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The Effects of Co-cured Versus Precured Carbon/Epoxy Face Sheets on the Modulus and Compression After Impact Strength of Honeycomb Sandwich Structure

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August 2022

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LIST OF ACRONYMS AND NOMENCLATURE

ATL	automatic tape laying
CAI	compression after impact
CLC	Combined Loading Compression
MSFC	Marshall Space Flight Center
$\mu\varepsilon$	microstrain
NDE	non-destructive evaluation
PAF	Payload Adaptor Fitting
SLS	Space Launch System
t_{max}	maximum thickness
t_{min}	minimum thickness

TECHNICAL MEMORANDUM

THE EFFECTS OF CO-CURED VERSUS PRECURED CARBON/EPOXY FACE SHEETS ON THE MODULUS AND COMPRESSION AFTER IMPACT STRENGTH OF HONEYCOMB SANDWICH STRUCTURE

1. INTRODUCTION

Honeycomb sandwich structure is typically manufactured by curing the carbon/epoxy face sheets directly on the core (either with or without a film adhesive between the face sheet and core). This is called a co-cured process and tends to cause fiber waviness since the honeycomb does not provide a continuous flat surface upon which the face sheets press against during cure. Since the viscosity of the epoxy can get rather low during cure, the plies nearest the core tend to sag into the core cells causing fiber waviness. It was of interest to a program at NASA that is designing and building a Payload Adapter Fitting (PAF) structure. The program sought to explore what so-called ‘knockdown factors’ were being taken due to ply waviness as opposed to manufacturing sandwich structure with precured face sheets in which no ply waviness would be present. In the precure process the face sheets are first cured on a conventional tool such that no fiber waviness is present. These cured face sheets are then bonded onto the honeycomb core in a secondary processing step.

At least one past study has shown co-cured face sheets can have a 25% lower undamaged compression strength than equivalent precured face sheets.[1] However, when damaged by an impact event, the precured and co-cured face sheets had the same compression strength. The authors could find no other data comparing mechanical properties of co-cured versus precured honeycomb sandwich structure. Thus, to obtain more data specific to the PAF sandwich structure, compression after impact (CAI) tests were performed with honeycomb core and face sheets that have been identified for use on the PAF structure. In addition, any change in compressive stiffness due to the fiber waviness was to be determined since stiffness and strength are both critical to the PAF structure.

Since it has been shown that the location of the load bearing 0° plies within a laminate can affect the measured CAI strength by 20%,[2] two quasi-isotropic face sheet lay-ups, $[-45/90/+45/0]_S$ (0° plies at the center of the laminate), and $[+45/0/-45/90]_S$ (0° plies one ply from surfaces), were tested for both precured and co-cured sandwich structure modulus and CAI strength. A study published in July 2022,[2] in which only co-cured sandwich structure was tested, it was found that the face sheets that had the 0° plies at the center had a significantly higher CAI strength. The study herein would demonstrate if the fiber waviness might have been a contributor.

2. MATERIALS AND SPECIMENS

The face sheets of the sandwich specimens tested in this study consisted of Toray T1100 fiber with Toray 3960 epoxy resin. All the face sheets were manufactured by automatic tape laying (ATL) at NASA Marshall Space Flight Center (MSFC). The quasi-isotropic layup sequence for the face sheets was 8-ply $[–45/90/+45/0]_S$. The honeycomb sandwich structure was manufactured with the core ribbon ('L') direction aligning with the 0° fiber direction. A 90° rotation of this panel would give a face sheet with a lay-up of $[+45/0/–45/90]_S$ and the core loading taking place in the 'W' direction, but in the previous study it was found that the core orientation was not a factor in determining CAI results of impact damaged honeycomb sandwich structure.[2] Thus, the two types (orientations) of specimens could be cut from the large sandwich panel by cutting specimens in the 0° and 90° directions.

The sandwich structure has a layer of Solvay FM® 300–2M epoxy film adhesive placed over the honeycomb core prior to the automated tape laying process used to manufacture the face sheets. The core used was aluminum honeycomb with a density of 4.5 lb/ft^3 and a thickness of 1 in. The cell size was 0.125 in which is relatively small and will thus minimize the fiber waviness due to the co-cure process.

