Elevated Temperature, Notched Compression Performance of Out of Autoclave Processed Composites[¥]

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ABSTRACT

Curved honeycomb sandwich panels composed of carbon fiber reinforced toughened-epoxy polymer facesheets are being evaluated for potential use as payload fairing components on the NASA heavy-lift space launch system (HL-SLS). These proposed composite sandwich panels provide the most efficient aerospace launch structures, and offer mass and thermal advantages when compared with existing metallic payload fairing structures. NASA and industry are investigating recently developed carbon fiber epoxy prepreg systems which can be fabricated using out-of autoclave (OOA) processes. Specifically, OOA processes using vacuum pressure in an oven and thereby significantly reducing the cost associated with manufacturing large (up to 10 m diameter) composite structures when compared with autoclave. One of these OOA composite material systems, CYCOM® 5320-1, was selected for manufacture of a 1/16th scale barrel portion of the payload fairing; such that, the system could be compared with the well-characterized prepreg system, CYCOM® 977-3, typically processed in an autoclave. Notched compression coupons for each material were obtained from the minimum-gauge flat laminate $[60/-60/0]_S$ witness panels produced in this manufacturing study. The coupons were also conditioned to an effective moisture equilibrium point and tested according to ASTM D6484M-09 at temperatures ranging from 25 ˚C up to 177 ˚C. The results of this elevated temperature mechanical characterization study demonstrate that, for thin coupons, the OHC strength of the OOA laminate was equivalent to the flight certified autoclave processed composite laminates; the limitations on the elevated temperature range are hot-wet conditions up to 163 °C and are only within the margins of testing error. At 25 ˚C, both the wet and dry OOA material coupons demonstrated greater OHC failure strengths than the autoclave processed material laminates. These results indicate a substantial improvement in OOA material development and processing since previous studies have consistently reported OOA material strengths on par or below those of autoclave processed composite laminates.

1. INTRODUCTION

NASA is engaged in an effort to develop a Heavy Lift- Space Launch System (HL-SLS) with an initial lift capability of 70-100 mT and evolvable up to 130 mT, both aluminum alloy and honeycomb sandwich carbon fiber reinforced polymer (CFRP) architectures have been considered for the manufacture of the payload fairings. Aluminum-lithium alloys used in metallic structure are well understood and certified for use in launch systems[1,2].

The high specific strength and stiffness of CFRP sandwich structure make it an attractive alternative in the lightly-loaded, complex curvature geometry of the proposed HL-SLS fairing architecture. The mass of the fairing structure is not the only factor influencing the material selection decision. Other technical considerations, such as temperature capabilities, acoustic transmission, and development and manufacturing costs, are also heavily weighted factors in the material down-select process for the construction of a payload fairing that can achieve the 10 m diameter structure for potential use on the 130 mT SLS. There are currently no commercially available autoclaves in the U.S large enough to build a full 10 m barrel or the quarter segment of a 10 m petal. The state-of-the-art (SOA) in fabrication of aerospace quality CFRP structure using toughened epoxy prepreg tape like the Cycom® IM7/977-3 material requires that the robotically placed prepreg tape be vacuum-bagged and cured under elevated temperature (≈ 120°C) and pressure (≈ 690 kPa) in an autoclave. The costs estimated to build, operate, and maintain a new autoclave of the size needed to fabricate CFRP structure for proposed future HL-SLS vehicles is prohibitively high for the purposes of the SLS program. Therefore, the aerospace materials industry has recently developed aerospace CFRP epoxy prepreg systems that can be processed out-of-autoclave (OOA), to significantly lower the fabrication costs while maintaining similar structural performance as compared to autoclave processed structure. For example, the recently developed Cycom® 5320-1 toughened epoxy prepreg tape can be robotically placed on rigid tooling and then oven cured in a vacuum bag using only atmospheric pressure (101 kPa) for consolidation of both monocoque and sandwich structure. Initial studies [3-6] have demonstrated that the resulting thermal and mechanical properties of these new OOA CFRP are comparable to autoclave processed toughened epoxy CFRP. These positive initial results indicate that the OOA CFRP systems have the potential to significantly lower the cost to manufacture large-scale CFRP structure for future NASA space flight vehicles. While CFRP sandwich offer a light-weight alternative to metallic structure, the lower damage tolerance inherent to CFRP structures typically results in reductions to the design allowables (knockdowns) [7].

