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A Quantitative Damage Tolerance Comparison of High Strength and High Modulus Carbon Fiber Sandwich Structure

A.T. Nettles, W.E. Guin, and C.C. Wolfe
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LIST OF ACRONYMS

ATL	automatic tape layering
BVID	barely visible impact damage
CAI	compression after impact
MSFC	Marshall Space Flight Center
NDE	nondestructive evaluation
OHC	open hole compression
PAF	payload adapter fitter
SLS	Space Launch System

NOMENCLATURE

t_{min}	minimum thickness
t_{max}	maximum thickness
L	core ribbon

TECHNICAL MEMORANDUM

A QUANTITATIVE DAMAGE TOLERANCE COMPARISON OF HIGH STRENGTH AND HIGH MODULUS CARBON FIBER SANDWICH STRUCTURE

1. INTRODUCTION

While high modulus carbon fiber does not have comparable damage tolerance characteristics to high strength carbon fiber, during a program examining material usage in the manufacture of a payload adapter fitter (PAF) for NASA's Space Launch System (SLS) rocket, the question arose as to how much less damage tolerant a structure made of high modulus carbon fiber would be compared to one made of high strength carbon fiber. While there is plenty of damage tolerance data on sandwich structure with high strength carbon fiber/epoxy matrix face sheets, there is little to no information about the damage tolerance of sandwich structure with high modulus carbon fiber face sheets. This is understandable as structures that would use high modulus carbon fiber over high strength carbon fiber are stiffness critical and usually have large margins on strength. However, this particular piece of hardware may not have a large strength margin.

The compression after impact (CAI) strength of the sandwich structure considered for use on the PAF was the metric to evaluate damage tolerance for the PAF program. Thus, a comparison of high strength versus high modulus carbon fiber with respect to CAI was considered in this study with an assessment of just how much more CAI strength could be retained by the high strength carbon fiber for a given impact severity level.

2. MATERIALS

The carbon/epoxy face sheet materials used in this study both have the same matrix resin (Hexcel® 8552) to isolate the damage tolerance effects of just the carbon fiber. The two carbon fibers used were high strength IM7 and high modulus HM63, both manufactured by Hexcel. Table 1 shows some of the properties of these two fiber/resin systems using data supplied by the vendor.

Table 1. Some key composite properties of the two fiber/resin systems used in this study (data from Hexcel).

Composite Property	IM7/8552	HM63/8552
0° Tensile Strength	395 ksi	361 ksi
0° Tensile Modulus	23.8 Msi	35.7 Msi
0° Short Beam Shear	18.5 ksi	14.5 ksi
0° Compressive Strength	245 ksi	196 ksi
Open Hole Compressive Strength	48.9 ksi	36 ksi
Fiber Strain to Failure	1.8%	1.0%
Fiber Volume Fraction	60%	60%

Of note in the above table, the fiber strain to failure has long been known as one of the key parameters governing damage resistance with higher strain-to-failure fibers performing much better than lower strain-to-failure fibers.[1,2] The IM7 fiber has a strain to failure of 1.8% and the HM63 fiber has a strain to failure of 1%, which indicates that the IM7 laminates should have better damage resistance. The unnotched compression strength is 25% higher for the IM7 fiber and the open hole compression strength is higher for the IM7 fiber system by 36% which indicates the HM63 is more notch-sensitive since the drop in strength is significantly lower than 25% (which can be a good predictor of CAI strength for a given damage size). Thus, for the HM63 carbon fiber, the combination of more damage for a given impact energy combined with the lower compression strength and higher notch sensitivity for a given amount of damage should all three combine to cause the HM63 fiber sandwich structure to have much lower CAI strength values when compared on the basis of impact energy.

The sandwich structure was manufactured by cocuring the face sheets to an aluminum honeycomb core. The core had a density of 4.5 lb/ft^3. All the face sheets were manufactured by automatic tape laying (ATL) at NASA's Marshall Space Flight Center (MSFC). The IM7/8552 tape had an areal weight of 190 g/m^2 and the HM63/8552 tape had an areal weight of 160 g/m^2. This difference will cause the HM63/8552 face sheets to be slightly thinner than the IM7/8552 face sheets for a given lay-up. This face sheet thickness difference can be accounted for when comparing CAI values.[3] The layup for the face sheets was 8-ply $[+45/90/-45/0]_s$ quasi-isotropic. The honeycomb sandwich structure was manufactured with the core ribbon (‘*L*’) direction aligning with the 0° fiber direction. The sandwich structure had a layer of FM300-2M epoxy film adhesive placed over the core material prior to the ATL process used to manufacture the face sheets.

The sandwich structure was cured in an autoclave with a pressure of 40 psi and a temperature of 350 °F. The flat sandwich panels made for use in this study were 36 by 36 in. The sandwich structure showed good consolidation and typical fiber waviness of the face sheets on the honeycomb core panels was noted as seen in the cross-sectional photomicrographs (cut in the 0°-direction) of the specimens as shown in figure 1. The thickness values of the face sheets on the honeycomb panels varied from a minimum at the cell walls (t_{min}) to a maximum between the cell walls (t_{max}) as noted in figure 1. A nominal value for the face sheet thickness can be used based on the average of numerous random thickness measurements.

Using photomicroscopy and measuring tools contained within the software attached to the microscope, the nominal face sheet thicknesses of the specimens tested was measured and found to be 0.050 inches for the IM7 fiber face sheets and 0.039 in for the HM63 fiber face sheets.

