



Damage Tolerance of Candidate Sandwich Structure for the Space Launch System (SLS) Payload Adapter Fitting (PAF)

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TABLE OF CONTENTS

1. INTRODUCTION	1
2. MATERIALS USED	2
3. IMPACT DAMAGE TESTING.....	7
4. COMPRESSION-AFTER-IMPACT TESTING	12
5. FAILURE MECHANISMS.....	17
6. CONCLUSIONS.....	23
REFERENCES	25

LIST OF FIGURES

1. Cross-sectional schematic of sandwich structure used in this study	2
2. Cross section photomicrographs (width direction or 90°-direction) showing face sheet waviness of inner plies (plies closest to the core) on honeycomb core specimens (top pictures) and no waviness of plies on foam core specimens (bottom pictures)	4
3. Typical plot to determine modulus values	5
4. Photographs of various impacts with a 0.5 in impactor on cloth covered foam sandwich structure. An impact severity level of 9.5 ft•lb was chosen as the level of BVID	8
5. Photographs of BVID for each of the configurations tested	8
6. Flash Thermography of BVID damage for the samples tested in this study	9
7. Cross-sectional pictures of damage due to BVID for the specimen configurations used in this study	10
8. BVID load-deflection curves for the impact event for the five types of specimens tested	11
9. Photograph of fixture used for assessing CAI strength of sandwich specimens	12
10. Location of strain gages on front and back of each CAI specimen	13
11. Bar chart summarizing the CAI strength results from the tests on the specimens used in this study. Shaded bars indicated cloth covered specimens and red outline indicates larger size impactor. Standard deviation bars are included with each bar	16
12. Possible modes of failure of sandwich structure	17
13. Photographs of post failure CAI specimens with foam core (left) and honeycomb core (right)	20
14. Photographs of core failure in post CAI foam core specimen (face sheets removed)	21
15. Foam core of figure 14 with “shear plug” removed with slight finger pressure	22

LIST OF TABLES

1. Select properties of the core materials used in this study	2
2. Areal weight of the specimens used in this study	3
3. Modulus measurements of each of the four types of specimens used in this study.	6
4. Normalized modulus values of the four types of (6-in tall) specimens tested.	6
5. Impact energy level considered BVID for each of the 5 configurations tested in this study	9
6a. Results of CAI strength tests on foam core, cloth covered specimens using a 0.5-in impactor (BVID = 9.5 ft•lb). Weight of PAF made with this sandwich structure = 7,791 lb•m	14
6b. Results of CAI strength tests on foam core, cloth covered specimens using a 1-in impactor (BVID = 13.4 ft•lb). Weight of PAF made with this sandwich structure = 7,791 lb•m	14
6c. Results of CAI strength tests on foam core, bare specimens using a 1.0-in impactor (BVID = 3.6 ft•lb). Weight of PAF made with this sandwich structure = 6,321 lb•m ...	14
6d. Results of CAI strength tests on honeycomb core, cloth covered specimens using a 0.5-in impactor (BVID = 3.5 ft•lb). Weight of PAF made with this sandwich structure; 1-in-thick core = 8,820 lb•m, 0.5-in core = 6,909 lb•m	15
6e. Results of CAI strength tests on honeycomb core, bare specimens using a 0.5-in impactor (BVID = 3.0 ft•lb). Weight of PAF made with this sandwich structure; 1-in-thick core = 7,350 lb•m, 0.5-in core = 5,439 lb•m	15

LIST OF ACRONYMS

BVID	barely visible impact damage
CAI	compression after impact
PAF	Payload Adapter Fitting
SLS	Space Launch System

NOMENCLATURE

b	specimen width
c	core thickness
E_c	compressive modulus of the core
E_{Ff}	flexural modulus of the face sheet
E_f	modulus of the face sheet
G_c	core shear modulus
L	height of sandwich structure
PMI	polymethacrylimide
PVC	polyvinyl chloride
t	face sheet thickness
t_{max}	minimum thickness at cell walls of the face sheets on the honeycomb panels
t_{min}	maximum thickness at cell walls of the face sheets on the honeycomb panels
t_c	core thickness
σ_C	compression strength of the composite face sheet laminate

TECHNICAL MEMORANDUM

DAMAGE TOLERANCE OF CANDIDATE SANDWICH STRUCTURE FOR THE SPACE LAUNCH SYSTEM (SLS) PAYLOAD ADAPTER FITTING (PAF)

1. INTRODUCTION

As the design of the payload adapter fitting (PAF) for the Space Launch System (SLS) has been evolving, the material of which to make this part has been identified as composite sandwich structure. The core and face sheet materials used to make this sandwich structure are also evolving and this study presents the experimental results of damage tolerance testing of four types of sandwich structures that have been considered. Although the major design driver of the PAF is stiffness and not strength, a knowledge of the damage tolerance of the structure is warranted. Most loads experienced by the PAF structure will be in-plane compression; thus, this study concentrates on the in-plane compression strength of representative sandwich structure specimens with barely visible impact damage (BVID). The PAF is a truncated cone with a minimum diameter of about 170 inches at the top and a maximum diameter of about 335 inches at the bottom and an overall height of about 82 in, thus giving a total surface area of about 735,000 in². While the launch vehicle hardware should be protected throughout its prelaunch life, rogue events that can cause damage are still a possibility. This study is not meant to address large scale damage or damage to the part other than in the acreage (the uniform portion of the structure that does not consist of joints or other detailed areas), but to address the most probable type of damages (localized small impacts) in the vast majority of the structure (the acreage).

The main difference in sandwich structure identified for use to make the PAF has been with the core. Rohacell foam core and aluminum honeycomb core have both been identified for use to manufacture the sandwich structure that will be used to construct the PAF. The face sheets have remained similar with the only difference being the addition of an outer cloth ply to both sides of the sandwich structure. This study will examine the compression-after-impact (CAI) strength of aluminum honeycomb and foam core sandwich structure with carbon/epoxy face sheets both with and without an addition of an outer cloth ply on both sides. BVID will be defined for each configuration and this impact severity level used for the CAI testing.

2. MATERIALS USED

The face sheets of the sandwich specimens tested in this study consisted of Hexcel® HexTow® IM7 carbon fiber with Hexcel® 8552-1 epoxy resin and were co-cured to the core. All the face sheets were manufactured by automatic tape laying (ATL) at NASA’s MSFC. The layup for the face sheets was 8-ply [+45/0/-45/90]_s quasi-isotropic. The 0° fiber direction was aligned with the L direction of the honeycomb core. Some of the sandwich specimens contained an outer ply of woven 8-harness weave IM7/8552 carbon/epoxy placed at ±45° to the specimen loading direction. This woven cloth was placed on both sides of the specimen and was included in some of the design configurations of the PAF in the hopes of aiding in impact damage resistance and fiber breakout upon any drilling operations. The sandwich structure had a layer of FM® 300-2M epoxy film adhesive placed over the core material prior to the automated tape laying process used to manufacture the face sheets. Two types of core that have been included in some of the design configurations of the PAF were tested in this study: aluminum honeycomb with a density of 4.5 lb/ft³ and a thickness of 1.0 in and Rohacell® Hero71 Polymethacrylimide (PMI) foam core with a density of 4.7 lb/ft³ and a thickness of 0.5 in. The compressive and shear properties of the two types of core (as given by vendor data) are compared in table 1. A generic schematic of the cross-section of the sandwich structure used in this damage tolerance study is shown in figure 1. Specimens with no cloth on the outer surface will be termed ‘bare’ throughout this manuscript.

Table 1. Select properties of the core materials used in this study.

	Compression Strength	Compression Modulus	Shear Strength	Shear Modulus
4.5 lb/ft ³ AL Honeycomb	690 psi	185 ksi	L direction: 440 psi W direction: 255 psi	L direction: 70 ksi W direction: 28 ksi
4.7 lb/ft ³ PMI Foam	160 psi	6.9 ksi	189 psi	4.1 ksi

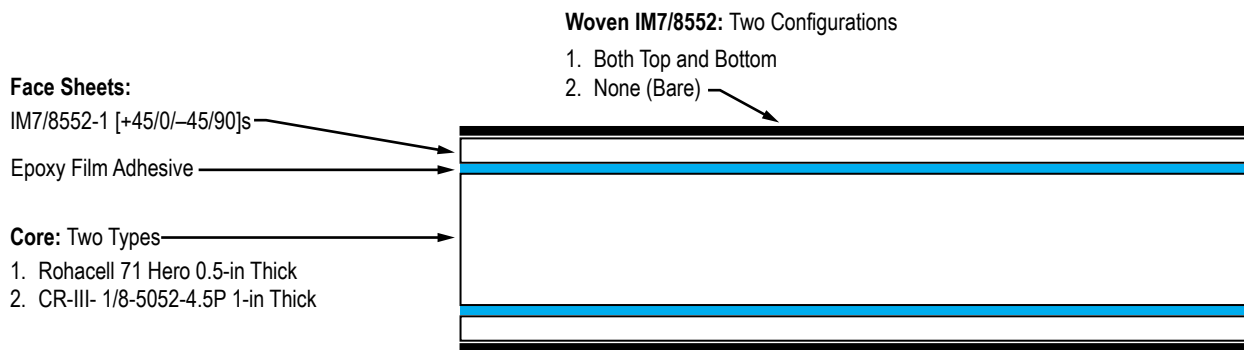


Figure 1. Cross-sectional schematic of sandwich structure used in this study.

As can be seen from table 1, the foam core has much lower strength and stiffness properties. Apparently, the PAF Program Office considered using the foam core rather than the honeycomb core despite the lower mechanical properties since the foam could more easily be formed to fit the curvature of the PAF and was also more readily available.

