NASA/TM—2009–215900

Hot/Wet Open Hole Compression Strength of Carbon/Epoxy Laminates for Launch Vehicle Applications

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June 2009

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ASTM	American Society for Testing and Materials
CMH	Composite Material Handbook
CSZ	Cincinnati sub-zero
ETW	elevated temperature wet
KS	Kennedy Space Center
OHC	open hole compression
RH	relative humidity
RT	room temperature
TM	Technical Memorandum
T_g	glass transition temperature

TECHNICAL MEMORANDUM

HOT/WET OPEN HOLE COMPRESSION STRENGTH OF CARBON/EPOXY LAMINATES FOR LAUNCH VEHICLE APPLICATIONS

1. INTRODUCTION

Measuring the open hole compression (OHC) strength of polymer matrix composites is a useful way to test the effects of discontinuities that cause a stress concentration.[1] The 'environmental knockdown' or 'hot/wet' factor for laminates is usually found by testing conditioned specimens to determine OHC strength.[2] This approach is easier, less costly, and can be better controlled than testing impact-damaged laminates at environmental extremes.

The design of structural composite laminates typically takes into account the hot/wet performance of the material since matrix dominated properties tend to be reduced with increasing temperature and humidity. Aircraft must consider these extreme environmental factors since they can experience high temperatures for hours and the humidity levels the airplane may experience are not known. However, since single-use launch vehicles have a lifetime of minutes, the composite materials used on these vehicles may not be subjected to the extreme and lengthy environmental conditions imposed on aircraft composite structures.

Because moisture may adversely affect the resin-dominated strength properties of carbon/epoxy laminates at elevated temperatures, the procedure in American Society for Testing and Materials (ASTM) Standard D 5229[3] was developed to force moisture into the test specimen. This standard calls for the saturation of the specimen (i.e., no more water can be forced in) before subsequent mechanical testing to assess the effects of moisture on the laminate. Aircraft use this unrealistically high moisture level as a 'worst case' scenario to be conservative because of the extreme variation in flight patterns and conditions. Following fabrication of a composite launch vehicle, the environments experienced by the hardware are known. Since the actual moisture absorption of the composite material can be either predicted, or directly measured, applying standard aircraft testing procedures to launch vehicles may result in an over-designed structure with increased weight.

The objective of the study described in this Technical Memorandum (TM) is to determine the loss of OHC strength of the material system being used on the Ares I composite interstage as separate functions of moisture absorption and elevated temperature. This will assist in determining if hot/wet testing should be performed for the realistic conditions experienced by the interstage and if so, what magnitude of environmental knockdown can be expected. Since composite materials are considered for use on launch vehicles solely to reduce weight, it is prudent to minimize the mass of the structure while still maintaining proper safety margins.

2. ENVIRONMENTAL EFFECTS ON OPEN HOLE COMPRESSION STRENGTH

Composite Material Handbook 17 (CMH-17), Vol. 2[4] contains laminate property data including the hot/wet OHC strength of a quasi-isotropic laminate for some fiber/resin systems. Table 1 is a sampling of some of the OHC strength data (available in the open literature) for quasi-isotropic carbon fiber/epoxy material systems. For the data listed in table 1, the specimens were saturated prior to testing although the dwell times of the specimens at temperature are not known and the test methods may have varied from ASTM D 6484.[5] The limited data does provide a qualitative example of hot/wet knockdown effects published for notched quasi-isotropic compression specimens.

Table 1. Open hole compression strengths of quasi-isotropic carbon/epoxy laminates.

Carbon Fiber/Epoxy Resin	Room Temperature (ksi)	180 W (ksi)	% Decrease	220 W (ksi)	% Decrease
AS4 Fabric/PR500[(a)]	45.3	36.3	19.9	–	–
AS4/997[(a)]	53.0	45.3	14.5	–	–
IM7/8552[(a)]	48.7	43.3	11.1	40.6	16.6
T300 Fabric /977-2[(a)]	43.3	39.1	9.7	–	–
IM7 Fabric /PR500[(a)]	44.7	–	–	35.2	21.3
IM7/977-2[(a)]	43.0	34.9	18.8	–	–
G30-500 Fabric /5276-1[(b)]	49	35	28.6	–	–
T800/T3900[(b)]	42	33	21.4	–	–
IM7/977-2[(b)]	45	37	17.8	–	–
IM7/8551-7[(b)]	42	37	11.9	36	14.3
AS4/8551-7[(b)]	44	38	13.6	–	–
IM7/977-3[(b)]	46.7	–	–	37.0	20.8
AS4/3501-6[(c)]	44.0	36.7	16.6	–	–

(a) Data from CMH-17[4]
(b) Vendor data
(c) DSTO-TR-2077 Australian DoD Technical Report, Air Vehicles Division[6]

The OHC strength knockdown factor for various quasi-isotropic carbon/fiber epoxy systems tested at 180 °F in hot/wet conditions is on the order of 10% to 20% with variation between the systems being tested. Variation in resulting OHC strengths for the same resin with different fibers is illustrated by the resin 977-2. The OHC strength for this resin with T300 fabric shows a 9.7% decrease at 180 °F wet verses ambient (room temperature (RT)), but with the IM7 unitape, the decrease is almost doubled at 17.8%.

Typically OHC strength data only include ambient dry and elevated wet results so an identification of the contribution of moisture versus heat on resulting OHC strength data is not usually possible. In CMH-17,[4] OHC strength data for AS4/PR500 carbon/epoxy is given at ambient versus elevated dry conditions so a comparison can be made for this material. Figure 1 shows the data in graphical form. The 'wet' specimens were conditioned at 160 °F and 85% RH for 2 weeks. The exact amount of moisture uptake was not given.

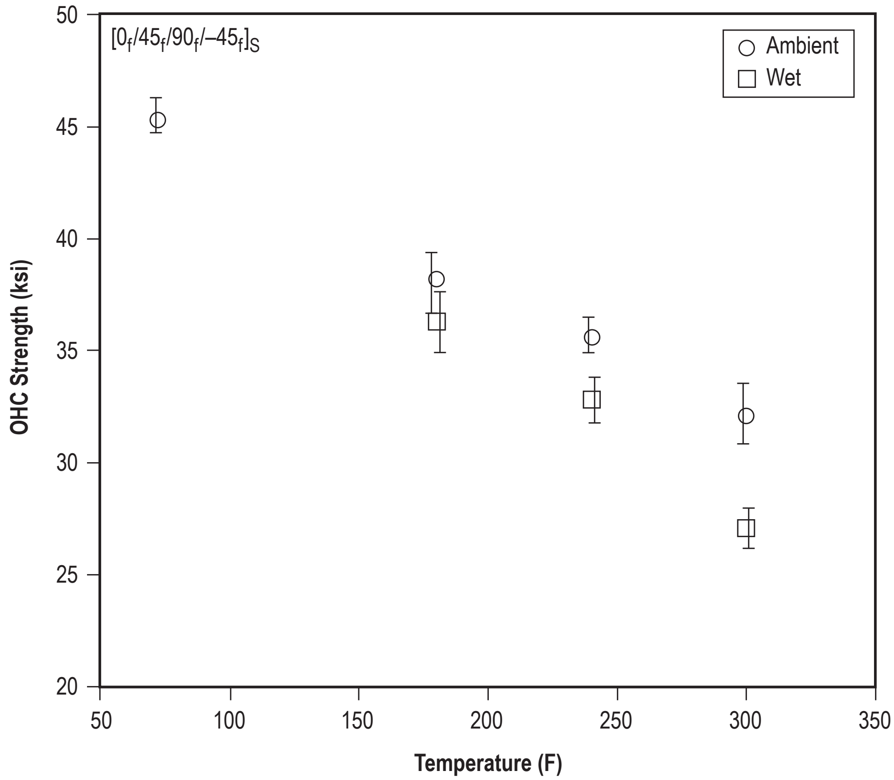

Figure 1. OHC strength versus temperature for 'wet' and ambient specimens of AS4/PR500.