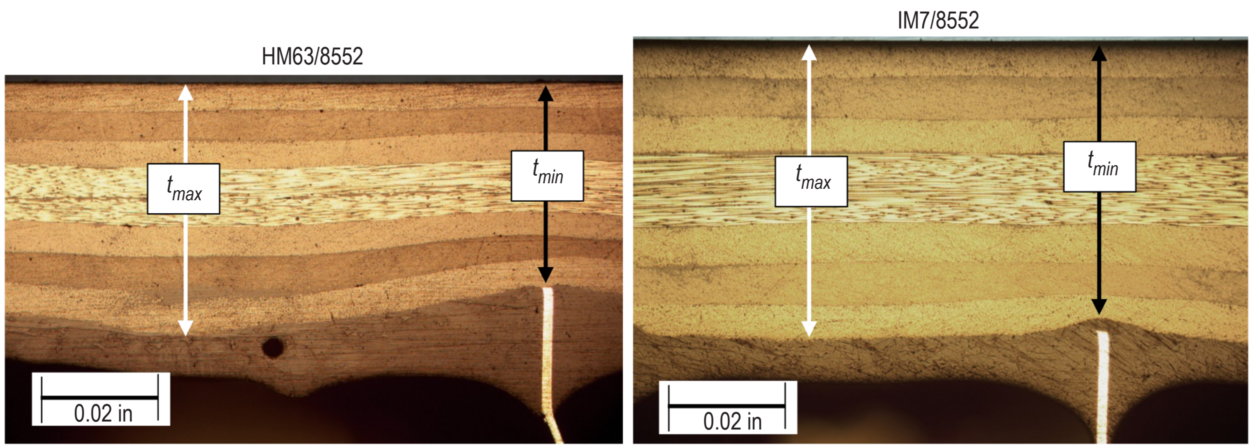

Figure 1. Cross section photomicrographs showing face sheet waviness of inner plies (plies closest to the core) on honeycomb core specimen.

The sandwich structure was cut into 6-in tall (direction of loading) by 4-in wide specimens using a diamond saw. The top and bottom edges of these specimens were then machined to ±0.001-in tolerance of parallelism using a vertical end mill with a solid carbide cutting tool (Onsrud 67-526 designed for carbon fiber machining). The side edges of the specimens were machined to be perpendicular to the top and bottom edges.

Undamaged strength testing of the honeycomb sandwich structure was not pursued in this study since the undamaged specimens exhibited end-brooming during compression testing, which is not a valid failure mode; this study concerns damage tolerance testing, therefore, undamaged strength values are irrelevant. The modulus of the sandwich structure was measured and found to be 8.7 Msi for the IM7/8552 face sheet specimens and 13.4 Msi for the HM63/8552 face sheet specimens.

3. IMPACT DAMAGE TESTING

Each sandwich specimen was impacted at its geometric center on the tool side face sheet since the tool side would be the outer side of the PAF structure and thus the most prone to impact damage. A caul plate was used on the bag side of the sandwich panel during fabrication and thus there was very little difference between the two face sheets. The impactor had a diameter of 0.5 inches and each specimen was placed on a solid steel plate during impact to give the highest rigidity, and thus most damage possible for a given impact energy.[3,4] This also ensured similar boundary conditions for all impacts. An instrumented drop weight impact apparatus was used to inflict damage to the specimens. A picture of the impact tester used is shown in figure 2. The selected impact energies were based on what was determined to be barely visible impact damage (BVID) for the HM63/8552 sandwich specimens tested (since it was known that this would be at the low end of impact energies for both types of face sheets). This impact energy was determined to be 0.6 ft•lb. An impact energy less than this and three larger than this were chosen for the remainder of impacts on the HM63/8552 face sheet sandwich specimens so that a residual strength curve could be constructed. Results of the impact tests showing the impact energy used, number of specimens tested, and the dent depth formed on the HM63/8552 specimens are summarized in table 2. The dent measurements were taken at least 24 h after impact to allow for any 'relaxation' of the dent depth.

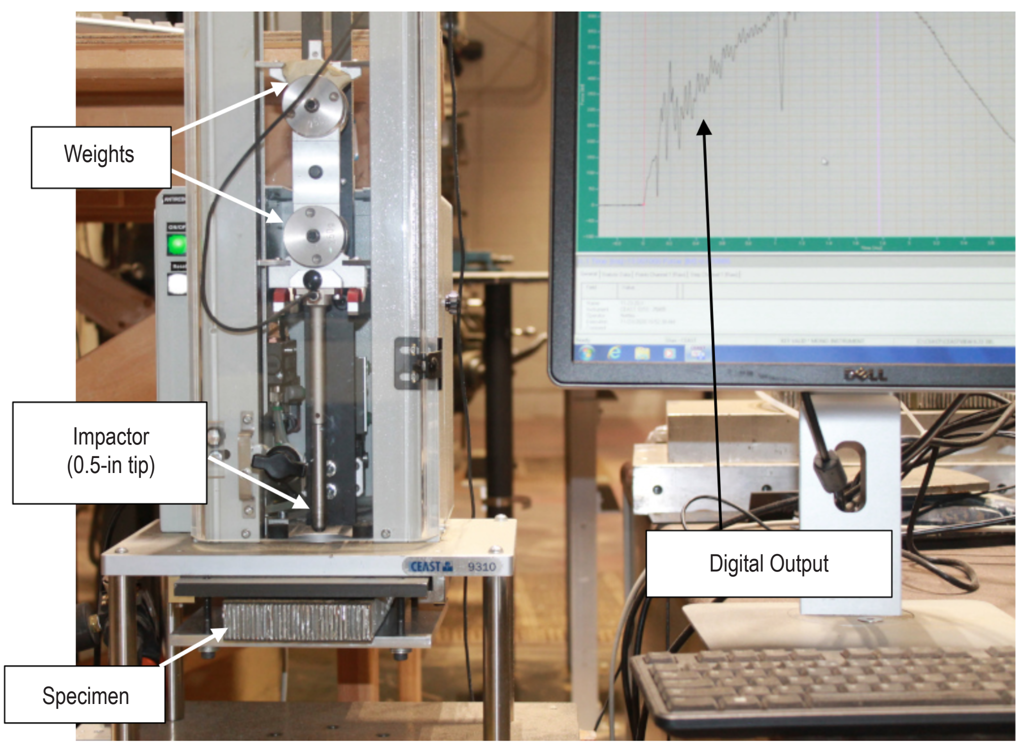

Figure 2. Photograph of instrumented impactor used in this study

Table 2. Summary of results from impact testing on the HM63/8552 face sheet sandwich specimens.