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 damage tolerance study were 36 inches by 36 inches in size. The sandwich structure showed good consolidation and typical fiber waviness on the face sheets of the honeycomb core panels was present as noted in the cross-sectional photomicrographs of the four types of specimens as shown in figure 2. 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 2. 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 four types of specimens tested were measured and are included in table 2. Note that the honeycomb core sandwich specimens had a lower measured face sheet thickness value than the equivalent face sheet on the foam core sandwich structure. This is due to the localized high compaction pressure that the cell walls of the honeycomb induce on the face sheet during cure causing ‘thin spots’ that have a high fiber volume fraction and skew the average thickness to a lower value.

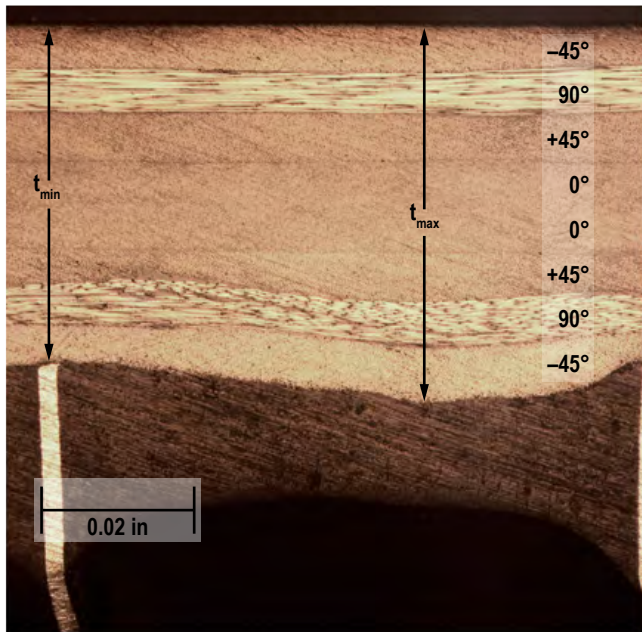
Table 2. Areal weight of the specimens used in this study.

Sandwich Structure Type	Nominal Face Sheet Thickness (in)	Areal Weight (lbm/in ²)		Approximate Weight of PAF Structure (lbm)	
		Core Thickness		Core Thickness	
		1-in	0.5-in	1-in	0.5-in
Foam Core, Bare	0.059	N/A	0.0086	N/A	6321
Foam Core, With Cloth	0.072	N/A	0.0106	N/A	7791
Honeycomb Core, Bare	0.049	0.0100	0.0074*	7,350	5,439
Honeycomb Core, With Cloth	0.066	0.0120	0.0094*	8,820	6,909

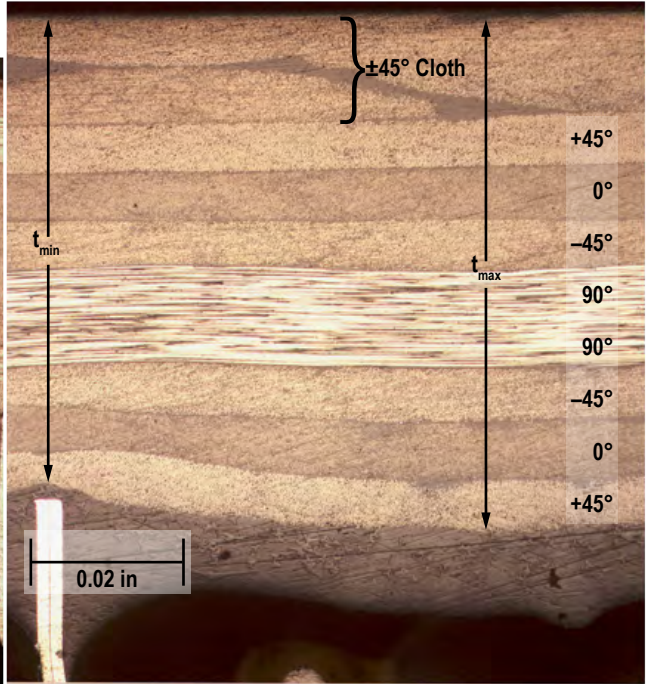
*Calculated values, not directly measured.

Note that the bare honeycomb core specimens had a lay-up of $[-45/90/+45/0]_S$ versus the lay-up of $[+45/0/-45/90]_S$ for the other three types of specimens used. This difference is not expected to significantly alter the stiffness and strength measurements taken in this study, and upon completion of the study there was no evidence that this minor change in layup had an effect on the results.

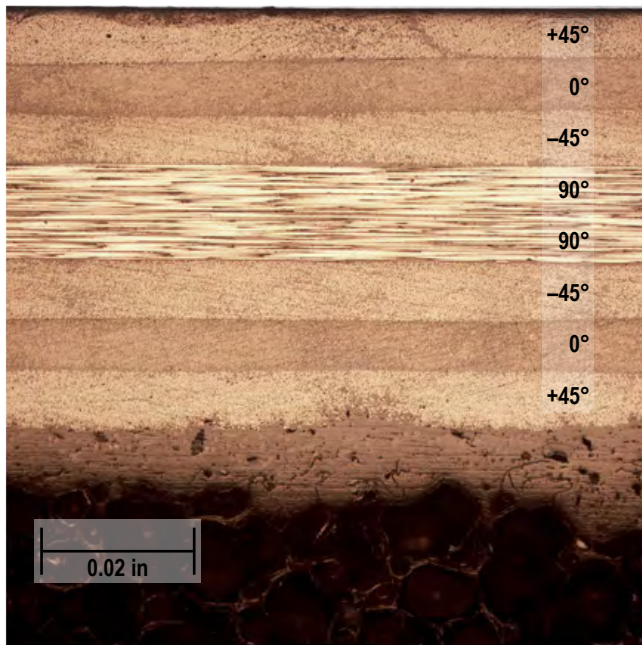
The areal weight (weight per unit surface area) of each of these sandwich structures was measured and the results are presented in table 2. Note that the units of weight are in pound mass (lbm) to avoid confusion with load applied to the specimen by the load frame which is measured in pounds of force (lbf). Since the honeycomb core is twice as thick as the thickness of the foam core, in order to obtain a better comparison on a weight basis between the foam core and the honeycomb core specimens, the areal weight of honeycomb core specimens with a 0.5-in thickness



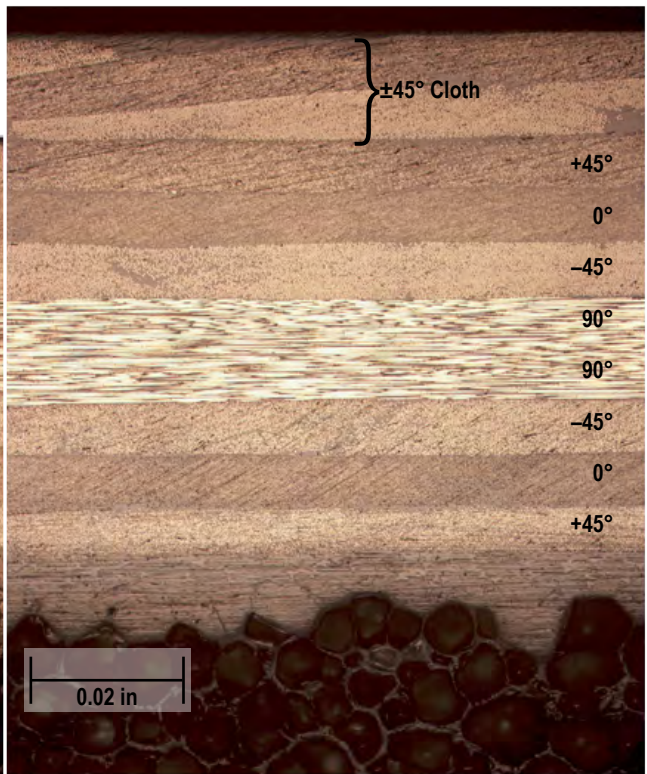
(a) Honeycomb Core, Bare



(b) Honeycomb Core, With Cloth



(c) Foam Core, Bare



(d) Foam Core, With Cloth

Figure 2. Cross section photomicrographs (width direction or 90°-direction) showing face sheet waviness of inner plies (plies closest to the core) on honeycomb core specimens (top pictures) and no waviness of plies on foam core specimens (bottom pictures).

are also included. These values were calculated based on the measurements from the 1.0-in thick honeycomb core and the core having a density of 4.5 lb/ft³. For the damage tolerance aspects of the sandwich structure in this study, this comparison is contingent upon the honeycomb core specimens not changing failure mode during CAI testing from the 1.0-in thickness core to the 0.5-in thickness core. Since face sheet failure was the failure mode (as will be seen later in the results section), it was assumed that the 0.5-in honeycomb core would fail in the same manner. Also included in table 2 is an estimate of the overall weight of the PAF structure if made of each of the four listed types of sandwich structure. Adding an outer layer of cloth to the sandwich structure will add an additional 1,470 lbs to the overall weight of the PAF. This equates to a 23% increase in weight for the foam core structure, a 20% increase in weight for the 1 inch thick honeycomb core structure and a 27% increase in weight for the 0.5 inch thick honeycomb core structure.

The line modulus (in pounds per unit width) of each of the four types of sandwich structure tested in this study were measured and the results are shown in table 3. A typical plot used to arrive at this value is shown in figure 3 for a foam core specimen with no fabric. This modulus value is the line load needed on each of the four sandwich structures to cause a strain of 100%. These values can be divided by the respective face sheet thicknesses (times 2 since each specimen has 2 face sheets) to obtain the more familiar modulus in lbf/in² and these values are also included in table 3.