From this figure, it is evident that moisture and temperature interact to cause more OHC strength degradation as temperature increases for saturated specimens. In addition, it appears that increasing temperature is more detrimental to the OHC strength than the moisture content. Table 2 summarizes the percent drop in OHC strength from temperature and moisture separately.

Table 2. Reduction in OHC strength of AS4/PR500 due to temperature and moisture.

Temperature (°F)	Dry Value (ksi)	% Reduction from 70 °F due to Temperature	Elevated Temperature Wet (ETW) Value (ksi)	Additional % Reduction due to Moisture	Total % Reduction from 70 °F Dry to ETW
70	45.3	–	–	–	–
180	38.2	15.7	36.3	4.2	19.9
240	35.6	21.4	32.8	6.2	27.6
300	32.1	29.1	27.1	11.1	40.2

It is evident that large knockdowns must be taken if the structure is to experience aircraft-like elevated temperatures, especially if the structure must be designed to airplane standard ‘saturation’ conditions.

If the actual environment that the launch vehicle hardware will experience is used instead of the harsh ones used for aircraft, it is possible that an additional weight savings can be realized. Figure 2 shows the results of a Kennedy Space Center (KSC) Corrosion Technology Laboratory Atmospheric Corrosion Test Site exposure of laminates made of the material system (IM7/8552) to be used for the Ares I composite interstage. The program requirement is for a 6-mo ‘pad stay,’ which equates to 6 mo of atmospheric exposure. Even at a longer pad stay, the laminates had a weight gain of ≈0.5% that can be considered a worst case scenario.

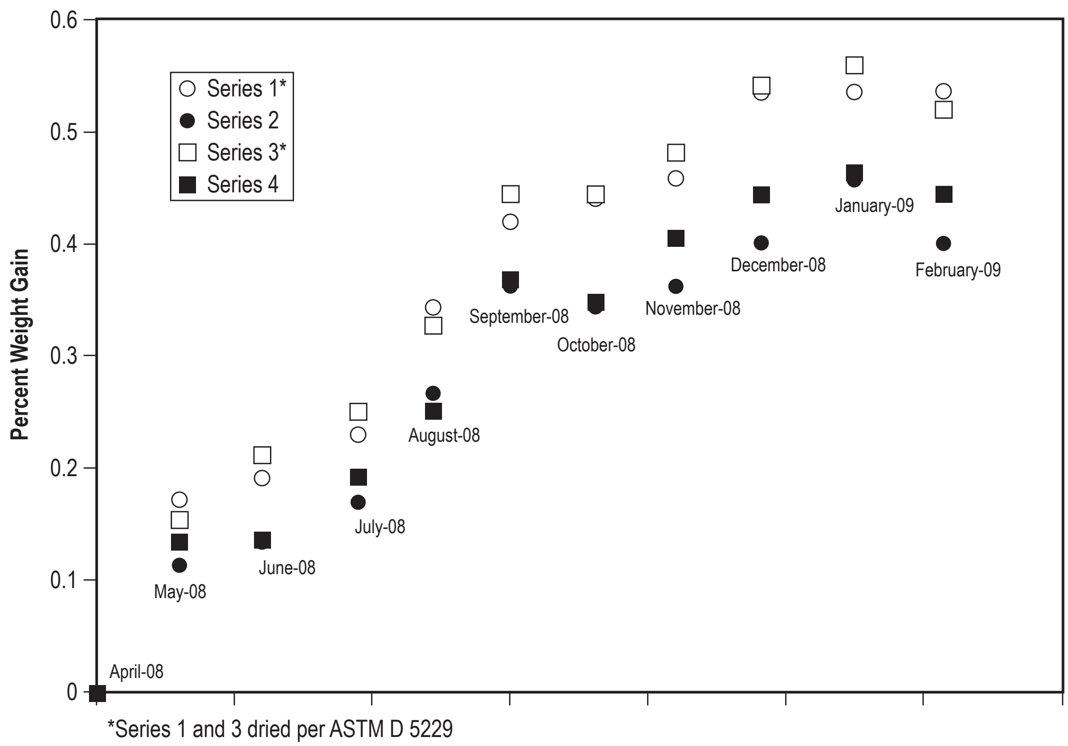

Figure 2. Results of beach exposure specimens of 18-ply IM7/8552 laminates.

This TM proposes to provide a better understanding of the effects of moisture and heat on the resulting OHC strength of laminates of IM7/8552 carbon/epoxy in order to evaluate whether testing to more realistic conditions could result in a weight savings due to lower knockdown factors. In order to accomplish this, OHC specimens were tested at a variety of moisture contents and temperatures to evaluate the sensitivity of these parameters.

3. MATERIALS AND TESTING

The material used in this study consisted of IM7/8552 carbon/epoxy with a per-ply thickness of 0.006 in. This particular resin has a glass transition temperature (T_g) of 392 °F dry and 309 °F wet. The layup of the laminate was $[+45,0,-45,0,90,0,0,90,0]_S$ which makes an 18-ply directional specimen with more zero-degree plies in the loading direction. Panels were fabricated as a 24- by 24-in laminate from which the specimens were cut. Cure was in an autoclave at 55 psi pressure and 350 °F for 120 min. From the 24- by 24-in panel, 3- by 1-in specimens were machined with a 0.125-in-diameter hole at its center as shown schematically in figure 3. The 3-in side was parallel to the zero-degree fibers. Since the specimens were to be end-loaded, the loaded edges were machined to within a 0.001-in tolerance.

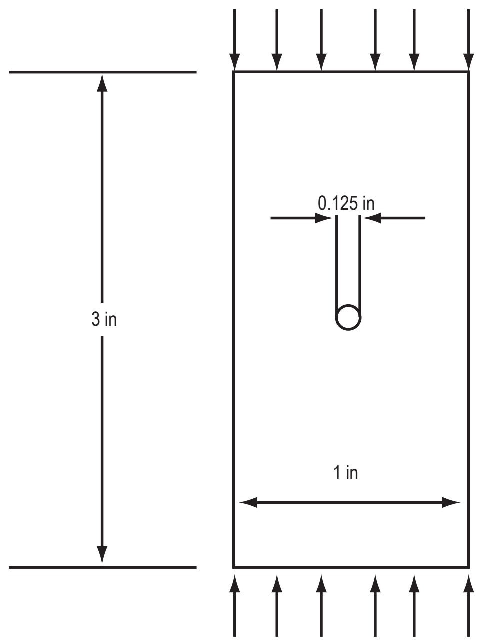

Figure 3. Schematic of specimens used in this study.

