



Damage Tolerance Study of Carbon Fiber/ Epoxy Sandwich Structure in Support of the SLS Payload Adapter Fitting (PAF)

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LIST OF ACRONYMS

AFP	automated fiber placement
BVID	barely visible impact damage
CAI	compression after impact
MSFC	Marshall Space Flight Center
NDE	Non-Destructive Evaluation
PAF	payload adaptor fitting
SLS	Space Launch System

TECHNICAL MEMORANDUM

DAMAGE TOLERANCE STUDY OF CARBON FIBER/EPOXY SANDWICH STRUCTURE IN SUPPORT OF THE SLS PAYLOAD ADAPTER FITTING (PAF)

1. INTRODUCTION

A payload adaptor fitting (PAF) has been manufactured at NASA's Marshall Space Flight Center (MSFC) in support of the Space Launch System (SLS) program. This structure is essentially a large cone made up of eight curved "lobes" that are joined together. The lobes were manufactured via automated fiber placement (AFP). The PAF will carry predominantly compressive loads, thus compression strength will be the focus of this study. The lobes are a sandwich structure made with aluminum honeycomb and carbon/epoxy face sheets. The lobes will be inserted into metallic rings at the top and bottom to form the full cone. Both front and back exterior surfaces of each lobe have a plain weave fabric placed at $\pm 45^\circ$ to the vertical direction. The face sheet of each lobe is thickest at top and plies are dropped as the cone reaches the main acreage in the bottom of the cone.

Compression after impact (CAI) strength of sandwich structure is one of the leading metrics being used to evaluate suitability of the PAF for the SLS program. This study was undertaken to evaluate the compression strength of sections of acreage of the PAF that have been damaged by impact.

One aspect that needed to be addressed was where to evaluate impact damage on any of the lobes. In general, a part made from the sandwich structure is most vulnerable where the face sheets are thinnest. This is the bottom half of the structure, which also represents the area most likely to experience foreign object impact damage since it consumes the most area of the conical structure. Thus, the core and lay-up that makes up the bottom half of the structure were chosen.

Another aspect that needed to be considered was where along the bottom section of the lobe to take the specimens from. The lobes were manufactured with the load bearing 0° fibers aligned in the same direction (not radially) with the center fibers being parallel to the loading direction, as sketched in figure 1. Thus, most of the lobe has fibers that will be loaded off-axis to the 0° direction. Since the load introduction into the PAF will be displacement driven by two metallic end rings being compressed toward one another, the off-axis regions will experience less load than the centerline of the lobe since the lay-up of the face sheets contain more 0° plies than other angles (i.e., it is highly directional in the 0° direction). Thus, the center section where the fibers are parallel to the loading direction was chosen since this area will be the most highly loaded and would represent a worst-case scenario for location of damage. In addition, "off-axis" loading was shown to have similar CAI strength to "on-axis" loading in a previous study.¹

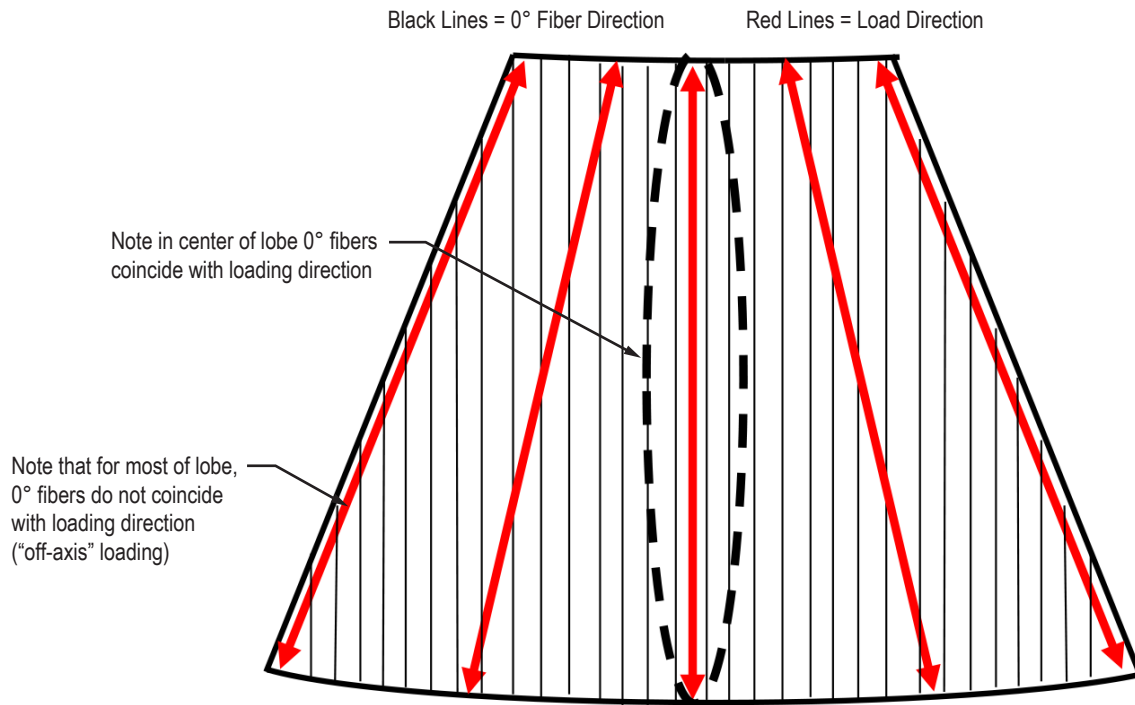


Figure 1. Schematic of “off-axis” loading on a lobe of the PAF structure.

2. MATERIALS

The sandwich structure used in this study was manufactured by co-curing the face sheets to aluminum honeycomb core. The core was 0.625-in thick and had a density of 4.5 lb/ft³. All the face sheets were manufactured by AFP at NASA's MSFC. The T1100/3690 carbon/epoxy prepreg tape that made up the face sheets had an areal weight of 190 g/m². The honeycomb sandwich structure was manufactured with the core ribbon ("L") direction aligning with the 0° fiber direction. The 8 ply face sheets had a lay-up of $[\pm 45_f/+45/0/-45/0/-45/0/+45]_T$. The outer ply of fabric was a plain weave T1100/3690 that was hand laid up on the tool before the fiber placement of the tape began for the outer (tool side) surface of the cone. Another ply of the plain weave was placed on the inner surface of the cone (bag side) before bagging and curing. The sandwich structure had a layer of FM300-2M epoxy film adhesive placed between the core and face sheet during the automated tape laying 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 24-in by 48-in in size. The sandwich structure showed good consolidation with very little porosity as shown in figure 2. Typical fiber waviness of the face sheets on the honeycomb core panels was noted. 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 shown in the top cross-sectional photomicrograph in figure 2. A nominal value for the face sheet thickness can be found 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 0.05 in.

