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ABSTRACT

A payload adaptor fitting (PAF) structure has been manufactured at NASA's Marshall Space Flight Center (MSFC). The PAF structure is essentially a large cone made of carbon/epoxy sandwich structure. The PAF structure contains numerous (about 1000) holes at the top and bottom to secure the carbon/epoxy structure in aluminum rings with bolts. In an effort to obtain higher quality holes, both sides of the PAF structure are covered with an additional, non-structural, ply of woven carbon/epoxy placed at ±45° to the vertical direction. This study evaluated the quality of the holes on sandwich structure both with and without the outer woven carbon/epoxy plies via open hole compression (OHC) strength testing. Results showed a 14% increase in strength of the cloth covered sandwich structure, which did not surpass the 18% added weight due to the outer woven plies.

1.0 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 to form the cone. The lobes are sandwich structure made with aluminum honeycomb core and carbon/epoxy face sheets. The lobes will be inserted into metallic rings at the top and bottom of the cone to form the full cone. The honeycomb structure that makes up the acreage of the PAF structure closes out and the face sheets taper to a solid thick laminate at the top and bottom to enhance bearing strength. Both front and back exterior surfaces of each lobe have a plain weave fabric placed at ±45° to the vertical direction to help prevent laminate damage during drilling and machining (i.e. trimming the lobes to final size). These extra plies of woven fabric add extra weight to the structure and a balance between enhanced compression properties (the PAF structure experiences predominantly compressive loads) due to higher quality holes and added mass needs to be assessed.

The many holes (nearly 10000 total) drilled in the PAF structure are at the top and bottom of the lobes to attach to metallic rings to form the large cone. Thus, placing the woven fabric across the entire acreage of the structure, rather than only at the solid laminate at the ends is questionable since the drilled holes are only at the top and bottom of the PAF structure. Since bearing loads have been shown not to be sensitive to hole quality [1-6] in carbon/epoxy in which the bolts are lightly torqued, the use of woven fabric for suppressing drilling damage is debatable.

If a hole or cutout does need to be machined for purposes other than bolt bearing loads, then the quality of the hole may matter. One study found that high feed rates when drilling caused more delamination around the perimeter of the hole resulting in lower open hole compression (OHC) strength values for the laminate [7]. Two studies found a 9% reduction in OHC strength due to delaminations around a hole in carbon/epoxy laminates [5,8]. Similar results were found in [9]. One study using two drilling methods, one of which produced holes with more damage, found no statistical difference in OHC strength values [10].

The experimental study presented in this paper will examine the quality of holes drilled in aluminum honeycomb carbon/epoxy face sheet sandwich structure both with and without an outer layer of woven fabric. The effects of hole quality will be assessed by loading the specimens in compression until failure. An assessment will then be made of the value of adding the woven fabric based on the added weight.

2.0 MATERIALS

The sandwich structure used in this study was manufactured by co-curing T1100/3690 carbon/epoxy face sheets to aluminum honeycomb core. Two panels were manufactured: one with face sheets manufactured from unidirectional tape (192 gsm, 33.5% resin content) and one manufactured with the same unidirectional tape and an outer ply (on both face sheets) of a plain weave carbon epoxy (196 gsm, 35% resin content). The core was 0.625 inches thick and had a density of 4.5 lb/ft^3. All the face sheets (except for the outer woven plies which were laid up by hand) were manufactured by automatic fiber placement (AFP) at NASA's MSFC. The honeycomb sandwich structure was manufactured with the core ribbon ("L") direction aligning with the 0° fiber direction for the specimens with the woven plies on the outside. The honeycomb core was inadvertently rotated 90º for the specimens without the woven plies on the outside. This was deemed not to be a problem since it has been shown that the direction of the core has little to no effect on the notched compression strength of sandwich structure [11].

The specimens with a layer of woven fabric on the outer surfaces of the face sheets had a lay-up of $[\pm45_f/+45/0/-45/0/-45/0/+45]_T$. The outer ply of fabric was a plain weave carbon/epoxy 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 lobe. Another ply of the plain weave was placed on the inner surface of the lobe (bag side) before bagging and cure. The sandwich structure had a layer of FM209-1M epoxy film adhesive placed between the core and face sheet during the automated tape laying process used to manufacture the face sheets. The specimens with no woven ply material on the outer surfaces had the same lay-up as the ones with the woven ply minus the ±45º cloth outer plies. A schematic of the two types of honeycomb structure used in this study are shown in figure 1.

For both types of specimens, 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 inches by 48 inches 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 (as is characteristic of co-cured honeycomb sandwich structure). 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 with the woven ply was found to be 0.050 inches and the thickness of the face sheets without the woven ply was 0.044 inches.