The sandwich structure was cured in an autoclave with a pressure of 40 psi and a temperature of 350 °F. The two flat sandwich panels made for use in this damage tolerance study (one panel with co-cured face sheets and one panel with precured face sheets) were 36 in by 36 in. The sandwich structure showed good consolidation, and typical fiber waviness of the face sheets on the co-cured honeycomb core panels was noted in the cross-sectional photomicrographs (cut parallel to the direction of loading) of the two types of specimens as shown in figure 1. The notation used for these four types of specimens are labeled in the figure. The thickness values of the face sheets on the co-cured 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 1. A nominal value for the co-cured face sheet thickness can be found based on the average of numerous random thickness measurements. A quantitative assessment of the severity of the waviness was not undertaken since there were no other data to compare to.

Note that the thickness of the precured face sheets is constant with no high and low values like in the co-cured face sheets. The measured thickness of the precured face sheets was found to be 0.056 in via microscopic measurements and measurement tools built into the microscope's software. This presents a slight problem when comparing precured and co-cured specimens since the average thickness (and thus the thickness which would normally be used for stress calculations) of the co-cured face sheets was 0.051 in based on numerous thickness measurement across random areas of the cross sections. This smaller measured thickness of face sheet on the co-cured specimens will bias the results presented as stress to the high end even though the same amount of material is used for both pre and co-cured face sheets. Thus, the results from these tests will be presented in line load (load divided by specimen width) to failure for a direct comparison. One can divide this value by two times the face sheet thickness to get a stress value; however, the 'correct' face sheet thickness to use for co-cured structure can be debated.

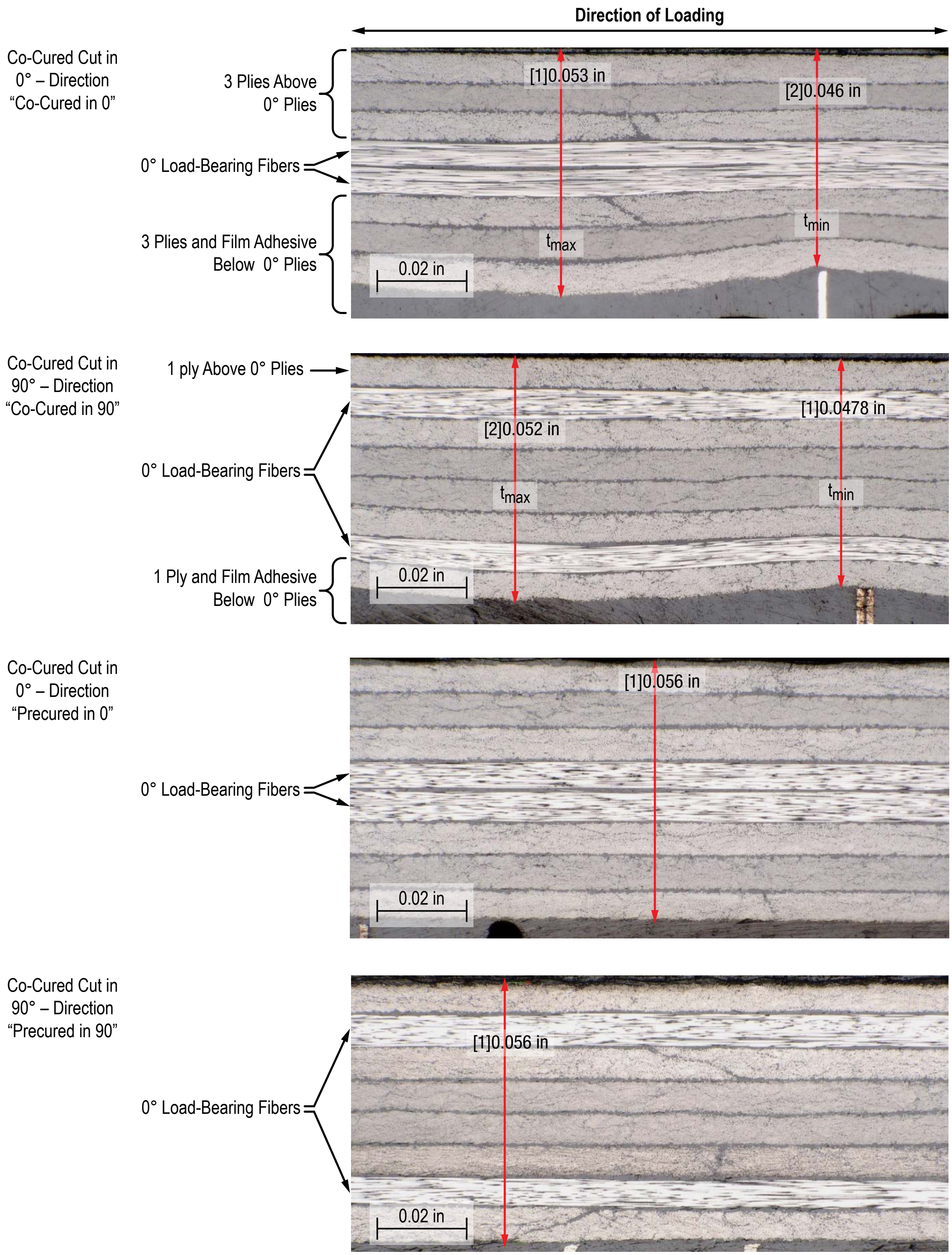
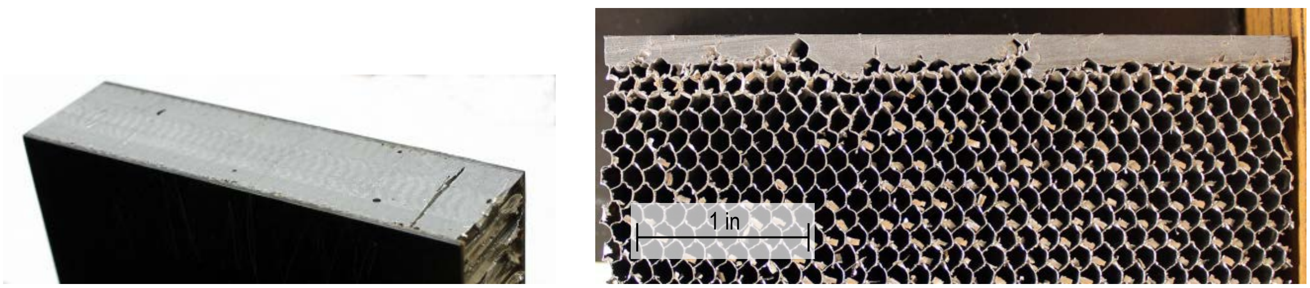


