The Effects of Off-Axis Loading on the Compression After Impact Strength of Quasi-Isotropic Face Sheet Honeycomb Core Sandwich Structure

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Abstract

This study presents experimental results of compression after impact (CAI) testing of aluminum honeycomb core sandwich structure with face sheets made of co-cured T1100/3960 quasi-isotropic carbon/epoxy when tested at +22.5º and -22.5º with respect to the 0º fibers. In a previous study examining the CAI strengths of honeycomb sandwich structure [1], it was found that specimens had different CAI strengths, based on a [-45/90/+45/0]s layup, depending on whether they were tested in the 0º direction (face sheet layup of [-45/90/+45/0]s) or 90º direction (face sheet layup of [+45/0/-45/90]s). The CAI strength results showed that the specimens tested in the 90º direction had a 19% drop in CAI strength compared to specimens tested in the 0º direction. This was attributed to the 0º load bearing plies in the 0º direction specimens being "tucked in" at the center of the specimen thus providing more stability against microbuckling. This raised the question as to what CAI strength would specimens tested at +22.5º (face sheet layup of [-22.5/-67.5/+67.6/+22.5]s) and -22.5º (face sheet layup of [-67.5/+67.5/+22.5/-22.5]s) have compared to specimens tested in the 0º and 90º direction. Results presented in this study show that the specimens loaded at +22.5º and -22.5º have a similar average CAI strength compared to the specimens loaded in the 0º direction. The specimens loaded in the 90º direction exhibit 16% lower average CAI strength. Additional specimens were tested in the +45º direction to put the 0º load bearing fibers on the outside of the specimen to see if this would decrease the strength as has been documented for undamaged strength. These specimens have average CAI strength values between the 0º direction average CAI strength values and the 90º direction average CAI strength values.

Key Words: sandwich structure, damage tolerance, compression after impact (CAI) strength, co-cure, off axis loading, quasi-isotropic stacking sequence

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Introduction

During a program examining what material and layup to use to manufacture a payload adapter fitting (PAF) for NASA's Space Launch System (SLS) rocket, compression-after-impact (CAI) tests were performed on specimens cut from a large aluminum honeycomb sandwich structure with T1100/3960 carbon/epoxy quasi-isotropic face sheets [1]. During this testing, some specimens were cut in both the 0º and 90º directions to give two different layup sequences of a quasi-isotropic laminate. In theory the results should have been the same (as long as the rotation did not cause the outermost plies of the face sheet to be oriented parallel to the loading direction [2]). Some of the specimens in [1] were tested with the W-direction of the core oriented in the compressive loading direction with the face sheets having a lay-up of [+45/0/-45/90]s where the 0° plies were orientated in the loading direction. Thus a 90° rotation gave specimens tested with the L-direction of the core in the loading direction and the face sheets having a lay-up of [-45/90/+45/0]s where the 0° plies were oriented in the loading direction. For a given level of impact damage severity the specimens loaded in the core L-direction had significantly higher CAI strength values. In a previous study [3] it was determined that the orientation of the core was not a factor in the CAI strength results, thus

it appeared to be the face sheet layup with respect to the loading direction that was the factor causing the different CAI strength results.

Since it has been shown that undamaged QI laminates have the same undamaged compression strength when tested at 22.5º to the 0º fibers [4], it was surmised that the location of the 0° plies *coupled with a stress concentration* was most likely responsible as confirmed by the results of other researchers [5] involving quasi-isotropic laminates. Thus, while undamaged compression strength values of quasi-isotropic laminates are essentially independent of direction of loading, when a stress concentration is present, the compression strength appears to be dependent on the direction of loading.