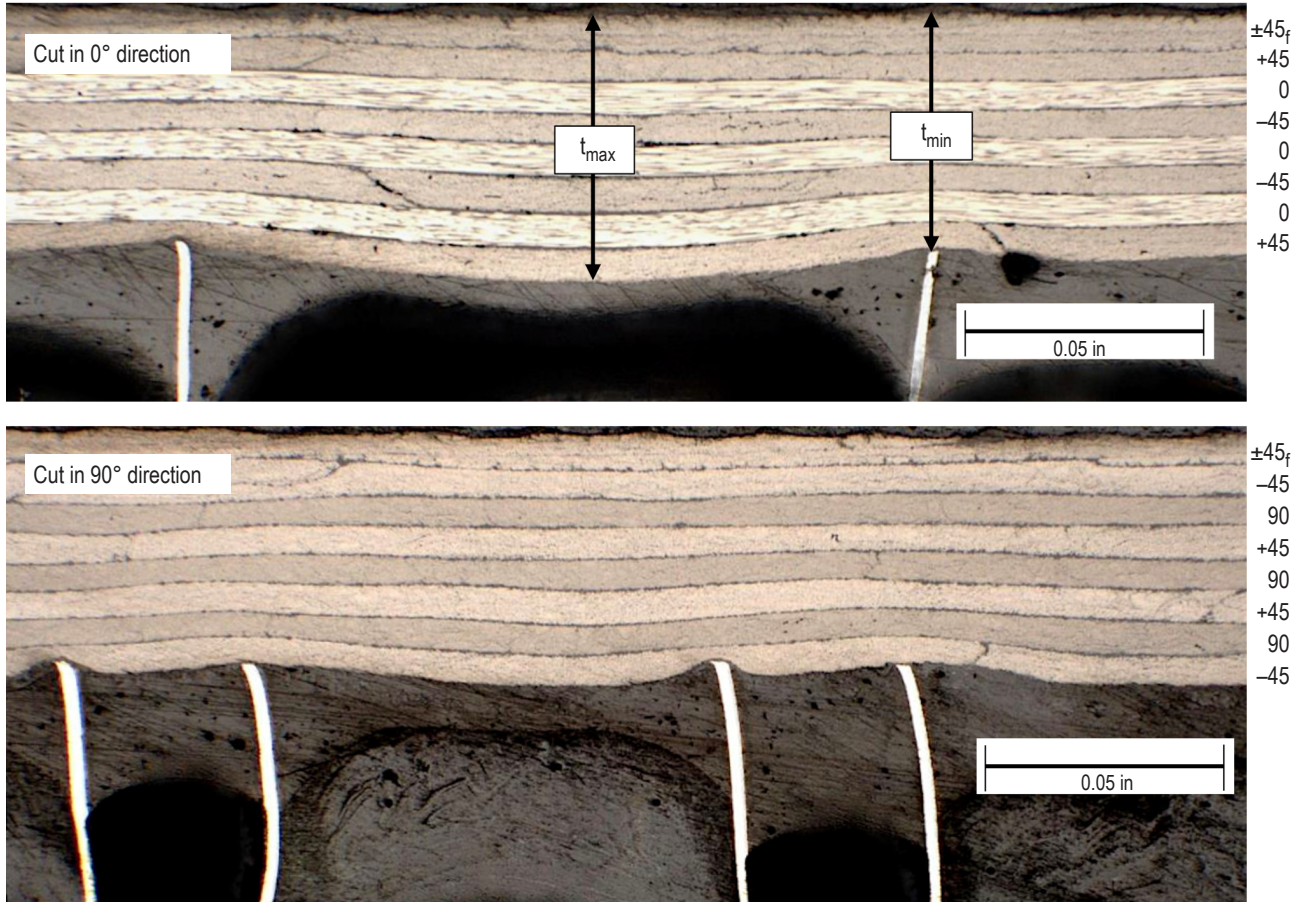


Figure 2. Cross section photomicrographs showing face sheet waviness of inner plies (plies closest to the core) on the honeycomb core specimens used in this study. 0° and 90° views shown.

The large 24×48-in sandwich panel was cut into 6-in tall (direction of loading) by 4-in wide specimens using a diamond saw. The specimens were cut such that the loading direction was parallel to the core “w” direction, thus giving a sandwich layup of $[\pm 45_f/+45/0/-45/0/-45/0/+45/\text{CORE}]_S$.

For the specimens impacted at all but the highest impact energy used, the ends needed to be potted to prevent end brooming during the CAI tests that were to be performed. This was accomplished by crushing the core about 1/4-in deep across the top and bottom of the specimen and filling these “channels” with paste epoxy resin as shown in figure 3. This prevented end-brooming.

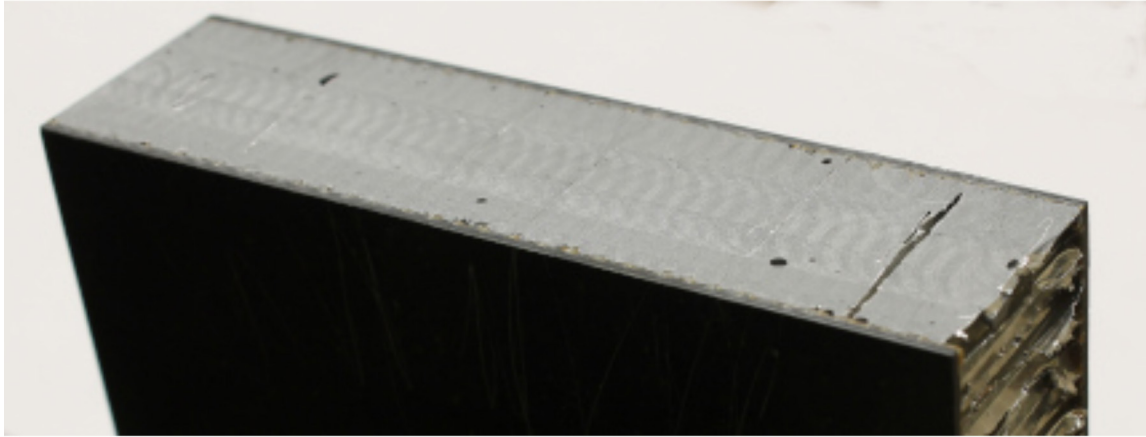


Figure 3. Picture of epoxy placed in top and bottom of the sandwich specimens to prevent end-brooming.

Once the epoxy cured, the top and bottom edges of these specimens were 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 (even with potting the ends with epoxy) which is not a valid failure mode, and this study concerns damage tolerance testing; undamaged strength values are not relevant since the structure must be designed to damage tolerance strength values, not pristine values.

2.1 Impact Damage Testing

Each sandwich specimen was impacted at its geometric center on the tool side face sheet since the tool side is to be the outer side of the PAF structure and thus the most prone to impact damage. The impactor had a diameter of 0.5 in and each specimen was placed on a steel plate with a 2.5-in circular opening and clamped on top with a steel plate with a small circular opening to allow the impactor to pass through and hit the specimen. A blunt tipped impactor was chosen over a sharp tipped impactor since an impact by a sharp object is more readily visible and thus a blunt impactor represents a worst-case scenario when barely visible impact damage (BVID) is governing the initial inspection process.² While the sandwich specimen has a high stiffness rigidity, it is not infinite and some flexing of the PAF honeycomb structure will occur during a foreign object impact event (unless the impact is at the bottom of the structure near where the steel ring is located). The boundary condition of the impact event was chosen to represent the actual structure as close as possible. Some flexure that may develop during the impact was allowed by the 2.5-in opening in the bottom plate. This may be important when considering BVID and the amount of damage associated with it.

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 4. The selected impact energies were based on what was determined to be BVID (with the peel ply still on the surface) to easily visible damage without the peel ply present. Impact energy levels between these two extremes were chosen for the remainder of impacts on the sandwich specimens so that residual strength curves could be constructed. Results of the impact tests showing the impact energy used, number of specimens tested, width of damage as detected by thermography, the dent depth formed, and the maximum load of impact on the specimens are summarized in table 1. The dent measurements were taken at least 24 hours after impact to allow for any “relaxation” of the dent depth. The maximum load of impact is the largest load recorded during the impact event.