A 'Northrop' fixture[7] was used to prevent global buckling of the specimen. Figure 4 shows a photograph of the fixture in the test chamber prior to testing. While the majority of OHC is based on ASTM D 6484,[5] the 'Northrop' method has been shown to give comparable results with a smaller specimen. The smaller specimen makes mechanical testing less costly and easier to perform.[8] The recommended hole size is chosen to give a width/hole diameter ratio greater than six,[9] and in this study, a ratio of eight was used. Figure 5 shows a front and side view of a failed specimen after testing.

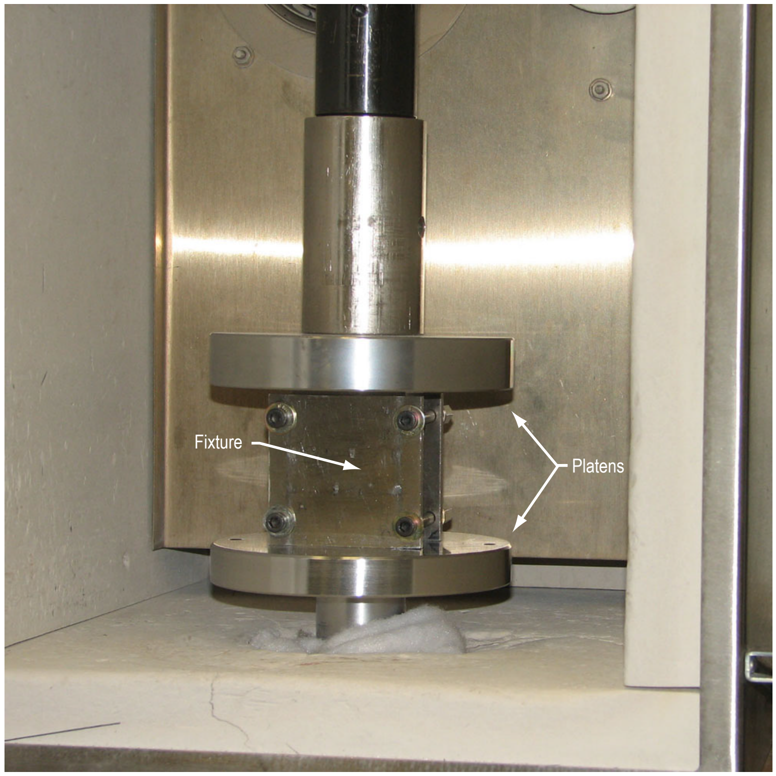

Figure 4. Test specimen and fixture in environmental chamber prior to compression testing.

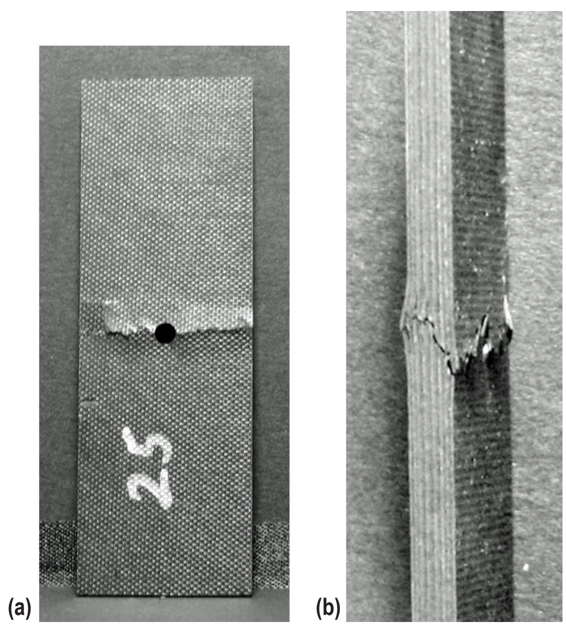

Figure 5. Front (a) and side (b) view of failed OHC specimen.

The specimens were randomly chosen for the various tests to prevent any bias that might result from taking groups of specimens from the same area of the large panel. The specimens were conditioned in a Cincinnati Sub-Zero (CSZ) MicroClimate® environmental humidity chamber at elevated temperature and relative humidity. A picture of the humidity chamber used is shown in figure 6 and the specimens in the chamber are shown in figure 7. The specimens were periodically removed and weighed on a Mettler AE200® scale to determine the amount of moisture they had absorbed as a percentage of total material weight. A picture of a specimen being weighed is shown in figure 8. Once a 'desired amount' of moisture had been absorbed, specimens were removed from the environmental chamber and placed in plastic bags. The 'desired amount' of moisture absorption was scheduled to be from 0.1%–1.0% weight increase in increments of 0.1%, however this was not achieved due to testing constraints. Subsequent mechanical testing was performed within 48 hr after removal from the chamber using an Instron 5582® with a 22,500-lb load cell.

In many instances, specimens were not conditioned before mechanical testing. These specimens could contain some moisture with the amount depending on many factors such as type of epoxy, cure time, and laboratory storage conditions before mechanical testing. In this study, some specimens were not conditioned to see how much the unconditioned OHC strength deviated from specimens whose moisture content was strictly controlled. This was done in an attempt to determine the criticality of the moisture conditioning of specimens before performing OHC strength tests on laminates rather than simply machining the specimens, storing them in laboratory conditions, and then performing the mechanical testing.

Figure 6. Environmental humidity test chamber used to wet condition specimens.