In a manufacturing study conducted at HITCO Carbon Composites, Inc®, Gardena, CA, several 1/16th scale panels of the barrel portion of the proposed 10m diameter HL-SLS payload fairing were fabricated using different toughened epoxy prepreg systems and different fabrication methods. These 2.44 m x 2 m curved CFRP sandwich panels were fabricated by automated tape laying (ATL) of 15.2 cm wide prepreg tape onto a rigid composite tool. The $[60/-60/0]_S$ CFRP face-sheets over 50 kg/m^3 aluminum honeycomb core sandwich part was then vacuum bagged and cured either in autoclave (AU) or in an oven by the OOA, vacuum bag oven (VBO) process. The autoclave processed curved sandwich panel contained face-sheets of Cycom® IM7/977-3 and the OOA processed curved sandwich panel contained facesheets of Cycom® T40-800b/5320-1. In a subsequent mechanical characterization study [6], test coupons were extracted from these two sandwich panels and the edge-wise compression (EWC) and compression after impact (CAI) strengths were determined according to the ASTM standard and literature recommendations for CAI testing of sandwich coupons, respectively. After a trial and error process, an impact energy of 2.03 N-m was used to produce barely visible damage with an average dent depth in the impacted facesheet of 0.76 mm. The EWC and CAI results reported in this study [6] indicated that sandwich coupons fabricated using either the AU prepreg system or the OOA prepreg were statistically equivalent throughout the hot/wet testing regime of 25˚C to 135˚C. The EWC and CAI testing performed in this previous study to determine and compare the damage tolerance of the proposed sandwich composite construction provides useful information for design of the fairing structure to survive launch after BVID damage that could occur in the structure during pre-flight shipping and assembly. The compression failure of the sandwich coupons are influenced by several factors such as honeycomb bond-line adhesive strength, light-weight Al-core crush, and the interaction of these other materials with the CFRP face-sheets, both during impact and application of the compressive test loads. These factors influence the comparison of the AU laminate to the OOA laminate damage tolerance and mechanical performance. Therefore, in this current study laminate coupons were obtained from the [60/-60/0]$_S$ flat laminate witness panels fabricated at HITCO during the manufacture of the 1/16th scale sandwich panels. The damage tolerance of these AU and OOA laminate coupons was determined by introducing damage in the laminate as a notch, or hole, for determination of the open-hole compression (OHC) failure strength at elevated temperatures.

1.1 BACKGROUND NOTCHED COMPRESSION

In addition to thermal and acoustic loads, the HL-SLS payload fairing is expected to predominantly be lightly loaded in compression during flight. Composite laminate defects, or in-situ rogue flaws in the form of porosity, can occur unpredictably during the manufacture of the composite sandwich structure. These defects act as stress concentrations in the laminate, serving to lower the laminate compressive strength. The OHC test is helpful in combination with various developed numerical damage models [7-9] to predict CFRP structural performance containing these types of defects. Because a carefully drilled hole induces an easily reproducible defect, the test is useful for comparison of the compressive performance using different constitutive materials with the same reinforcement orientation. The OHC test method provides a controlled simulation of a natural defect in a composite structure and provides the structural designer an “engineering property” of the knockdown in strength associated with introducing fastener holes. It is assumed that the worst acceptable laminate flaws will be missed by non-destructive evaluation (NDE), but will cause a laminate strength reduction no worse than that caused by a 6.35 mm (0.25 in.) diameter hole [9]. Failure in notched CFRP under compressive loading initiates at the stress concentration location due to micro-buckling of the 0° fiber reinforcement parallel to the load path [10-17]. Under increasing loads, the micro-buckling crack progresses away from the notch accompanied by delamination and matrix cracking in the off-axis plies. Damage in the micro-buckled zone increases until the crack reaches a critical length resulting in ultimate compressive failure. While the OHC test method was developed as a coupon level laminate test, the compliant resin matrix and the fiber-to-matrix interface play a significant role in the failure of composites under compressive loads as compared to tensile loading. In tension, the fiber reinforcement plays the dominant role in the composite ultimate strength [15]. The reinforcement displacements associated with micro-buckle of the 0° fiber leads to local delamination when the local strain necessary to accommodate the fiber displacement exceeds the matrix resin ductility [9]. These localized delaminations progress to macroscopic delaminations at ultimate compressive failure. Linear correlations are reported for comparisons of laminate OHC strength with Iopescu composite shear strength and both unnotched compression (UNC) and OHC strength decrease with increasing mode I fracture toughness [11].

1.2 OHC TEST COUPON THICKNESS

The test procedure to determine the notched compressive strength of CFRP material is recommended in ASTM D6484-09 [18]. Section 8.2.1 of the standard stipulates that the nominal thickness of the balanced, symmetric laminate shall be 4.0 +/- 1mm. The nominal thickness of the witness panels fabricated at HITCO was 0.860+/- 0.005 mm, well below the coupon thickness recommended in the standard. Test coupons with thickness less than 3mm used to determine the notched compressive strength of CFRP will likely result in global buckling which increases the local stress at the hole resulting in lowered ultimate OHC strength [19]. In a study by Lee and Soutis [20] to determine the OHC coupon material volume effects on ultimate failure strength, quasi-isotropic laminates fabricated from IM7/8552 with a thickness of 2mm and diameter/width (D/w) ratio= 0.2 were reported to have an average OHC strength 4% lower than laminates tested with the ASTM recommended thickness of 4mm and D/w=0.2. Despite using anti-buckling vertical knife edges on the 32mm x 32 mm x 2mm coupons, back-to-back strain gages near the open hole indicated out-of-plane bending, which increased with increasing axial load. In the current study, the BOEING BSS-7260 OHC test fixture recommended in ASTM D6484M-09 was utilized to reduce the risk of global buckling. Using this fixture, the 203 mm x 38 mm gage section of the OHC coupons are face-supported by 12.7 mm thick stainless steel bars to prevent buckling except within a cutout region approximately 25.4 mm x 12.7 mm coincident with the open hole. Neither strain gages nor extensometers were utilized in this current study to compare the OHC strength of coupons fabricated in autoclave and OOA in the minimum gage $[60,-60,0]_S$ laminate configuration. The OHC strength is reported without knowledge of whether localized buckling occurred in the region surrounding the open hole and, therefore, should be considered conservative.

