LOW VELOCITY IMPACT OF SANDWICH COMPOSITE PLATES

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ABSTRACT
Impact and compression after impact properties of plain weave carbon fiber sandwich composites were investigated in this study. Impact tests were conducted on different sample types to obtain information about absorbed energy and force. The different samples consisted of foam filled and hollow honeycomb cores with four layer carbon fiber sheets on one or both sides. The impact and compression after impact data provided valuable information to allow for comparisons between the different sample types. Also, the compression after impact tests were conducted in order to determine the reduction in compressive strength when comparing impacted to non-impacted samples.

INTRODUCTION
The use of woven fabrics as face sheets in composite panels is increasing due to interlacing of fiber bundles possessing high ratios of strain to failure in tension, compression or under impact loads. The core, which is typically a low strength, lightweight material, provides the distance between the face sheets required to significantly increase the overall stiffness. The high stiffness, lightweight nature of the sandwich composite makes it an ideal choice for the aerospace industry. The primary concern with carbon fiber sandwich composites is low and high velocity impact. After an impact, there is a drastic reduction in compressive strength due to delamination and core damage [1]. While several studies have been conducted on high velocity impact, studies on low velocity impact are of equal interest. Low velocity impacts can include situations such as tool drops and hailstorms.

In this study, sandwich plates with different combinations of carbon fiber and cores were subjected to low velocity impacts at energies ranging from 5 J to those that caused complete penetration. The low impact energy samples were considered since even in the absence of fiber breakage, the laminate mechanical performance can be drastically affected [2]. After impact, compression tests were conducted to determine the remaining compressive strength. In-plane compression is the critical load for impact-damaged specimens, since strength reductions are the largest under this type of loading [3]. The different combinations of 100 mm x 100 mm samples used in this study are listed below.

- Foam filled honeycomb core with a 4-layer carbon fiber sheet on one side (26 mm thickness, 58 g avg. weight) and on both sides (27 mm thickness, 75 g avg. weight)
- Hollow honeycomb core with a 4-layer carbon fiber face sheet on both sides (27 mm thickness, 41 g avg. weight)
- Foam core (24 mm thickness, 42 g avg. weight)

The impact and compression tests were conducted in order to obtain energy, force, and compressive strength information, which can be used for comparisons. The energy and force data can be used, for example, to determine the benefits of utilizing foam core with a carbon fiber sheet on both sides compared to on one side. The compression after impact data can be used to determine how much reduction in compressive strength occurs as a result of different impact energies.

SAMPLE CONSTRUCTION
A hand-layup method shown in Figure 1 was used to construct the different sample types. The major components required for this method are a vacuum pump, vacuum bagging, spiral tubing and sealant tape. Polyurethane foam filled (FF) and hollow honeycomb (HH) were used as cores. The honeycomb structure was constructed out of craft paper. The foam filled and hollow honeycomb sheets were purchased from General Plastics. The hand-layup method provided high quality samples with minimal defects. New techniques were developed, which almost eliminated common problems of surface ripples and dry patches. In addition, a new method was designed for constructing samples with a hollow honeycomb core that eliminated epoxy pooling inside the cavities. This method also prevented the carbon fiber fabric from lifting into the cavities, which can occur as a result of the vacuum.

Plain weave carbon fiber fabric from BGF Industries was used for this study. The carbon fiber fabric had the following properties.

Yarn Type = 3 K	Weight = 193 g / m^2
Thickness 0.3048 mm	Count = 12.5 x 12.5

The epoxy consisted of F-82 resin and TP-41 hardener, which was allowed to cure under a 600 mm Hg vacuum for a minimum of 8 hours. The cured properties of the epoxy, purchased from Eastpointe Fiberglass, are listed below.