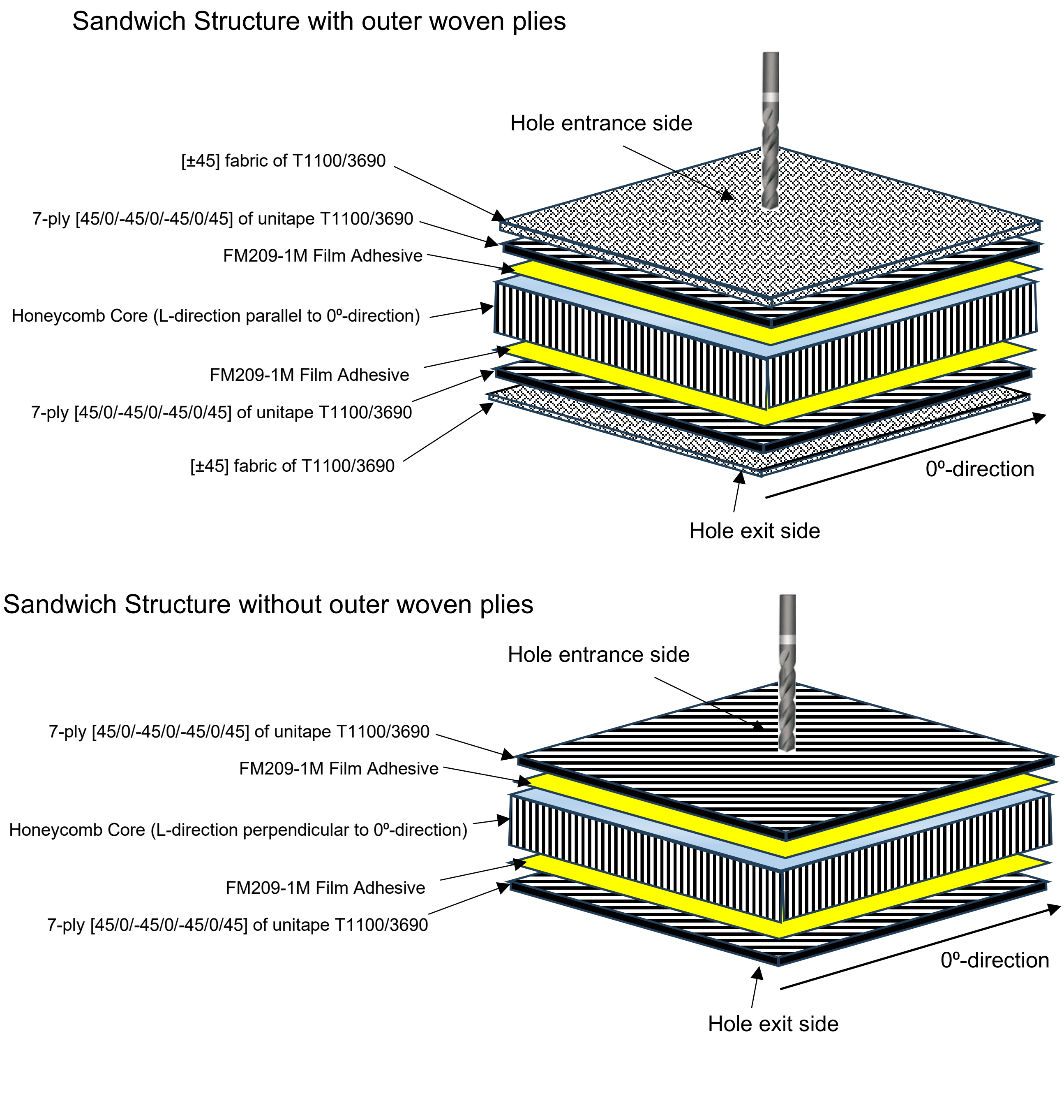
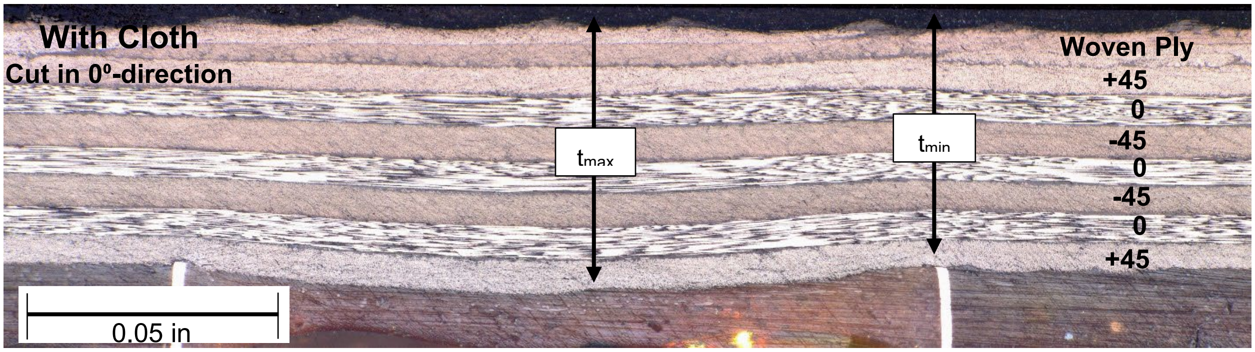


Figure 1. Schematic of the two types of sandwich structure used in this study.



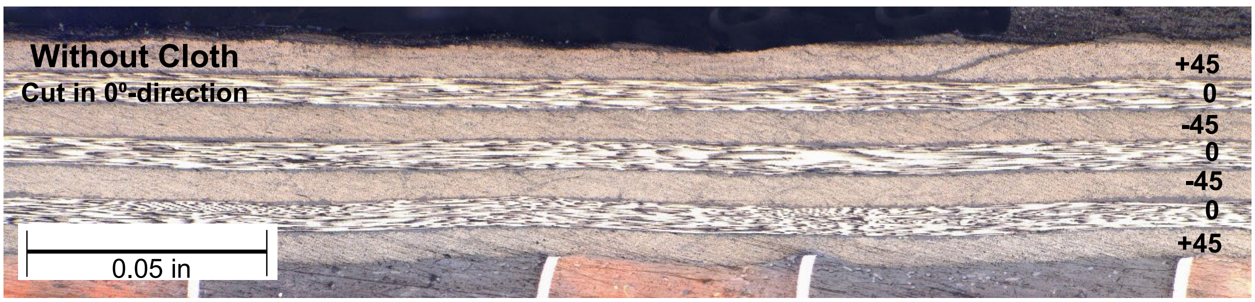
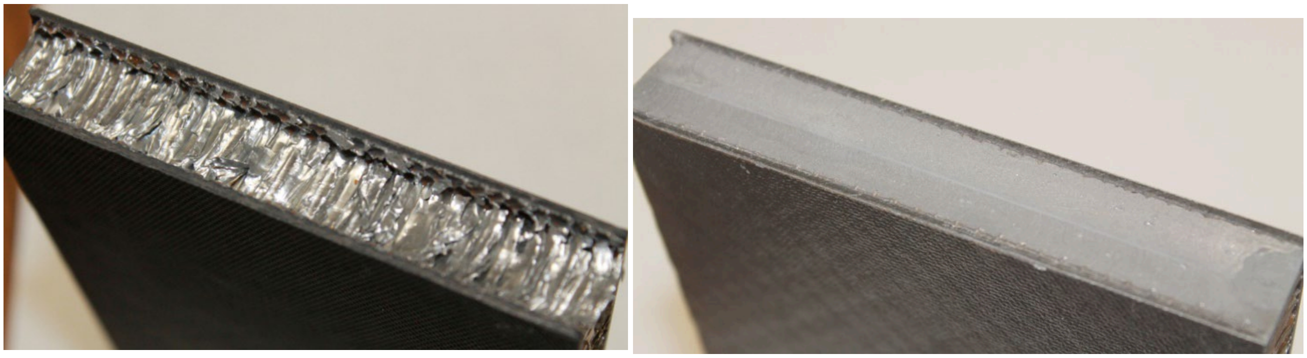


Figure 2. Cross section photomicrographs of specimen face sheets with and without outer ply of woven cloth.