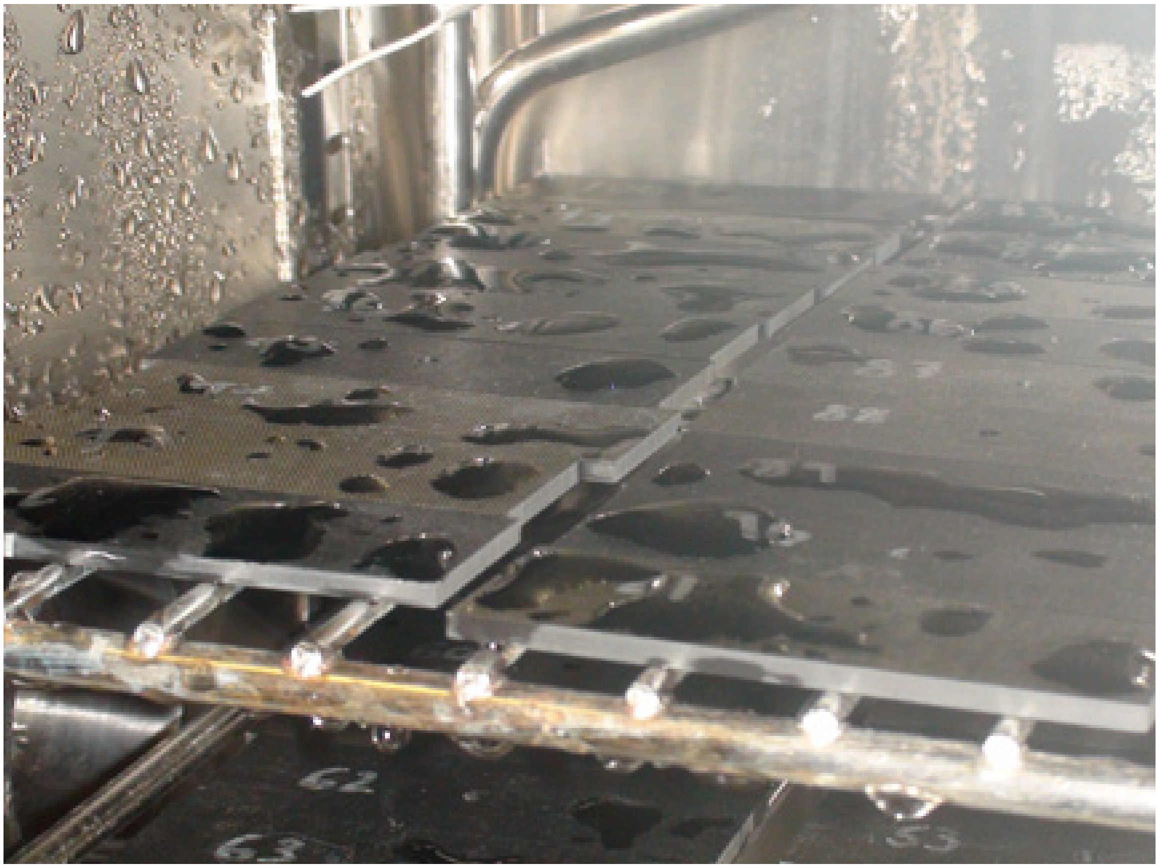

Figure 7. OHC test specimens in the humidity chamber.

Figure 8. Specimen being weighed.

4. RESULTS

4.1 Unconditioned Specimens

The first set of OHC testing was performed on unconditioned specimens to obtain a strength versus temperature profile for IM7/8552 with a layup sequence of $[+45,0,-45,0,90,0,0,90,0]_S$. A total of five specimens were tested at each of five elevated temperatures between 150 °F and 300 °F. Ten specimens were tested at room temperature and 15 were tested at 120 °F. A thermocouple was placed in the hole of the specimen being tested and once the thermocouple indicated the specimen had reached the desired temperature, the specimen was held at that temperature for 10 additional minutes before beginning compression testing at a constant crosshead rate of 0.05 in/min. Table 3 lists the test temperatures and resulting OHC strengths with a plot of the data given in figure 9. The raw data are presented in table 4.

Table 3. Test temperatures and results for OHC strength versus temperature of unconditioned specimens.

Temperature (°F)	Strength (ksi)	% Decrease From Room Temperature	Standard Deviation (ksi)
RT	72.6	–	1.7
120	70.4	3.0	4.2
150	70.4	3.0	4.1
180	67.3	7.3	3.6
220	65.8	9.4	4.9
260	64.6	11.0	2.1
300	60.6	16.5	3.0

The data show that on unconditioned specimens, the strength drops about 7% from RT to 180 °F and about 9% from RT to 220 °F. At temperatures greater than ≈150 °F, the strength drop is basically linear with increasing temperature through the range of temperatures tested.

A second set of OHC testing was performed on unconditioned specimens to obtain strength versus dwell time data at 220 °F for this material. This set of experiments was to determine the importance of the laminate being subjected to a given temperature for short versus long periods of time since all composite components on a launch vehicle will experience only brief excursions to the upper use temperature. A thermocouple was not used in these tests since the material was not intended to have a uniform temperature throughout its volume to simulate actual flight conditions for a launch vehicle.

A total of five specimens were tested at each of five dwell times at 220 °F. The test fixture was heated to 220 °F before each specimen was loaded. After loading the specimen, the fixture

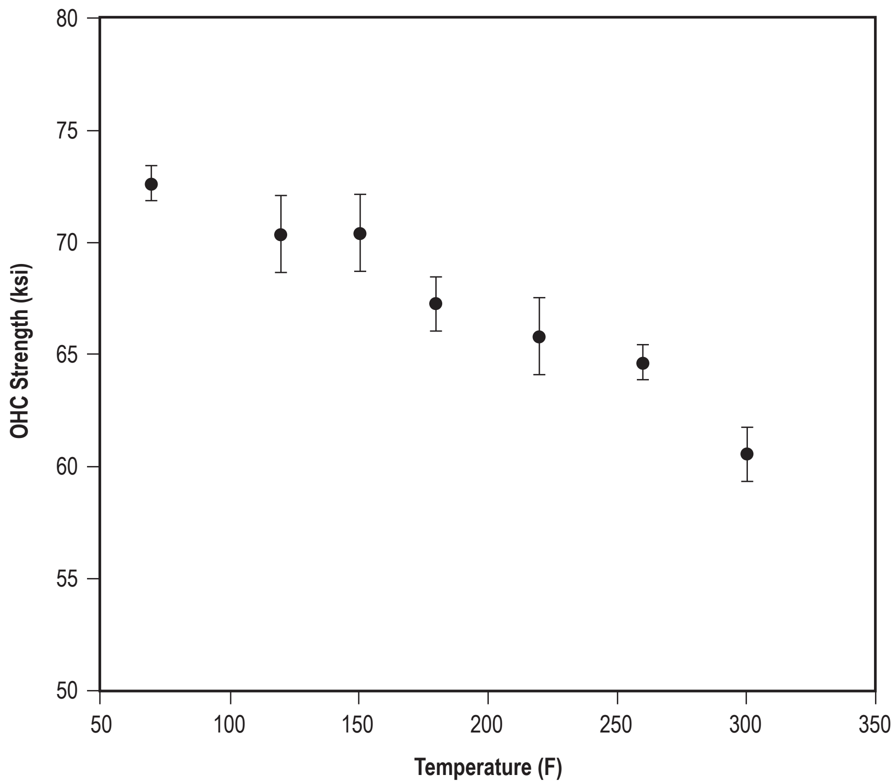

Figure 9. OHC strength versus temperature for unconditioned specimens.

was placed in the oven for the prescribed time period and then compression testing commenced. Table 5 shows the test dwell times and results for this set of data and figure 10 shows this data plotted as OHC strength versus dwell time. The raw data are presented in table 6.

The data show that on unconditioned specimens, the strength is independent of dwell time at 220 °F for up to 30 min. Much longer dwell times may have a more pronounced effect, but time at temperature for such a length of time is not applicable to launch vehicle hardware. The specimens that 'dwelled' for 10 and 30 seconds actually experienced a hot environment for a longer period due to the time needed to secure the specimen in the hot fixture plus the time needed to apply load until the specimen failed. Regardless, the data demonstrate that the 'dwell time' is of no consequence to the notched compression strength of composite laminates used on expendable launch vehicles.