γ = 11.1 kN / m^3	Tensile Strength = 63.6 MPa
Compressive Strength = 131 MPa	Cure Time = 9-12 Hours

To create the samples with the FF core, a layer of epoxy was applied before each layer of carbon fiber was placed. Special care was taken to insure an adequate amount of epoxy was used in addition to being evenly spread out. After the four layers were placed, the vacuum bagging was carefully spread over the sample insuring no wrinkles would form when the vacuum was applied. Any wrinkles that form on the vacuum bagging will affect the surface finish of the sample. A roller and a rubber squeegee were used to remove the extra epoxy and trapped air.

The HH core samples required three steps to construct. The first step involved creating two carbon fiber sheets with three layers each. Next, a carbon fiber layer was placed on top of the three-layer, hardened carbon fiber sheet. After the epoxy was spread out, the hollow honeycomb was positioned on top. A foam pad was placed on top of the hollow honeycomb in order to prevent the vacuum from reaching the cavities. This prevented the epoxy pooling and carbon fiber lifting. The other side of the sample was constructed in the same way, but the foam pad was not required since the other attached carbon fiber sheet prevented the vacuum from causing the above problems.

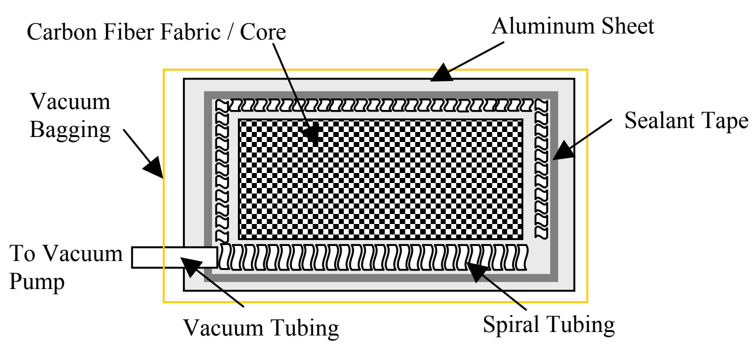

Figure 1. Sample construction setup

TEST METHOD

An Instron Dynatup drop tower, Model 9250HV, was used for impact testing. This machine is capable of impacting samples at energies of up to 826 J utilizing a spring-assist. For this study, all samples were impacted with a 7.35 kg drop weight. Since the drop weight was not changed, the different impact energies were achieved by adjusting the drop height. A pneumatic clamping fixture, with a 76.2 mm (3in) diameter opening, secured each sample during impact. The samples were impacted with a 12.2 mm (0.5in) diameter striker, constructed out of high strength steel. Impulse software was used in order to display and store the impact data.

The compression tests were conducted using a 50 kip MTS fatigue test system. The testing fixture was designed similar to a Boeing Model No. CU-CI fixture [4]. This fixture is specifically designed to prevent buckling when compression testing thin carbon fiber sheets. However, for this study, the supports designed to prevent buckling were not used because of the adequate sample thickness.

LOW VELOCITY IMPACT RESULTS

Foam Core

The maximum force developed by the foam core was 0.96 kN at impacts of both 10 J and 20 J (Fig. 2). The maximum absorbed energy was 17.7 J and occurred at an impact of 20 J (Fig. 3). The maximum force for the 25 J impact was about 15% below the 20 J impact. The difference between maximum forces resulted from the honeycomb structure. When the striker impacted the honeycomb structure, higher forces and more absorbed energy were developed. However, when the striker missed the honeycomb structure, it simply overcame a small shear stress and pushed out the foam. Another factor was how much of the honeycomb structure the striker hit at impact. As a result of the non-homogeneous nature of the foam core, the force and absorbed energy results included more variation when comparing samples impacted at the same energy. This variation was larger than other sample types, which were not as dependent on the honeycomb structure.