The PAF is a conical structure that is made of 8 lobes joined together, thus the loading direction with respect to the load bearing 0º fibers will not be constant across an entire lobe as sketched in Figure 1. It was of interest to see what CAI strength would result if the specimens where cut from the quasi-isotropic panel at angles of +22.5º (face sheet layup of [-22.5/-67.5/+67.6/+22.5]s) and -22.5º (face sheet layup of [-67.5/+67.5/+22.5/-22.5]s). Angles of ±22.5º were chosen as they are midway between any of the ply angles which are 45º apart.
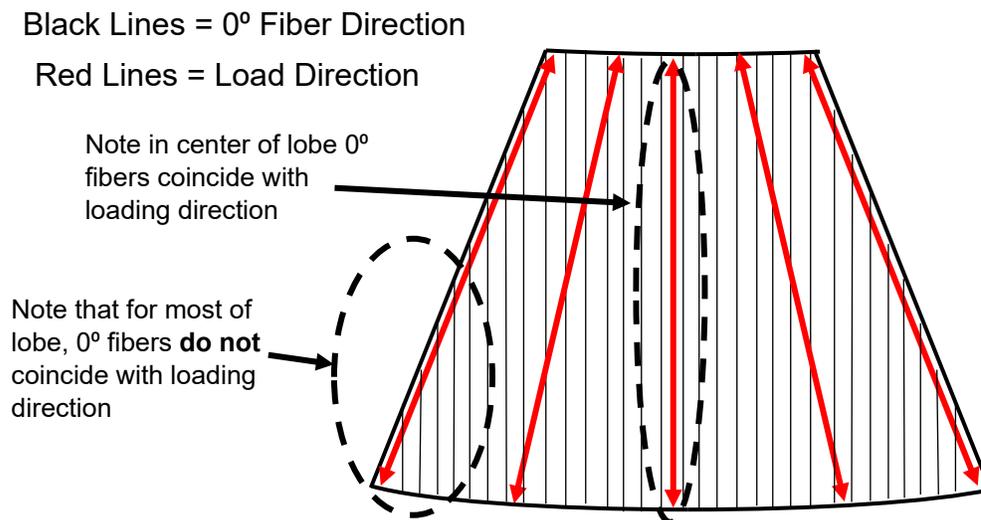
Figure 1. Schematic of "off-axis" loading on lobe of the PAF structure.

Note that for most of the lobe that the load direction does not coincide with the 0° fiber direction.

For the off-axis specimens used in this study, the main load bearing plies are at $\pm 22.5^\circ$. It was expected that the -22.5° specimens would have a higher CAI strength since the four load bearing plies were "tucked in" at the center of the specimen analogous to the results in [1] in which the 0° load bearing plies being "tucked-in" to the center of the specimens was deemed responsible for the higher strength. In addition, the $+22.5^\circ$ specimens had a load bearing ply on the outer surface which has been shown to be detrimental to the undamaged compression strength of a laminate [2]. A load bearing $+22.5^\circ$ ply is nearest to the honeycomb core and thus has the most ply waviness, however, this ply waviness has been shown not to affect the CAI strength of co-cured sandwich structure compared to pre-cured face sheets [1] for similar sandwich structure.

Experimental details

Materials

The carbon/epoxy face sheet material used to manufacture the sandwich specimens in this study was T1100/3960 since this is the fiber/resin system chosen for the PAF structure. The sandwich structure was manufactured by co-curing the face sheets to aluminum honeycomb core with a density of 72 kg/m^3, cell size of 3.175 mm and thickness of 2.54 cm. The sandwich structure had a layer of FM300-2M epoxy film adhesive placed over the core prior to the automated tape laying process used to manufacture the face sheets. All sandwich structure was cured in an autoclave with a pressure of 276 kPa and a temperature of 177°C. The flat sandwich panel made for use in this study was 61 cm by 122 cm in size.

The layup sequence for the face sheets was 8-ply [-45/90/+45/0]s quasi-isotropic. The honeycomb sandwich structure was manufactured with the core L- direction aligning with the 0° fiber direction. The large panel could be cut into specimens to be tested in the 0°, 90°, +22.5º and -22.5º directions to give a total of 4 types of QI specimens. These 4 specimens will be designated as 0º QI, 90º QI, +22.5º QI and -22.5º QI.

The sandwich structure showed good consolidation except at the plies closest to the core which did contain some porosity. This porosity was measured to be about 1.8% of the laminate volume. Typical fiber waviness of plies closest to the core that is characteristic of co-cured honeycomb structure was noted. Figure 1 shows cross-sectional photomicrographs (cut parallel to the loading direction) of the four types of specimens. 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 the first photograph in figure 1. A nominal value for the face sheet thickness was 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 thickness of the sandwich structure tested was measured and was found to be 1.27 mm.