The panels were weighed and the areal weight of the sandwich structure with the woven cloth was found to be 0.0106 lb/in^2 and the areal weight of the sandwich structure without woven cloth was found to be 0.0090 lb/in^2. Thus, adding the outer plies of woven fabric to the sandwich structure adds about 18% more weight.

The two 24 × 48-inch sandwich panels were cut into 6 inch tall (direction of loading) by 4 inch wide specimens using a diamond saw. The specimens were cut such that the loading direction was parallel to the 0º fibers.

For all specimens the ends needed to be "potted" to prevent end brooming during the compression tests that were to be performed. This was accomplished by crushing the core about ¼ inch deep across the top and bottom of the specimen and filling these "channels" with paste epoxy resin as shown in figure 3.



Core crushed at end to create channel

Channel filled with epoxy

Figure 3. Picture of epoxy placed at end of sandwich specimen to prevent end brooming.

Once the epoxy had cured, the top and bottom edges of these specimens were machined to ±0.001-inch 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.

3.0 DRILLING OF HOLES

Each sandwich specimen had a 0.2520-inch diameter hole drilled completely through the specimen at its geometric center. The holes were made by first drilling through the specimen with a 15/64-inch brad point twist drill (solid carbide, uncoated, two flute, 25° helix with 140° brad point). This was then followed by reaming the hole with a .2520-inch reamer (solid carbide, uncoated, straight flute, 45° lead). This drilling methodology was used since this was what was used on the PAF hardware. The side of the specimen where the drill bit entered will be referred to as the "entrance" side and the side where the drill bit exited will be referred to as the "exit" side (as shown schematically in figure 1). The hole drilling was alternated between the two types of specimens so one type of specimen would not have holes drilled with a newer drill bit than the other. No backing plate was used on the exit side of the specimens since the inside of the cone could not (easily) have a backing mechanism during drilling operations.

A picture of the drill bit and reamer used is shown in figure 4.

Figure 4. Photograph of drill bit (left) and reamer (right) used to make holes in the specimens.

Photographs of the drill bit entrance and exit sides of holes in the woven fabric ply covered specimens and “bare” (no outer fabric ply) specimens are shown in figure 5. Hereon the specimens with **no** woven ply will be referred to as “bare” specimens and those **with** the woven cloth on the outer surfaces will be referred to as “covered” specimens. In general, more damage appeared on the exit side of the bare specimens than the covered ones. Slightly more damage appears on the entrance side for the bare specimens. Note the weave pattern on the photographs of the specimens in figure 5. This is the “mark off” or imprint of the peel ply and not the outer ply of woven fabric (which cannot be seen in these pictures). Figure 5 shows the direction of compression loading and notes that the highest stresses due to the hole are at the edge of the hole parallel to the direction of loading.