4.2 Conditioning of Specimens

The specimens were conditioned in three batches. The first batch was conditioned at 180 °F and 83% relative humidity (RH) to ≈0.7% moisture gain by weight. Some specimens were tested for OHC strength and others were left in laboratory conditions (70 °F, 50% RH) to be monitored for weight loss. The second batch was conditioned at 150 °F and 100% RH to saturation (≈1.2% weight gain). The third batch was first dried and then conditioned at 150 °F and 100 % RH and periodically measured for moisture content. At each measurement for moisture content, some of the

Table 4. Data from all unconditioned OHC specimens tested at various temperatures.

Specimen I.D.	Test Temperature (°F)	OHC Strength (ksi)
OHC-RT-1	70	73.8
OHC-RT-2	70	71.6
OHC-RT-3	70	72.6
OHC-RT-4	70	75.2
OHC-RT-5	70	72.2
OHC-RT-6	70	71.9
OHC-RT-7	70	71.1
OHC-RT-8	70	71.2
OHC-RT-9	70	75.2
OHC-RT-10	70	70.7
OHC-120-1	120	64.9
OHC-120-2	120	74.3
OHC-120-3	120	67.7
OHC-120-4	120	75.0
OHC-120-5	120	64.8
OHC-120-6	120	76.1
OHC-120-7	120	75.0
OHC-120-8	120	80.3
OHC-120-9	120	65.9
OHC-120-10	120	75.8
OHC-120-11	120	65.8
OHC-120-12	120	72.9
OHC-120-13	120	69.2
OHC-120-14	120	68.1
OHC-120-15	120	70.4

Specimen I.D.	Test Temperature (°F)	OHC Strength (ksi)
OHC-150-1	150	69.3
OHC-150-2	150	66.3
OHC-150-3	150	70.9
OHC-150-4	150	68.4
OHC-150-5	150	77.0
OHC-180-1	180	65.5
OHC-180-2	180	66.4
OHC-180-3	180	64.1
OHC-180-4	180	67.0
OHC-180-5	180	73.4
OHC-220-1	220	67.1
OHC-220-2	220	62.3
OHC-220-3	220	62.4
OHC-220-4	220	63.5
OHC-220-5	220	73.9
OHC-260-1	260	65.1
OHC-260-2	260	61.2
OHC-260-3	260	64.1
OHC-260-4	260	66.5
OHC-260-5	260	66.2
OHC-300-1	300	57.7
OHC-300-2	300	63.0
OHC-300-3	300	61.2
OHC-300-4	300	57.2
OHC-300-5	300	63.8

Table 5. Results for OHC strength versus dwell time at 220 °F of unconditioned specimens.

Dwell Time (min)	Strength (ksi)	Standard Deviation (ksi)
0.17	66.5	2.7
0.5	66.5	2.0
3	66.4	3.3
10	65.8	4.9
30	67.5	1.8

specimens were removed and tested for OHC strength. Moisture uptake (and loss) versus square root of time for the three specimen batches is shown in figure 11.

Table 6. Data from all unconditioned OHC specimens tested at 220 °F for various dwell times.

Specimen I.D.	Dwell Time (min)	OHC Strength (ksi)
OHC-220-017-1	0.17	63.5
OHC-220-017-2	0.17	63.9
OHC-220-017-3	0.17	70.5
OHC-220-017-4	0.17	67.0
OHC-220-017-5	0.17	67.5
OHC-220-05-1	0.5	69.5
OHC-220-05-2	0.5	65.2
OHC-220-05-3	0.5	66.0
OHC-220-05-4	0.5	64.5
OHC-220-05-5	0.5	67.2
OHC-220-3-1	3	67.3
OHC-220-3-2	3	67.5
OHC-220-3-3	3	70.1
OHC-220-3-4	3	61.2
OHC-220-3-5	3	65.9

Specimen I.D.	Dwell Time (min)	OHC Strength (ksi)
OHC-220-10-1	10	67.1
OHC-220-10-2	10	62.3
OHC-220-10-3	10	62.4
OHC-220-10-4	10	63.5
OHC-220-10-5	10	73.9
OHC-220-30-1	30	66.1
OHC-220-30-2	30	70.1
OHC-220-30-3	30	67.4
OHC-220-30-4	30	65.6
OHC-220-30-5	30	68.4

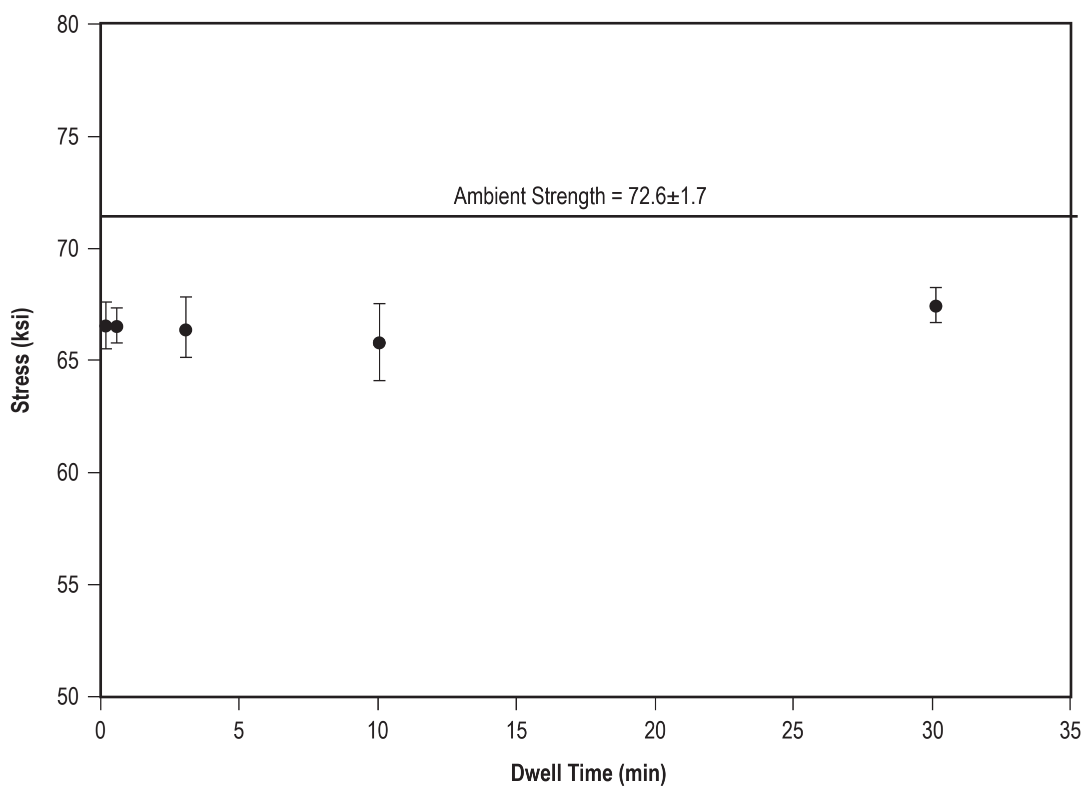

Figure 10. OHC strength versus dwell time at 220 °F for unconditioned specimens.