1.3 ENVIRONMENTAL EFFECTS

In addition to comparing the ambient OHC strength of $[60,-60,0]_S$ laminates fabricated in autoclave using Cytec IM7/977-3 to laminate fabricated OOA using T40-800b/5320-1, the effects of moisture and elevated temperature (up to 177°C) on the OHC strength were also determined. The barrel portion of the SLS is predicted to reach up to 200°C at maximum aerodynamic pressure (max Q) during ascent. The time at this temperature is on the order of a few minutes and will necessitate the use of a cork thermal protection system (TPS) on the outer skin of the fairing sandwich epoxy matrix composite structure. The dry and wet glass transition temperatures (Tg) of the two matrix polymers in addition to other relevant material properties reported by the material suppliers are found in Table 1. At temperatures approaching the wet-Tg of the epoxy matrix, the OHC strength and resin modulus are expected to decrease significantly due to plasticization of the epoxy from moisture [20-22]. The failure mode at both ambient and in the hot/wet environment is expected to be similar and attributed to fiber microbuckling in the axial loaded fibers. In notched compression testing of sixteen-ply quasi-laminates fabricated from carbon fiber/epoxy XAS/914C, Kellas reports [23] OHC strength reduction of 50% at 130°C/wet versus only an 18% reduction at 130°C/dry. The hot/wet OHC coupons tested by Kellas were conditioned to 1.4% moisture gain at testing. In another study, Nettles [24] reports that the average OHC strength following the Northrup OHC test standard with 3.2 mm diameter hole prepared from Hexcel® IM7/8552 laminate $[45/0/-45/0/90/0/0/90/0]_S$ results in a 13.6% reduction for the 104 °C/wet condition versus a 9.4 % reduction for the 104°C/dry condition. These 104 °C/wet coupons were conditioned to 0.7% moisture mass gain based on a previous study conducted at Kennedy Space Center (KSC). The KSC study was conducted to determine the moisture gain of IM7/8552 composite laminates subjected to a 4,320 hrs atmospheric exposure intended to simulate a six month “pad-stay” for a composite launch structure. The KSC atmospheric exposure study resulted in a maximum moisture gain of 0.5%. Nettles also reports that OHC strength only varied within the test error for coupons tested at 104°C with moisture weight gain from 0.2% up to 1.2% for the IM7/8552 laminate. The well-characterized Hexcel 8552 and Cycom® 977-3 epoxy materials, as well as the newly developed Cycom® 5320-1 are all assumed to be high-functionality epoxies synthesized for demanding aerospace environments with similar potential for moisture absorption. Other factors that affect the moisture absorption of epoxy matrix composite laminates include surface quality, fiber volume fraction (FVF) and void volume fraction (VVF). Elevated VVF in CFRP will result in greater susceptibility to moisture penetration [24]. Results of photo-microscopy and acid digestion of the sandwich panels fabricated at HITCO using the OOA 5320-1 material has not indicated an issue with FVF < 60% or a VVF greater than 3%, however there are localized voids visible in photo-microscopy of the composite facesheets of this sandwich structure [26]. Porosity of the witness panels is reported in the results of this current study. The hot/wet OHC strengths reported in the current study were obtained from coupons moisture-conditioned until the effective moisture equilibrium was achieved according to the procedure recommended by the FAA [27].

Table 1. Constitutive Material Properties Provided by the Material Suppliers

Material	Supplier	Property				
		Dry Tg (^{O}C)	Wet Tg (^{O}C)	Tensile Strength (Mpa)	Tensile Modulus (Gpa)	Density (g/cc)
IM7 Carbon Fiber(12K)	Hexcel	N/A	N/A	5654	276	1.78
T40 Carbon Fiber (12K)	Cytec (originally Amoco)	N/A	N/A	5650	290	1.81
977-3	Cytec	190	165	NR	NR	1.29
5320-1	Cytec	NR	163	NR	NR	1.31

2. Experimentation

2.1 OHC TEST COUPON PREPARATION

Thirty-five IM7/977-3 OHC coupons were prepared from a 91.5 cm x 91.5 cm $[60,-60,0]_S$ flat laminate panel fabricated at HITCO by ATL of 15.2 cm tape slit from a roll of uni-directional IM7/977-3 prepreg supplied by Cytec with the following specifications: F.A.W.=145 gsm, resin content = 33% by weight. The slit prepreg tape was placed on a flat aluminum tool, debulked, vacuum-bagged and cured in an autoclave under elevated temperature and pressure according to the supplier recommended procedures. This witness panel was cured alongside the 2.44 m x 2 m curved IM7/977-3 CFRP sandwich panel referred to in previous publications [6,29] as MTP-6003.