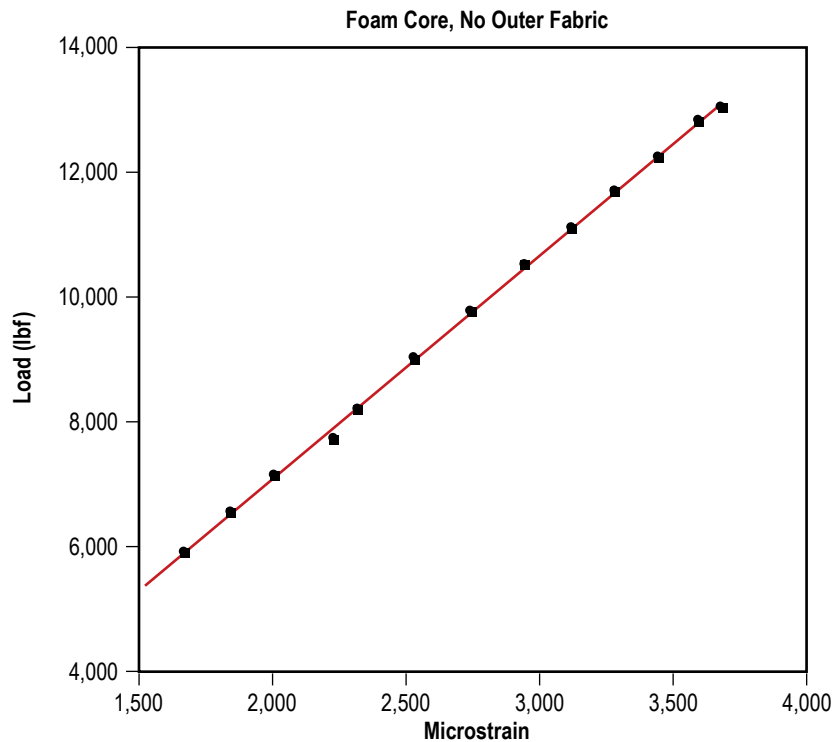


Figure 3. Typical plot to determine modulus values.

Table 3. Modulus measurements of each of the four types of specimens used in this study.

Specimen Type	Line Modulus (lbf/in)	Modulus (MSI)
Foam Core, Bare	885,600±25,600	8.6±0.25
Foam Core, With Cloth	974,400±16,600	6.8±0.12
Honeycomb Core, Bare	882,000±12,400	9.0±0.13
Honeycomb Core, With Cloth	972,800±6,000	7.4±0.05

Note how the thinner face sheet thickness measurements for the honeycomb core sandwich structure cause the modulus value to be higher than the foam core sandwich structure. Although, the line modulus is slightly lower, probably due to the fiber waviness.

To examine how these four types of sandwich structure compare with respect to stiffness when weight is considered, the line modulus can be normalized (divided) by a line load density for each of the sandwich structures. Since the height of each specimen is 6 in, the areal density values in table 2 can be multiplied by 6 in to arrive at a line load density for the four types of specimens. This is tabulated in table 4. These line density values can be divided into the line modulus values to arrive at a weight normalized modulus and are also presented in table 4. This normalized modulus is the amount of load needed to cause a 100% strain per pound of sandwich structure (that is 6 in tall).

Table 4. Normalized modulus values of the four types of (6-in tall) specimens tested.

Specimen Type	Line Density (lbm/in ²)		Normalized Modulus (lbf/lbm)	
	Core Thickness		Core Thickness	
	1-in	0.5-in	1 in	0.5 in
Foam Core, Bare	N/A	0.0516	N/A	17,162,800
Foam Core, With Cloth	N/A	0.0636	N/A	15,320,800
Honeycomb Core, Bare	0.0600	0.0444*	14,000,000	19,560,000
Honeycomb Core, With Cloth	0.0720	0.0564*	13,500,000	17,248,000

*Calculated values, not directly measured.

Thus, when normalized by weight, the bare foam core sandwich structure is about 23% stiffer than the 1.0-in thick bare honeycomb core structure but would be 14% less stiff if 0.5-inch-thick honeycomb core was used. Note that the outer layer of fabric simply adds more weight (for both the foam and honeycomb core sandwich structures) and contributes little to the stiffness of the structure as seen from the line modulus measurements. Rotating the cloth 45° (so that it was at a 0/90° orientation) would add to the stiffness while still providing any benefits of impact protection and resistance to fiber break-out upon drilling operations.

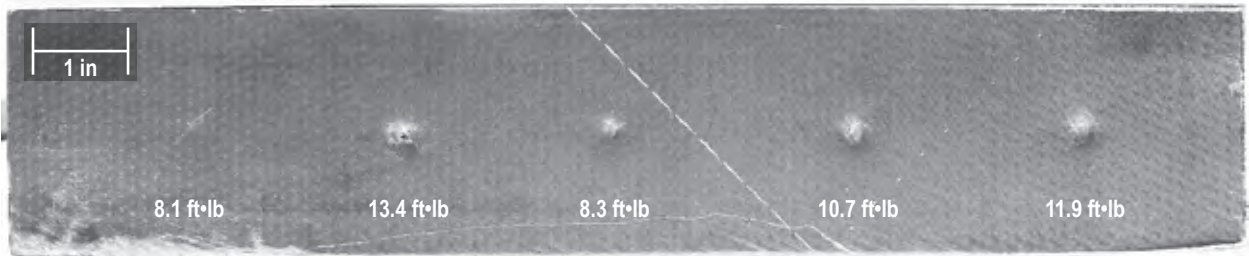
Undamaged strength testing of the honeycomb sandwich structure was not pursued in this study since the undamaged specimens exhibited end-brooming, which is not a valid failure mode and this study concerns damage tolerance testing, and undamaged strength values are not relevant anyway.

3. IMPACT DAMAGE TESTING

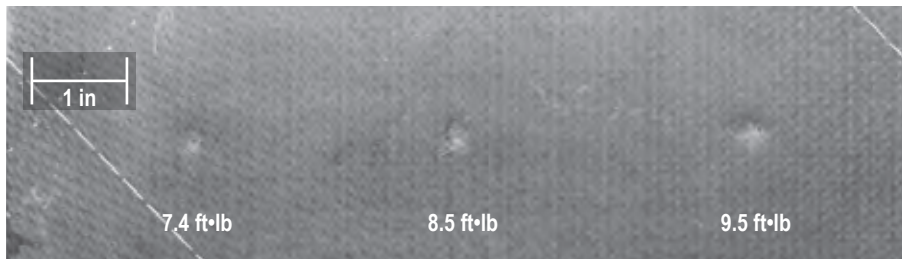
For each of the four types of sandwich specimens examined in this study, a BVID threshold needed to be established since this would be the major damage tolerance design criteria that the PAF structure will be designed to. Sections of each of the four different types of 36- by 36-in sandwich panels were cut out and used for an impact survey in which different impact energies were used and the visibility assessed as to what would constitute ‘barely visible.’ Using a BVID threshold works under the assumption that any foreign object impact event that might not be externally seen will not degrade the performance of the part to below limit load. Any impacts that are visible can be dispositioned for need for repair before launch.

Originally (i.e., with the honeycomb core specimens), this program utilized a 0.5-in-diameter impactor since this is the most commonly used size, however a larger diameter impactor can produce similar or more severe damage with less visibility^{1,2} and thus a larger impactor size was subsequently used for the foam core specimens. In order to directly compare the effect of impactor size, foam specimens with the fabric on the surfaces were impacted with a 0.5-in impactor to compare with honeycomb core specimens with the fabric on the surfaces that were also impacted with a 0.5-in-diameter impactor. It was assumed that if 0.5-in-thick honeycomb core was used, the BVID results would be similar.

A sample of visual damage produced by various levels of impact energy are shown in figure 4 for cloth covered foam core specimens impacted with a 0.5-in-diameter impactor. There are many variables which can affect what constitutes the already arbitrary ‘barely visible damage’ threshold. Such things as amount of light, angle of light, surface finish and color will all contribute making the sole use of photographs problematic. Using photographs such as those shown in figure 4, rather than using the actual impact damage sites, can also be problematic as the two-dimensionality of the photographs affects the amount of visual damage. The visual indications of BVID for each of the types of specimens tested in this study are shown in figure 5 and are only included to give the reader a general idea of what these impacts look like, but direct observation of the actual damaged specimens can only suffice to arrive at a meaningful BVID impact energy level and the data from the impact surveys on the other sandwich configurations and impactor sizes will not be presented.



(a)



(b)

Figure 4. Photographs of various impacts with a 0.5-in impactor on cloth covered foam core sandwich structure. An impact severity level of 9.5 ft•lbs was chosen as the level of BVID.