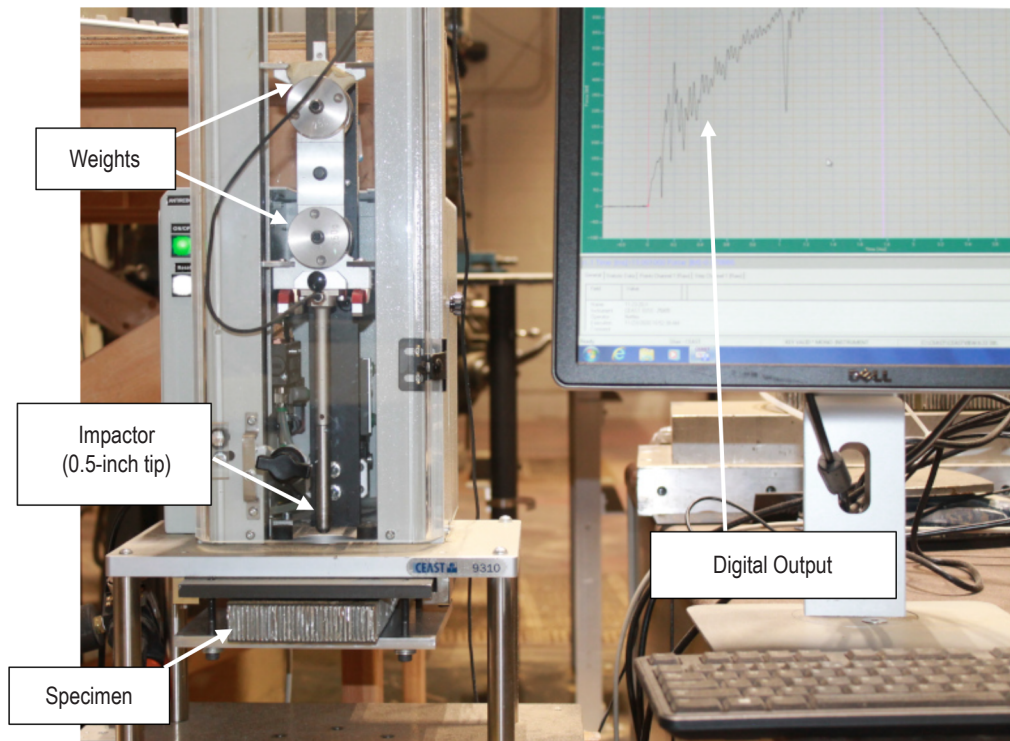


Figure 4. Photograph of the instrumented impactor used in this study.

Table 1. Summary of results from impact testing on the sandwich specimens used in this study.

Impact Energy (ft-lb)	Specimens Tested	Damage Width (in)	Dent Depth (mil)	Maximum Impact Load (lb)
6	4	0.57 ± 0.05	34 ± 2	903 ± 8
8	3	0.63 ± 0.09	43 ± 2	1054 ± 16
10	4	0.72 ± 0.07	64 ± 12	1140 ± 37
13	4	0.85 ± 0.02	98 ± 4	1142 ± 40
16	3	0.88 ± 0.04	113 ± 4	1195 ± 64

Figure 5 shows plots of the data in table 1. The damage width appears to increase linearly until the highest impact energy used at which point the damage width begins to “level out.” The dent depth appears to increase linearly with increasing impact energy. The maximum load of impact does not correlate with impact energy as well as the damage width or dent depth. The reasons for this are unknown, but in actual practice, any impact event on the hardware will not be instrumented and thus this parameter is purely an academic point anyway. Dent depth and damage width can both be measured after an impact event and are thus more important parameters.

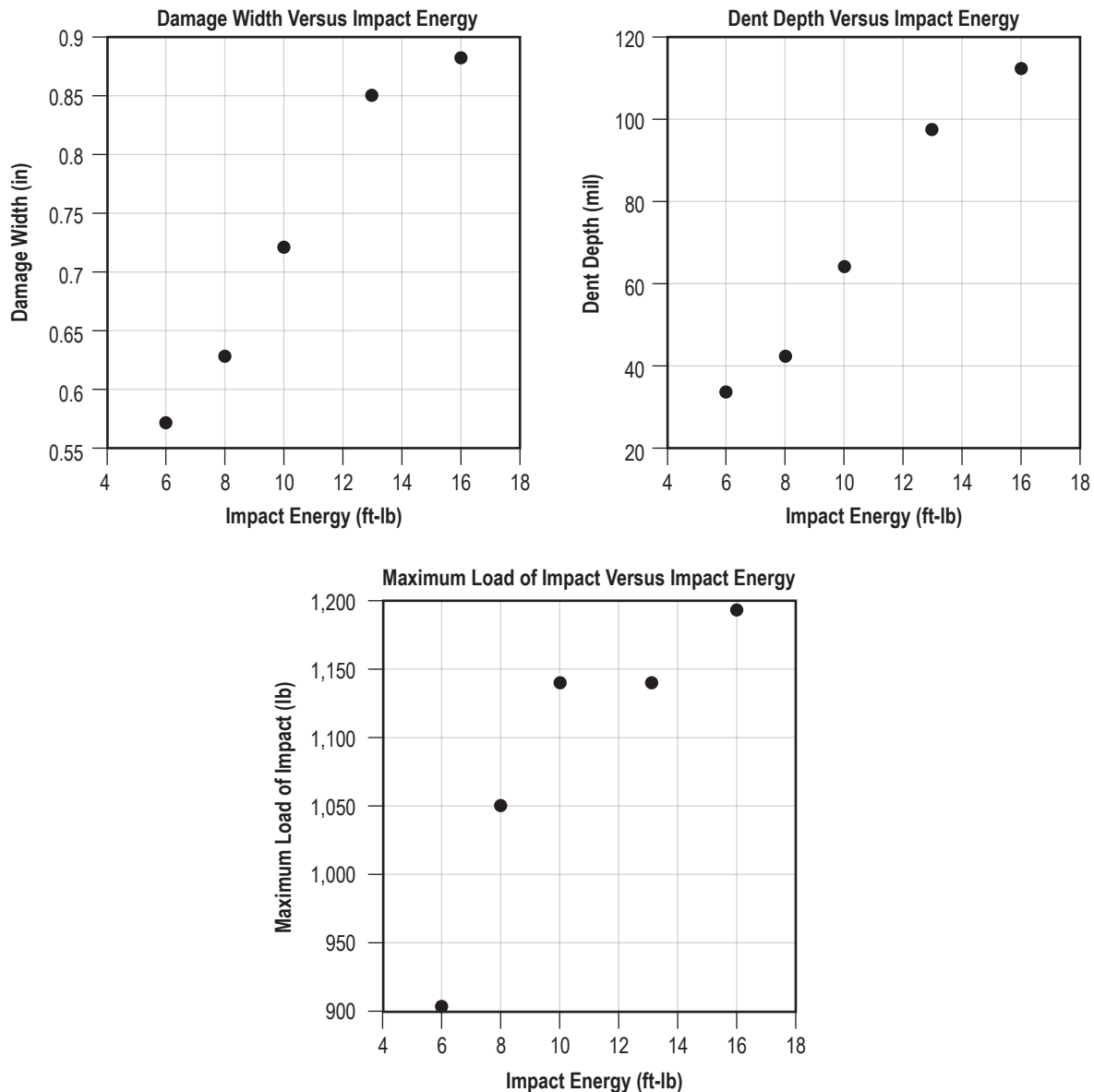


Figure 5. Plot of damage width (upper left), dent depth (upper right), and maximum load of impact versus impact energy (bottom) from table 1.

2.2 Visual Damage

While other measured parameters in this study were not affected by the presence of peel ply, the amount of visible damage is highly dependent upon the presence of peel ply. Thus, there are two damage severity levels at which to define BVID: one with peel ply on the surface and one without peel ply. As will be seen, the peel ply greatly enhances the visibility of an impact event while removal of the peel ply leaves a matte black surface that tends to “hide” the damage.

Examples of the visual damage caused by each of the five impact energies are shown in the photographs in figure 6. Visual damage both with and without the outer layer of peel ply present are shown. 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.