Likewise, thirty-five T40-800b/5320-1 OHC coupons were prepared from a 91.5 cm x 91.5 cm $[60/-60/0]_S$ flat laminate panel fabricated at HITCO by ATL of 15.2 cm tape slit from a roll of uni-directional T40-800b/5320-1 prepreg supplied by Cytec with the following specifications: F.A.W.=145 gsm, resin content = 33% by weight. The 5320-1 OOA prepreg is specially fabricated to provide a volume of un-wetted carbon fiber in the center-thickness of the prepreg to serve as a devolatization pathway during composite fabrication. The resin has been demonstrated to flow under VBO processing conditions to fill the dry fiber regions resulting in parts with FVF $\geq$ 60% and VVF$\leq$ 2.0 % [5, 29]. The optimum prepreg impregnation level to provide optimized ATL and AFP speeds and high quality laminates is currently under development by DoD, NASA, and industry. The rolls of T40-800b/5320-1 supplied to HITCO for this manufacturing study were >90% impregnated. The prepreg tape was placed by ATL on a flat Aluminum tool, debulked, vacuum-bagged and cured in an oven under elevated temperature and atmospheric pressure(<101 kPa) according to the supplier recommended procedures. This witness panel was cured alongside the 2.44 m x 2 m curved T40-800b/5320-1 OOA CFRP sandwich panel referred to in previous publications as MTP-6010.

The 91.5 cm x 91.5 cm witness panels were non-destructively evaluated by thermography and thru transmission c-scan and found to be free of any flaws greater than 12.7 mm (0.5 in) in diameter.

All OHC coupons were cut from the witness panels using a diamond impregnated wet-saw to the nominal coupon dimensions of 30.5cm x 3.8 cm according to recommendations in ASTM D6484(Procedure “B”), with the 30.5 cm coupon length parallel to the 0° fibers. After wet-saw, the ends of the coupons were machined using a tungston-carbide end-mill to ensure they were parallel within 0.0254 mm for compression loading. A 6.35 mm (0.25 in) diameter hole was cut in the center of each coupon using a diamond coated hole saw / core- drill bit mounted in a milling machine. The machined coupons were analyzed using optical microscopy to ensure the hole edges were within tolerance, uniform and clear of any burrs, delaminations, or other unexpected damage from the machining operation. The machining of the coupons resulted in final coupon dimensions such that the specimen width to hole diameter ratio, w/D, equaled 6 as recommended in the ASTM standard. According to ASTM D6484M-09 the preferred ratio of hole diameter to coupon thickness, D/h, should range from 1.5 to 3.0. Due to the thickness of the $[60/-60/0]_S$ witness panel utilized in this study, the ratio of all of the coupons tested was D/h = 7.4. The higher D/h ratio likely results in some out-of-plane bending near the site of the open-hole, thereby lowering the OHC failure strength reported herein.

2.2 COUPON MOISTURE CONDITIONING

After machining and inspection, all 70 OHC coupons were placed in a convective drying oven at 80°C for 120 hrs to ensure that both materials were at the same moisture content prior to conditioning in the environmental chambers.

Following Procedure “C” in ASTM D5229 [28], thirty OHC coupons and one 7.6 cm x 3.8 cm traveler coupon from each material set were evenly distributed on racks in a Tenney Environmental® VersaTenn III calibrated conditioning chamber. The traveler specimens did not contain through holes. These coupons were conditioned at 80°C and 85% relative humidity (RH) until the effective moisture equilibrium state was reached. Effective moisture equilibrium is defined in the FAA/AR-03/19 as less than 0.05% mass change within the span of a reference time period:

$$\frac{W_i - W_{i-1}}{W_b} < 0.0005$$

where, W_i = weight at current time, W_{i-1} = weight at previous time, and W_b = baseline weight prior to conditioning. The two traveler coupons were weighted every 24 hours during the first week of conditioning and then every 170 hr thereafter using a Mettler Toledo Micro-Balance®

analytical balance with accuracy to 0.1 mg. The FAA [27] recommended time period of 7 ± 0.5 days for weighing the traveler to determine equilibrium during conditioning was used in this study. After the traveler coupons reached the effective moisture equilibrium state, all sixty OHC test coupons were removed from the conditioning chamber and stored in sealed plastic bags at ambient temperature until OHC testing was completed (~1 week).