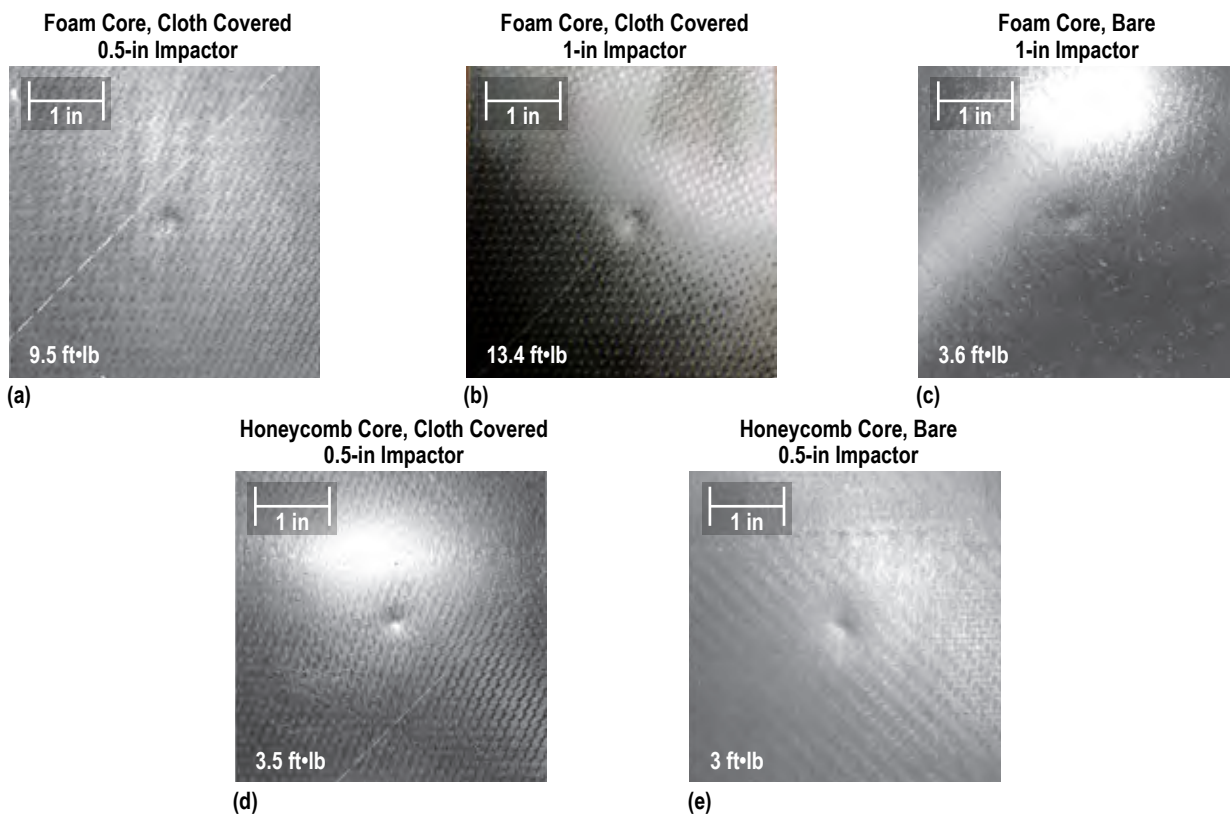


Figure 5. Photographs of BVID for each of the configurations tested.

Table 5 presents the selected levels of BVID for the five configurations used in this test program.

Table 5. Impact energy level considered BVID for each of the 5 configurations tested in this study.

Configuration	Impactor Size (in)	BVID Energy Level (ft-lb)
Foam Core, Cloth Covered	0.5	9.5
Foam Core, Cloth Covered	1.0	13.4
Foam Core, Bare	1.0	3.6
Honeycomb Core, Cloth Covered	0.5	3.5
Honeycomb Core, Bare	0.5	3.0

Note that the cloth covered foam core specimens were more difficult to see impact damage on with the 0.5-in diameter impactor compared to the cloth covered honeycomb core specimens and thus had to be hit at a higher impact energy to produce BVID. Without the outer cloth layer (i.e., bare specimens), the foam core specimens needed a slightly higher severity of damage as the honeycomb core specimens to cause BVID, but this is probably due mostly to the bare foam core specimens using the larger diameter impactor.

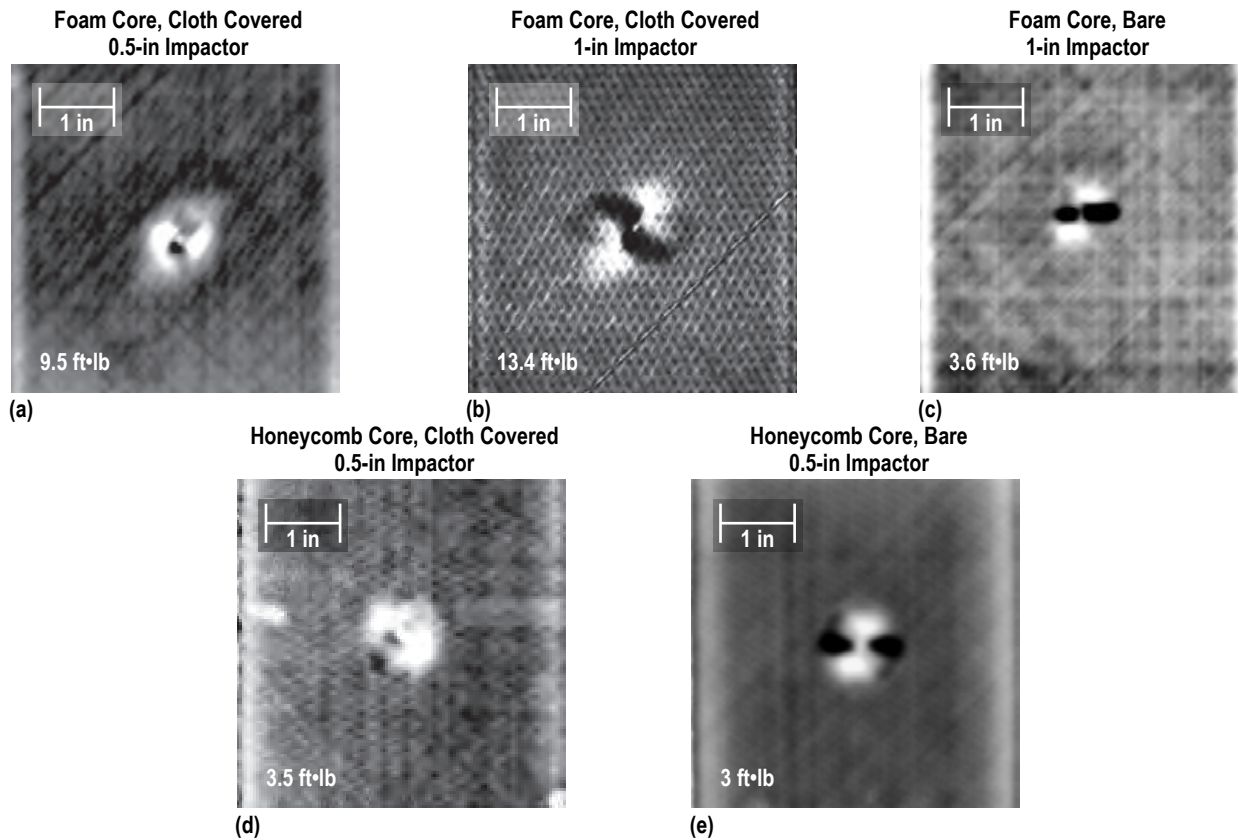


Figure 6. Flash Thermography of BVID damage for the samples tested in this study.

The amount of internal damage to each specimen was determined by flash thermography. Flash thermography signatures of each of the damage zones from the five configurations are shown in figure 6. These NDE (nondestructive evaluation) results are included to give an idea as to what can be expected to be found utilizing thermography techniques on the PAF when BVID is encountered.

Samples from each of the five configurations tested were cross-sectioned through the impact zone in the width (90°-direction) and photographs taken of the damage. These results are presented in figure 7, which is included to give the reader an idea of the amount of core and face sheet damage that is produced for each of the five levels of BVID used in this study.

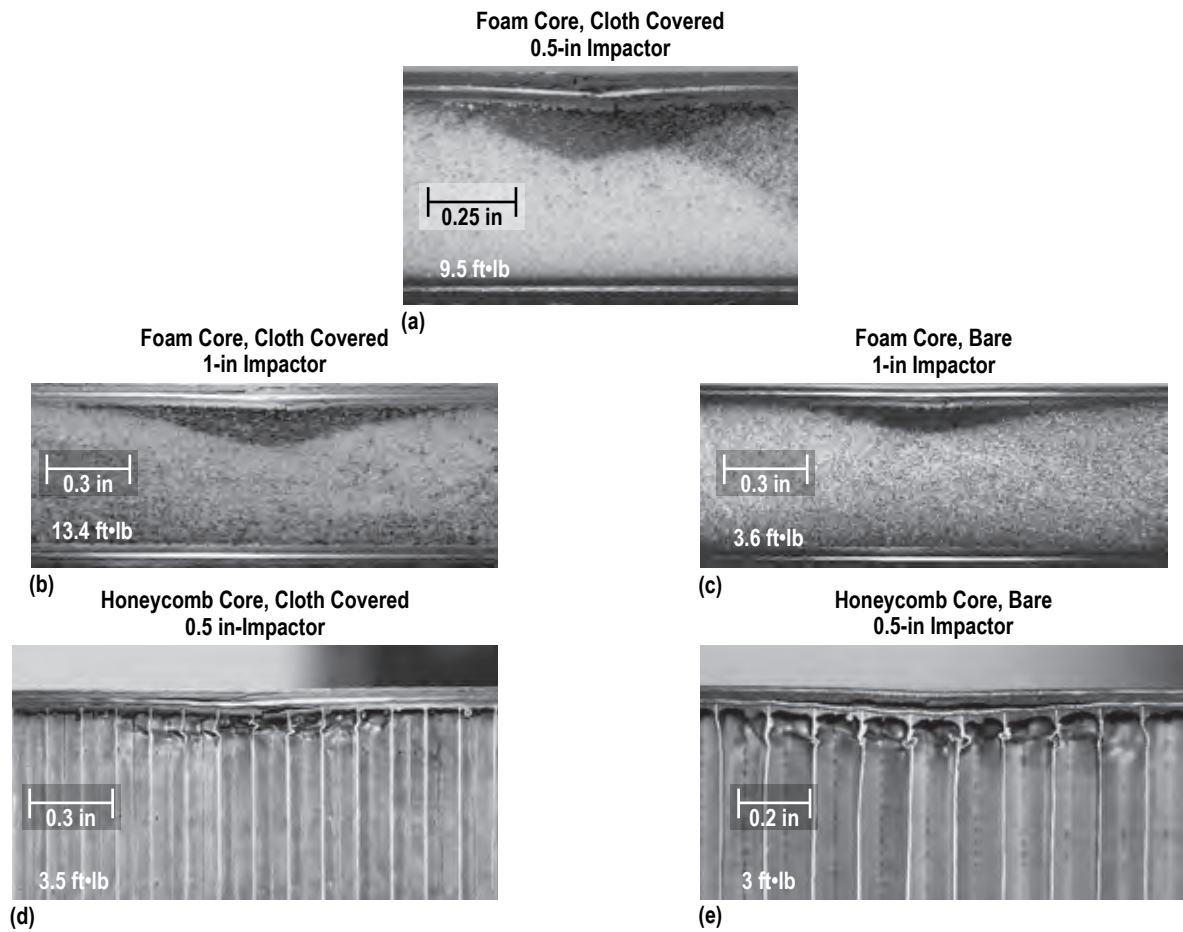


Figure 7. Cross-sectional pictures of damage due to BVID for the specimen configurations used in this study.