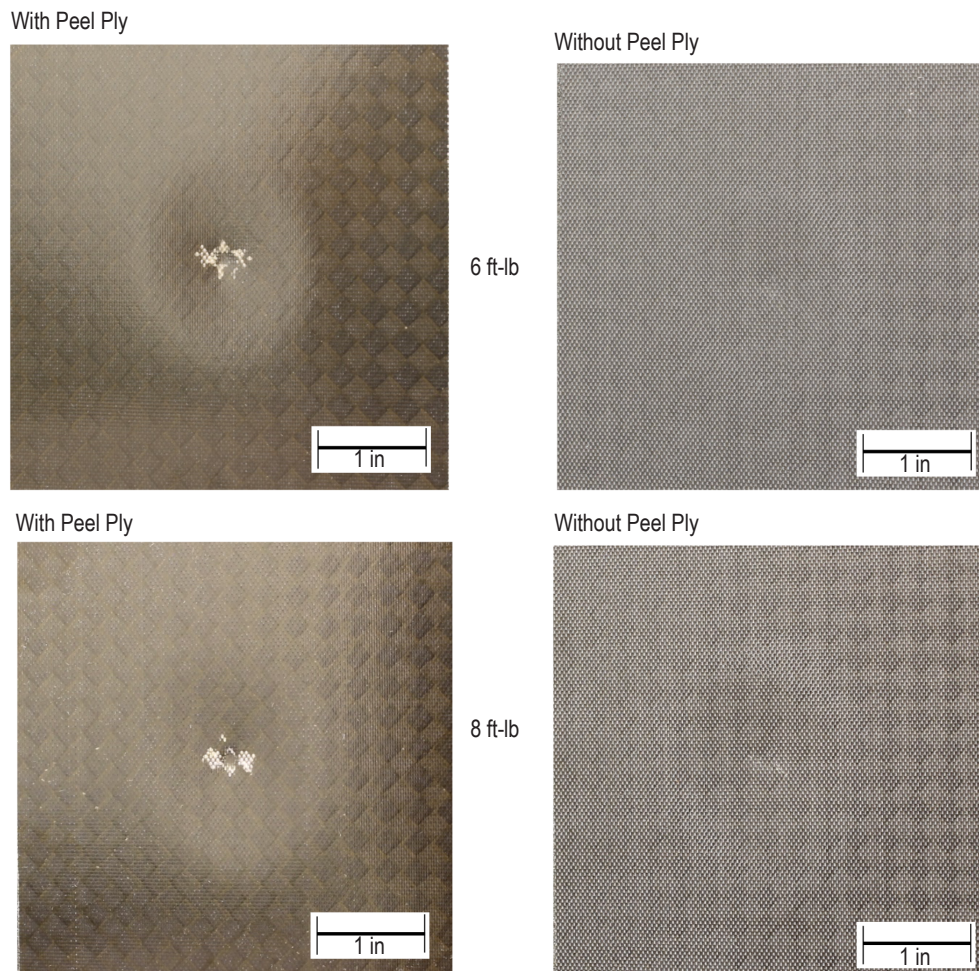
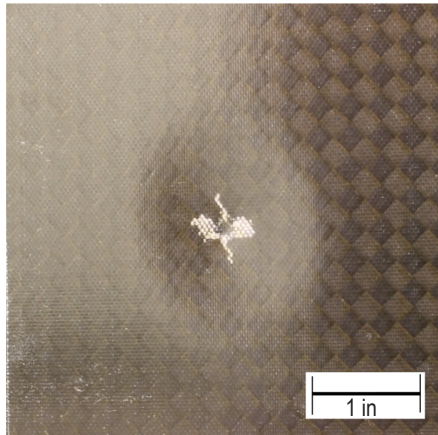
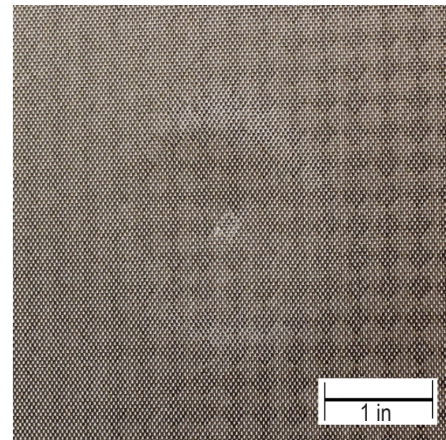


Figure 6. Photographs of various impacts with a 0.5-inch impactor on the honeycomb core sandwich structure used in this study both with and without outer peel ply attached.

With Peel Ply

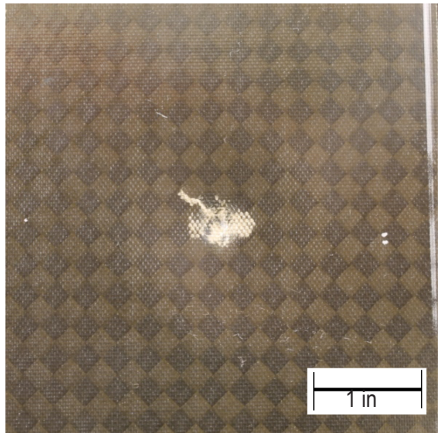


Without Peel Ply

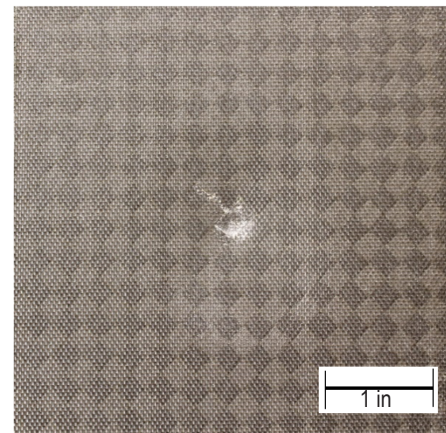


10 ft-lb

With Peel Ply

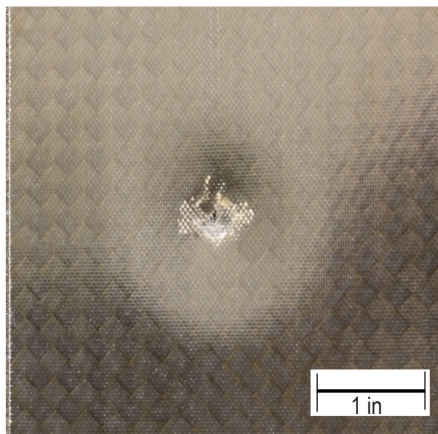


Without Peel Ply

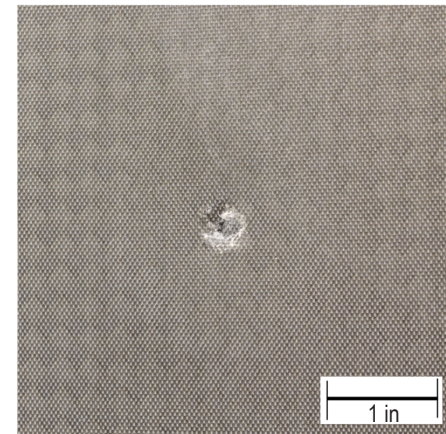


13 ft-lb

With Peel Ply



Without Peel Ply



16 ft-lb

Figure 6. Photographs of various impacts with a 0.5-inch impactor on the honeycomb core sandwich structure used in this study both with and without outer peel ply attached (Continued).

All the impacts with the peel ply present can be visually detected which will be beneficial in practice since even low energy impacts will be noted and can be dispositioned. However, when the peel ply is removed, the damage is not “barely visible” until about 13 ft-lb.

2.3 Instrumented Impact Data

Sample load-deflection data from each impact energy level are shown in figure 7. These specimens were impacted with the peel ply present, and it was assumed at this point in the study that impacts without peel ply would be nearly identical.