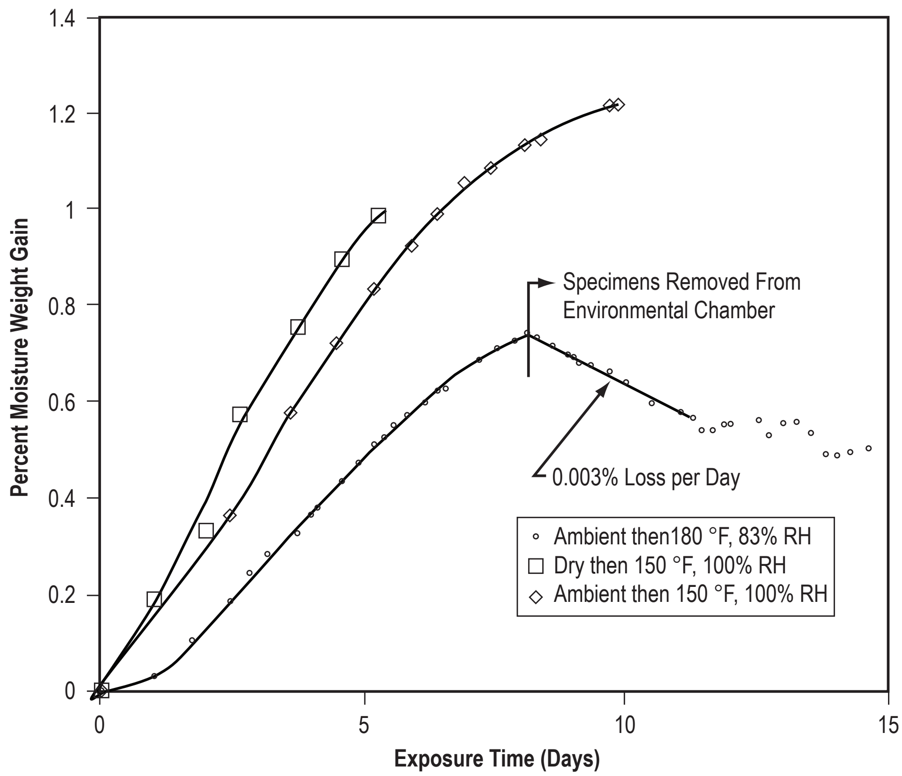

Figure 11. Percent moisture weight gain (loss) versus square root of days.

Note that the desorption of the moisture in the specimens after removal from the environmental chamber is about 0.003% weight per day. This indicates that if the percent moisture gain is to be known to the nearest 0.01% then the specimens should be isolated from the environment or tested within 3.3 days after removal from the humidity chamber.

As expected, the specimens that were dried prior to placement in the humidity chamber gained moisture slightly faster than those specimens that were not dried, when exposed to 150 °F and 100% RH conditioning. The 180 °F at 83% RH conditioning caused the specimens to gain weight more slowly than conditioning at 150 °F and 100% RH. The data show that for this particular laminate, one week of conditioning is all that is needed to obtain the 'worst case' value of 0.5% as determined in figure 2.

4.3 Open Hole Compression Strength of Conditioned Specimens Varying Test Temperature

The OHC strength testing of conditioned specimens was performed at various temperatures and humidity levels to determine the criticality of each of these variables. This section will examine the effects of varying test temperature with a given moisture level in the specimens.

The first set of tests was intended to determine the effect of temperature on OHC strength on specimens with 0.7% moisture at a given dwell time of 10 min. A total of three specimens were tested at each of five temperatures between 70 °F and 220 °F (five specimens were tested at 300 °F). Table 7 shows the results of the tests. The 0.7% moisture weight gain is a value higher than what can be expected for actual hardware. Also included in the data are RT wet OHC strength values for specimens conditioned to 1.0% weight gain. The results are plotted in figure 12 with the data from figure 9 superimposed. The raw data are presented in table 8.

Table 7. Results for OHC strength versus temperature for 0.7% weight gain conditioned specimens.

Temperature (°F)	Strength (ksi)	% Decrease from Room Temperature (0.7%)	% Decrease due to Moisture	Standard Deviation (ksi)
RT	73.7	–	0.15 (increase)	1.7
RT (1.0%)	74.1	–	2.1 (increase)	1.7
150	69.2	6.1	1.7	3.2
180	65.8	10.7	2.2	1.6
220	63.7	13.6	3.2	2.1
300	59.9	18.7	0.11	2.9

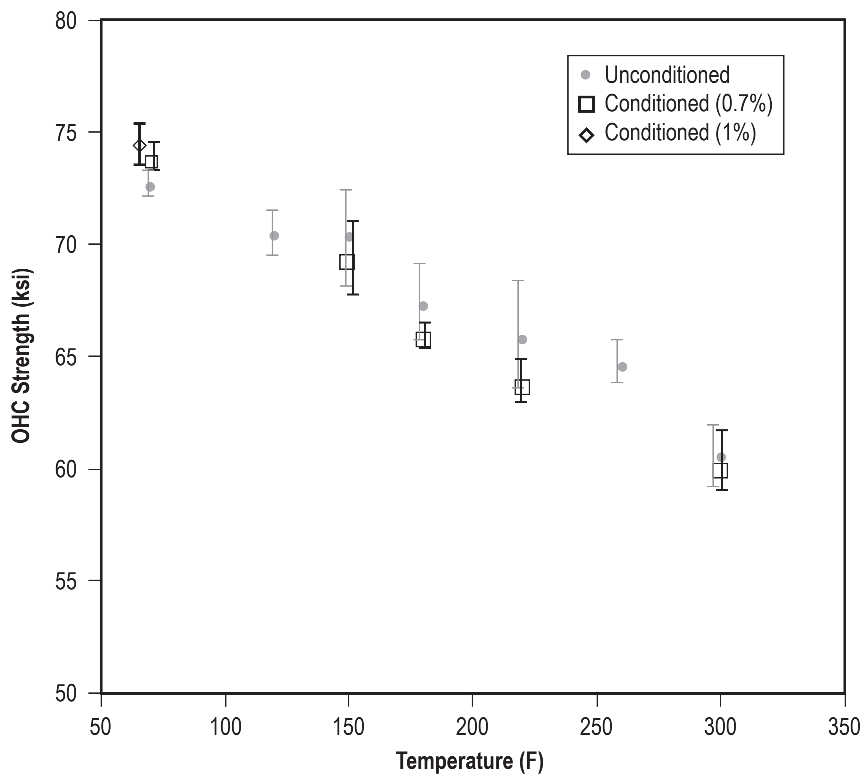

Figure 12. OHC strength versus temperature for 0.7% weight gain conditioned specimens.

The conditioned specimens did exhibit a lower OHC strength at elevated temperatures, but not to a large degree since the average value of the conditioned specimen is within the error bars of the unconditioned specimens. The specimens tested at RT show that the conditioned specimens actually failed at a higher OHC stress value than the unconditioned specimens, although not by an

Table 8. Data from all 0.7% weight gain OHC specimens tested at various temperatures.