The load-deflection curves of impact at the BVID level of each of the five types of specimen configurations used are shown in figure 8 and are presented for completeness since these plots are of little practical use with respect to the purpose of this study, but will be more thoroughly examined in a follow-on study comparing the damage tolerance of the honeycomb core versus the foam core in a more detailed manner.

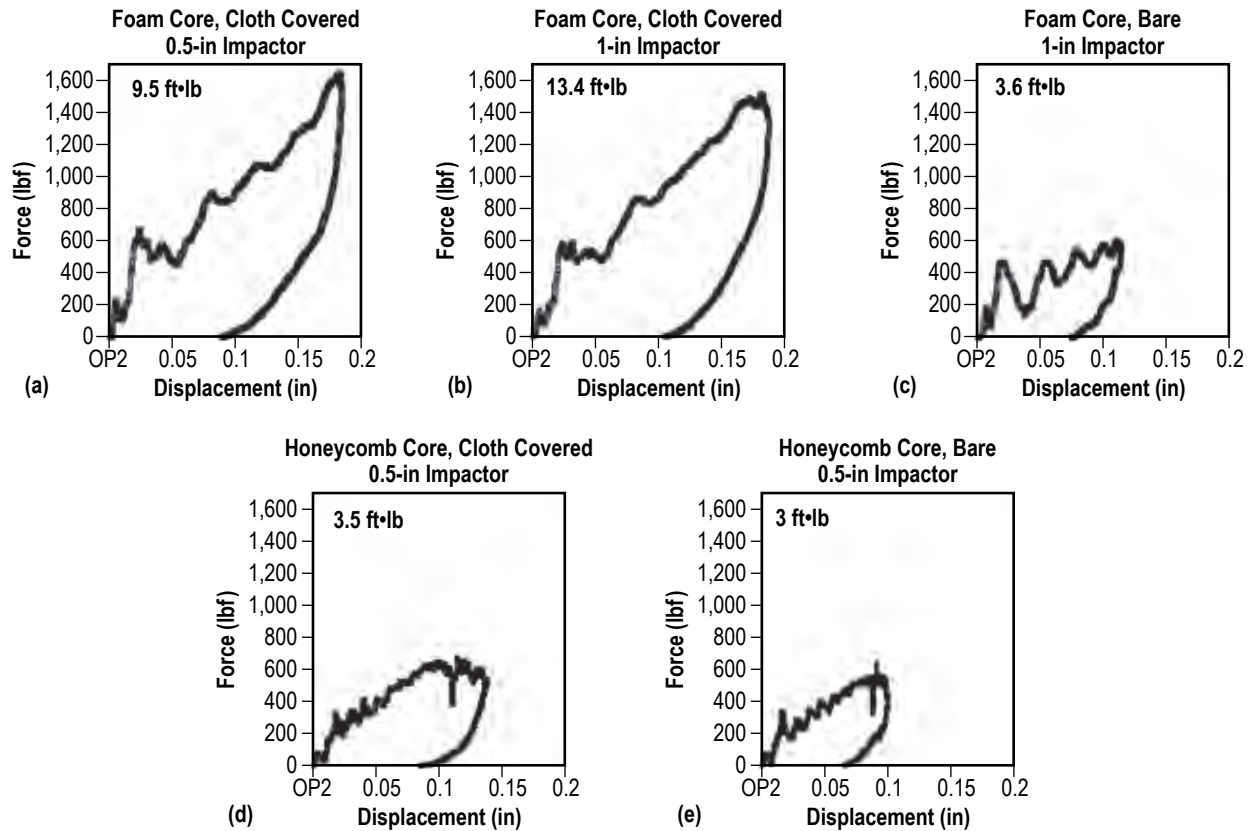


Figure 8. BVID load-deflection curves for the impact event for the five types of specimens tested.

4. COMPRESSION-AFTER-IMPACT TESTING

The impacted sandwich specimens were assessed for residual compression strength using the test fixture shown in figure 9. Three strain gages were placed on the specimen as diagramed in figure 10 to ensure even loading of each of the face sheets. The specimens were taken to approximately 2,000 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. The compression load aligned with the 0° fiber direction.

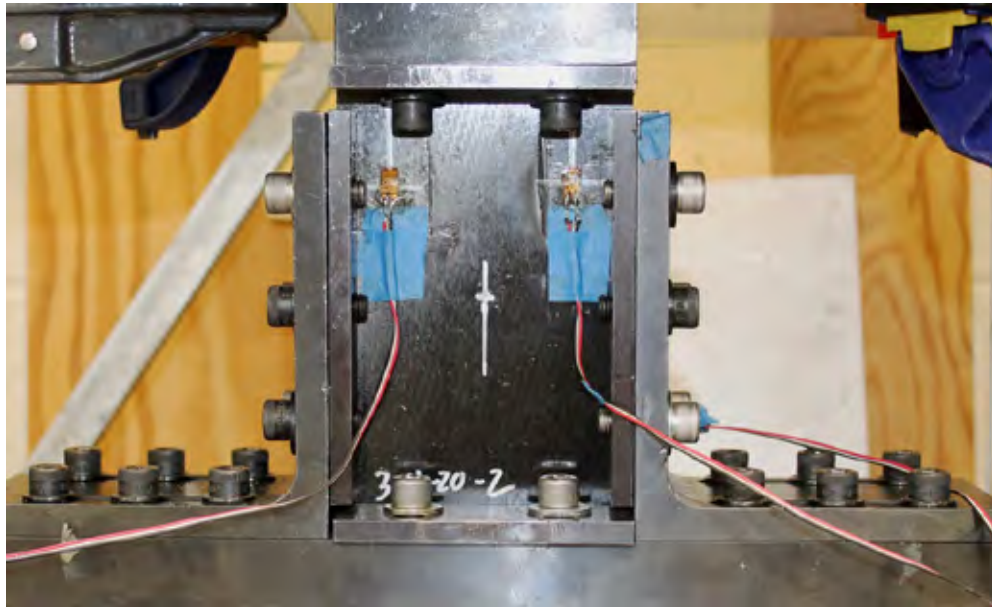


Figure 9. Photograph of fixture used for assessing CAI strength of sandwich specimens.

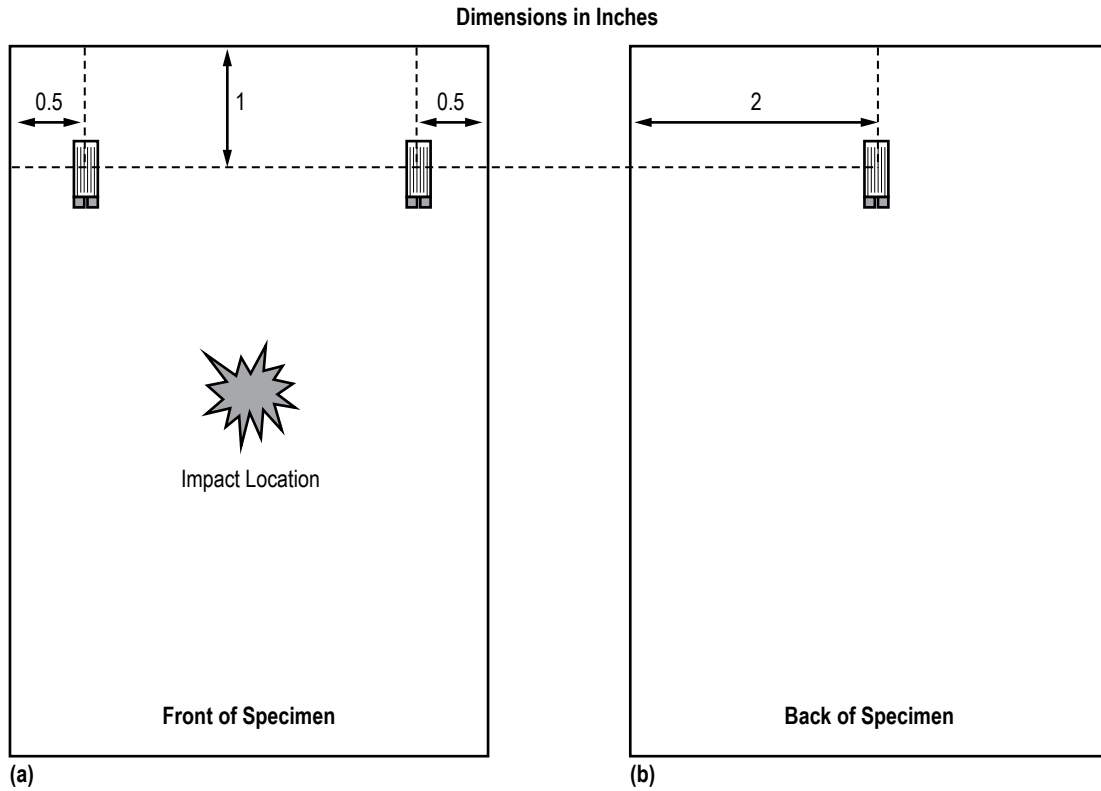


Figure 10. Location of strain gages on front and back of each CAI specimen.