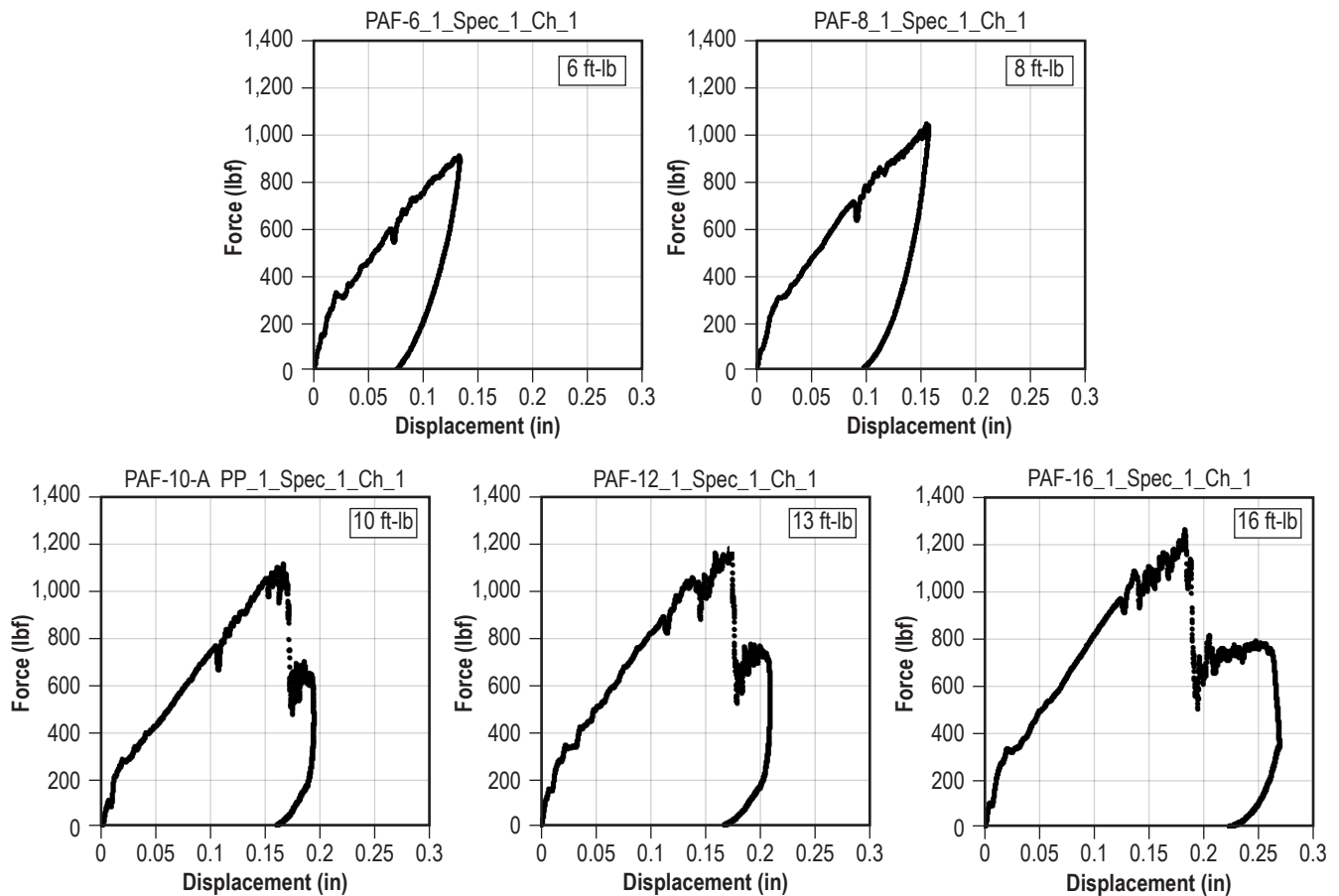


Figure 7. Load-deflection data of impacts on the honeycomb core specimens used in this study.

For 6 and 8 ft-lb energy levels, the curves are relatively smooth indicating little to no fiber breakage. For all impact energies, at about 300 pounds of impact load, the slope of the line decreases which indicates the formation of a delamination and thus a “softening” of the transverse stiffness. At the 10, 13, and 16 ft-lb energy levels, a sudden drop in load can be seen at the maximum load. This indicates fiber breakage. While of academic interest, these curves are not very practical since actual impact events on hardware are not instrumented. Nonetheless, these curves are included in this report for completeness.

2.4 Thermography Results

Non-Destructive Evaluation (NDE) in the form of flash thermography was performed on the impacted specimens, and samples from each impact energy level are presented in figure 8. The “damage width” is the maximum distance between two vertical lines from the farthest edges of the damage zone as shown on the first (6 ft-lb) NDE example. Damage width has been shown to be a good indicator of residual compression strength of an impact damaged sandwich structure.² The second example (8 ft-lb) indicates the location and direction of view for the photomicrographs shown later in figure 9. Unfortunately, whether these specimens were impacted with or without the peel ply was not recorded since it was assumed that the peel ply would have no effect other than for visual damage.

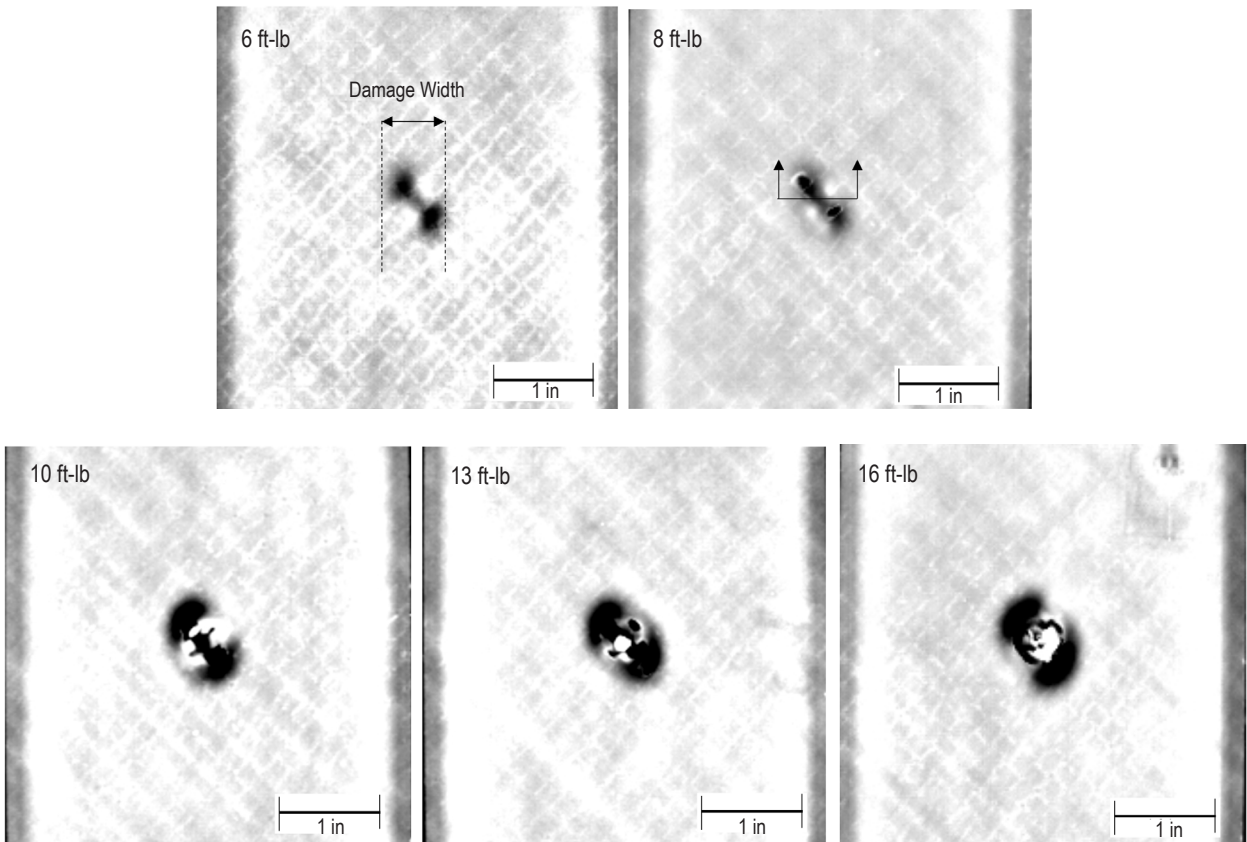


Figure 8. Thermography signatures of impacts on the honeycomb core specimens used in this study.