Figure 1. Cross-sectional schematic of honeycomb sandwich structure used with notation to be used for remainder of this study.

The sandwich panels were cut into 6-in tall (direction of loading) by 4-in wide specimens using a diamond saw. For the CAI testing, it was found necessary to reinforce the ends of the sandwich structure (called 'end potting') to prevent end brooming despite being impacted with a high severity level. This was accomplished by crushing the honeycomb at the top and bottom ends of each specimen to about a 0.25-in depth and then filling this channel with Loctite® EA9394 epoxy before machining the top and bottom ends flat and parallel. Figure 2 shows examples of the end potting technique used.

Once the potting epoxy cured, the top and bottom edges of the specimens were then machined to ±0.001 in tolerance of parallelism using a vertical end mill with a solid carbide cutting tool (Onsrud 67–526 designed for carbon fiber machining). The side edges of the specimens were machined to be perpendicular to the top and bottom edges.



(a) (b)

Figure 2. (a) Photograph of specimen that has been end potted to prevent end brooming failures. (b) Photograph of end-potted specimen with a face sheet removed to show depth of potting adhesive.

3. COMPRESSION AFTER IMPACT DAMAGE TESTING

3.1 Infliction of Impact Damage

An instrumented drop weight impact tower was used to impart impact damage to the sandwich specimens. The impactor had a 0.5-in diameter tip. A picture of the impact tester used is shown in figure 3. The selected impact energy was 10.5 ft lb based on what was found to be readily visible damage.