The CAI strength results are shown in Tables 6(a–e) using line load at failure. It was noted that the foam core specimens did not fail in the face sheet, but rather in the core. To normalize by weight, the load needed to fail the PAF structure is divided by the weight of the PAF structure. The load needed to break the PAF structure is simply the line load at failure multiplied by the perimeter of the top (smallest section) of the PAF. This perimeter is given by $\pi(170\text{in}) = 534\text{ in}$. Results based on 0.5-in thick honeycomb core are included for comparison. These results were not directly measured but inferred from the results on the 1.0-in thick honeycomb core.

The depth of the dent formed due to impact was measured with a digital depth gage with a 0.059-in radius tip and the results are presented in these tables for completeness. These values have been shown not to be a good indicator of amount of damage or predictor of residual strength.^{3,4}

Table 6a. Results of CAI strength tests on foam core, cloth covered specimens using a 0.5-in impactor (BVID = 9.5 ft•lb). Weight of PAF made with this sandwich structure = 7,791 lb•m.

Specimen	Dent Depth (in)	Specimen Width (in)	Load at Failure (lbf)	Line Load at Failure (lbf/in)	Normalized Strength (lbf/lbm)
1	0.0245	4.19	22,123	5,280	362
2	—	4.05	22,430	5,538	380
3	0.0240	4.01	20,297	5,062	347
4	0.0230	4.01	21,297	5,311	364
5	0.0235	4.13	21,603	5,361	367
6	0.0195	4.12	21,683	5,263	361
7	0.0230	4.14	21,224	5,127	351
8	0.0220	4.14	21,050	5,085	348
Average				5,253±159	360±11

Table 6b. Results of CAI strength tests on foam core, cloth covered specimens using a 1-in impactor (BVID = 13.4 ft•lb). Weight of PAF made with this sandwich structure = 7,791 lb•m.

Specimen	Dent Depth (in)	Specimen Width (in)	Load at Failure (lbf)	Line Load at Failure (lbf/in)	Normalized Strength (lbf/lbm)
1	0.0090	4.05	19,747	4,876	334
2	0.0065	4.00	22,054	5,514	378
3	0.0095	4.04	19,535	4,835	331
4	0.0160	4.05	19,191	4,739	325
5	0.0065	4.05	18,746	4,629	317
6	0.0105	4.04	20,428	5,056	346
7	0.0070	4.00	19,870	4,968	340
8	0.0085	4.12	22,368	5,429	372
9	0.0085	4.01	19,817	4,942	339
10	0.0110	4.07	18,798	4,619	316
11	0.0105	4.04	20,260	5,015	344
Average				4,966±289	340±20

Table 6c. Results of CAI strength tests on foam core, bare specimens using a 1-in impactor (BVID = 3.6 ft•lb). Weight of PAF made with this sandwich structure = 6,321 lb•m.

Specimen	Dent Depth (in)	Specimen Width (in)	Load at Failure (lbf)	Line Load at Failure (lbf/in)	Normalized Strength (lbf/lbm)
1	0.0050	4.05	17,141	4,232	358
2	0.0035	4.07	18,583	4,566	386
3	0.0030	4.05	18,510	4,570	386
4	0.0045	4.04	18,464	4,570	386
5	0.0045	4.10	18,575	4,530	383
6	0.0045	4.07	19,096	4,692	396
7	0.0045	4.10	18,680	4,702	397
Average				4,552±156	385±13

Table 6d. Results of CAI strength tests on honeycomb core, cloth covered specimens using a 0.5-in impactor (BVID = 3.5 ft•lb). Weight of PAF made with this sandwich structure; 1-in-thick core = 8,820 lb•m, 0.5-in core = 6,909 lb•m.

Specimen	Dent Depth (in)	Specimen Width (in)	Load at Failure (lbf)	Line Load at Failure (lbf/in)	Normalized Strength 1-in-Thick Core (lbf/lbm)	Normalized Strength 0.5-in-Thick Core (lbf/lbm)
1	0.0115	4.06	26,930	6,633	401	513
2	0.0110	4.04	25,771	6,379	386	493
3	0.0105	4.10	24,372	5,944	360	459
4	0.0110	4.10	25,140	6,132	371	474
5	0.0115	3.94	24,331	6,175	374	477
6	0.0120	4.02	25,743	6,404	387	495
7	0.0120	4.08	23,003	5,638	341	436
Average				6,186±328	374±20	478±25

Table 6e. Results of CAI strength tests on honeycomb core, bare specimens using a 0.5-in impactor (BVID = 3.0 ft•lb). Weight of PAF made with this sandwich structure; 1-in-thick core = 7,350 lb•m, 0.5-inch core = 5,439 lb•m.

Specimen	Dent Depth (in)	Specimen Width (in)	Load at Failure (lbf)	Line Load at Failure (lbf/in)	Normalized Strength 1-in-Thick Core (lbf/lbm)	Normalized Strength 0.5-in-Thick Core (lbf/lbm)
1	0.0130	4.07	21,215	5,213	379	512
2	0.0135	4.07	22,060	5,420	394	532
3	0.0160	4.07	21,916	5,385	391	529
4	0.0140	4.11	20,729	5,044	367	495
5	0.0150	3.84	20,756	5,400	393	530
Average				5,292±162	385±12	520±16

A bar chart summarizing these normalized strength results is shown in figure 11. The shaded bars indicate that the specimen was covered with cloth and the un-shaded bars represent bare specimens. The bars with red outline indicate a 1-in tup was used and the bars with a black outline indicate a 0.5-in impactor was used. The foam core sandwich structure results are presented on the left and the honeycomb core specimens are presented on the right.

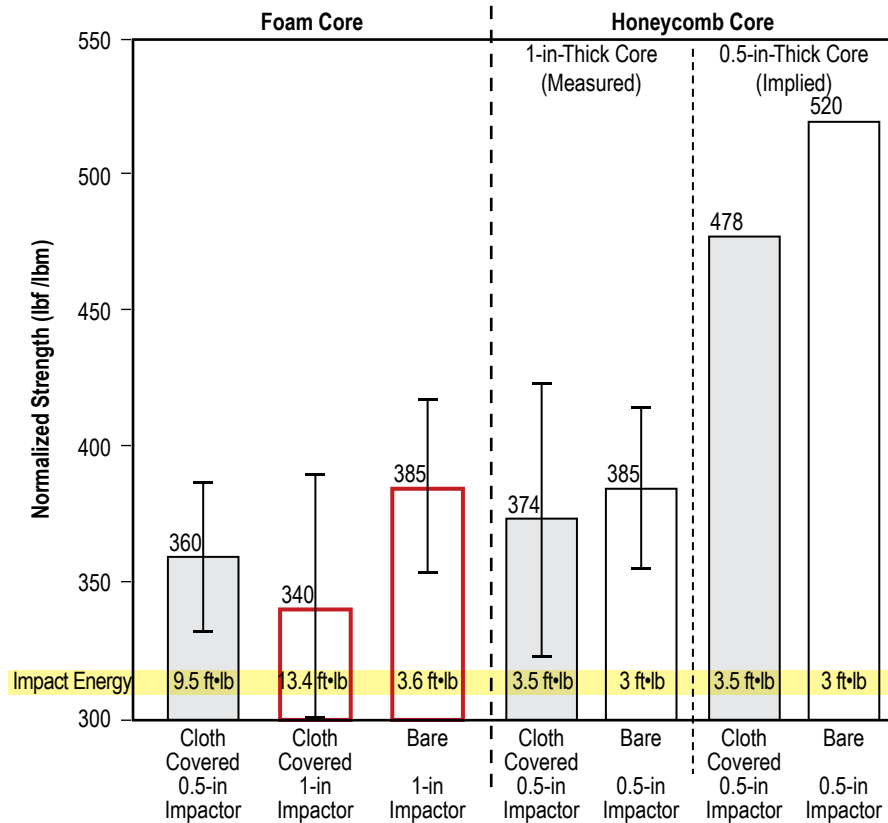


Figure 11. Bar chart summarizing the CAI strength results from the tests on the specimens used in this study. Shaded bars indicated cloth covered specimens and red outline indicates larger size impactor. Standard deviation bars are included with each bar.

As expected, the cloth covered foam specimens performed the worst since they had to be hit so hard to produce BVID. This highlights the importance of having a BVID at a low impact severity level so as to more easily detect damage that can degrade the compression strength. Such things as a smooth shiny surface can aid in having a BVID at a low impact severity level. For the two types of honeycomb core specimens, it can be noted that the addition of the outer ply of cloth does lead to a higher CAI strength at BVID, but this higher strength is negated by the added weight of the cloth. It is evident that if honeycomb core of equal thickness to the foam core had been used, the honeycomb core specimens would show significantly higher CAI strength performance.

5. FAILURE MECHANISMS

The mode of failure of the different specimens will briefly be presented even though this is of little practical interest to the PAF project since the strength values are the focus of this paper and these values will be used in the final design of the part. As noted earlier, it was clear that the two different types of core had different specimen failure mechanisms. The mode of failure may be of interest when explaining why the strength values might have been different for the foam and honeycomb core specimens. More detail about the differing failure mechanisms between the types of sandwich structure tested in this study will be published in a follow-on study.

An end-loaded sandwich panel (assuming undamaged) can fail in several ways. These are illustrated in figure 12 and consist of face sheet failure, macrobuckling, core shear buckling (shear crimping), and face sheet wrinkling.