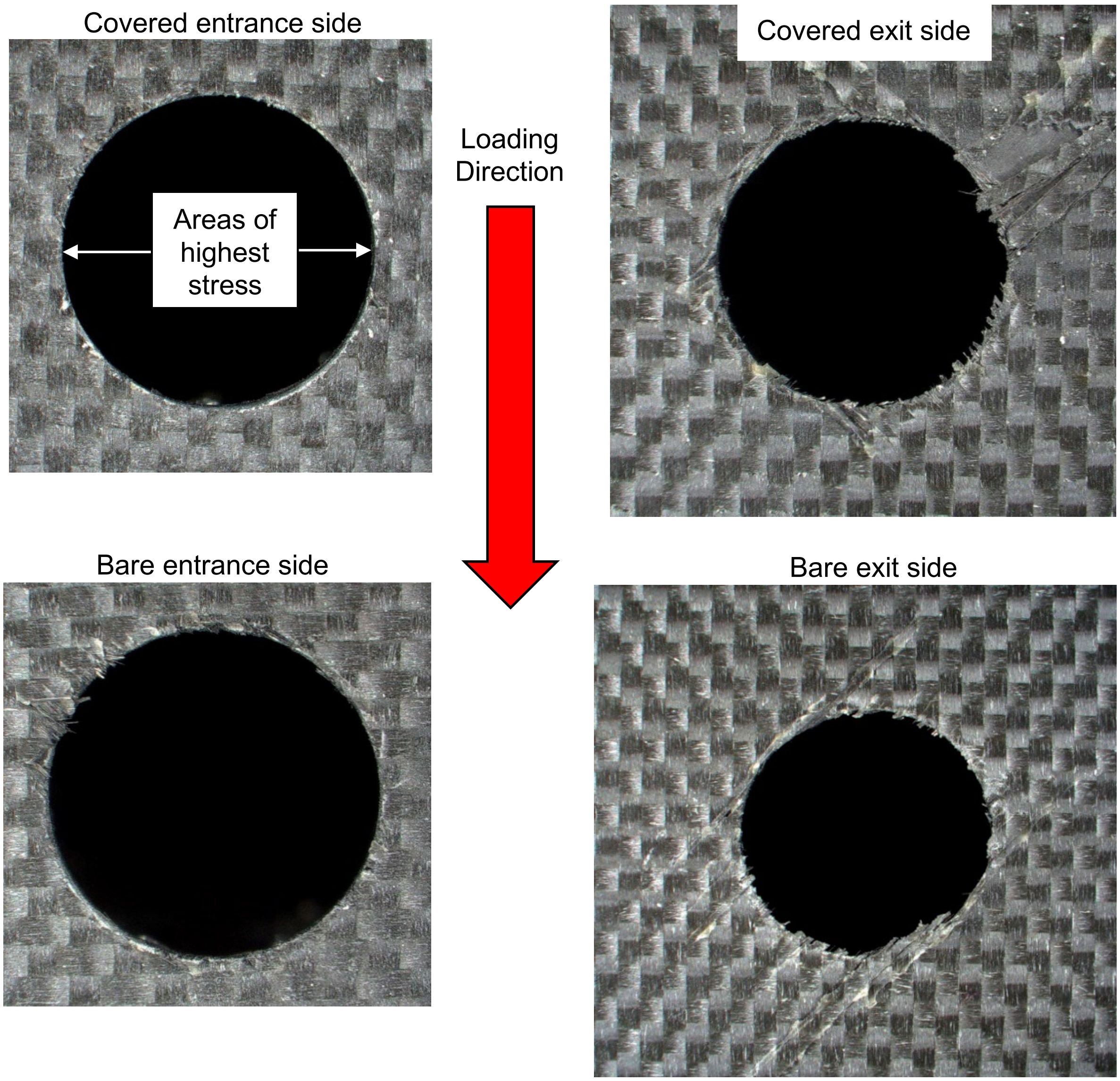


Figure 5. Photographs of the entrance and exit sides of holes drilled through the two types of sandwich structure. Visible weave pattern is mark off from peel ply, **not** the woven cloth layer.

3.1 Cross-Sectional Microscopy

To ascertain the quality of the holes and any difference between them in bare specimens versus the covered ones, some of the specimens were cross-sectioned though the holes at the area of highest stress and examined edge-on for damage at the edge of the hole. A schematic of a sectioned hole in a face sheet (honeycomb and bottom face sheet not shown) and the area being examined (dashed lines) for a cut in the 90º direction is shown in figure 6. Figure 7 shows the location of the cut and area to be examined made for a cut in the 0º direction.

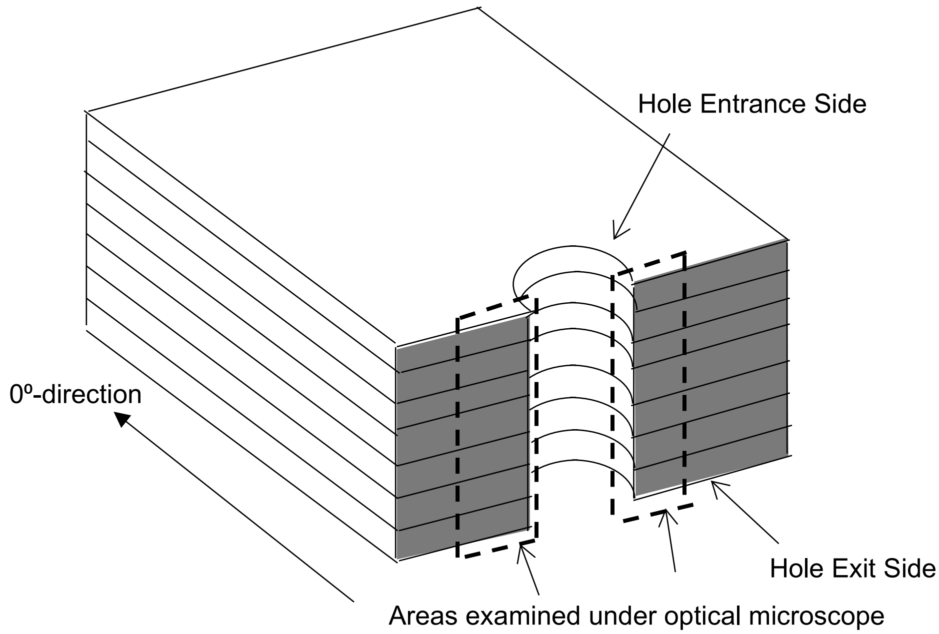


Figure 6. Schematic of area of observation of cross-sectioned hole in face sheet. 90º cut.

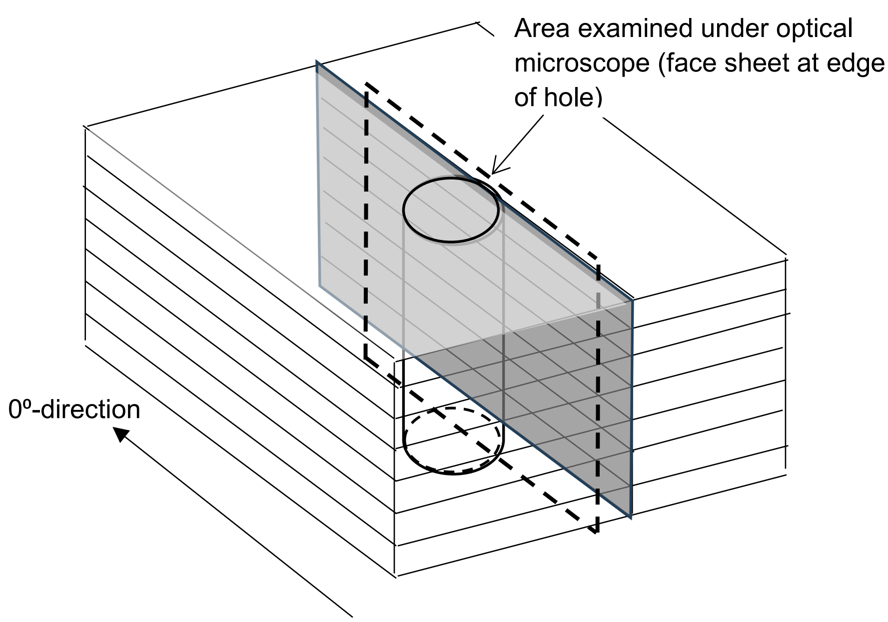


Figure 7. Schematic of area of observation of cross-sectioned hole in face sheet. 0º cut.

The cut edge to be examined was made by excising the hole from a 6-inch by 4-inch specimen in the form of a 1-inch by 2-inch section. The final cut at the hole was made by using a diamond blade wafering saw as shown in figure 8. Examples of the flaws at the edge of the holes as ascertained by microscopy are shown in figure 9 for the 90º cuts and figure 10 for the 0º cuts.