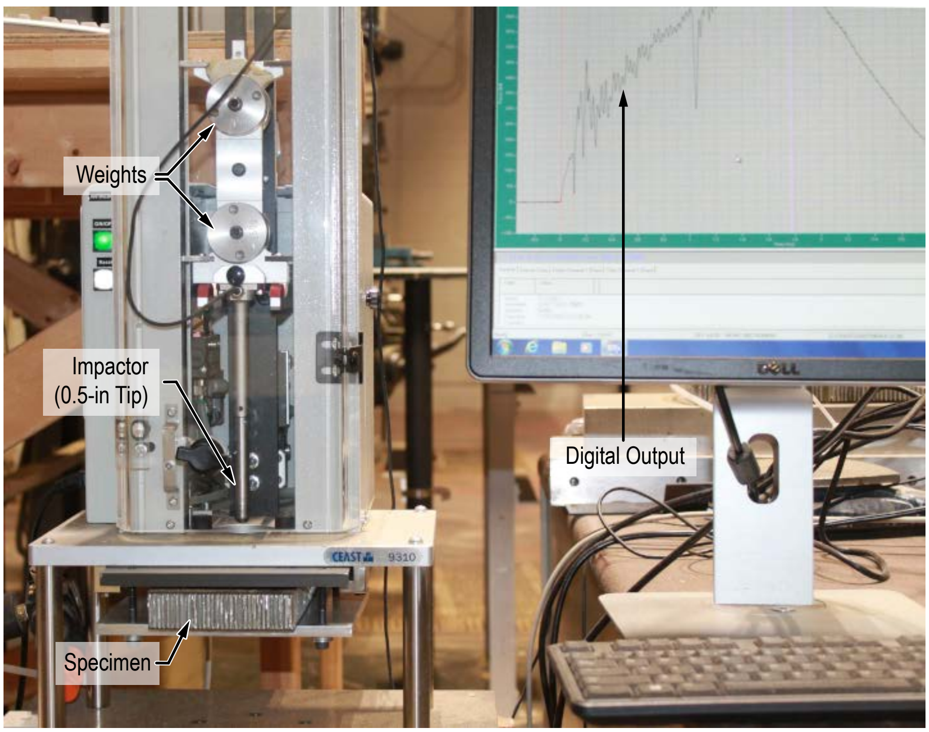


Figure 3. Photograph of instrumented impactor used.

Typical load-deflection curves of the instrumented impact output for each of the two types of specimens are shown in figure 4. These show some small differences between the precured and co-cured face sheet specimens. The co-cured face sheet specimens undergo a larger drop in load at the top of the load-deflection curve which is indicative of more damage being formed.

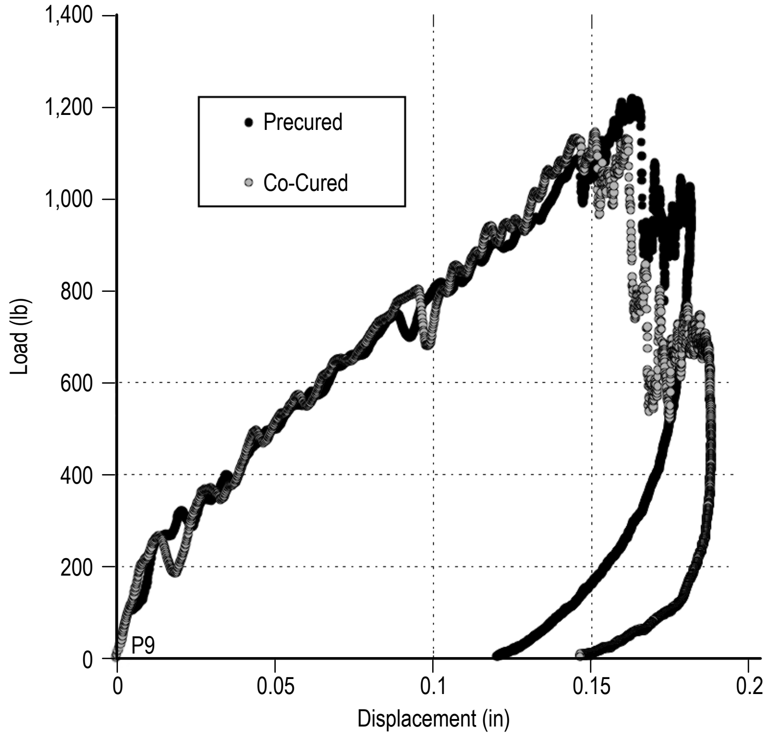


Figure 4. Typical load-deflection data from the 10.5 ft lb impacts on the precured and co-cured face sheet specimens.

Non-destructive evaluation (NDE) in the form of flash thermography was performed on the impacted specimens.Typical examples from co-cured and precured face sheet specimens are presented in figure 5. In general, the co-cured specimens showed slightly more damage than the precured specimens which aligns with the instrumented impact data in figure 4.