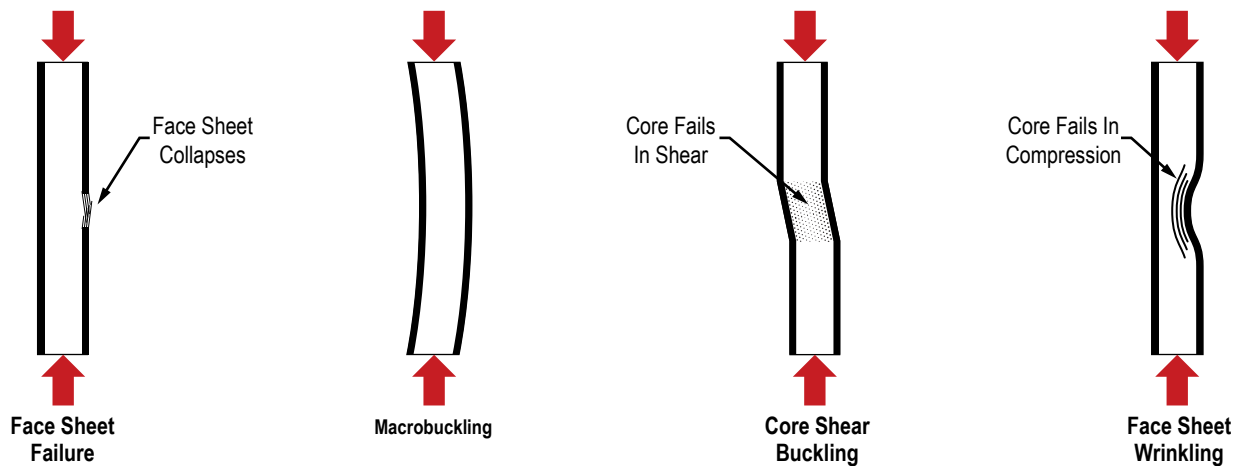


Figure 12. Possible modes of failure of sandwich structure.

Estimated values of failure for these are given in a number of publications and are all basically similar. A concise treatment of these four failure modes is given in “End Compressions of Sandwich Columns” by Fleck and Sridhar⁵ and the following equations are taken from there.

Face sheet failure occurs when the in-plane load being applied exceeds the load carrying capabilities of the composite face sheets. The load at which this occurs is given by:

$$P_f = 2tb\sigma_C \quad (1)$$

where t is the face sheet thickness, b is the specimen width and σ_C is the compression strength of the composite face sheet laminate. Note that the core thickness is not a factor for this failure mode.

The compression strength of the as manufactured face sheets on the honeycomb core (no cloth) was found in a previous study to be 99 ksi. It is assumed that the bare face sheets on the foam core would have at least this much strength since there is no fiber waviness. The extra ply of cloth adds significantly to the thickness but will do little for strength. Thus, using the measured thickness of each of the four types of specimens as given in table 2 and a face sheet strength value of 99 ksi will overestimate the failure load of the cloth covered specimens. These four estimated strength values, based on equation (1) and using a nominal specimen width of 4 in, are given by:

- Foam core bare = 46,700 lbf.
- Foam core cloth covered = 57,000 lbf.
- Honeycomb core bare = 38,800 lbf.
- Honeycomb core cloth covered = 52,300 lbf.

These values are just estimates of load to fail each type of specimen to compare with the other three failure modes.

Macrobuckling failure occurs when the in-plane load being applied exceeds the buckling load of the sandwich structure with the dimensions and boundary conditions being tested. This buckling load is given by:

$$P_B = \frac{2\pi^2 b t c^2 E_f}{L^2} \quad (2)$$

where c is the core thickness plus one face sheet thickness, E_f is the modulus of the face sheet and L is the height of the sandwich structure. This equation is for a panel with fixed ends and free edges. The buckling load would be higher for simply supported edges which is probably closer to the actual situation in this study. Using the values of E_f as given in table 3 and a value of L as 6 in, the four loads at which buckling can be expected to occur for the specimens used in this study are given as:

- Foam core bare = 347,000 lbf.
- Foam core cloth covered = 351,000 lbf.
- Honeycomb core bare, 1-in-thick core = 1,063,000 lbf.
- Honeycomb core cloth covered, 1-in-thick core = 1,215,000 lbf.
- Honeycomb core bare, 0.5-in-thick core = 291,000 lbf.
- Honeycomb core cloth covered, 0.5-in-thick core = 343,300 lbf.

All of these values are much higher than any of the face sheet failure loads, so specimen buckling would not be expected.

Core Shear Buckling can occur if the core has a low shear modulus and is thus not stiff enough to prevent the two face sheets from locally buckling together as individual plates. The core shear buckling load is given by:

$$P_s = bt_c G_c \quad (3)$$

where t_c is the core thickness and G_c is the core shear modulus.

Using the core shear modulus values given in table 1, the loads at which core shear buckling can be expected to occur for the specimens used in this study are given as:

- Foam core bare = 8,200 lbf.
- Foam core cloth covered = 8,200 lbf.
- Honeycomb core bare = 280,000 lbf.
- Honeycomb core cloth covered = 280,000 lbf.
- Honeycomb core bare, 0.5-in-thick core = 140,000 lbf.
- Honeycomb core cloth covered, 0.5-in-thick core = 140,000 lbf.

Thus, the foam core specimens should fail by core shear failure before they fail by face sheet failure. The honeycomb core specimens are still governed by face sheet failure even if the core is only 0.5-in thick.

Face sheet wrinkling can occur if the compressive modulus of the face sheet is low and does not prevent one of the face sheets from buckling inward toward the other face sheet. The load at which this occurs is given as:

$$P_w = 0.3(E_{Ff}E_cG_c)^{1/3} \quad (4)$$

where E_{Ff} is the flexural modulus of the face sheet (in the direction of loading) and E_c is the compressive modulus of the core. Classical lamination theory was used to estimate E_{Ff} and a value of 3.3 MSI was used in equation (4). The four loads at which face sheet wrinkling can be expected to occur for the specimens used in this study are given as:

- Foam core bare = 22,700 lbf.
- Foam core cloth covered = 22,700 lbf.
- Honeycomb core bare = 128,800 lbf.
- Honeycomb core cloth covered = 128,800 lbf.

As with the face sheet strength calculations, the core thickness does not enter into these calculations.

For the honeycomb core sandwich specimens, the load of buckling, core shear failure, and face sheet wrinkling are all well above the face sheet failure load of $\approx 38,800$ lbf as calculated from equation (1). However, for the foam core specimens, both the core shear failure load ($\approx 8,200$ lbf) and the face sheet wrinkling load ($\approx 22,700$ lbf) are both lower than the load at which the face sheets are expected to fail ($\approx 38,800$ lbf). Failures of a foam core and a honeycomb core specimen are shown in figure 13.

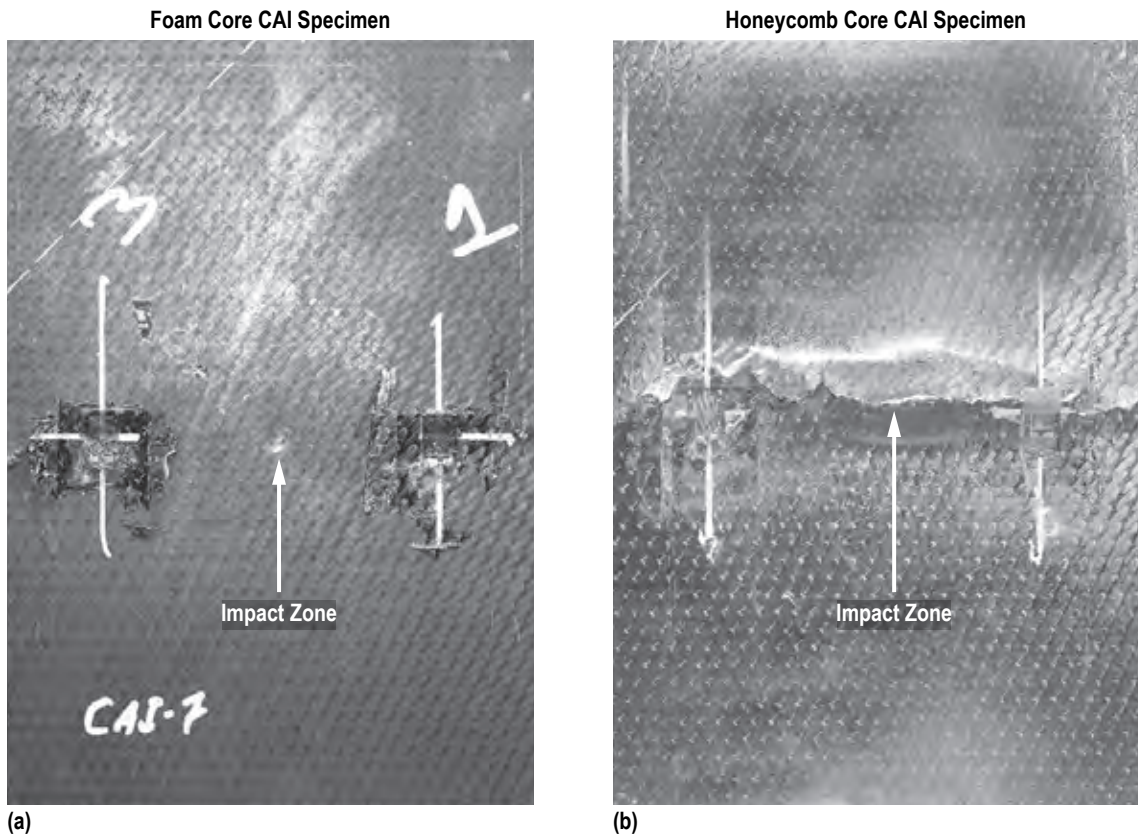


Figure 13. Photographs of post failure CAI specimens with foam core (left) and honeycomb core (right).