Specimen I.D.	Test Temperature (°F)	OHC Strength (ksi)
OHC-07-RT-1	70	71.8
OHC-07-RT-2	70	74.4
OHC-07-RT-3	70	75.0
OHC-1.0-RT-1	70	76.0
OHC-1.0-RT-2	70	74.0
OHC-1.0-RT-3	70	74.9
OHC-1.0-RT-3	70	76.9
OHC-1.0-RT-3	70	71.2
OHC-1.0-RT-3	70	73.7
OHC-1.0-RT-3	70	73.9
OHC-1.0-RT-3	70	74.0
OHC-1.0-RT-3	70	74.8
OHC-1.0-RT-3	70	71.7
OHC-07-150-1	150	69.3
OHC-07-150-2	150	72.4
OHC-07-150-3	150	66.0
OHC-07-180-1	180	64.0
OHC-07-180-2	180	66.5
OHC-07-180-3	180	66.8
OHC-07-220-1	220	65.8
OHC-07-220-2	220	61.6
OHC-07-220-3	220	63.6
OHC-07-300-1	300	64.1
OHC-07-300-2	300	61.3
OHC-07-300-3	300	56.6
OHC-07-300-4	300	58.6
OHC-07-300-5	300	59.1

appreciable amount. This highlights the reason that RT wet tests are usually not performed. The decrease in OHC strength from ambient to 180 °F wet is 10.7% which is comparable to the value (11.1%) given in reference 4 even though the laminate in this study has a larger percentage of zero-degree plies. The decrease in OHC strength from ambient to 220 °F wet is 12.3% which is smaller than the value (16.6%) given in reference 4. From the data it is evident that environmental conditioning of this laminate for notched compression strength will have little or no effect on the results.

4.4 Conditioned Specimens Varying Humidity

This section examines the effects on OHC strength of varying moisture levels at a given temperature of 220 °F. Table 9 shows the results that are plotted in figure 13. The raw data are presented in table 10.

Table 9. Results for OHC strength versus moisture weight gain at 220 °F.

% Weight Gain*	Strength (ksi)	% Decrease From Dry	Standard Deviation (ksi)
0.0	66.2	–	3.4
0.189	63.0	4.8	2.1
0.332	62.8	5.1	2.9
0.572	63.2	4.5	3.2
0.754	63.5	4.1	1.8
0.894	63.6	3.9	2.5
1.2	62.2	6.0	2.9

*Specimens originally dried per ASTM D 5229.

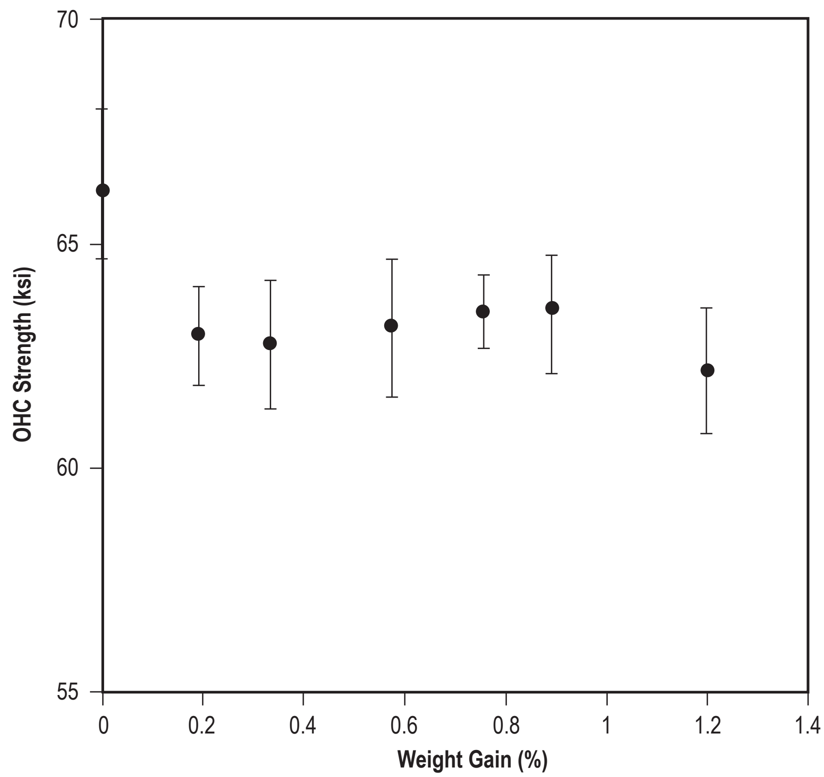

Figure 13. OHC strength versus percent moisture weight gain for specimens at 220 °F.

The data suggests that the amount of moisture in the specimen has little effect on the OHC strength for a given temperature. Drying the specimen before testing may increase the OHC strength slightly, but typically launch vehicle hardware is not ‘dried out’ before flight.

Results from the earlier tests at 220 °F are superimposed on figure 13 and presented in figure 14.

Table 10. Data from OHC specimens tested at 220 °F and varying moisture content.

Specimen I.D.	% Weight Gain	OHC Strength (ksi)
OHC-DRY-1	0	61.4
OHC-DRY-2	0	65.3
OHC-DRY-3	0	67.5
OHC-DRY-4	0	65.8
OHC-DRY-5	0	73.9
OHC-DRY-6	0	64.6
OHC-DRY-7	0	63.4
OHC-DRY-8	0	65.4
OHC-DRY-9	0	66.8
OHC-DRY-10	0	68.3
OHC-189-1	0.189	64.1
OHC-189-2	0.189	64.9
OHC-189-3	0.189	61.3
OHC-189-4	0.189	64.8
OHC-189-5	0.189	66.6
OHC-189-6	0.189	59.7
OHC-189-7	0.189	61.4
OHC-189-8	0.189	61.5
OHC-189-9	0.189	62.7
OHC-189-10	0.189	62.5
OHC-332-1	0.332	61.4
OHC-332-2	0.332	62.8
OHC-332-3	0.332	63.7
OHC-332-4	0.332	63.7
OHC-332-5	0.332	62.4
OHC-332-6	0.332	68.4
OHC-332-7	0.332	59.5
OHC-332-8	0.332	57.7
OHC-332-9	0.332	64.3
OHC-332-10	0.332	64.5
OHC-572-1	0.572	60.8
OHC-572-2	0.572	62.7
OHC-572-3	0.572	63.0
OHC-572-4	0.572	68.9
OHC-572-5	0.572	65.0
OHC-572-6	0.572	59.9
OHC-572-7	0.572	59.2
OHC-572-8	0.572	60.9
OHC-572-9	0.572	67.1
OHC-572-10	0.572	64.4