2.3 OHC TEST PROCEDURES

Except for the coupon thickness previously discussed, the procedures recommended in ASTM D6484M-09 were followed for OHC testing. The objective was to determine the OHC failure strength from valid failures of minimum gage CFRP multi-directional laminate proposed as face-sheet in the sandwich structure of a HL-SLS fairing. The ratio of ungripped specimen length to specimen width ratio was maintained at 2.7 utilizing the BSS-7260 OHC test fixture recommended in the standard. Following Procedure "B" in the standard, the coupons were loaded in the fixture and the four grip bolts tightened to 7 N-m (60 in-lbf) prior to loading the coupon fixture between the flat platens of the test frame. A 0.1 mm thick shim was used at the intersection of the support plates and the long grips to ensure that a maximum gap of 0.076 mm existed between the gage section of the coupon and the face supports of the fixture as determined using a feeler gage. For testing of the five room temperature-dry (RT-dry) and five RT-wet coupons from each material set, the test fixture and coupons were preloaded at a displacement rate of 10 mm/min to 23 N (100 lbf) and the torque level of the four grip bolts were rechecked. No changes in torque were noted after preloading these 20 RT coupons. Elevated temperature testing was performed at: 100 °C, 135 °C, 150 °C, 163 °C and 177 °C. For the elevated temperature testing, the test fixture containing the OHC coupons was loaded between the flat platens of the test frame and the platens and fixture were contained within a convective oven (MTS Environmental ® Model # 651) . To reduce downtime between tests, the stainless steel BSS-7260 OHC test fixture was heated in the test chamber to the desired test temperature. When the fixture reached the desired temperature it was removed from the environmental test chamber. The test coupon was loaded into the fixture and the bolts tightened to the recommended torque of 7 N-m. The test fixture containing the coupon was then placed back in the heated test chamber centered between the two heated test platens. The fixture was held in the chamber until a thermocouple attached to the long grips [19] at the cut-out window reached the desired test temperature within ±1.0°C. Approximately five to ten minutes was required to return the fixture to the required test temperature. The fixture was then held at this temperature for three minutes before applying a preload of 23N. The test fixture and coupon were preloaded at 10 mm/min to 23 N (100 lbf) and the preload was released at 10 mm/min until the load registered was approximately 7 N. All displacement and load instrumentation was zeroed and the test was begun by applying load to the fixture in displacement-control mode. The cross-head displacement used was 2 mm/min resulting in failure within the recommended range of 1 to 10 minutes. Force versus displacement was recorded for each coupon tested and the failure mode investigated to determine validity according to recommendations in ASTM D6484M-09. The OHC failure strength is calculated according to:

$$F^{ohcu} = P_{max} / A$$

where, F^{ohcu} = ultimate open-hole compression strength (MPa), P_{max} = maximum force prior to failure (N), A = gross cross-sectional area of test coupon, disregarding hole (mm^2).

3. Results and Discussion

3.1 EFFECTIVE MOISTURE EQUILIBRIUM

The sixty coupons from both material sets intended for RT-wet and hot/wet OHC testing were conditioned at 80C/85%RH until the traveler specimens reached the effective moisture equilibrium. After 1300 hr, both materials met this criterion. However, as shown in Figure 1, the OOA fabricated T40-800b/5320-1 laminate reached the effective moisture equilibrium point of 1.15% compared to the AU processed IM7/977-3 coupons which equilibrated at moisture mass gain of 0.86%. The traveler specimens from both material sets were left in the chamber and continued to be weighed weekly up until 1900 hrs. The resulting mass changes indicate that both travelers continued to absorb moisture, so additional testing would be needed to measure the effects of absolute moisture equilibrium content.

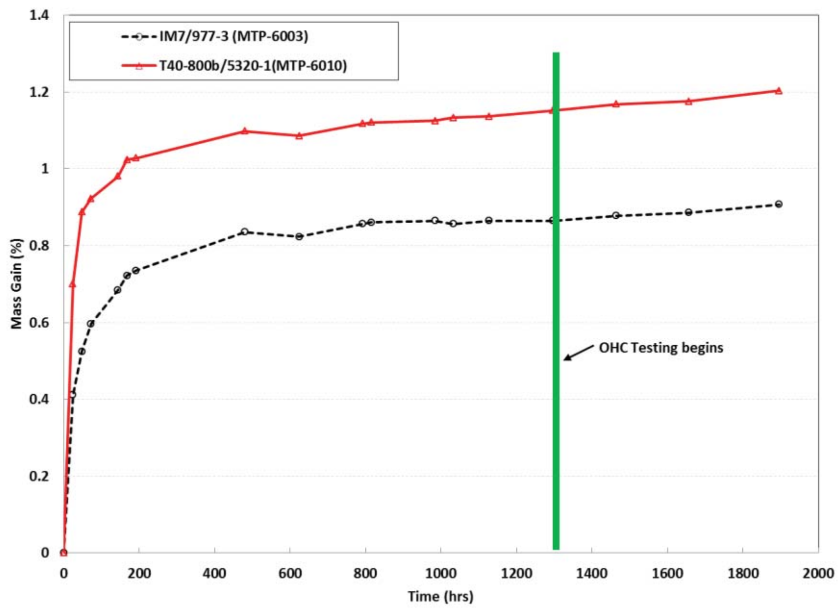


Figure 1. Moisture absorption of IM7/977-3 and T40-800b/5320-1 $[60/-60/0]_S$ laminates in 80°C/85%RH environment.