Quantitative data for the damage size (as determined by the width of the damage region seen in the thermography images) were given earlier in table 1. This data is important as thermography can easily be performed in the field to disposition the severity of damage and can give a good indication of residual strength, as will be seen later in this report and as was seen in reference 3.

2.5 Cross-Sectional Microscopy

Since the thermography results cannot ascertain the through thickness extent of damage, one impact from each of the six types of impact conditions was cross sectioned in the width direction of the specimen as indicated in the 8 ft-lb sample in figure 8. These photomicrographs are shown in figure 9. As with the thermography specimens, whether these impacts occurred with or without peel ply was not recorded.

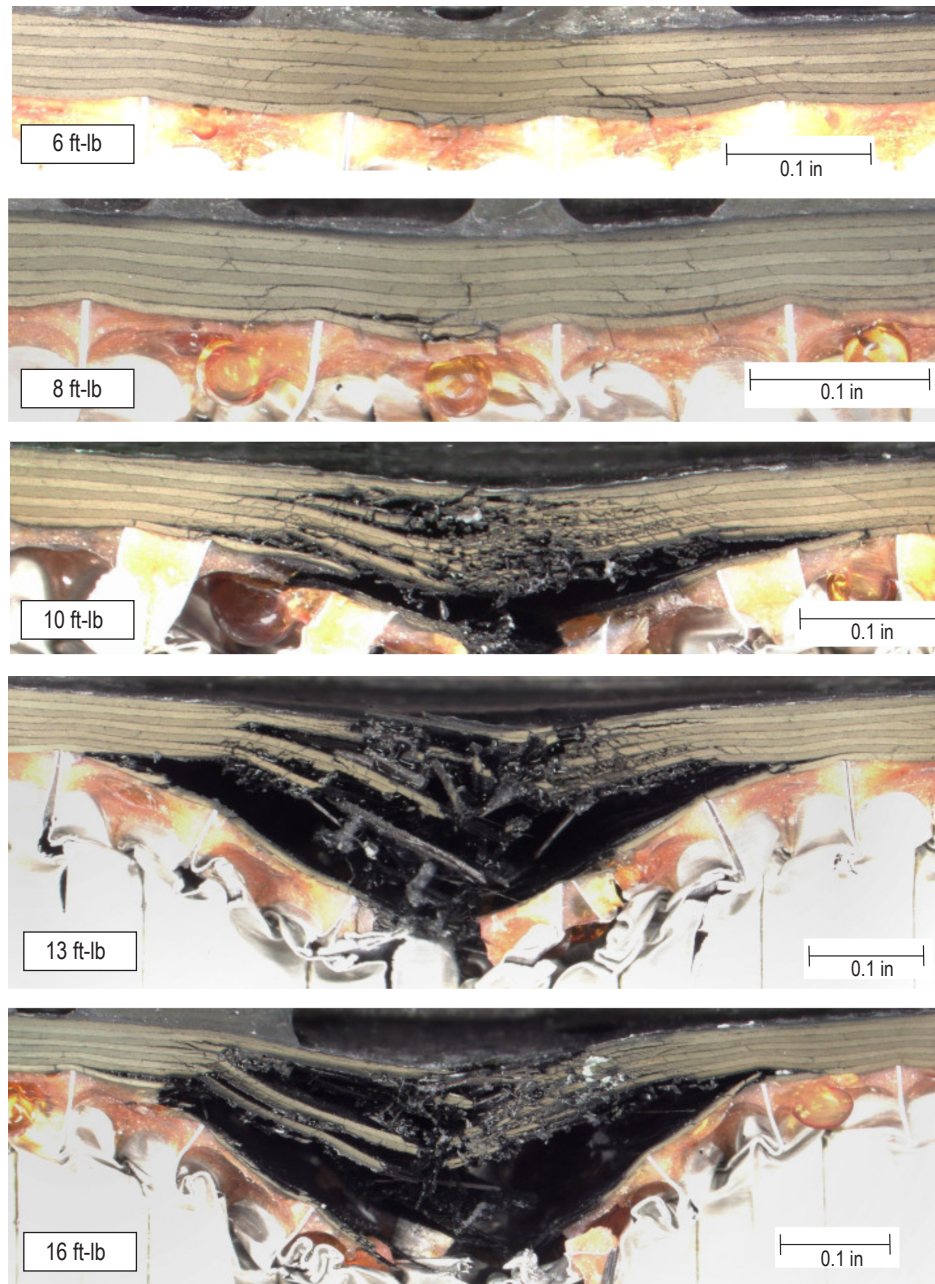


Figure 9. Cross-sectional photomicroscopy of impacts on the honeycomb core specimens used in this study. Cuts made in the 90° direction as shown in figure 8.

The depth of damage varies quite a bit, especially considering the damage width does not vary to a great extent. Thus, if the CAI strength data are different, despite being of similar size, then it is likely due to the extra damage in the through thickness direction.

2.6 Compression After Impact Testing

The impacted sandwich specimens were assessed for residual compression strength using the test fixture shown in figure 10. Three strain gages were placed on the specimen as diagrammed in figure 11 to ensure even loading of each of the face sheets. The specimens were taken to approximately 1,000 microstrain and if one gage was lower than the others by more than 10%, shims were placed under the edge that was reading 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.

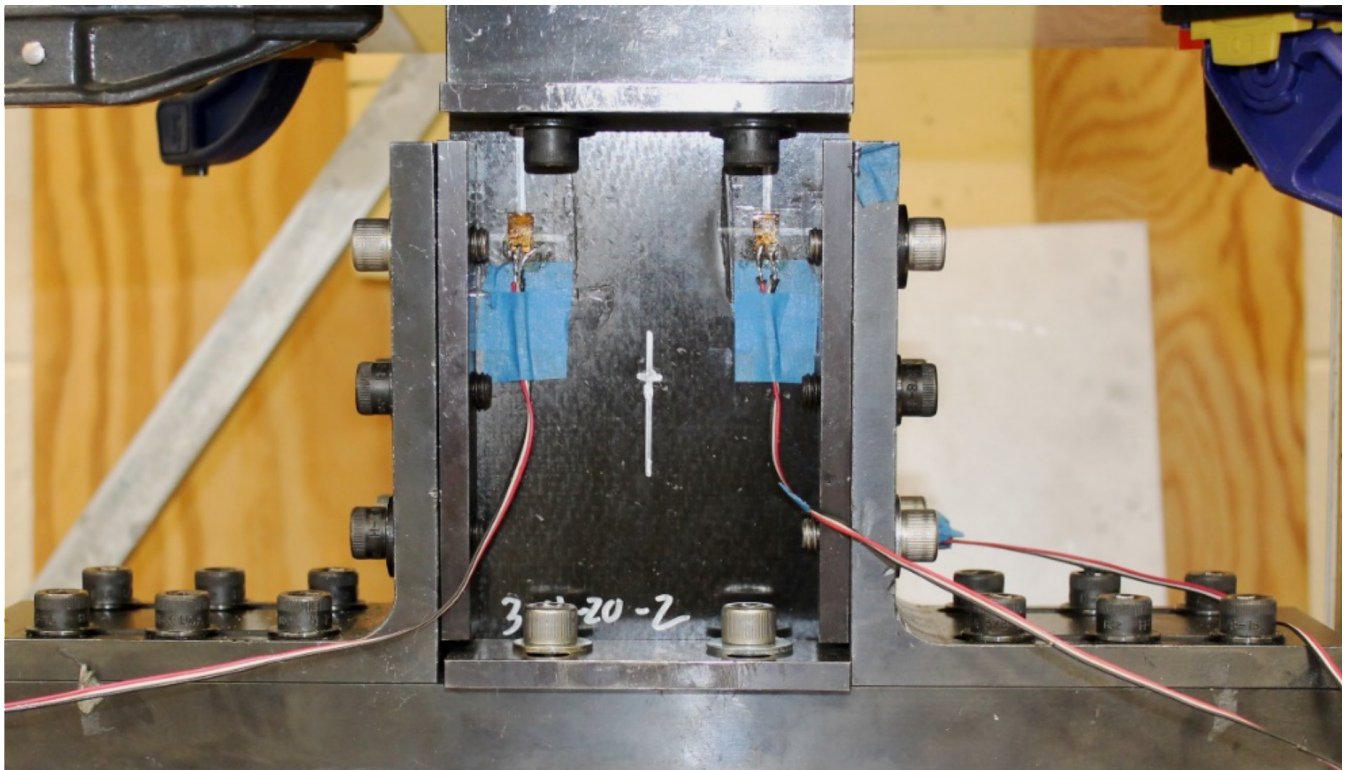


Figure 10. Photograph of the fixture used for assessing CAI strength of the sandwich specimens.