Specimen I.D.	% Weight Gain	OHC Strength (ksi)
OHC-754-1	0.754	63.0
OHC-754-2	0.754	63.5
OHC-754-3	0.754	62.7
OHC-754-4	0.754	60.1
OHC-754-5	0.754	64.7
OHC-754-6	0.754	65.1
OHC-754-7	0.754	63.9
OHC-754-8	0.754	63.7
OHC-754-9	0.754	66.5
OHC-754-10	0.754	50.3
OHC-894-1	0.894	65.1
OHC-894-2	0.894	57.3
OHC-894-3	0.894	64.2
OHC-894-4	0.894	66.1
OHC-894-5	0.894	62.6
OHC-894-6	0.894	64.3
OHC-894-7	0.894	65.2
OHC-894-8	0.894	65.0
OHC-894-9	0.894	63.5
OHC-894-10	0.894	62.5
OHC-SAT-1	1.20	62.0
OHC-SAT-2	1.20	62.9
OHC-SAT-3	1.20	60.3
OHC-SAT-4	1.20	61.9
OHC-SAT-5	1.20	61.6
OHC-SAT-6	1.20	60.7
OHC-SAT-7	1.20	59.3
OHC-SAT-8	1.20	63.1
OHC-SAT-9	1.20	54.7
OHC-SAT-10	1.20	66.4
OHC-SAT-11	1.20	64.5
OHC-SAT-12	1.20	60.5
OHC-SAT-13	1.20	58.2
OHC-SAT-14	1.20	63.3
OHC-SAT-15	1.20	65.4
OHC-SAT-16	1.20	64.9
OHC-SAT-17	1.20	60.3
OHC-SAT-18	1.20	63.2
OHC-SAT-19	1.20	64.8
OHC-SAT-20	1.20	66.0

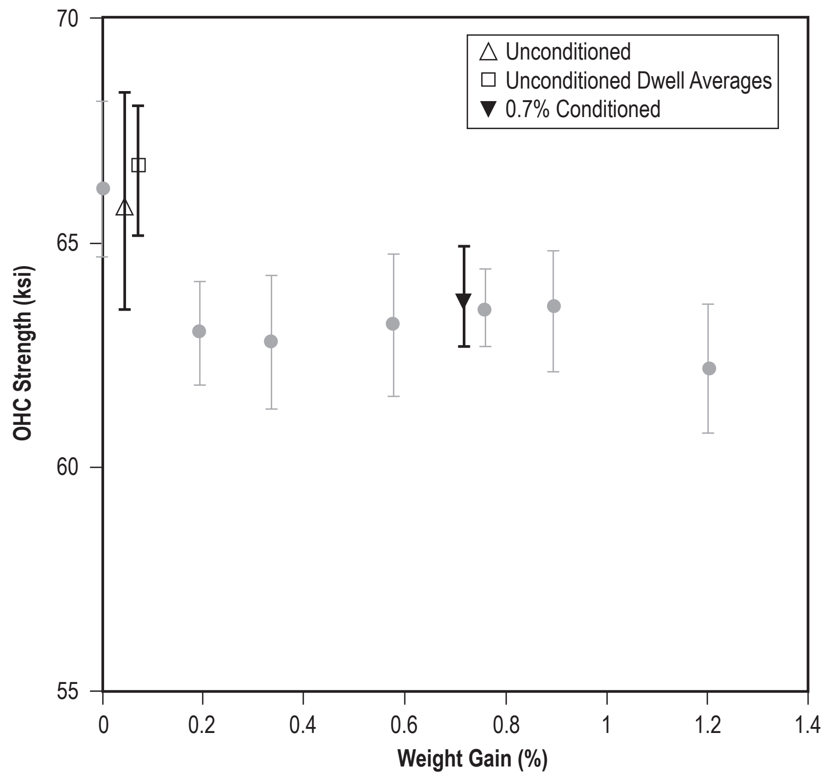

Figure 14. Plot of all OHC data tested at 220 °F.

5. CONCLUSIONS

It should be noted that all testing was below this resin's wet T_g so no dramatic changes in strength were to be expected. The conclusions to be drawn from the tests of this study include the following:

- The OHC strength knockdown for the material and layup used in this study, which separated moisture effects from temperature, was at the lower end of the 10%–20% strength drop seen in table 1. This is not unexpected as the laminate in this study was directional, not quasi-isotropic.

- Unconditioned OHC specimens have about 5% more strength than conditioned specimens at 220 °F.

- The same trend in OHC strength behavior was seen in the specimens in this study as those presented in figure 1, however the magnitude of strength drop was more severe than in this study. An explanation for this could be the high directionality of the laminates in this study.

- OHC strength tends to drop in a linear fashion with increasing temperature. For the fiber/resin tested in this study, about a 10% decrease in strength was found in both conditioned and unconditioned specimens from RT to 220 °F.

- Time that the specimen dwells at temperature (up to 30 min at 220 °F in this study) has no effect on the OHC strength.

- When conditioned specimens are removed from the environmental chamber and placed in laboratory conditions, moisture can be slowly lost. For the material in this study, testing should be completed within 3.3 days to prevent a moisture loss of more than 0.01%.

- Specimens conditioned to 0.7% moisture weight gain showed essentially no difference in OHC strength compared to unconditioned specimens when tested at elevated temperatures. Specimens tested at RT actually demonstrated a slight strength increase. Actual flight hardware can realistically expect a maximum moisture weight gain of ≈0.5%.

- The OHC strength drop from RT to 180 °F wet was 10.7% which is close to the 11.1% given in reference 4. The drop was 12.3% from RT to 220 °F wet which is smaller than that given in reference 4 (16.6%).

- Once the moisture content has reached approximately 0.2% weight gain, additional moisture gain has an insignificant effect on the OHC strength for the material and layup sequence examined in this study.

- For the relatively small drop in 'hot-wet' notched strength for the specimens in this study, the cost and schedule of testing conditioned specimens should be balanced with the actual fidelity of the allowable that is needed. Other knockdown factors such as factor of safety, A-Basis, and damage tolerance will all contribute much more to the lower allowable value used to design the structure.

- Weight savings on the interstage are not likely to be realized by assessing realistic conditions as opposed to harsh aircraft environment since such little knockdown (≈5%) was caused by the environmental conditioning.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01–06–2009	Technical Memorandum	

4. TITLE AND SUBTITLE

Hot/Wet Open Hole Compression Strength of Carbon/Epoxy Laminates for Launch Vehicle Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

A.T. Nettles

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

8. PERFORMING ORGANIZATION REPORT NUMBER

M–1259

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITOR'S ACRONYM(S)

NASA

11. SPONSORING/MONITORING REPORT NUMBER

NASA/TM—2009–215900

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified-Unlimited
Subject Category 24
Availability: NASA CASI 443–757–5802

13. SUPPLEMENTARY NOTES

Prepared by Materials Processes and Manufacturing Department, Engineering Directorate

14. ABSTRACT

This Technical Memorandum examines the effects of heat and absorbed moisture on the open hole compression strength of carbon/epoxy laminates with the material and layup intended for the Ares I composite interstage. The 'knockdown' due to temperature, amount of moisture absorbed, and the interaction between these two are examined. Results show that temperature is much more critical than the amount of moisture absorbed. The environmental knockdown factor was found to be low for this material and layup and thus obtaining a statistically significant number for this value needs to be weighed against a program's cost and schedule since basis values, damage tolerance, and safety factors all contribute much more to the overall knockdown factor.

15. SUBJECT TERMS

Composites, hot/wet, environmental effects, open hole compression

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	32	STI Help Desk at email: help@sti.nasa.gov / STI Help Desk at: 443-757-5802

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

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Space Administration
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Marshall Space Flight Center, Alabama
35812