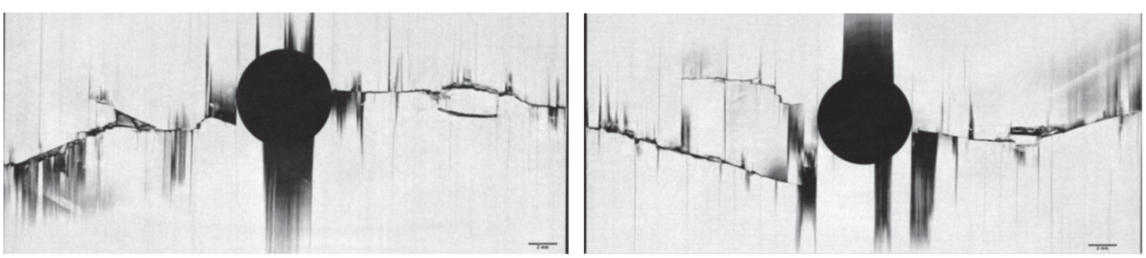
3.2 HOT/WET OHC STRENGTH

Seventy $[60,-60,0]_S$ coupons were tested in OHC at environmental conditions ranging from RT-dry to 177C-wet. Sixty-five of the failures were judged to be valid according to the ASTM D6484M-09 standard. Most of the failures were of the type "LGM" defined in the standard as laminate compressive failure laterally across the center of the hole, with 0° fiber kinking or buckling. The five invalid failures occurred at various temperatures in both material sets and were located within 5.0 mm of the fixture "short" grips and are attributed to the stress concentration caused by this discontinuity. Both of the material sets had at least four valid OHC failure strength values from which to calculate the average and standard deviation at each of the test conditions. Digital photos of failed specimens from each material set which are representative of the "LGM" failure mode are shown in Figure 2.

While the visual inspection of the failed laminate coupons satisfies the ASTM procedure for determining validity, the reduced coupon thickness warranted further investigation of the failure mode. To ensure that these minimum gage coupons did indeed fail due to microbuckling of the 0° fiber reinforcements located in the center of the $[60/\text{-}60/0]_S$ laminate, an x-ray technique was utilized to determine the failure mode of the 0° fibers.

Figure 2. Image of representative OHC failure mode "LGM" in $[60/\text{-}60/0]_S$ coupons, IM7/977-3 tested at RT-dry on the left and T40-800b/5320-1 tested at 177°C-wet on the right.

Micro-CT NDE was performed at the site of the OHC failure because this technique allows layer by layer analysis. Top-down images of the 0°–ply damage is shown in Figure 3 for 100°C-wet coupons from both material sets. Despite additional damage, such as ply-splitting emanating from the open-hole in both coupons, the image analysis indicates a micro-buckling failure mode. Failure is assumed to have started at the edge of the hole and moved away in the direction perpendicular to the compressive load towards the outside edges of the coupons. The CT image also captures the broken fibers collected inside of the crack that is also reported in the literature from dye-penetrant x-ray and SEM of cross-sectioned coupons.



A **B**

Figure 3. Micro CT images of the 0° ply of the $[60/\text{-}60/0]_S$ of failed IM7/977-3 coupon (A) and failed T40-800b/5320-1 (B) both tested at 100°C-wet, showing fiber micro-buckle kink-band in addition to ply splitting resulting from delamination at ultimate failure.

These images showing the failure mode, or kink-band, of the load-bearing reinforcements indicates that the coupons failed due to micro-buckle at the region of the high stress concentration created by the open-hole.The validity of the failure modes observed on the surface of the coupons as well as the evidence from CT-scan of the micro-buckle of the 0° fibers indicates that the 0.860 mm thick OHC coupons failed in a similar manner to the 4.0 +/- 1.0 mm thick coupons reported in the literature. However, neither of these failure mode analyses provides information to indicate that global buckling of the thin coupons did not increase the amount of stress at the open-hole and thereby lower the resulting failure strength. All of the coupons from both material sets were prepared and tested following the same procedures. Therefore, while conservative, the resulting average failure strength values are valid for the purpose of comparing the effects of moisture and temperature on the OHC strength of $[60/-60/0]_S$ laminates fabricated from Cycom® 977-3 cured in an autoclave and Cycom® 5320-1 cured by the OOA method. The results of the study are shown for comparison in Figure 4 with the error bars representative of one standard deviation calculated from at least four coupon failures per condition. The coefficients of variation (CV) calculated for both material sets at each test condition were all 4%<CV<11%. In general, the trend for both materials is decreasing OHC strength with increasing temperature, as expected. Comparisons based on the mean values shown in Figure 4 indicate that moisture conditioning had little effect on the OHC strength of either of the materials tested at RT. This indicates that to determine the knockdown in RT OHC strength associated with moisture ingress in these matrix epoxies, a higher degree of moisture absorption is required than recommended in the FAA standard.