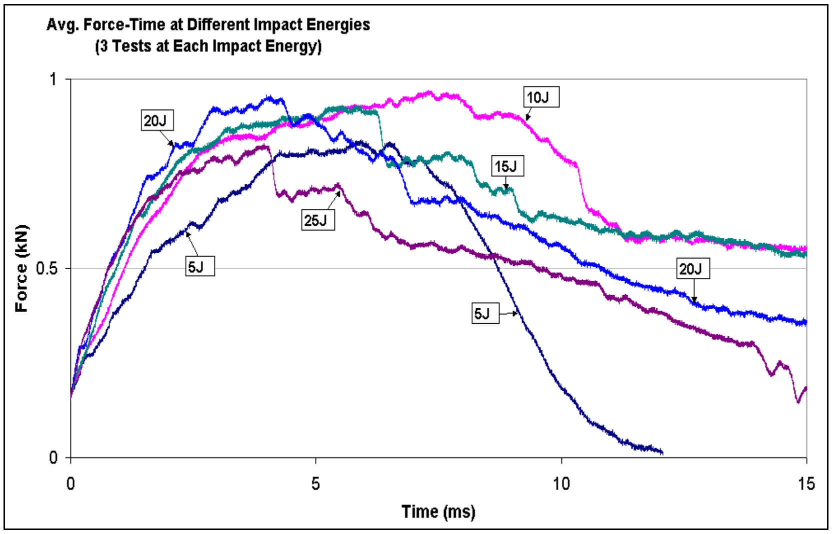

Figure 2. Force vs. Time response for foam core

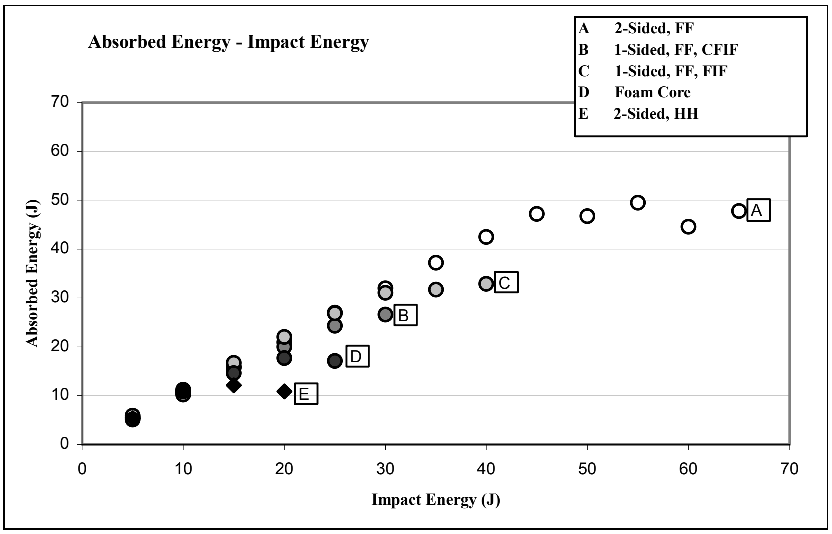

Figure 3. Absorbed vs. Impact Energy for all sample types

<u>1-Sided, FF, 4-Layer Carbon Fiber, Impacted Carbon Fiber First</u>

The maximum force developed by the 1-sided samples, carbon fiber impacted first (CFIF) was 1.65 kN at an impact of 30 J (Fig. 5). The maximum absorbed energy was 26.6 J and occurred at an impact of 30 J (Fig. 3). In general, the maximum forces for the 1-sided samples, CFIF, were very close. This could be a result of the similar damage areas seen at all impact energies. With this type of impact, the carbon fiber face sheet cracked in a circular manner that corresponded to the striker diameter as can be seen in Figure 4a. This cracking area was consistent for all impact energies and as a result limited the damage area from spreading. In addition, the samples did not experience any noticeable delamination. The added force required for delamination between the carbon fiber sheet and the foam core would have improved the impact properties.

a b c

Figure 4. a) Front impact damage of 1-sided, CFIF samples
b) Rear impact damage of 1-sided, FIF samples
c) Compression testing damage of 2-sided, FF samples