Face Sheet	Impact Energy (ft•lb)	Specimens Tested	Dent Depth (mils)
HM63/8552	0.3	7	3.1±0.4
	0.6	6	5.0±0.8
	1.1	5	7.9±0.9
	2.3	5	27.1±2.1
	3.2	3	36.2±4.6

For the IM7/8552 face sheet sandwich specimens, the impact energies were chosen based on those used for the HM63/8552 face sheet sandwich specimens. However, since the IM7/8552 face sheets were 28% thicker than the HM63/8552 face sheets, the impact energies needed to be adjusted for a fairer comparison. In Nettles' "Normalizing Impact Energy by Face Sheet Thickness for Composite Sandwich Structure Compression After Impact Testing,"[5] it was shown that for IM7/8552 face sheet sandwich structures on the order of 8-plies thick, that normalizing the impact energy by the face sheet thickness to the 2.5 power gave the best comparison of CAI results. Thus, for impact energies on a 0.039-in-thick face sheet a 0.050-inch-thick face sheet would need to be hit $(0.05/0.039)^{2.5} = 1.86$ times harder. Thus, when adjusted for thickness differences, the 'equivalent' impact energies for the IM7/8552 face sheets based on those chosen for the HM63/8552 face sheet (as presented in table 2) would be 0.6, 1.1, 2, 4.3 and 5.9 ft•lbs.

For ease of reference and comparison between the two types of face sheets, the five impact levels will be designated as Level I, II, III, IV and V. Table 3 lists these levels and the value of impact energy with the IM7/8552 specimens normalized by face sheet thickness.

Table 3. List of the five impact severity levels used, and the equivalent impact energy based on face sheet thickness.

Impact Severity Level	Impact Energy for HM63/8552 Face Sheet (ft•lb)	Equivalent Impact Energy for IM7/8552 Face Sheet (ft•lb)
I	0.3	0.6
II	0.6	1.1
III	1.1	2.0
IV	2.3	4.3
V	3.2	5.9

The results of the impact tests showing the impact energy levels used, number of specimens tested, and dent depth formed on the IM7/8552 face sheet specimens are summarized in table 4.

Table 4. Summary of results from impact testing on the IM7/8552 face sheet sandwich specimens.

Face Sheet	Impact Energy (ft•lb)	Specimens Tested	Dent Depth (mils)
IM7/8552	0.6	3	4.3±0.8
	1.1	3	7.3±1.2
	2.0	3	11.0±1.3
	4.3	3	33.0±2.8
	5.9	3	46.5±5.0

Note that the dent depth values are slightly larger than for the HM63/8552 face sheet specimens. This will be discussed more later.

A sample of visual damage on the HM63/8552 and IM7/8552 face sheet specimens produced by each of the various levels of impact energy are shown in figure 3. For all these specimens, the photographs were taken with the camera flash mode on since this tended to best highlight the damage. Note that the 0.3 ft•lb impact can be 'seen' in the photograph; however, under normal room light the damage was not obvious like it was at the 0.6 ft•lb energy level. It should be noted that in practice the amount of visual damage in the field will vary depending upon such factors as the available lighting, the angle of the lighting, and the surface finish of the specimen.

In these photographs the IM7/8552 face sheet dents appear to be slightly larger than the 'equivalent' impacts on the HM63/8552 face sheet specimens. Since the impact energy normalization is based on CAI strength and not dent depth, perhaps this is because the IM7/8552 face sheet specimens were hit with more impact energy. Dent depth has been shown not to be a good indicator of CAI strength[4] so this may be a moot point, however a more visible dent is beneficial in the field as it is more likely to be detected and thus dispositioned before launch.

With respect to visual damage, it was initially thought that the high-modulus fiber would more easily show low-level impacts, which would actually be an advantage for space launch vehicle applications since BVID is the criteria for which it is most commonly designed. If impacts are more readily visible, then a higher design strength can be used for the structure since all damage above BVID will be dispositioned. However, for the HM63/8552 face sheet used in this study, this did not appear to be the case as even at the lower unnormalized impact energy levels (0.6 and 1.1 ft-lbs) the dent depths were approximately equal.