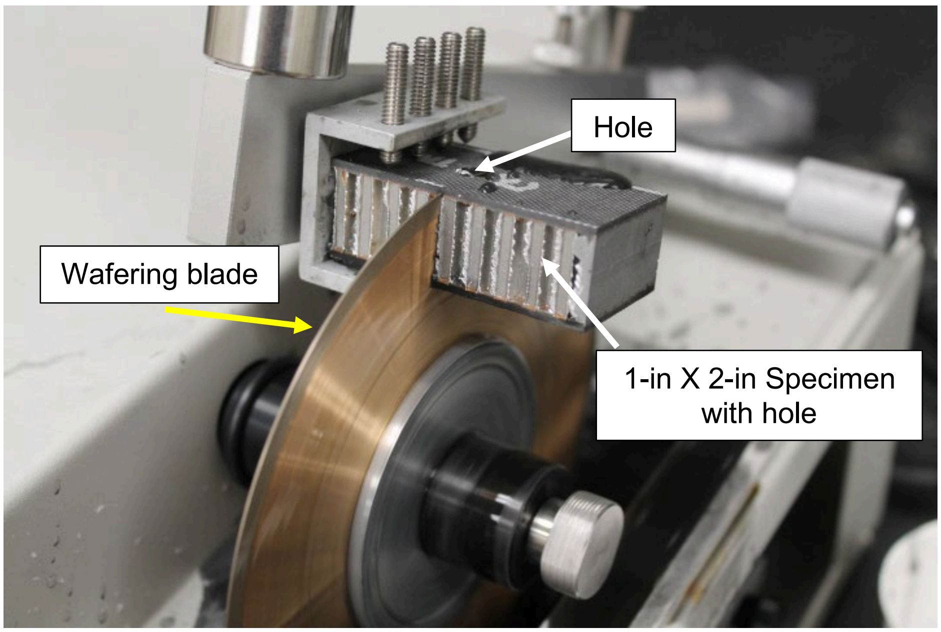


Figure 8. Photograph of wafering saw used to section specimens through hole.

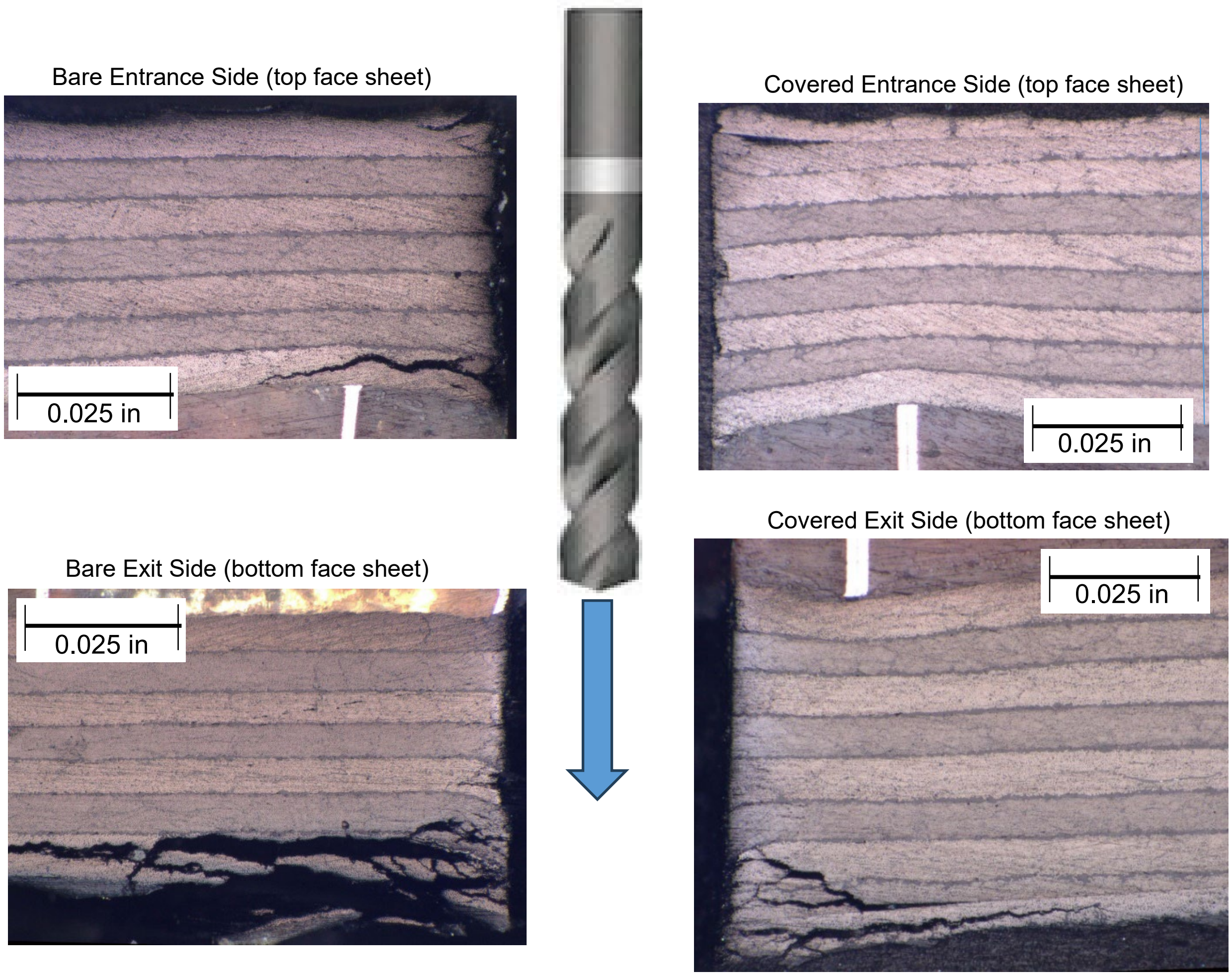


Figure 9. Examples of cross-sectional microscopy of holes. Cuts in 90º direction.