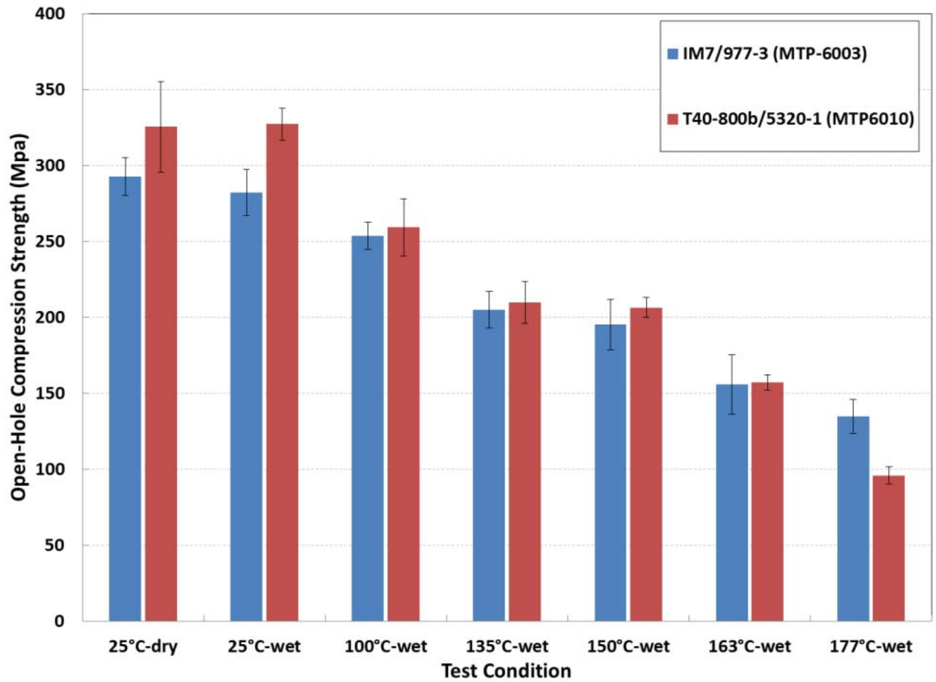
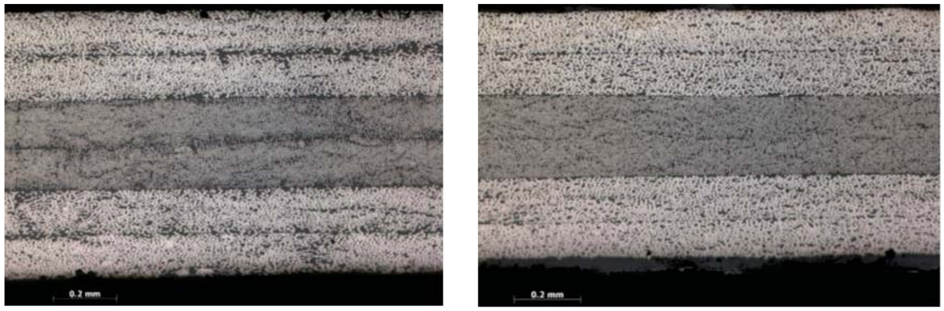


Figure 4. Average OHC Strength of AU fabricated IM7/977-3 and OOA fabricated T40-800b/5320-1 from RT-dry to 177°C-wet

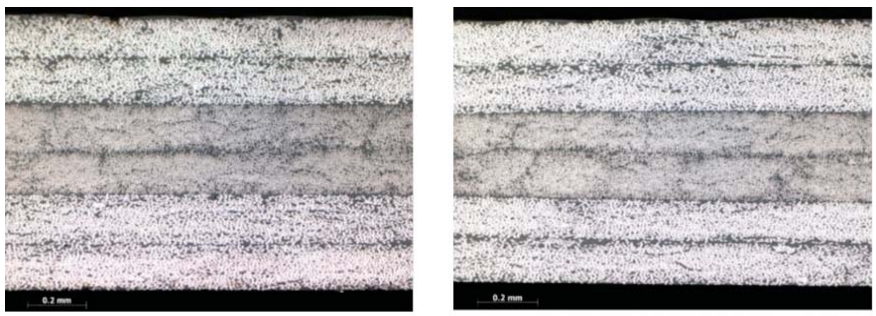
The higher OHC strength of the OOA material tested at RT-dry and RT-wet is consistent with results of EWC and CAI testing of these two materials used as facesheet in sandwich coupons [6]. As the test temperature increases above ambient, the OHC strength of the moisture conditioned IM7/977-3 and the T40-800b/5320-1 composites are equivalent within the standard deviation. Since the wet-Tg of both of these toughened epoxies is reported to be approximately 164 °C, the OHC failures observed at 163 °C and 177 °C are 50% lower than the OHC strength of the materials at the RT-dry test condition. This confirms the general rule-of-thumb, that the max use temperature of epoxy CFRP structure should be maintained at least 25 °C(50 °F) below the measured Tg. In fact, the largest decrease in OHC strength for both materials occurs during the 13 °C increase in temperature between 150 °C and 163 °C where the OHC strength is reduced by greater than 20% for both materials. In a previous study conducted at NASA [29], the effects of fabrication methods on the mechanical performance of CFRP was determined using various aerospace prepreg materials including AU processed IM7/977-3 and OOA processed T40-800b/5320, a previous version of the Cycom® 5320-1 epoxy matrix tested in the current study. Quasi-isotropic laminates with the following ply-stacking sequence $(0/0/45/45/90/90/-45/-45/-45/-45/90/90/45/45/0/0)_2$ were laid-up by hand and processed in AU according to the supplier recommended procedures. The un-notched compressive (UNC) strength and OHC strength of IM7/977-3 were reported for these 32-ply laminates. Utilizing a combined load compression (CLC) fixture and coupons 13.97 cm long x 1.27cm wide, the average (UNC) strength of IM7/977-3 at RTD was reported as 439±19 MPa. Using coupons that were 30.48 cm long, 3.81 cm wide, 4.43 ± 0.1 mm thick, and having a 6.35 mm (0.25 in) hole resulted in a RT-dry OHC strength of 348±16 MPa. The average RT-dry OHC strength of the 0.860 mm thick coupons tested in the current study is 292 ± 12 MPa. The 16% difference in measured OHC strength is not surprising given the difference in coupon thickness as well as the difference in the number of 0° fiber plies in the two different laminates. For a cured ply thickness (CPT) of 0.14 mm, the 32-ply quasi- laminate contains a combined thickness of 1.12 mm of load-bearing 0° reinforcement versus the 0.28 mm of 0° fiber plies in the $[60/-60/0]_S$ laminate coupons. The UNC strength of the $[60/-60/0]_S$ laminate was not collected in the current study, however, valid EWC values for this laminate used as face sheet over low density honeycomb was reported in a previous NASA study [6] for both materials. While the bonded honeycomb provides added stiffness to the EWC coupons,the compressive load is carried by the thin face-sheets. The average RT-dry EWC strength reported in [6] for the IM7/977-3 sandwich coupons was 437 ± 56 MPa, and for the T40-800b/5320-1, the average EWC strength at RT-dry was 449 ± 37MPa. Using these published EWC values for $[60/-60/0]_S$ face-sheets, the compressive strength knockdown due to the open-hole in the minimum gage IM7/977-3 laminate is 33% and for the T40-800b/5320-1 OOA laminate the knockdown is 28%. The compressive strength knockdowns are comparable, but slightly higher than the 21% knockdown in compressive strength reported for the 32-ply quasi IM7/977-3 coupons tested in [29]. This difference would support earlier assertions that the OHC testing using these thin laminates will result in slightly conservative reporting of OHC strength. However, it should also be noted that other results reported for the effect of an open hole on the compressive strength of multi-directional laminates indicate the knockdown from the UNC strength is typically in the 40-50% range for 6.0 to 7.0 mm diameter open holes [14-16].