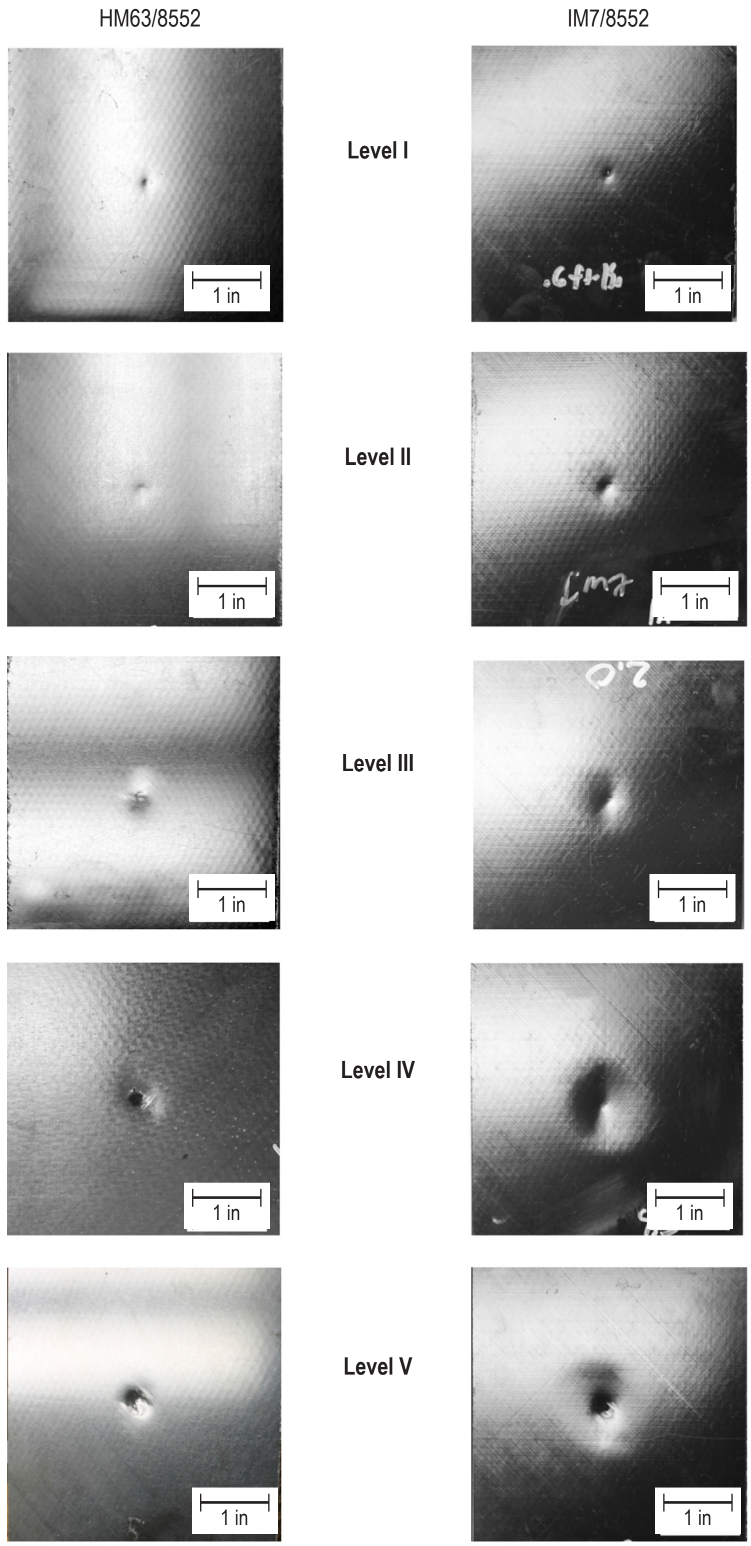

Figure 3. Photographs of various impacts with a 0.5 in impactor on honeycomb core sandwich structure with HM63/8552 and IM7/8552 face sheets.

Nondestructive evaluation (NDE) in the form of flash thermography was performed on the impacted specimens, and samples from each face sheet at each of the impact energy levels are presented in figure 4.

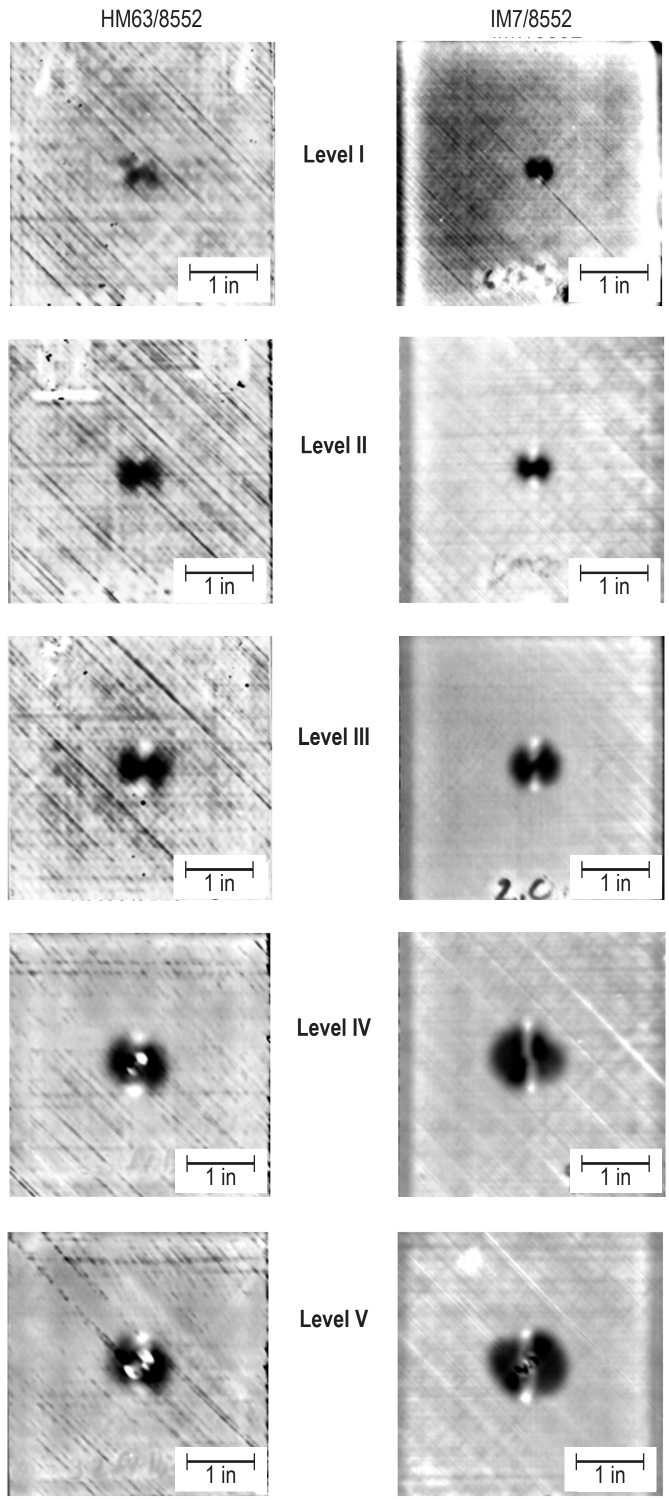

Figure 4. Thermography indications of various impacts on honeycomb core specimens used in this study.