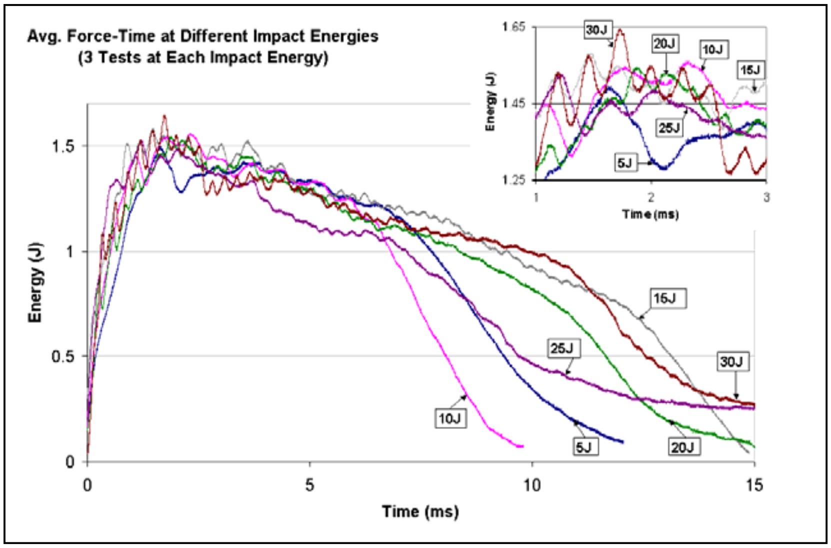

Figure 5. Force vs. Time response for 1-sided, FF, carbon fiber impacted first

1-Sided, FF, 4-Layer Carbon Fiber, Foam Impacted First

The maximum force developed by the 1-sided samples, foam impacted first (FIF), was 1.87 kN at an impact of 35 J (Fig. 6). The maximum absorbed energy was 32.9 J and occurred at an impact of 40 J (Fig. 3). There is a noticeable difference between the 1-sided samples FIF and those CFIF. The FIF samples achieved a maximum force 13% higher and an absorbed energy 24% higher than the CFIF samples. This significant improvement results from the larger damage area experienced by the FIF samples. As the striker penetrated the foam, the drop weight was slowed and the loading was spread over a larger area on the bottom carbon fiber sheet. Since the force was applied to a larger area, more energy was required to crack and delaminate the carbon fiber sheet. The damage area for the total penetration of the bottom carbon fiber sheet can be seen in Figure 4b. The delamination area cannot be seen very well, but typically had a radius between 20-30 mm.

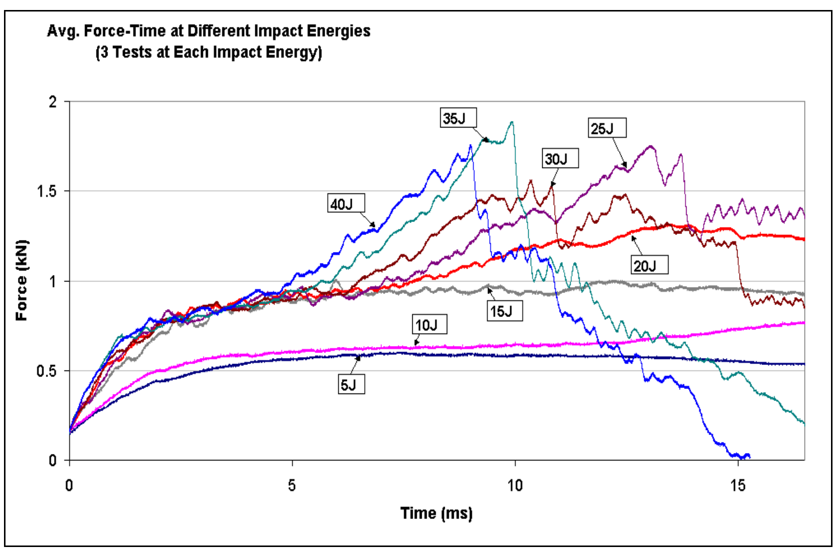

Figure 6. Force vs. Time response 1-sided, FF, foam impacted first

2-Sided, FF, 4-Layer Carbon Fiber (Both Sides)