After testing seventy OHC coupons, a sampling of the failed coupons from both materials and at least one from each test condition were cross-sectioned 12.7 mm beneath the center of the hole, polished, and photographed under a microscope for the purpose of determining the consolidation quality. All of the coupons taken from the flat laminate witness panels fabricated at HITCO were of high quality and void-free as shown in the photo-microscopy in Figures 6 and 7.



RT-dry 150°C-wet

Figure 6. Photo-microscopy at 100X of $[60/-60/0]_S$ IM7/977-3 laminate.



RT-wet 163°C-wet

Figure 7. Photo-microscopy at 100X of $[60/-60/0]_S$ T40-800b/5320-1 laminate.

4. Summary

The OHC strength and CAI strength provide useful design data for structure intended to sustain compressive loads such as those expected for the proposed sandwich composite payload fairing of future NASA HL-SLS vehicles. The large, up to 10 m diameter, barrel portion of the payload fairing and its four separate petals exceed the current capacity of available autoclaves in the United States, therefore, newly developed OOA composite materials are under consideration for these large structures. The barrel of the fairing is predicted to reach up to 200°C during launch. Therefore, the hot/wet damage tolerance performance of the proposed composite structures is of importance to determine the thickness of required TPS to maintain the outer composite face-sheet below acceptable operating temperatures. The hot/wet OHC strength of the minimum gage $[60/-60/0]_S$ laminate proposed for the face-sheet of the fairing sandwich structure was determined for the OOA composite T40-800b/5320-1 and compared to the well-characterized AU processed IM7/977-3 at test conditions ranging from RT-dry to 177°C-wet. Both the ASTM D6484M-09 standard for OHC and the literature state that the OHC failure strength is not a fixed value solely dependent on the constitutive materials but depends on the stacking sequence, ply thickness, and total thickness of the laminate. Despite the relatively thin coupons, 93% of the coupons failed in a valid manner as determined by x-ray inspection of the failure regions. OHC testing of the thin multi-directional laminates likely involved some global buckling of the coupon despite the use of the BSS-7260 fixture. Any out-of-plane bending of the coupon near the hole increases both the complexity and magnitude of the stress. Therefore, the OHC failure strength values reported in this study should be treated as conservative for the purpose of design.

Nonetheless, all coupons from both material sets were the same geometry and tested identically, the comparison of the hot/wet OHC strength of the AU fabricated composite to the OOA fabricated composite is considered valid. The results of the testing indicate that at RT-dry and RT-wet, the OOA composite exhibits slightly higher OHC strengths than the AU fabricated composite. The difference in OHC strength for the moisture conditioned specimens versus dry was insignificant at RT. Cross-sectioning and photo-microscopy of seven coupons from each material set indicated comparable high consolidation quality with no evident porosity. Elevated temperature testing of the wet coupons up to the wet Tg indicated that the OHC performance was equivalent within the testing standard deviation and the OHC strength of both material sets above 150°C was reduced by 50% from the measured RT-dry strength. Based on the results of this elevated temperature study the OHC strength of the OOA fabricated T40-800b/5320-1 is equivalent to the IM7/977-3 laminates fabricated in autoclave. Therefore based on this work and the results of previous reports comparing these two systems it is recommended that the OOA material be considered as a strong candidate to lower the cost to fabricate future NASA HL-SLS CFRP fairing structure.

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