sectioned as previously shown in Figure 3 and subjected to a monotonically increasing tensile load until failure occurred. Nominal in-plane specimen dimensions were 38 mm x 330 mm (1.5 in x 13 in). Axial strains were measured using an extensometer with a relatively large gage length of 50 mm (2 in). A relatively large gage length was used because the elastic modulus of HexMC varies substantially from one point to another [4]. The level of variation can be as high as ±19% and is a reflection of the local through-thickness chip structure and orientation. A large gage length was therefore used so as to provide a nominal measure of modulus that does not reflect point-to-point variations.

The modulus measurements obtained for each of the three panel thicknesses are tabulated in Table 2 and plotted in Figure 7. Recall that the initial 152 mm wide ply stack was centered in the mold prior to compression molding (see Figure 2a). Since each specimen were nominally 38 mm wide, specimens 2L ® 2R were machined from the regions of the mold occupied by the ply stack prior to compression molding, as indicated in Figure 7. In contrast, specimens 3L® 6L and 3R® 6R were machined from (initially) empty regions of the mold.

The modulus measurements for specimens 3L, 4L and 3R, 4R do not differ substantially from those measured for the central specimens. However, a significantly higher tensile modulus was measured for specimens 5L, 6L and 5R, 6R. That is, the modulus increased as the edge of the mold was approached. Recalling that the fiber volume fraction was found to be constant across the width of the panel, the increase in modulus was attributed to the increased levels of fiber alignment near the edge.

Tensile modulus was found to increase with panel thickness. Based on Figure 7 the modulus over the central regions defined by specimens 4L through 4R (inclusive) were considered to represent “typical” values for each of the three panel thicknesses. The average modulus measured over this central region (only) for each panel thickness is included in Table 2 and plotted in Figure 8. The average modulus for the 5.8 mm thick panel (30.9 GPa) was found to be 31% higher than the modulus measured for the 2.3 mm panel (23.5 GPa). Once again, fiber volume fraction was constant for all three panel thicknesses, and therefore cannot account for the measured increase. The source of this increase in stiffness with panel thickness has not yet been identified.

Table 2: Tensile Modulus Measurements for High Flow Panels

	Panel Thickness		
	2.3 mm (0.09 in)	3.6 mm (0.14 in)	5.8 mm (0.23 in)
Ave ± Std Dev All Specimens, GPa (Msi)	26.8 ± 6.23 (3.88 ± 0.903)	31.5 ± 11.7 (4.57 ± 1.69)	39.6 ± 15.0 (5.75 ± 2.18)
Maximum, GPa (Msi)	38.6 (5.59)	57.5 (8.34)	70.4 (10.2)
Minimum, GPa (Msi)	19.4 (2.81)	19.9 (2.89)	27.5 (3.99)
Average ± Std Dev, Spec 4L® 4R, GPa (Msi)	23.5 ± 3.19 (3.40 ± 0.463)	25.6 ± 2.73 (3.71 ± 0.395)	30.9 ± 2.91 (4.48 ± 0.422)

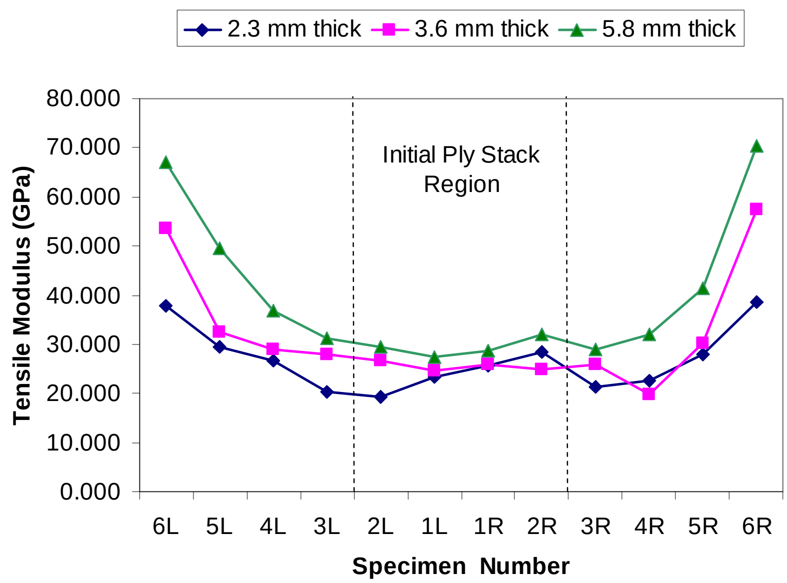


Figure 7: Tensile modulus measurements across the width of the high-flow test panels

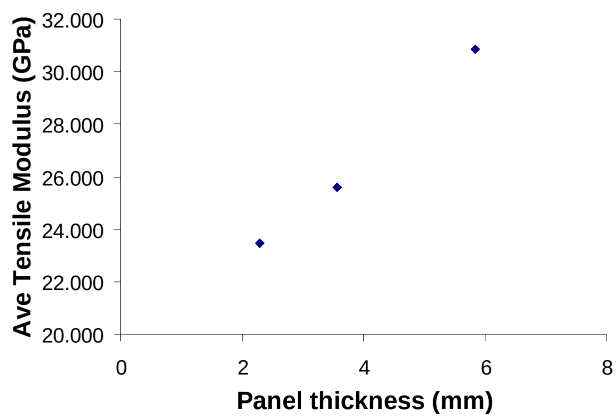


Figure 8: Average tensile modulus measured for high-flow specimens 4L through 4R (inclusive)