The foam core specimen shown in figure 13 had its face sheets removed from the core using a bandsaw and the failure within the core is shown in figure 14.

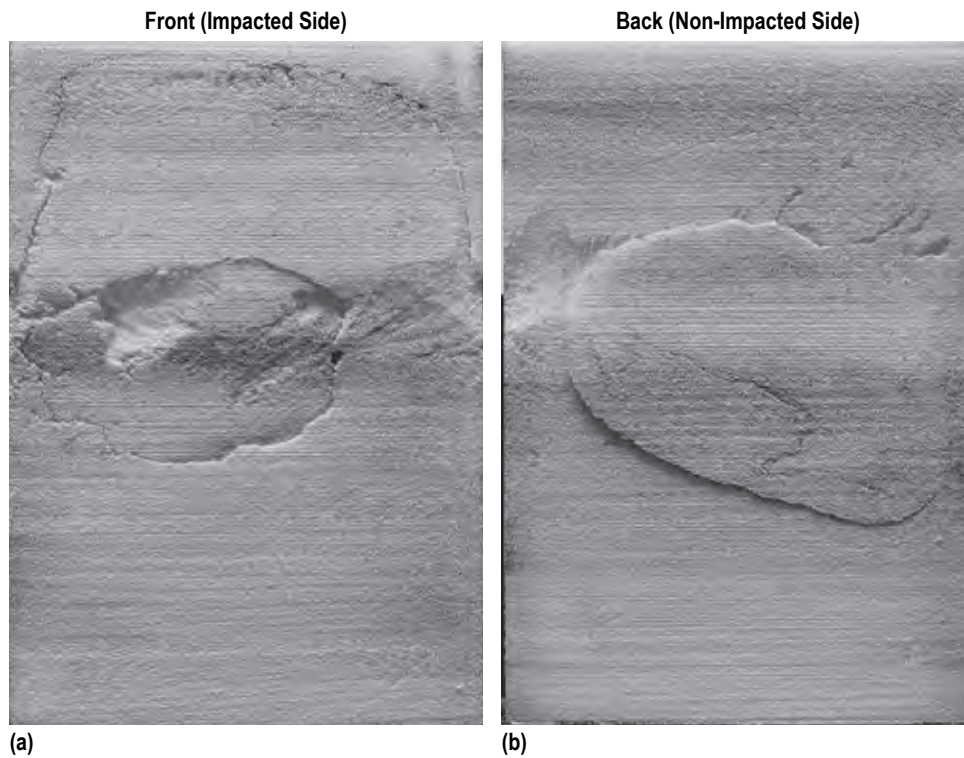


Figure 14. Photographs of core failure in post CAI foam core specimen (face sheets removed).

With slight finger pressure, the failure in the core seen in figure 14 could be seen as a ‘shear plug’ that separates from the rest of the foam core and is shown in figure 15.

In reference 5, undamaged PVC foam core sandwich specimens with a shear modulus values of about one half (1.9 ksi) and one and one half (6.4 ksi) that of the foam core used in this study (4.1 ksi) all failed by core shear regardless of specimen dimensions with the exception of one particularly long specimen that failed by global buckling. Only when a foam core with a shear modulus about four times greater (16 ksi) was utilized did face sheet compression failure occur. Thus, the core shear failure of the foam core specimens used in this study were not surprising.

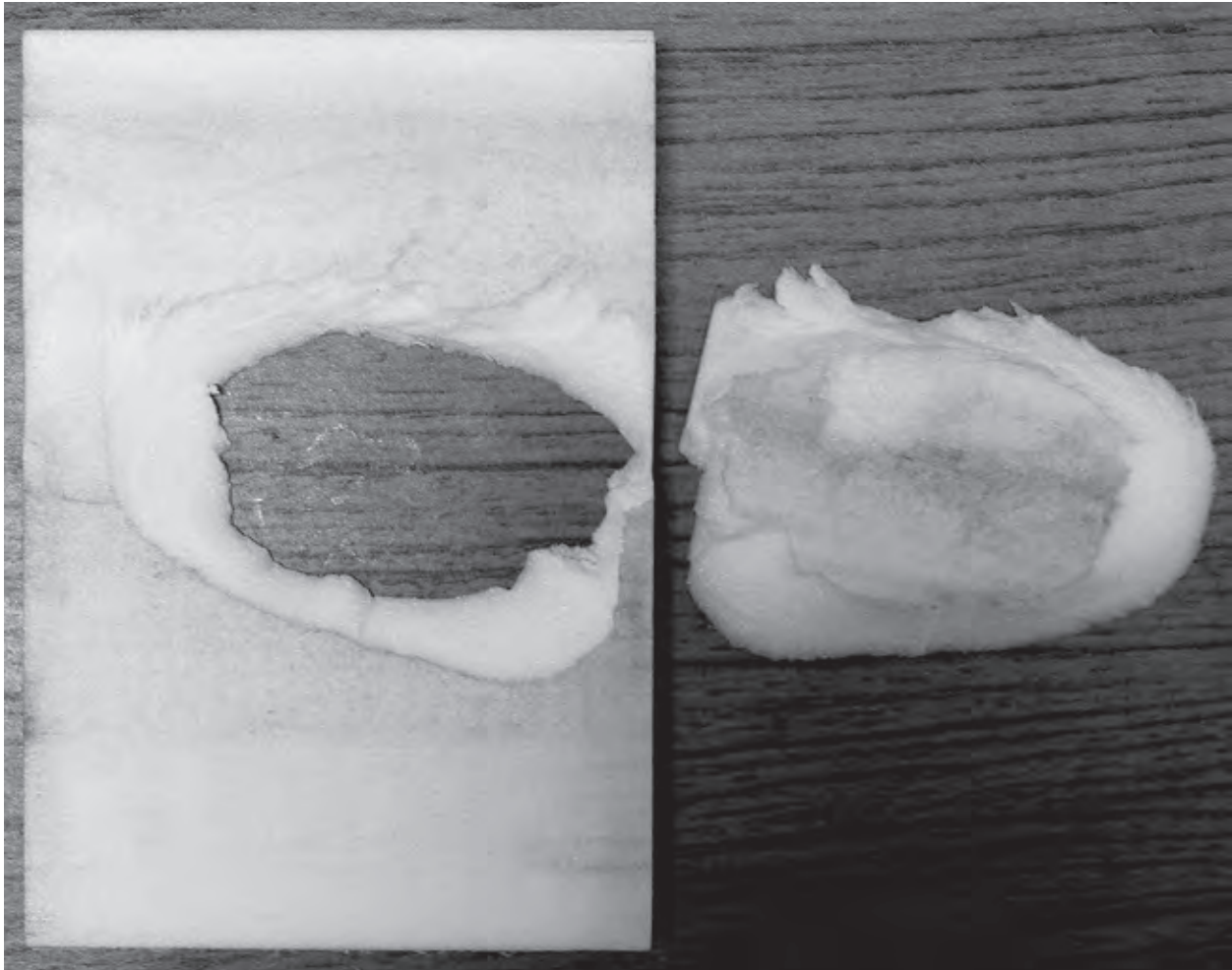


Figure 15. Foam core of figure 14 with ‘shear plug’ removed with slight finger pressure.

Three damage tolerance studies utilizing foam core sandwich structure⁶⁻⁸ had specimens that failed due to face sheet failure. All these studies used foam core with a density higher than what was used in this study. The lowest density core used was 5 lbf/ft³ but this particular study⁶ used high impact energies (30 ft•lb).

One damage tolerance study utilizing foam core sandwich structure⁹ had specimens that failed in the foam core near the face sheet/core bondline, and this study used very lightweight core (3.3 lbf/ft³ density). Thus, the density of foam core used for damage tolerance testing can influence the failure mechanism of the CAI tests.

6. CONCLUSIONS

For the sandwich structure used in this study, the following observations were made:

- An outer layer of fabric placed at $\pm 45^\circ$ to the loading direction does not enhance the damage tolerance of sandwich structure when BVID is used as the critical parameter since it tends to mask the visual damage and higher impact energies are needed to produce BVID, especially on sandwich structure with foam core.
- Rohacell foam and aluminum honeycomb core specimens fail in compression by different mechanisms for the core densities used in this study. The low shear modulus of the foam core produced core shear buckling failures. The honeycomb specimens failed by face sheet failure.
- A larger diameter impactor may give more conservative CAI strength results since a higher impact energy level appears to be needed to cause BVID.
- Despite the differing failure mechanisms, the type of core appears not to have a significant effect on CAI strength at the levels of BVID chosen for this study when comparing a 1-in-thick honeycomb to a 0.5-in-thick foam, but had a 0.5-in honeycomb core been used, the CAI strength results would be expected to be significantly higher at the cost of a lower buckling load.

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14. ABSTRACT This Technical Memorandum presents results from a damage tolerance study undertaken in support of the payload adapter fitting (PAF) for the Space Launch System (SLS) program at NASA's Marshall Space Flight Center (MSFC). The study consisted of determining the compression-after-impact (CAI) strength of candidate carbon/epoxy face sheet sandwich structure that has been identified for potential use to manufacture the PAF hardware. Two types of core material that have been considered for use on the PAF structure were used in this study. One was an aluminum honeycomb and the other was a Rohacell foam. Levels of barely visible impact damage (BVID) were determined for the types of sandwich structure tested in this study and this level of damage was used for CAI strength testing. It was found that the honeycomb core sandwich structure failed by face sheet failure and the foam core sandwich structure failed by core shear failure. CAI strength values were normalized by weight of the sandwich structure since lower mass is desirable for this structure.					
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