The sandwich structure was cut into 15.2 cm tall (direction of loading) by 10.2 cm wide specimens using a diamond saw. The top and bottom edges of these specimens were then machined to ±0.0025 mm 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.
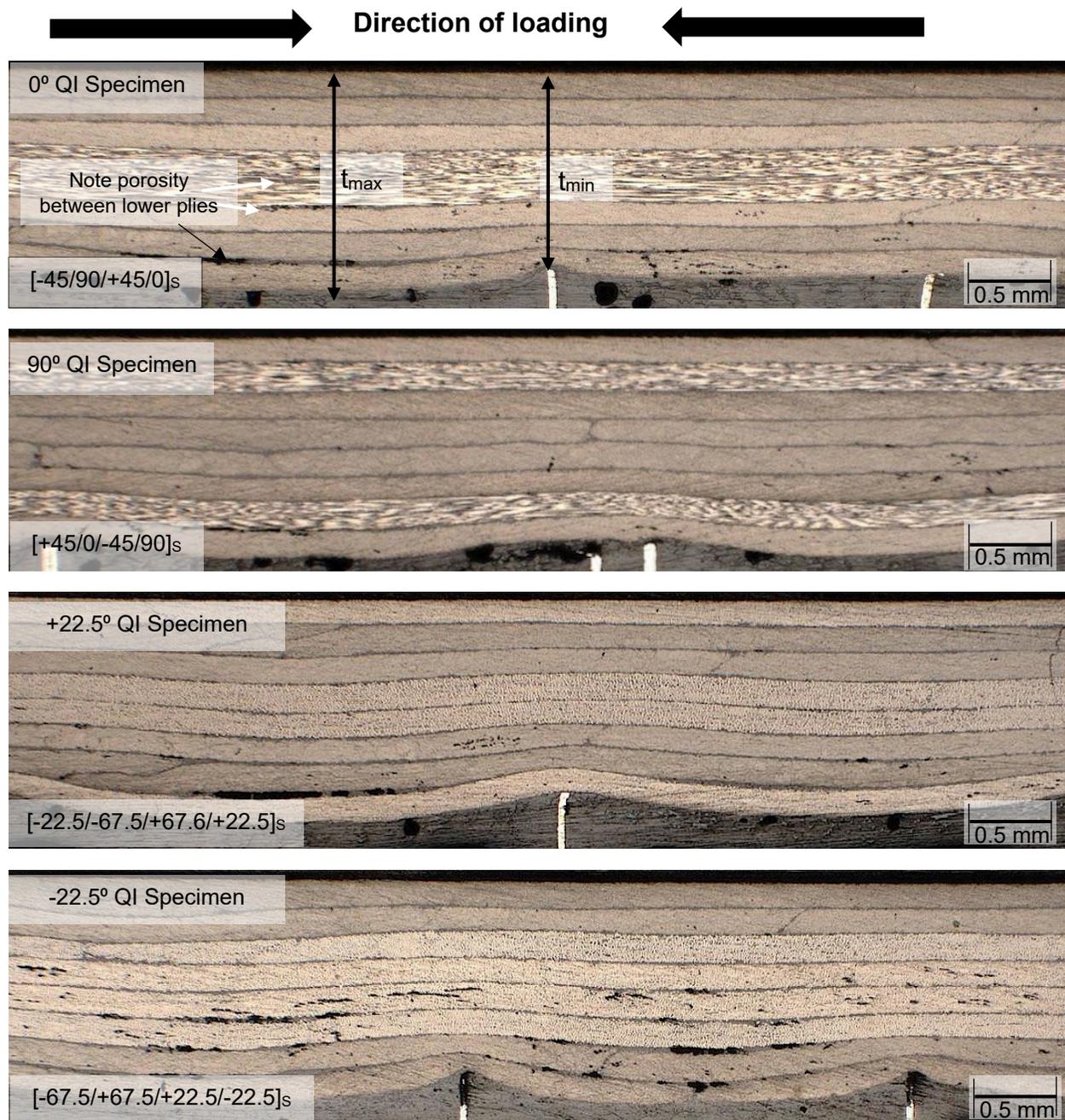
Figure 1. Cross section photomicrographs of the 4 types of quasi-isotropic specimens tested in this study.