The size of the damage appears to be about the same or even slightly larger for the IM7 face sheet sandwich structure for any given impact severity level. As with the dent depth data, it must be noted that the IM7/8552 face sheet specimens were hit harder at each level and this ‘equivalent’ impact energy is based on CAI strength and not necessarily on damage size, although damage size has been found to be a good indicator of CAI strength.[4]

Examples of the through thickness severity of the damage in the face sheets are shown in the cross sections presented in figure 5. These cuts were made through the center of the damage zone in the 90° direction (width direction).

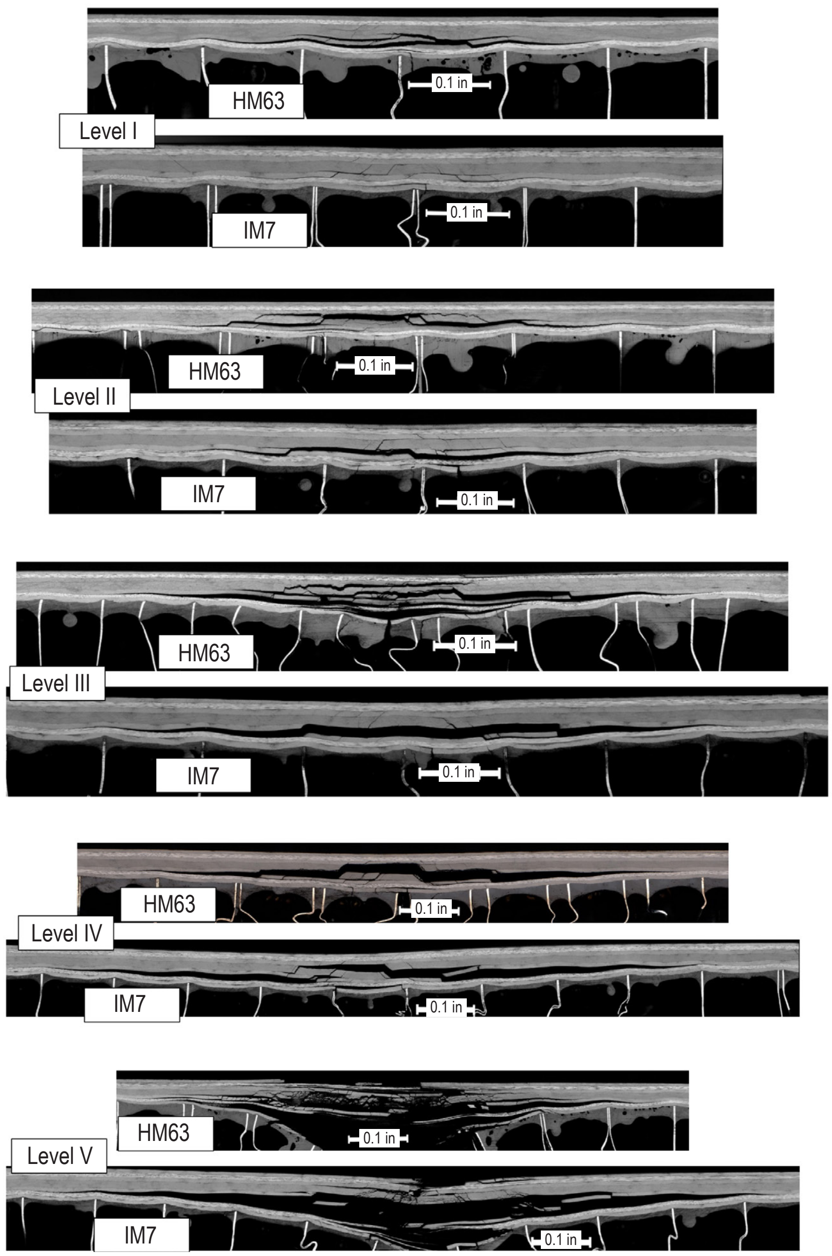

Figure 5. Cross-sectional photomicroscopy of various impacts on honeycomb core specimens used in this study. Cuts are made in the 90° direction.

In general, the HM63/8552 specimens show more through thickness damage than the IM7/8552 specimens, which is not surprising given that the HM63 fiber has a lower strain to failure ratio (i.e., is more brittle). This caused the energy of impact in the IM7/8552 specimens to form slightly longer delaminations (rather than fiber breakage) as noted in the thermography images shown in figure 4.

4. COMPRESSION AFTER IMPACT TESTING

The ultimate goal of this study was to compare these specimens on the basis of residual compression strength. The impacted sandwich specimens were assessed for residual compression strength using the test fixture shown in figure 6. Three strain gages were placed on the specimen as diagramed in figure 7 to ensure even loading of each of the face sheets. The specimens were taken to approximately 1,000 microstain compression and if one gage was lower than the others by more than 10%, shims were placed under the edge that read low until the gages were even. During compression testing, the gages were monitored and if any deviation greater than 10% occurred, the test was stopped, and shims would be rearranged until the gages read within 10% of each other all the way until failure of the specimen.