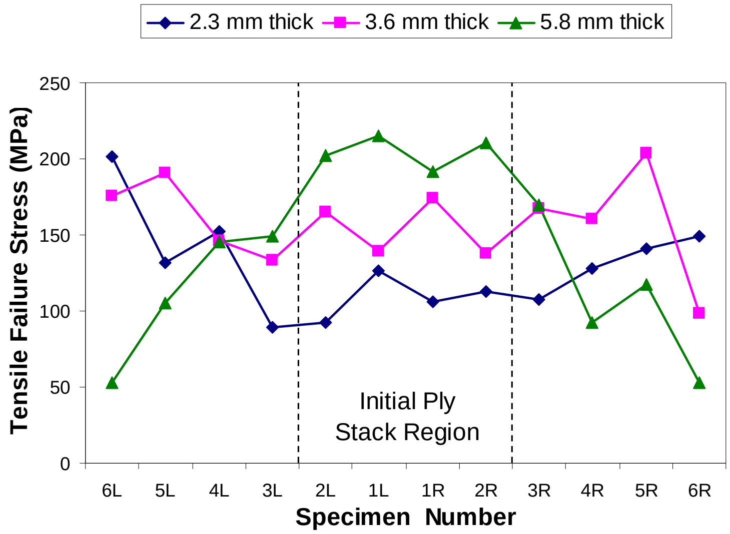


Figure 9: Tensile failure stress across the width of the high-flow test panels

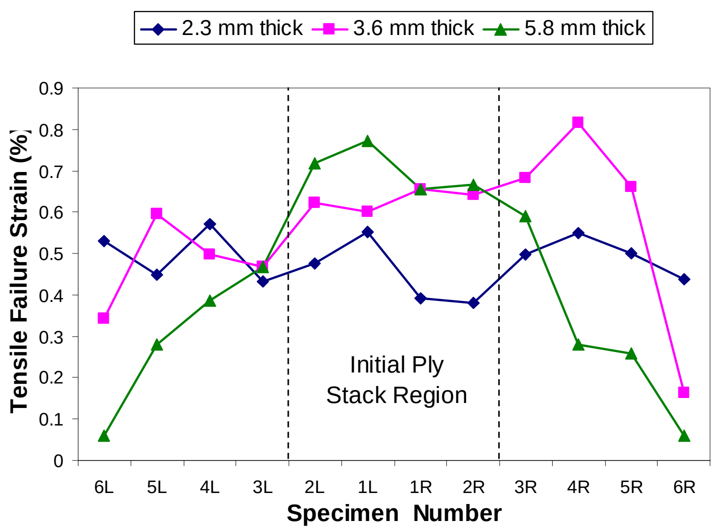


Figure 10: Tensile failure strain across the width of the high-flow test panels

2.4 Tensile Strength

Tensile fracture stress and fracture strains are plotted in Figures 9 and 10, respectively. In the central regions of the panel fracture stress and strains seem to increase with panel thickness. However, this trend seems to be reversed near the left and right edges of the panel. This may be due to fiber alignment near the edges of the panel, as previously discussed. However, given the large scatter in measured strength values, as well the small number of tests performed to date, no statistically valid conclusions can be reached at this time. Additional testing is needed to clarify these trends.

3. SUMMARY

A multi-year study with an ultimate goal of simplifying certification of Discontinuous Fiber Composite (DFC) parts has been undertaken by members of AMTAS (Advanced Materials for Transport Aircraft Structures), which is one of two university groups that together form the Joint Advanced Materials & Structures (JAMS) Center of Excellence. HexMC®, a DFC system produced by the Hexcel Corporation, is being used as a model material. The multi-year study will involve tests and analyses at both the coupon level and at the component level.

This paper has focused on tensile tests performed using HexMC coupon specimens that had been machined from special ‘high-flow’ panels. The high-flow panels experienced far higher levels of material flow during the compression molding process than normally occurs during production of an DFC actual part. Panels of three different thicknesses were produced and tested: 2.3 mm, 3.6 mm, and 5.8 mm (0.09 in, 0.140 in, and 0.230 in).

It was found that high levels of material flow had little or no impact on fiber volume fraction. Fiber/chip orientations were also found to remain nearly random, even in regions of the panel that had experienced substantial levels of material flow. Orientation did occur near the boundaries of the mold cavity. In these latter regions the fiber/chips tend to become aligned with the boundary, causing an increase in modulus measured parallel to the boundary.

For a given panel thickness the nominal tensile modulus remained more-or-less constant throughout interior regions of the panel, reflecting essentially random fiber/chip orientation. Tensile modulus increased markedly in regions near the panel boundary, where fiber/chip alignment occurred. An unexplained observation was that the nominal tensile modulus increased with panel thicknesses. The nominal stiffness of the 5.8 mm thick panel was 31% higher than the nominal modulus measured of the 2.3 mm panel. The source of this increase in stiffness with panel thickness has not yet been identified.

4. REFERENCES

1. For more information about AMTAS-JAMS see http://depts.washington.edu/amtas/
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3. ASTM Standard D3172, 2009, "Standard Test Methods for Constituent Content of Composite Materials," ASTM International, West Conshohocken, PA, 2003, DOI: 10.1520/D3171-09, www.astm.org
4. Feraboli, P., Peitso, E., Cleveland, T., and Stickler, P, “Modulus Measurement for Prepre-based Discontinuous Carbon Fiber/Epoxy Systems”, Journal of Composite Materials, Vol 43, No 19, pp 1947-1965 (2009).