Impact Damage Testing

Each sandwich specimen was impacted at its geometric center on the tool side face sheet although there was very little difference in the two face sheets since a caul plate was used on the

bag side of the sandwich panel during fabrication. The tool side will be on the outer surface of the PAF structure and thus more prone to impact damage. The impactor had a diameter of 12.7 mm 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. This also ensured similar boundary conditions for all impacts. The impact energy (14.1 J) was selected based on what used in a previous study [1].

An example of the visual damage that was formed is shown in figure 2. Note that the aluminum honeycomb that crushes under the impact location tends to "hold" a dent approximately 30 mm in diameter around the impact location. A central damaged region of crushed fibers is seen at the impact location and has a diameter of approximately 7 mm.
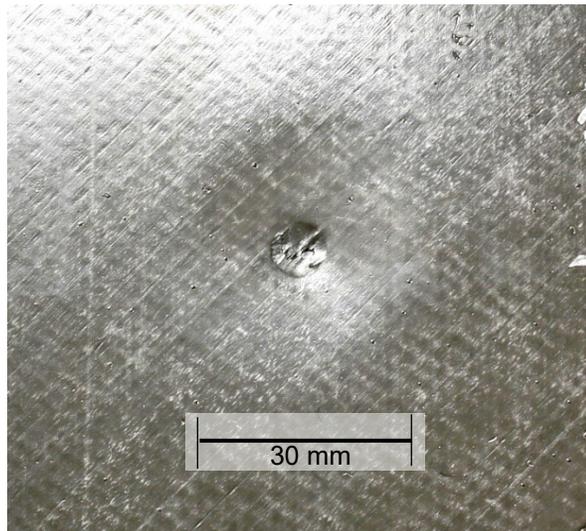
Figure 2. Visual damage of a 14.1 J impact with a 12.7 mm diameter impactor on the sandwich structure used in this study.

Non-destructive evaluation (NDE) in the form of flash thermography was performed on the impacted specimens and a sample signature from a 0⁰ QI specimen is presented in figure 3.

Flash thermography was chosen since this is the type of NDE that will be used as the part goes through its life from fabrication to launch. The shape of the damage zone is peanut shaped and at about a 60° angle to the 0° fibers of a 0° QI specimen.
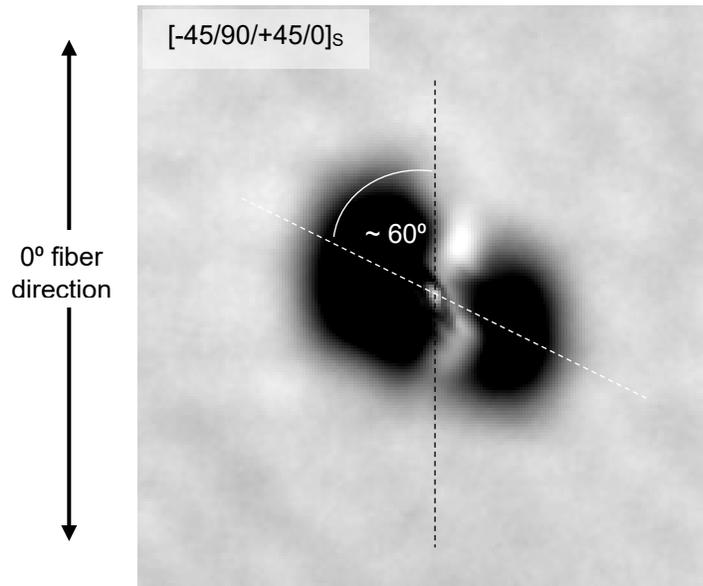
Figure 3. Thermography signature of a 14.1 J impact on honeycomb core sandwich structure tested in this study.

The typical through thickness damage (which cannot be ascertained from the thermography results) can be seen in the cross-section shown in figure 4 which was sectioned through the center of the damage zone. This photomicrograph is included to give the reader an idea of the amount of through thickness damage caused by the impacts in this study.