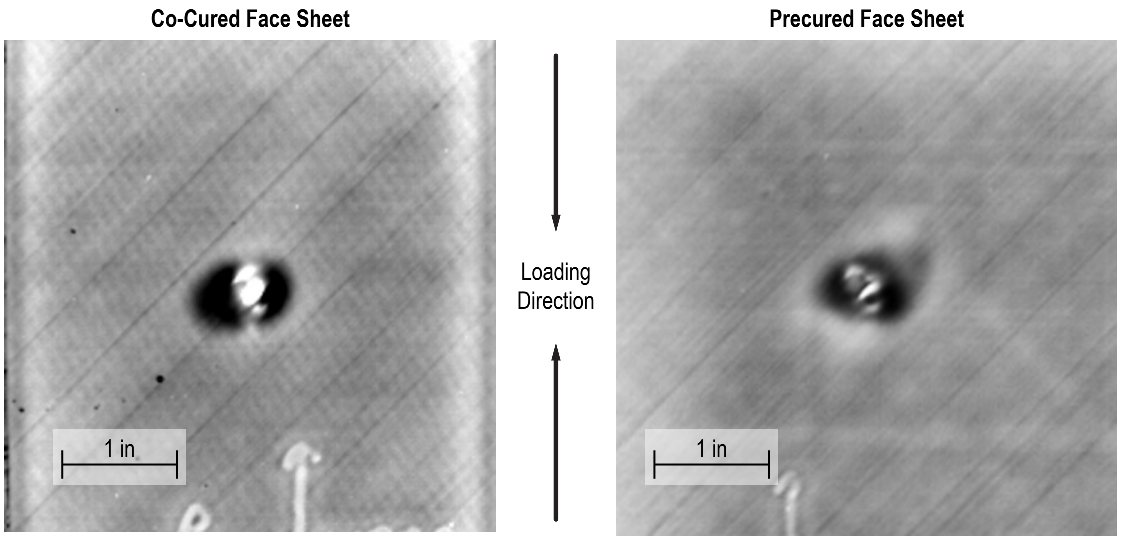


Figure 5. Thermography signatures of 10.5 ft lb impacts on T1100/3960 face sheet honeycomb core specimens.

Examples of the through-thickness severity of the damage in the impacted face sheet are shown by the cross sections presented in figure 6. These cuts were made through the center of the damage zone parallel to the loading direction. Cross-sectional microscopy photographs of these impacted specimens showed highly localized damage and the precured face sheet specimens showed slightly less damage as was indicated by the thermography results in figure 5.