The maximum force developed by the 2-sided samples with FF core was about 2.16 kN at an impact of 55 J (Fig. 8). This is the largest force reached by the carbon fiber sheets, exceeding the 1-sided carbon fiber samples, FIF and CFIF, by 15% and 31% respectively. The maximum absorbed energy peaked at 49.5 J, which occurred at an impact of 55 J (Fig. 3). This represents a 50% increase above the 1-sided samples, FIF, and an 86% increase above the 1-sided samples, CFIF. A visual inspection of the damage area for the top and bottom carbon fiber sheets illustrated a significant difference. The top sheet experienced cracking corresponding to the outside diameter of the striker. However, when the striker penetrated the bottom sheet, a larger damage area with delamination occurred. This delamination area had a consistent radius between 20-30 mm.

The damage area for the 2-sided, FF samples and the 1-sided, FIF samples were very similar, which is shown on Figure 4b. Three force curve groupings were illustrated when considering Figures 7 and 8. Figure 7 consists of the samples where the striker penetrated the top carbon fiber sheet and only slightly into the foam core, impacts 5-20 J, and significantly into the foam core, impacts 25-35 J. Figure 8 consists of the samples that penetrated the top carbon fiber sheet, the foam core, and either partially or fully penetrated the bottom carbon fiber sheet.

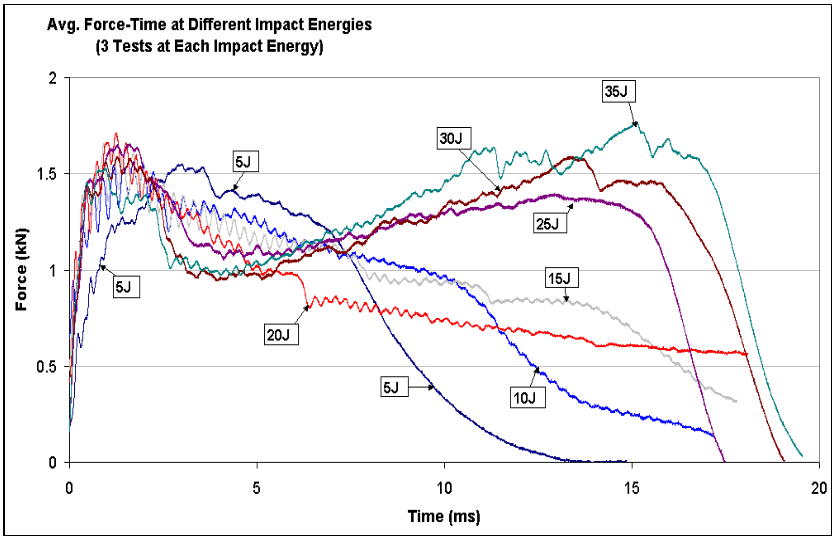

Figure 7. Force vs. Time response 2-sided, FF (Impact Energies 5-35J)

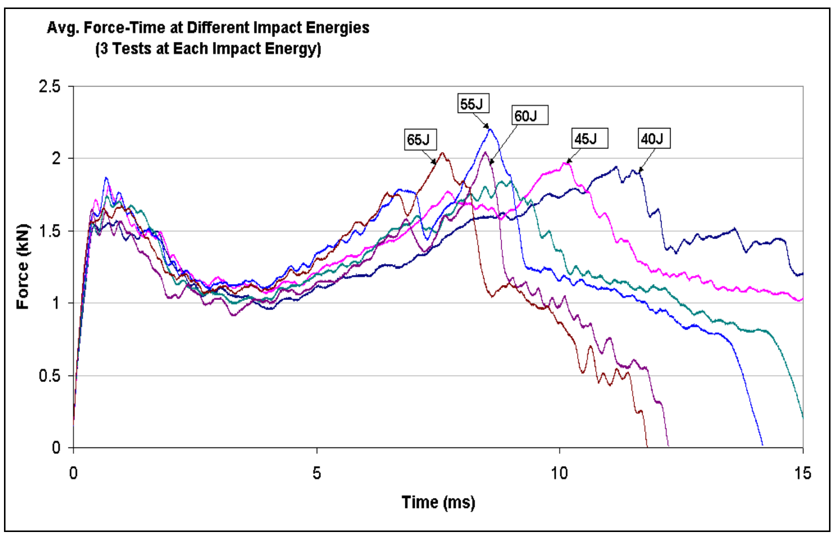

Figure 8. Force vs. Time response 2-sided, FF (Impact Energies 40-65J)