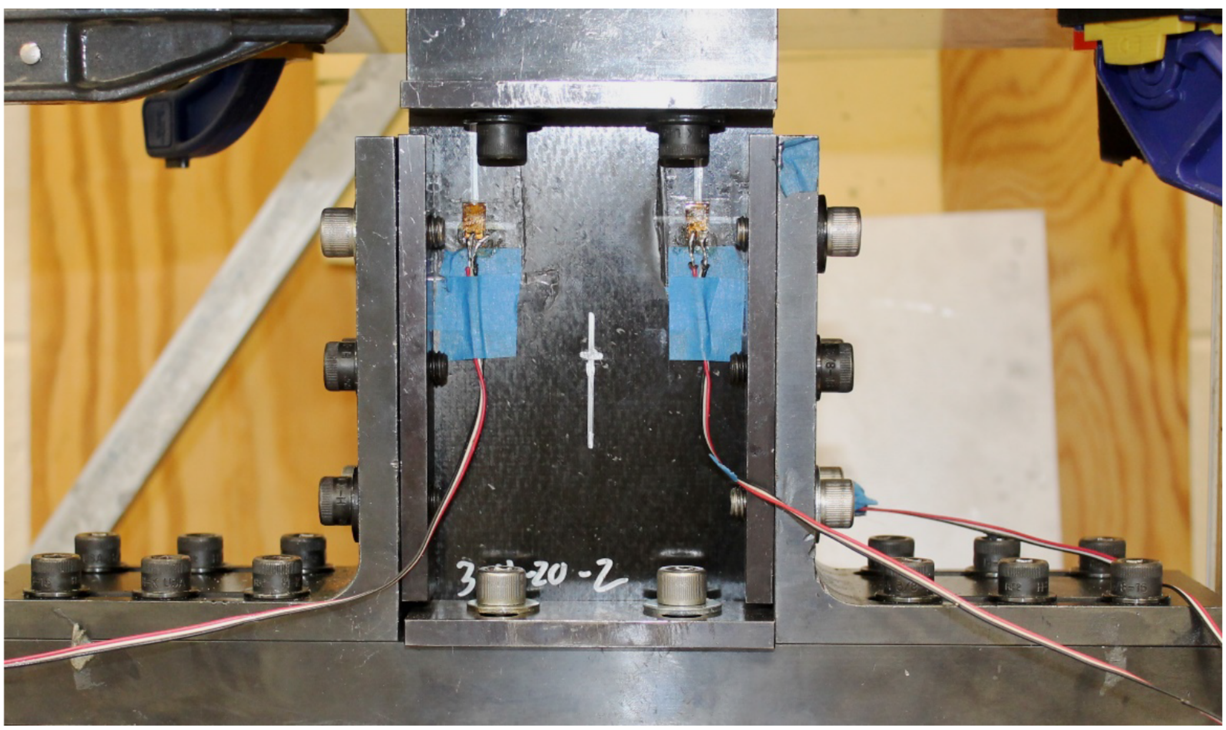

Figure 6. Photograph of fixture used for assessing CAI strength of sandwich specimens.

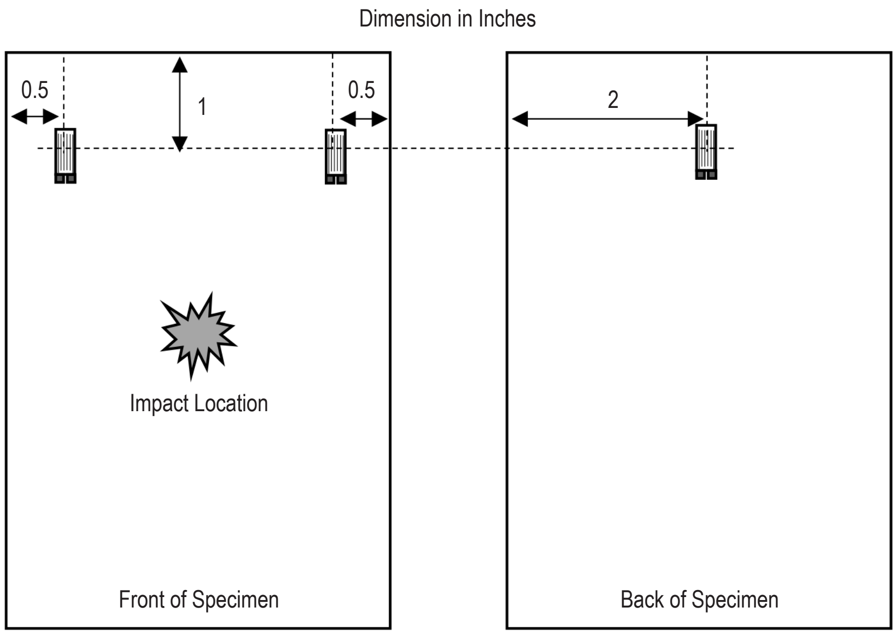

Figure 7. Location of strain gages on front and back of each CAI specimen.

For the specimens impacted at the lowest two impact energies for each of the two types of fibers used, the ends needed to be potted to prevent end brooming. This was accomplished by crushing the core about 0.25 in deep across the top and bottom of the specimen and filling these ‘channels’ with paste epoxy resin as shown in figure 8. This prevented end brooming except for the IM7/8552 face sheet specimens impacted at the lowest energy. Rather than further modify the ends of the IM7/8552 face sheet specimens, a second, more severe impact energy (3 ft•lbs) was included in the study to help complete the CAI curve that will be presented later.

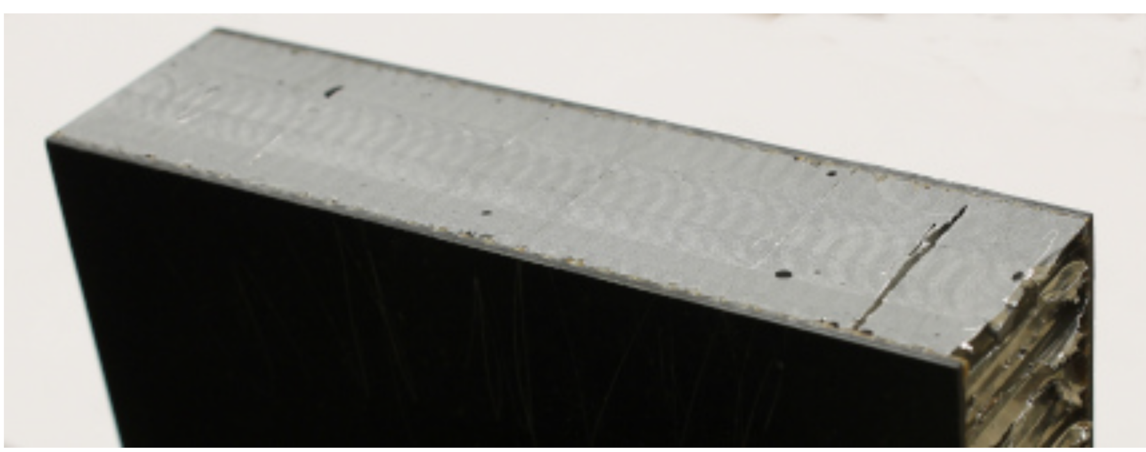

Figure 8. Image of potted end of CAI specimen.