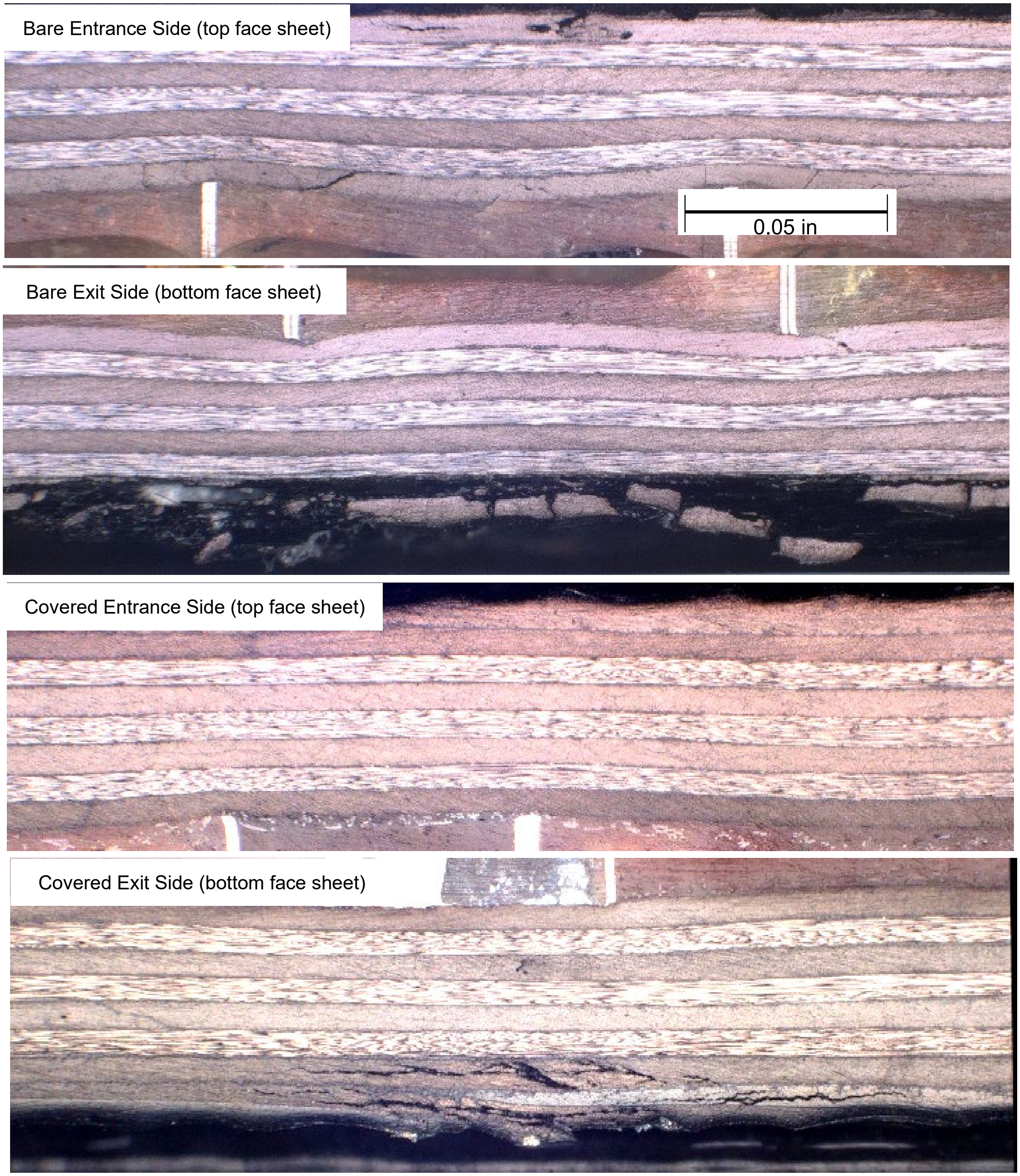


Figure 10. Examples of cross-sectional microscopy of holes. Cuts in 0º direction. Direction of drilling is down in all 4 photographs.

It appears that most of the damage due to drilling of these specimens is on the exit side of the specimen. In the 0º cross-section photomicrographs (figure 10), damage extends up to the bottom most 0º ply on the exit side of the covered specimens. For the bare specimens, the bottom most 0º ply on the exit side is completely unsupported by the ply beneath it due to damage induced by the drilling process.

While most of the damage is on the exit side of the sandwich structure, small damages were seen on many of the specimens at the entrance side, however, these were quite benign compared to the damages on the exit side.

Figure 11 is a schematic of the formation of the damage due to the drilling of a hole through a carbon fiber face sheet aluminum honeycomb sandwich structure. Assuming a twist drill is used, at the start of drilling the hole, the drill bit causes cause a "lifting" motion as the tip cuts material and that material in removed by travelling up along the faces of the flutes. Upon drill bit exiting, the drill bit presses down but there is nothing to support the outer, bottommost ply and this pressing force can cause delamination and ultimately fiber break out. This is why a backing plate is used whenever possible. The film adhesive that bonds the core to the face sheets usually helps prevent face sheet damage by providing a means of support to the lamina upon which it is bonded to. (An exception can be seen in the upper left photograph of figure 9.)