<u>2-Sided, HH, 4-Layer Carbon Fiber Each Side</u>

The maximum force developed by the 2-sided samples with a HH core was 1.04 kN at an impact of 15 J (Fig.9). The maximum absorbed energy was 12.1 J at an impact of 15 J (Fig.3). The maximum force was 49% lower and maximum absorbed energy 76% lower compared to the 2-sided FF samples. This is a significant reduction in impact properties and illustrates the effectiveness of using a FF instead of HH core. A reason for the significant reduction could be the loss of bonding area between the carbon fiber sheets and the core in addition to the minimal stiffness of the HH core. The loss of bonding area significantly reduced the force required for delamination to occur. The combination of these two factors probably accounted for most of the force and absorbed energy reduction. The damage done to the top carbon fiber sheets of both the 2-sided HH and FF sample types were very similar. However, a significant difference occurred between the two when the bottom carbon fiber sheet was penetrated. The bottom carbon fiber sheet of the 2-sided HH samples experienced cracking at a radius only slightly larger than the top sheet, while the bottom carbon fiber sheet of the 2-sided FF samples had about twice the cracking radius and experienced delamination.

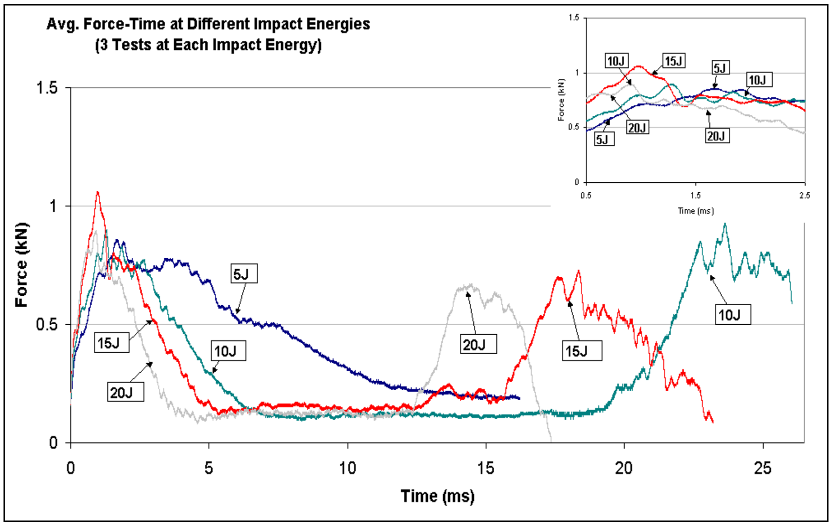

Figure 9. Force vs. Time response for 2-sided, HH

COMPRESSION TEST RESULTS

The maximum compressive stress, defined as compressive stress to failure, for the different sample types is shown on Figure 10. As can be seen, most samples followed a trend of decreasing compressive strength as impact energy increased. However, the maximum compressive strength was significantly affected depending on the type of failure that occurred. The 1-sided samples failed either by buckling, face sheet delamination, or face sheet cracking. The face sheet cracking occurred from the impact hole across the sample, perpendicular to the compressive load, as can be seen in Figure 4c. The 1-sided samples, FIF, had a maximum compressive strength of 7.4 MPa at an impact of 15 J. This represents a 40% increase over the same sample type not impacted at all. This difference resulted from the sample impacted at 15 J buckling at loadings much higher than required to buckle the non-impacted samples. This could be a result of slight eccentricities occurring when the compressive loading was applied. However, a significant difference was seen when considering the samples not impacted and those impacted at energies that caused failure, defined as total striker penetration. Table 1 represents the percentage decrease in maximum compressive strength of samples impacted at energies that caused failure compared to non-impacted samples.