5 mm
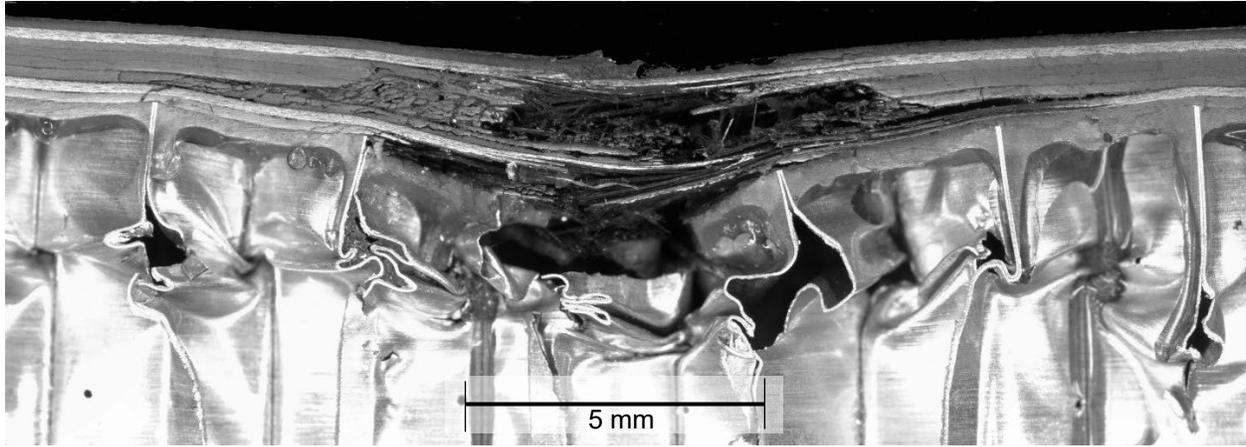
Figure 4. Cross-section of damage on an impacted specimen used in this study (This example specimen is a 90º QI cut in the loading direction).

Compression After Impact Testing

The impacted sandwich specimens were assessed for residual compression strength using the test fixture shown in figure 5. Three strain gages were placed on the specimen to ensure even loading of each of the face sheets. Two gages on the impact side were to ensure even loading across the specimen width and one gage on the opposite side to monitor for even loading across the specimen thickness. The specimens were taken to approximately 1000 microstrain compression 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 average CAI strength results (with +1 and -1 standard deviation) are presented in table 1.
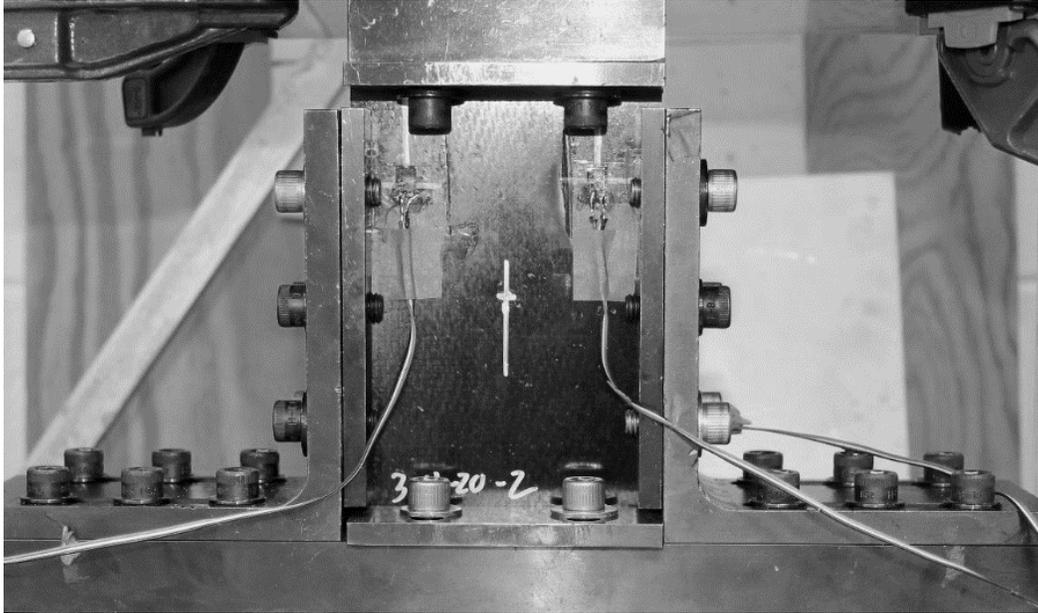
Figure 5. Photograph of fixture used for assessing CAI strength of sandwich specimens.