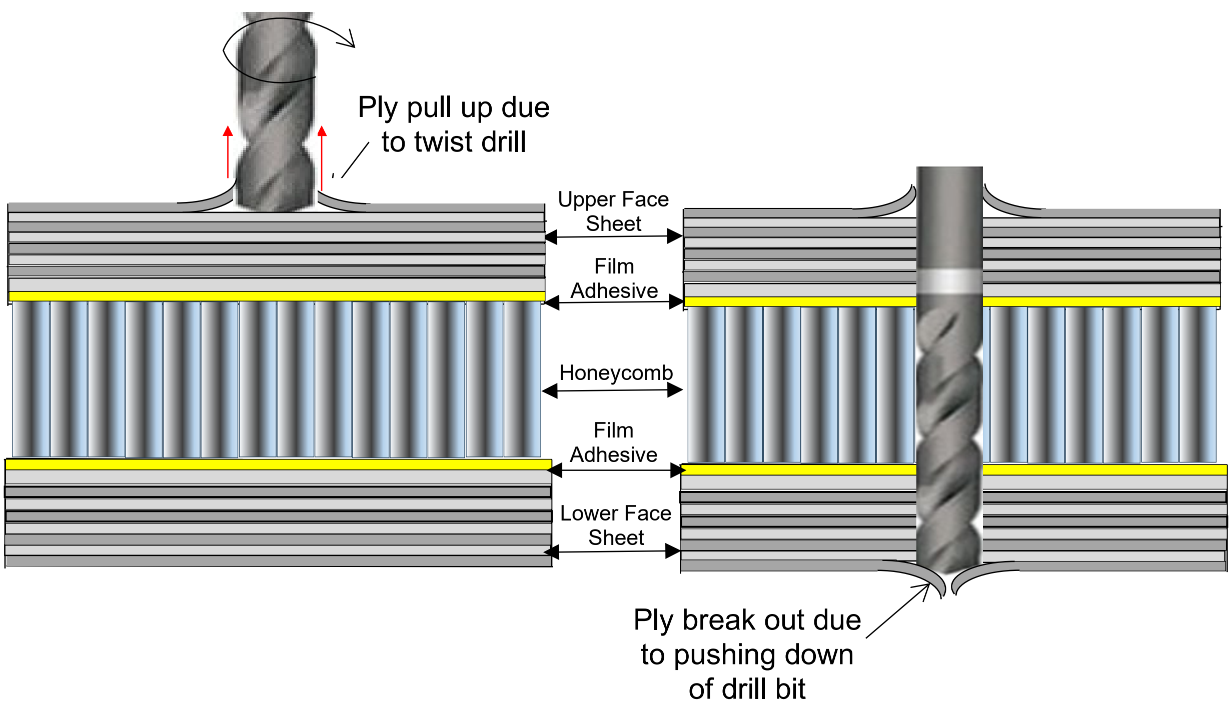


Figure 11. Schematic of hole damage formation during drilling of face sheets.

The reasoning to use outer layers of woven cloth (laid at ±45°) is to provide a "backing mechanism" that is sacrificial since the ±45° plies of woven material are not considered load bearing (although these plies do carry about 6% of the load as calculated from classical lamination theory).

4.0 OPEN HOLE COMPRESSION (OHC) TESTING

The sandwich specimens were assessed for compression strength using the test fixture shown in figure 12. Three strain gages were placed on the specimen as diagramed in figure 13 to ensure even loading of each of the face sheets. The specimens were taken to approximately 1000 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.

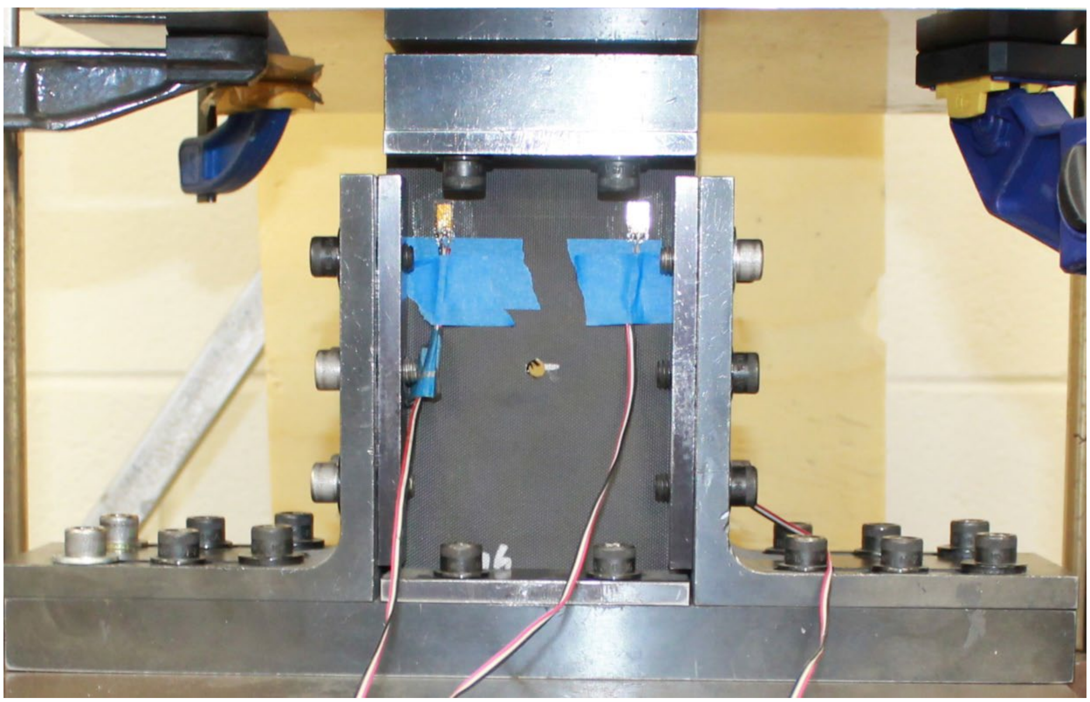


Figure 12. Photograph of fixture used for assessing CAI strength of sandwich specimens.

Figure 14 shows a bare and a covered specimen after compression failure. The failure morphology was as expected with the failure zone emanating perpendicular to the loading direction from the edge of the holes.