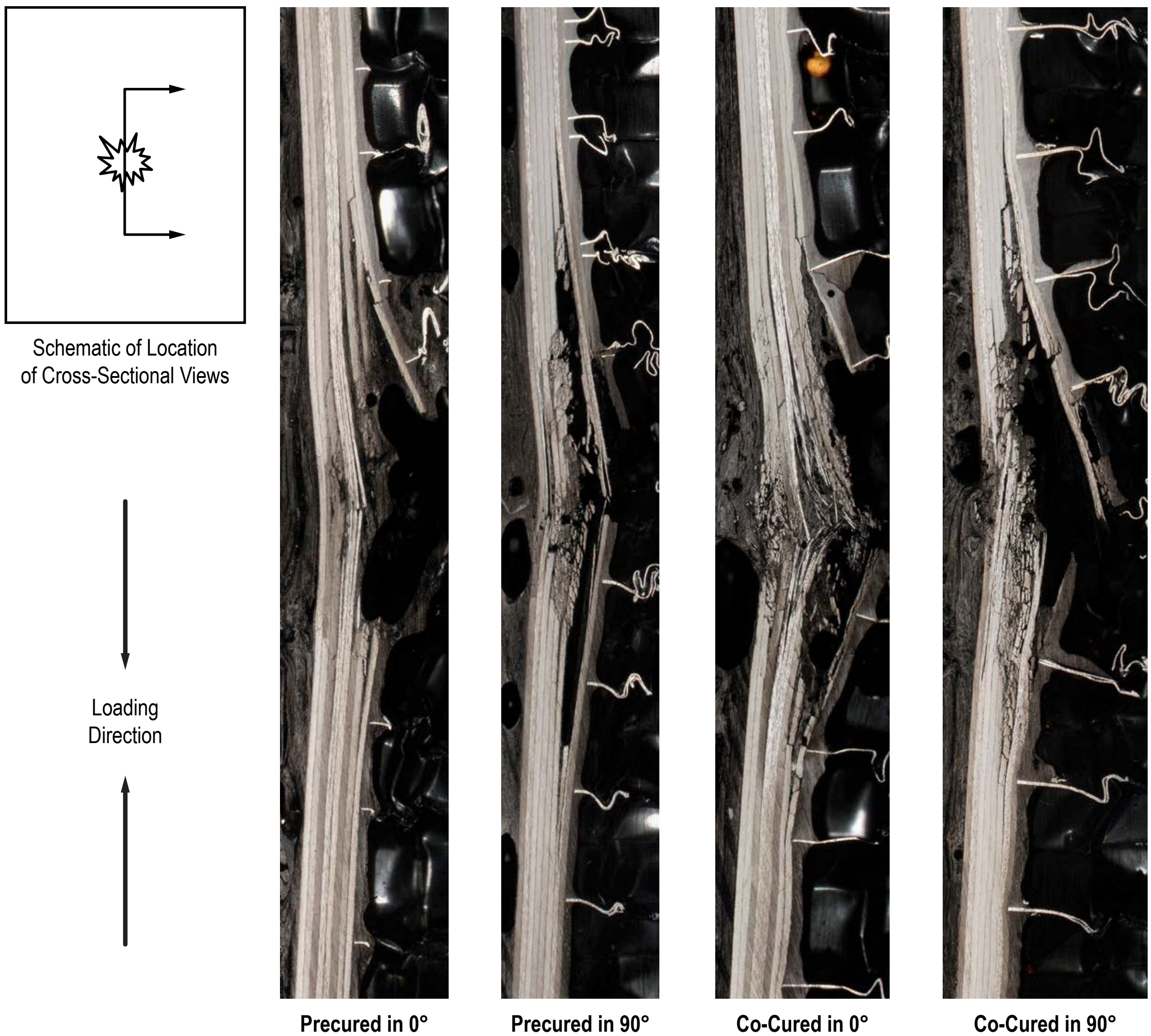


Figure 6. Cross sectional photomicroscopy of 10.5 ft lb impacts on T1100/3960 face sheet honeycomb core specimens. Cuts made in the loading direction.

3.2 Compression Testing

The impacted sandwich specimens were assessed for residual compression strength using the test fixture shown in figure 7. Three strain gages were placed on the specimen as diagramed in figure 8 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 1,000 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 until the specimen failed.

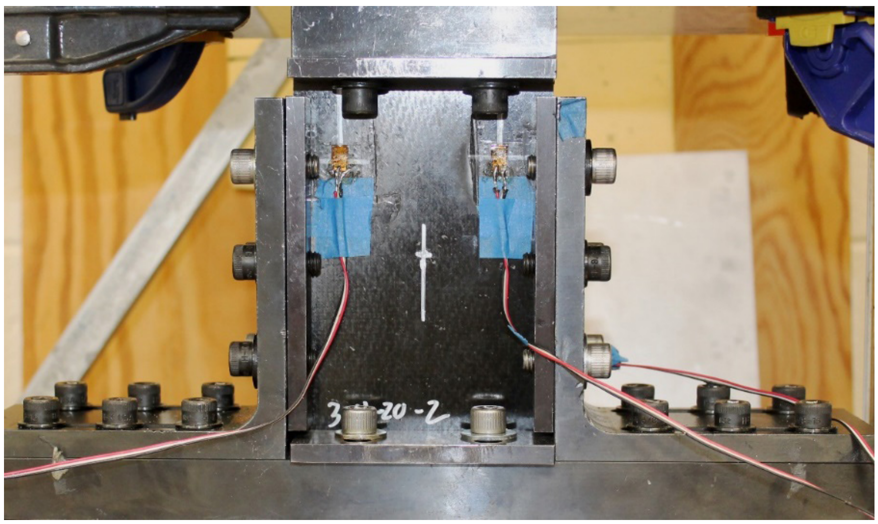


Figure 7. Photograph of fixture used for assessing CAI strength and modulus of sandwich specimens.