The typical failures of CAI specimens with both types of fiber are shown in figure 9. All failures were through the impact damage and ran perpendicular to the loading direction. In general, the IM7/8552 specimens showed a larger 'bulge' across the failure zone while the HM63/8552 specimens had failure zones that did not protrude out as much. This was attributed to the IM7 fibers having more stored energy at failure. When the fibers break, this energy goes into forming larger delaminations during the shock wave that occurs at failure. The CAI strength results are shown in table 5.

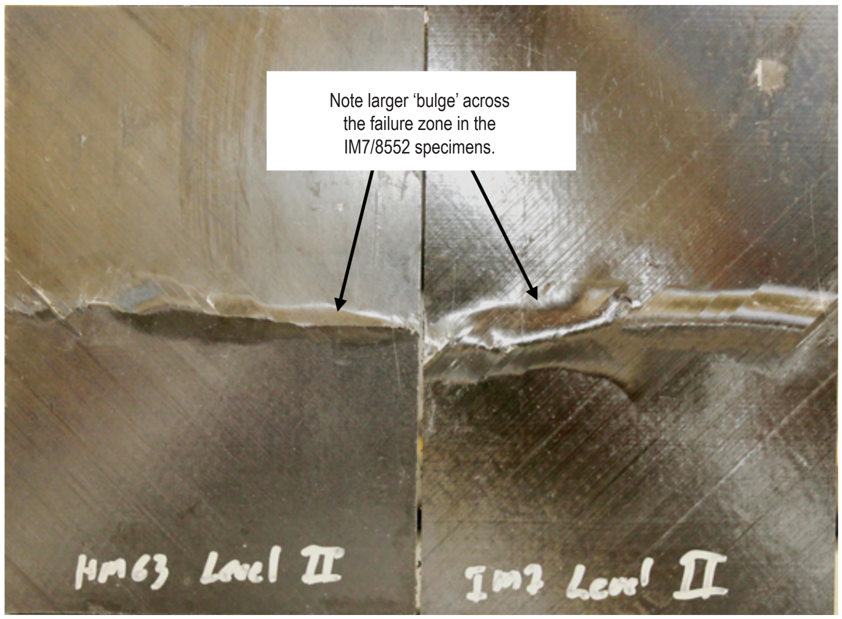

Figure 9. Picture of failed CAI specimens.

Table 5. Summary of CAI results of the sandwich specimens tested in this study.

Face Sheet	Impact Energy (ft•lb)	Specimens Tested	CAI Strength (ksi)
HM63/8552	0.3	7	41.9±3.2
	0.6	6	37.7±2.5
	1.1	5	34.7±1.7
	2.3	5	30.7±2.9
	3.2	3	28.6±1.6

Face Sheet	Impact Energy (ft•lb)	Specimens Tested	CAI Strength (ksi)
IM7/8552	0.6	3	N/A[1]
	1.1	3	68.5±0.9
	2.0	3	57.0±2.5
	3.0[2]	3	51.3±2.2
	4.3	3	42.6±1.8
	5.9	3	40.0±1.8

[1] Specimens exhibited end brooming

[2] Data added to complete CAI curve (Impact severity level between III and IV).

These results are plotted as a function of impact energy (not taking face sheet thickness differences into account) in figure 10 and as a function of impact severity level (which considers the differences in face sheet thickness for a fairer comparison) in figure 11.

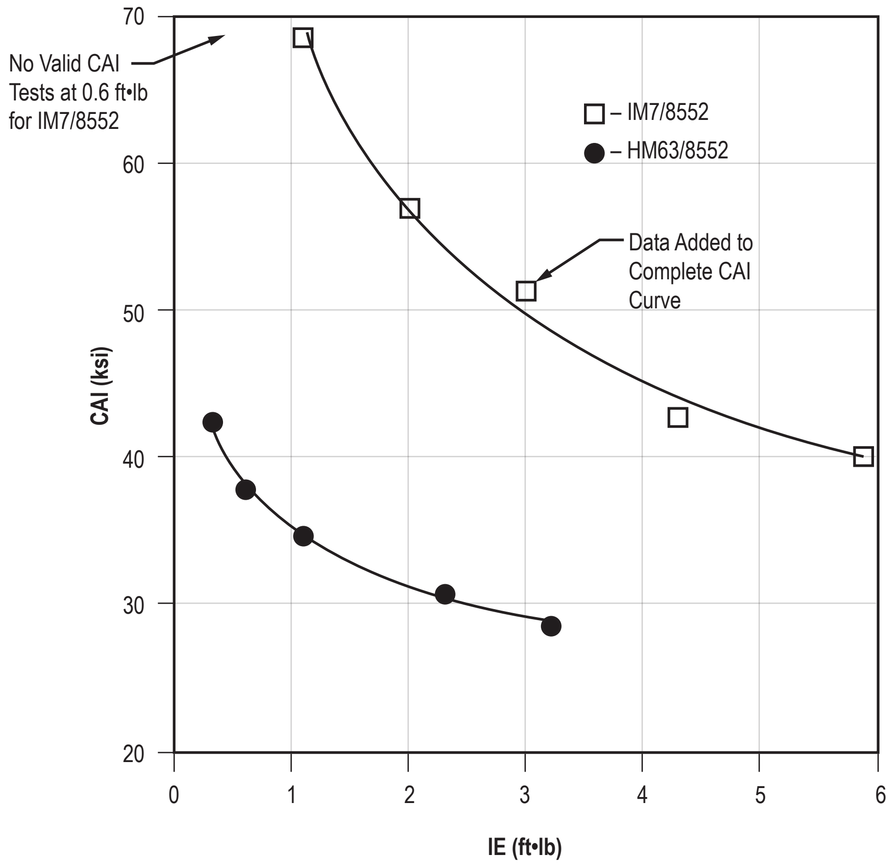

Figure 10. CAI results of HM63/8552 face sheet specimens and IM7/8552 face sheet specimens. Best fit power curve drawn through data, data not normalized by face sheet thickness.