Table 1. Percent decrease in compressive strength

SAMPLE TYPE	% Decrease
2-Sided, FF	53
1-Sided, FF, CFIF	29
1-Sided, FF, FIF	66
Foam Core	12
2-Sided, HH	33

The overall affect of impact on compressive strength is significant for the different sample types. The greatest decrease in compressive strength due to impact occurred by the FF samples that experienced delamination. These samples included those where a carbon fiber sheet was the last layer impacted. This consisted of the 2-sided, FF and the 1-sided samples, FIF. When the compressive load was applied to these samples, the delamination originally caused by impact quickly spread. This additional delamination eventually caused buckling at relatively low compressive loads compared to non-impacted samples.

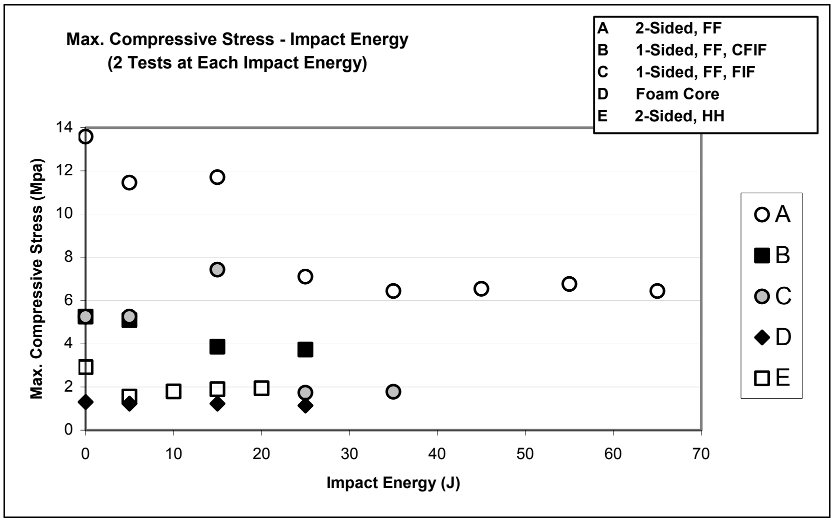

Figure 10. Max. Compressive Stress vs. Impact Energy

CONCLUSION
The information obtained from the impact and compression after impact tests was used to identify trends and make comparisons. Significant differences in impact properties occurred for the different sample types. The 2-sided, FF samples performed the best considering both impact and compression after impact testing. These samples were able to absorb a maximum of 49.5 J and withstand a compressive stress above 6 MPa, even after being impacted at energies that caused complete striker penetration. These values are significantly higher than all other samples types. The maximum compressive strength, comparing samples that experienced complete striker penetration, was over 70% higher than the 1-sided samples, CFIF, and over 250% higher than the 1-sided samples, FIF. The maximum absorbed energy was 49% higher than the 1-sided samples, CFIF, and 86% higher than the 1-sided samples, FIF. The low compressive strength for the 1-sided samples, FIF, resulted from buckling, which occurred at reduced compressive loads due to the delamination of the carbon fiber face sheet during impact. The 2-sided, HH samples performed considerably worse than the 2-sided, FF samples and both 1-sided sample impact types. The significant reduction in impact properties was primarily due to the poor stiffness and small bonding area.

ACKNOWLEDGEMENTS
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REFERENCES
[1] Vaidya, U.K., Impact response of integrated hollow core sandwich composite panels, *Composites-Part A,* 31, 761-772, 2000.
[2] Lee, Ming Lee, Instrumented impact and static indentation of composites, *Composite Materials*, 25, 204-222, 1991.
[3] Abrate, S., Impact on laminate composites: recent advances, Applied Mechanics Review, 47(11), 517-544, 1998.
[4] *Boeing Compression After Impact Test Fixture*. Wyoming Test Fixture Inc. <http://www.wyomingtestfixtures.com/Products/page26-27.htm>.