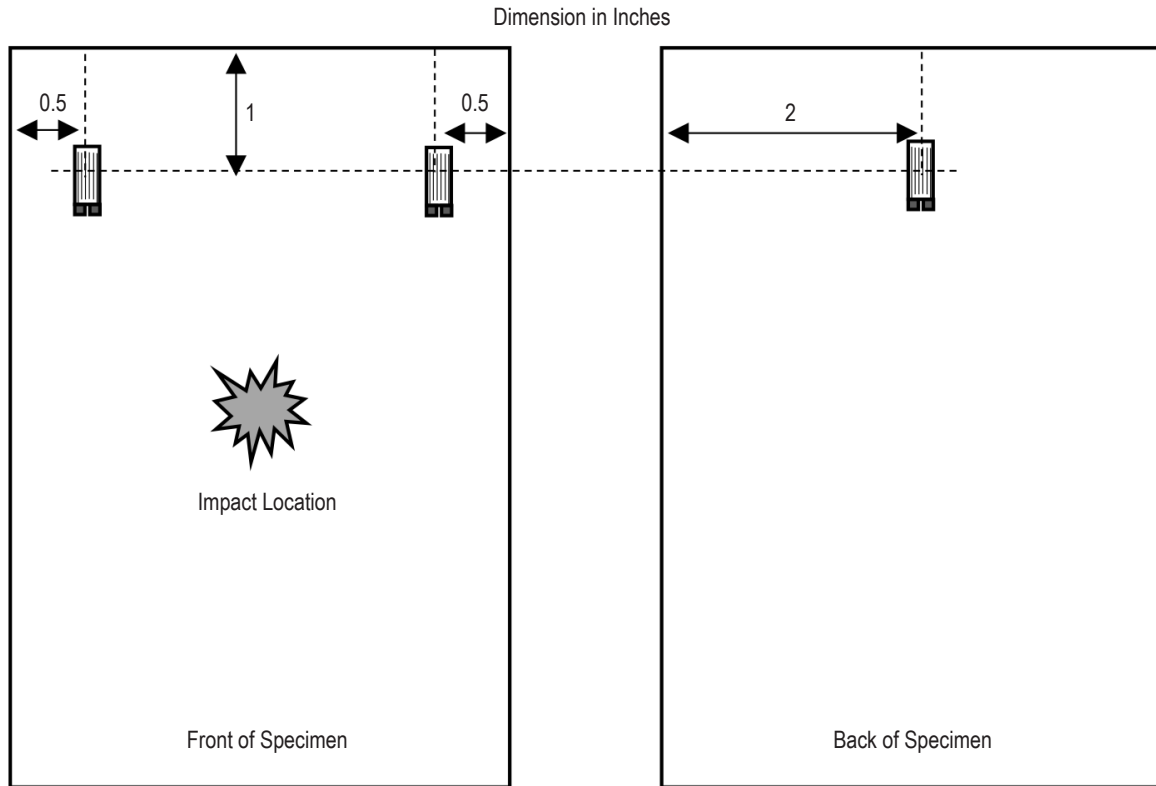


Figure 11. Location of strain gages on front and back of each CAI specimen.

The CAI strength results are presented in table 2.

Table 2. Summary of CAI results of the sandwich specimens tested in this study.

Impact Energy (ft-lb)	Specimens tested	CAI Strength (ksi)
6	4	68.2 ± 1.6
8	3	62.3 ± 4.2
10	4	58.1 ± 4.3
13	4	51.0 ± 5.0
16	3	50.0 ± 1.6

Each individual CAI strength result (as opposed to the average) is plotted as a function of impact energy in figure 12. A “best fit” power curve has been calculated for these data and is presented in the figure. A power curve fit has been shown to fit CAI versus other parameters (such as damage area and dent depth) well.³ Quite a bit of “scatter” is evident in the data, which is not unusual for CAI strength data, however these data appear to have more “scatter” than usual.

It was at this point in the study that the effect of peel ply on the CAI strength being important was brought into question since the scatter was larger than what is typically seen and pooling the data (if the peel ply does affect the CAI strength) will result in higher scatter.

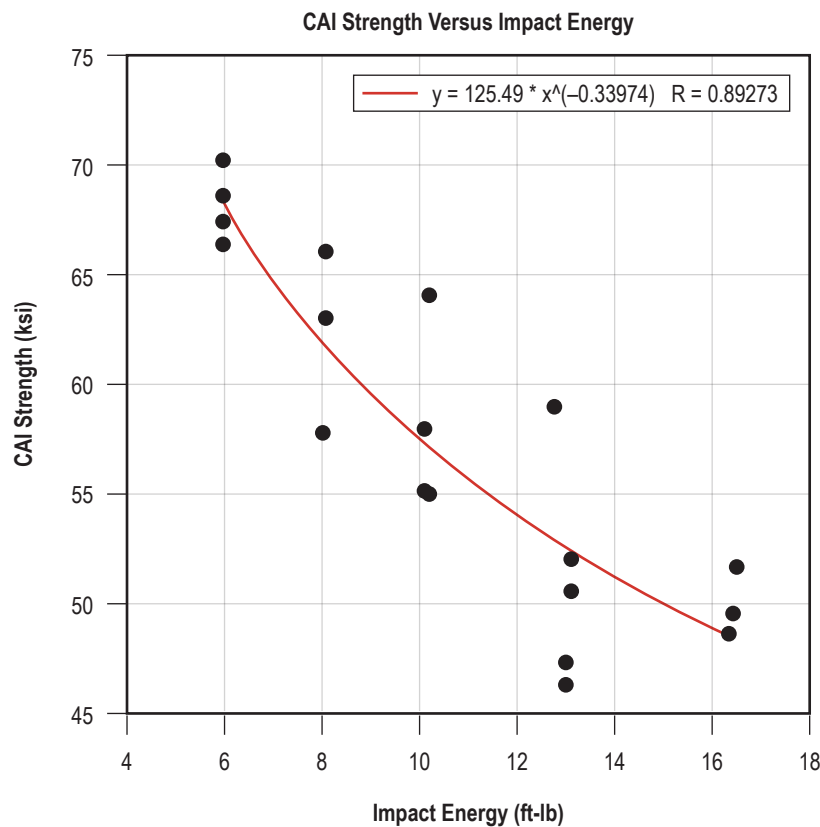


Figure 12. CAI strength versus impact energy results for the sandwich specimens tested in this study.

By averaging the CAI strength data (fig. 13) for each impact energy, the data appears more “well behaved,” and the power curve fit shows a much higher correlation coefficient ($R = \text{Value}$) than when the data are not averaged such as in figure 12. However, note that the standard deviation values are quite large with overlap between adjacent CAI strength values.