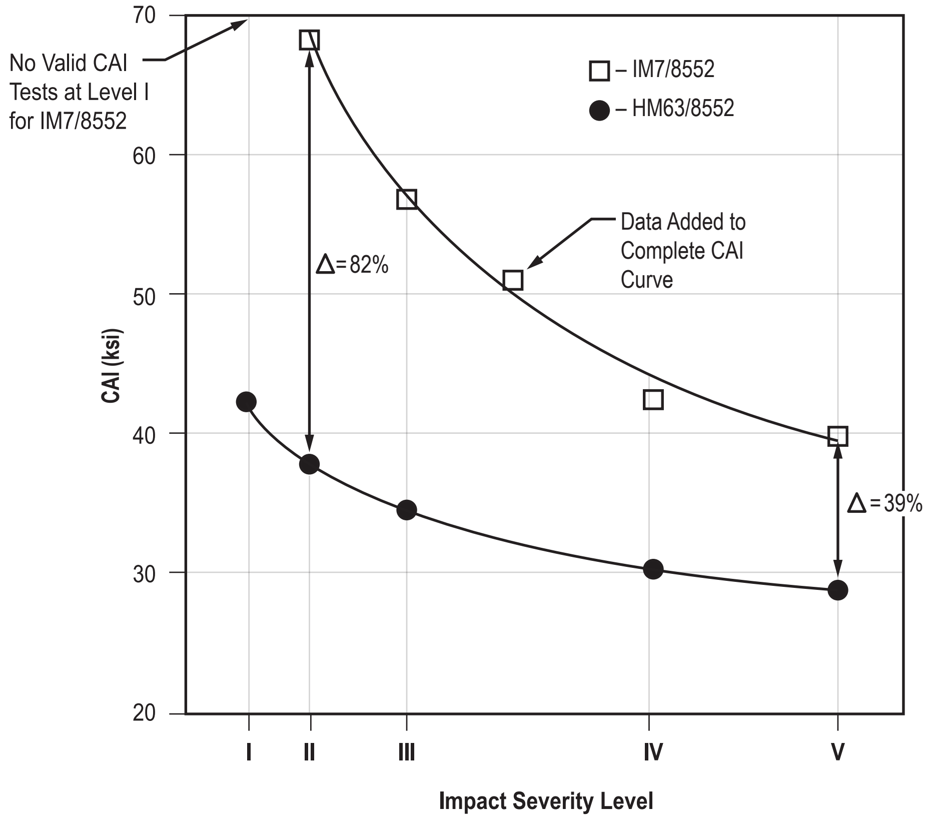

Figure 11. CAI results of HM63/8552 face sheet specimens and IM7/8552 face sheet specimens. Best fit power curve drawn through data, data normalized by face sheet thickness.

The higher modulus of the HM63/8552 face sheet laminates will give rise to a higher stress concentration factor which has been shown experimentally[6–9] and derived analytically.[10] Thus, for a given damage state, the HM63/8552 face sheet sandwich structure is expected to have a lower CAI strength; however, compounded with the fact that the HM63 fibers compressively buckle at a lower strain, this exacerbates the problem. Furthermore, given that the HM63/8552 face sheet specimens suffer slightly more damage for a given impact severity level. Then, the residual strength of the HM63/8552 face sheet specimens is expected to be lowered even more.

As the damage level becomes more severe, the difference in CAI strength of the two types of specimens becomes smaller as can be seen in figure 11. However even at the most severe impact levels used in this study, the IM7/8552 face sheet specimens have about 39% higher CAI strength which corresponds to the 36% higher open hole compression (OHC) strength (based on a 0.25-in hole).

5. CONCLUSIONS

The modulus is 35% lower for the IM7/8552 face sheet sandwich structure while the CAI strength can range from about 28% to 39% higher with lower impact severity levels showing a larger difference in strength. These values are valid for the impact severity ranges used in this study. While these results are not surprising, it is of value to quantify the CAI strength values so a decision can be made early in a program as to which fiber/resin system to use depending on the stiffness and strength requirements.

Based on the results presented by Nettles,[5] the impact energies used in this study were normalized by the face sheet thickness to the 2.5 power. This gave a more even comparison of the sandwich structure used in this study since one face sheet was 28% thicker than the other. For a more robust comparison, an analysis of specimens with equal face sheet thicknesses needs to be undertaken.

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14. ABSTRACT
This study presents experimental results of the compression after impact (CAI) testing of sandwich structure with face sheets made either with IM7/8552 high strength fiber or HM63/8552 high modulus fiber. While the HM63/8552 face sheet sandwich specimens would not be as damage tolerant as the IM7/8552 face sheet sandwich specimens, a quantitative measure of how much more damage tolerant the IM7/8552 face sheets were than the HM63/8552 face sheets was sought. Due to the IM7/8552 face sheets being 28% thicker than the HM63/8552 face sheets, the impact energies used needed to be adjusted for a fair comparison. The results show that the modulus is 35% lower for the IM7/8552 face sheet sandwich structure while the CAI strength can range from about 82% to 39 % higher with lower impact severity levels showing a larger difference in strength.

15. SUBJECT TERMS
High modulus carbon fiber, high strength carbon fiber, sandwich structure, damage tolerance, compression after impact (CAI) strength

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