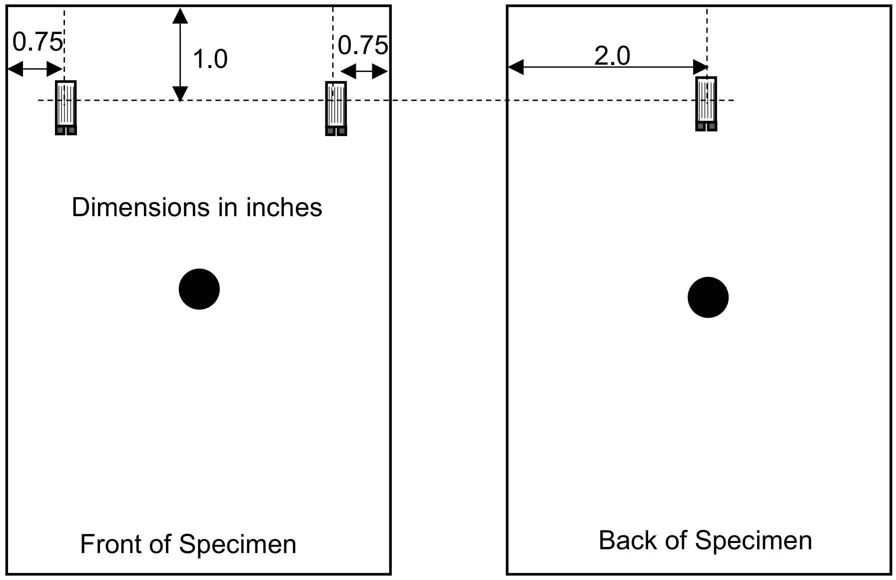


Figure 13. Location of strain gages on front and back of each OHC specimen

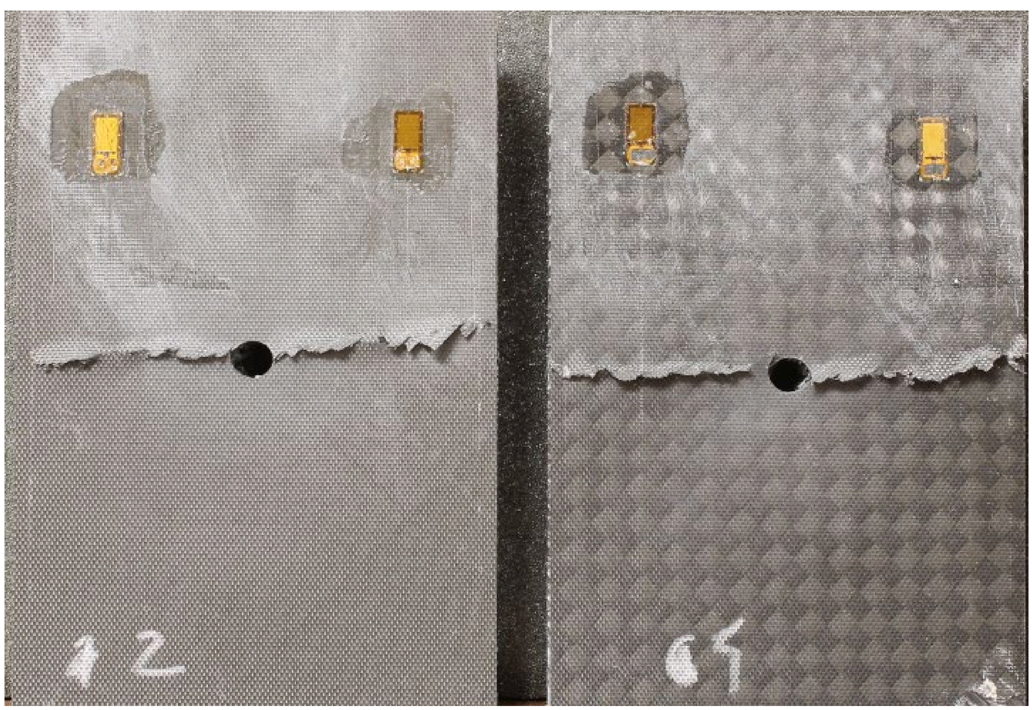


Figure 14. Photographs of failed OHC specimens. Bare specimen on left and woven cloth covered specimen on right.

The average OHC strength results are presented in table 1. The results are given both as line load (breaking load divided by specimen width) and breaking stress (breaking load divided by specimen width divided by the thickness of both face sheets together).

Table 1. Summary of average OHC results of the sandwich specimens tested in this study.

Specimen Type	Specimens tested	Average Line Load Strength (lb/in)	Average Breaking Stress (ksi)
Covered	6	5219±286	52.2±2.9
Bare	6	4596±447	52.2±5.1

The average breaking stress values are the same, however the covered specimens have thicker face sheets, and this larger cross-sectional area will drive the breaking stress level down. The question of interest is "how much load can the honeycomb structure carry?". This value is given by the line load values. When based on line load, the covered specimens can carry an average of 5219 pounds per inch of width of honeycomb sandwich structure and the bare specimens can carry 4596 pounds per inch. Thus, the covered specimens are 14% stronger than the bare specimens. Now the question is "does this extra load carrying capability justify the added weight?" It was found at the beginning of the program that the covered honeycomb sandwich structure weighed 18% more than the bare honeycomb sandwich structure. Thus, in this study, it was seen that it is probably not worth the 18% extra weight to get a 14% higher OHC strength. If the outer woven plies are deemed necessary for drilling "better" holes, then it is suggested that these outer plies be placed where holes are to be drilled and not across the entire acreage of the PAF structure. Or if the entire structure needs to be covered with the woven cloth material for improved hole quality, then place it in a $0^o/90^o$ configuration rather than a $\pm 45^o$ configuration to get more load carrying capability out of the woven cloth.

A study was conducted [12] to see if the 18% extra weight of the outer fabric ply was beneficial from a compression after impact standpoint in which case the outer woven plies across the entire PAF structure may be justified. That study found similar results to this one in that a 17% greater CAI strength was obtained at the barely visible impact damage (BVID) level which did not surpass the 18% added weight.

5.0 CONCLUSIONS

The purpose of this study was to investigate the benefits of adding outer plies of a woven carbon/epoxy to both sides of sandwich structure to give higher quality holes and thus higher open hole compression strength values and compare any increase to the added weight. In general, the woven cloth did produce higher quality holes as was seen by cross-sectional photomicroscopy. For both types of specimens tested (covered with a woven ply and bare) the entrance face sheet of the drill bit showed little damage. Most of the damage was in the lower or exit side face sheet. The OHC strength values showed that the increase in load carrying capability of the samples (14%) with the outer layer of woven fabric was not as high as the weight increase (18%) on a percentage basis.

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