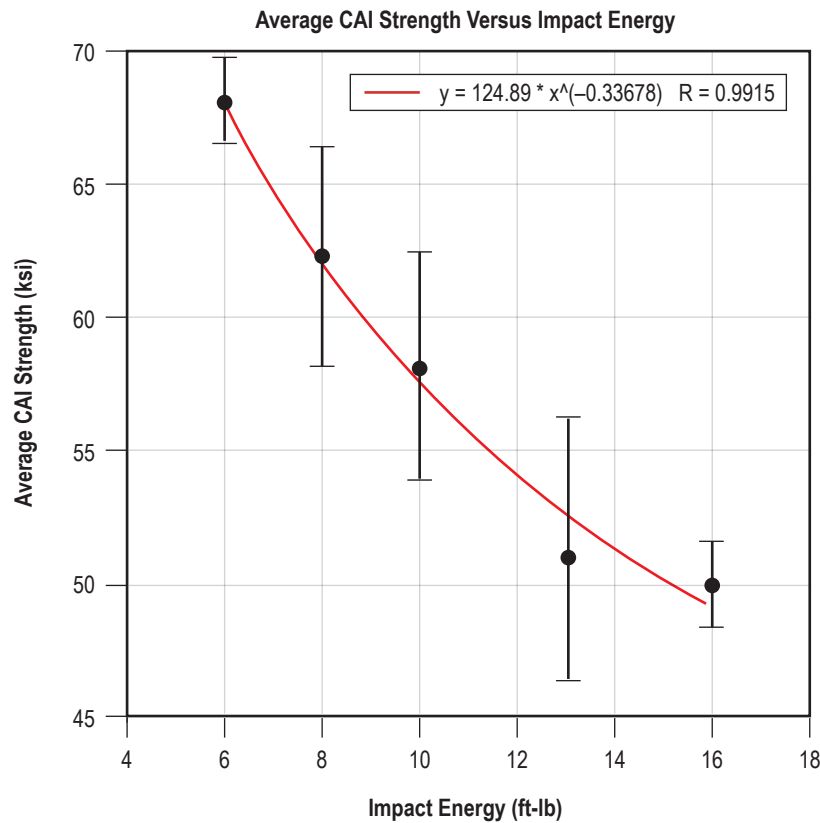


Figure 13. Average CAI strength versus impact energy results for the sandwich specimens tested in this study.

As stated earlier in this paper, the CAI strength tends to correlate well with the measured damage width. Figure 14 plots the CAI strength data versus damage width for each specimen tested and the data fit better than when plotting CAI strength versus impact energy (fig. 12). The “B-Basis” values for CAI strength versus damage width are also plotted in figure 14. The methodology for doing this can be found in reference 3.

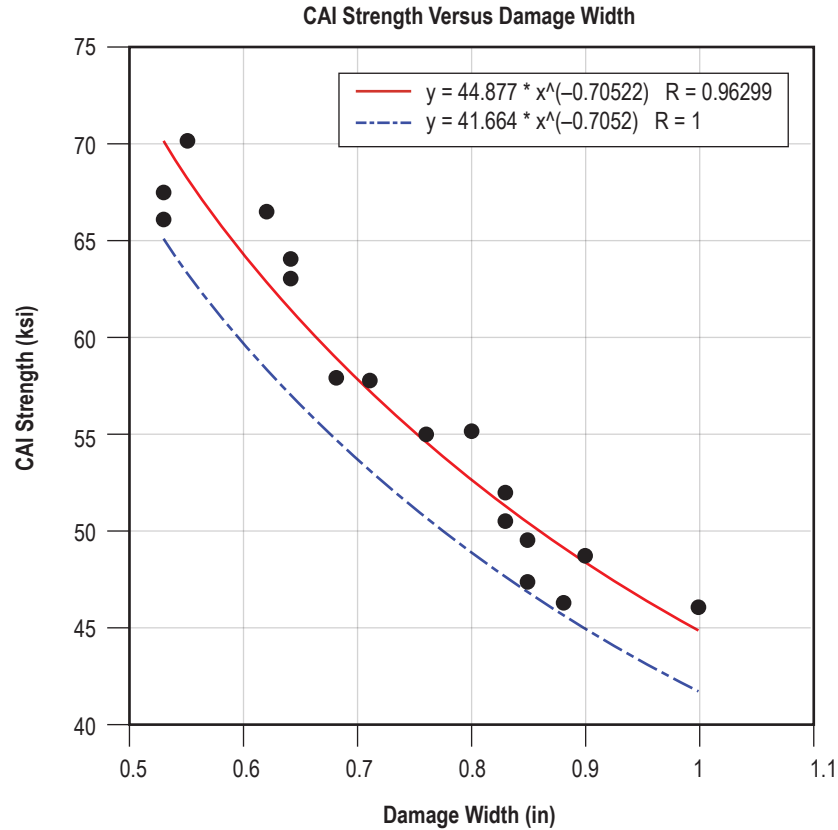


Figure 14. CAI strength versus damage width results for the sandwich specimens tested in this study.

Since these data correlate well, it is unlikely that the greater damage depth as ascertained from the cross-sectional photomicrographs in figure 9 has much of an influence on CAI strength (i.e., the planar damage size [width] governs the CAI strength more than any through thickness damage).

2.7 Effect of Peel Ply

One of the challenging aspects of this structure is that the outer layer of peel ply used during manufacture is to remain on the PAF until integration at the launch site, at which time the peel ply will be removed. While the impact results on the sandwich specimens were expected to not be affected by the presence of the peel ply since one layer of a much tougher material than peel ply had no effect on damage resistance or CAI strength in a study on carbon/epoxy face sheet sandwich structure done decades ago,⁴ ten specimens were impact tested at one of the mid-level impact energies (10 ft-lb) both with and without peel ply to assess any differences in damage resistance and damage tolerance due to the presence of the peel ply. Details of the method of impacting the specimen, measuring the damage size and CAI strength, have been supplied in more detail earlier in this paper. Results from these tests are presented in table 3.

Table 3. Summary of results from impact testing on the sandwich specimens to assess the effect of the presence of peel ply.

Impact Energy (ft-lb)	Peel Ply	Average Damage Width (in)	Average Dent Depth (mil)	Average Maximum Impact Load (lb)	Average CAI Strength (ksi)
10	Yes	0.64 ± 0.04	56 ± 8	1156 ± 35	65.8 ± 7.3
10	No	0.68 ± 0.11	72 ± 9	1095 ± 41	56.5 ± 9.9
% Difference with peel ply		-6	-29	+8	+14

The damage width changes little with the peel ply versus without the peel ply, but the dent depth is affected by the peel ply, with the peel ply yielding lower dent depth values. Despite this, the shiny surface of the peel ply makes the impact damage easier to see.

The maximum load of impact as measured by the instrumented impact tested is affected to some extent by the presence of the peel ply with the specimens with the peel ply showing a higher maximum load of impact with typically indicated more toughness. The CAI strength values show a higher value for the specimens with the peel ply on the surface, although the large amount of scatter makes this conclusion have less confidence than if the data were tighter. More tests are intended to be performed to better quantify the response of the material to the presence of the peel ply.

3. CONCLUSIONS

CAI strength versus impact energy and CAI strength versus damage size plots have been constructed to aid the PAF program office on decision making should the piece of hardware experience a foreign object impact. The data shows that the peel ply on the outer surface has a great effect on the amount of visible damage seen. The peel ply also influences the dent depth and CAI strength values. The peel ply causes a smaller dent depth but is easier to see than an equivalent impact on specimens without peel ply on the surface. The peel ply also tends to give the impacted sandwich structure higher CAI strength values, which is likely a result of the shallower dent depth and thus less damage.

It is suggested that the B-Basis curve of figure 14 be used as a conservative measure of CAI strength based on the size of the damage as measured by thermography until further testing is conducted.

It is also suggested that more testing be done to vet the effect of the peel ply on the damage characteristics of this sandwich structure.

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