Table 1. Summary of average CAI strength results of the sandwich specimens tested in this study (with +1 and -1 standard deviation)

| Specimen Type	Impact Energy (J)	Specimens tested	Average CAI Strength ± S.D. (ksi)
0º QI	14.1	5	382 ± 14
90º QI	14.1	7	321 ± 21
+22.5º QI	14.1	5	386 ± 14
-22.5º QI	14.1	5	391 ± 9

The average CAI strength results indicate that only the 90º QI specimen had a notable difference in average strength with an average CAI strength value 16% lower than the 0º QI specimens. This is consistent with the results found in [1].

The +22.5º QI and -22.5º QI CAI specimens had essentially the same average CAI strength results which negates the assumption that the -22.5º QI specimens would have a higher average CAI strength value since all four load bearing plies were "tucked into" the center of the face sheet.

Compression After Impact Testing of +45⁰ QI Specimens

As a check to see if 0° load bearing fibers on the outer surface of an impact damaged compressively loaded specimen would give lower results than if the load bearing fibers were not on the surface (as found in [2] for undamaged specimens), specimens were cut at $+45^{\circ}$ to give a layup of $[0/-45/90/+45]$s. These $+45^{\circ}$ QI specimens were impacted and tested for residual compression strength just as the other specimens in this study.

Figure 6 shows a cross-sectional photomicrograph (cut parallel to the loading direction) of a $+45^{\circ}$ QI specimen. The 0° load bearing fibers can be seen at the outer surface and at the ply closest to the core.
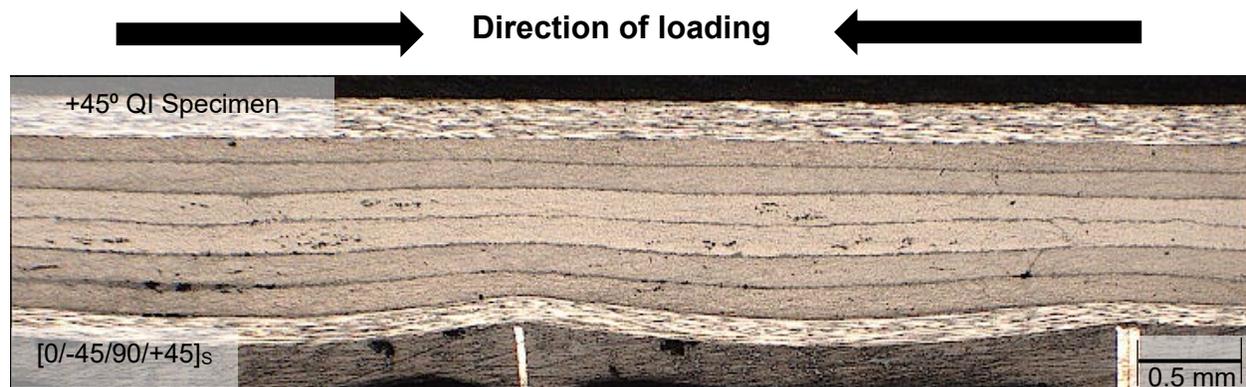
Figure 6. Cross section photomicrograph of a +45⁰ QI specimen tested in this study.

Four $+45^{\circ}$ QI specimens were tested for CAI strength and the average value was found to be 349 ± 7 MPa.

A graphic representation of the average CAI strength results of all the types of specimens tested (with +1 and -1 standard deviation) are given in figure 7.
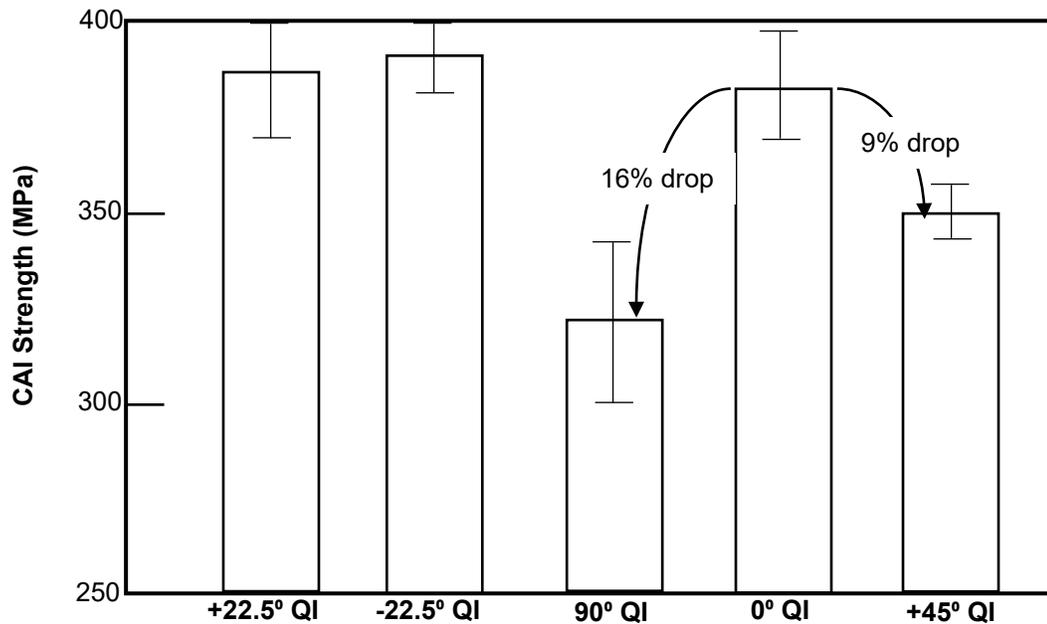
Figure 7. Graphic representation of average CAI strength results obtained in this study 9with +1 and -1 standard deviation bars)

The average CAI strength of honeycomb core sandwich structure with quasi-isotropic face sheets with a layup of [-45/90/+45/0]s (90º QI specimens) is notably different (16% lower) as noted earlier. When rotated at angles of +22.5º or -22.5º, there is no notable change in average CAI strength from the 0º QI specimens. Interestingly the -22.5º QI specimens did not have a higher average CAI strength than the +22.5º QI specimens even though all 4 load bearing plies were "tucked into" the middle of the laminate. It was theorized in [1] that tucking load bearing plies into the middle of a stacking sequence would give the highest CAI values, but this was not true in this case and perhaps only holds if the load bearing plies are 0º plies (fibers in direction of loading).

The most surprising result in this study was the specimens with 0º plies on the outside surface of the specimen (+45º QI) had an average CAI strength only 9% lower than 0º QI

specimens, but *9% higher* than the 90º QI specimens which had a +45º ply covering the 0º ply to help stabilize the fibers. According to results from [2] it was assumed that the +45º QI specimens should have had a lower value than the 90º QI specimens, but this was not the case in this study. More testing of +45º QI and 90º QI specimens need to be conducted to ascertain the physical reason for this.

Conclusions

Based on the results of this study, it appears that the PAF (and similar type of QI face sheet) sandwich structure(s) will have essentially the same CAI strength regardless of the region where the damage occurs if the rotation of the center load bearing 0º fibers does not exceed ±22.5º.

The reasons why the +22.5º QI and -22.5º QI specimens had similar strengths when it was thought that the -22.5º QI specimen should have been higher since all 4 load bearing plies were at the center of the face sheet layup is unknown and needs further study.

From the data in this study, a conservative estimate of the CAI strength of sandwich structure can be found using the CAI strength value of a 90º QI specimen (lay-up of [+45/0/-45/90]s).

It should be noted that the severity of impact in this study was rather severe and perhaps a smaller impact energy level would produce different results. In addition, the material used in this study is much more damage tolerant than "typical" toughened fiber/resin systems such as IM7/8552 [6].

References

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