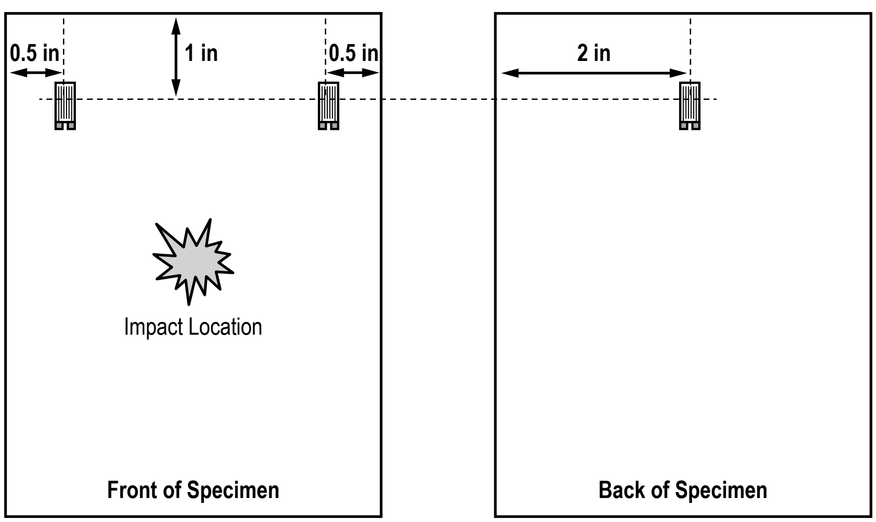


Figure 8. Location of strain gages on front and back of each CAI specimen.

The CAI results are shown in table 1 and are presented in terms of line load to failure (failure load divided by specimen width) since the slight differences in face sheet thicknesses would bias the results to make the co-cured specimens appear stronger. The data in table 1 are presented graphically in figure 9.

Table 1. Summary of CAI results of precured and co-cured face sheet sandwich specimens tested.

Specimen Type	Impact Energy (ft lb)	Specimens Tested	Average CAI Strength (lb/in)
Precured Face Sheet in 0	10.5	7	5813±554
Precured Face Sheet in 90	10.5	6	4949±350
Co-cured Face Sheet in 0	10.5	5	6016±211
Co-cured Face Sheet in 90	10.5	5	4860±132

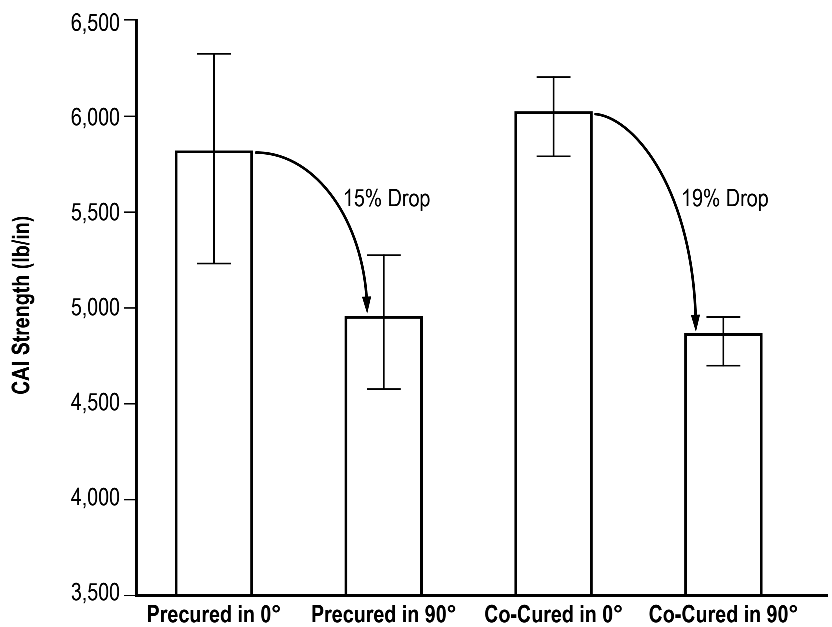


Figure 9. Graphic representation of CAI data of T1100/3960 face sheet specimens presented in table 1.

For any given direction of testing (0° or 90°), there appears to be no difference in the CAI strength values between co-cured and precured face sheets which was also seen in a study published in 2008.[1]

The results show a 15% drop in CAI strength for the precured face sheet specimens rotated by 90° and a 19% drop in CAI strength for the co-cured face sheet specimens when rotated by 90°. Although these drops in average CAI strengths are significant, the standard deviation bars do overlap for the precured face sheet specimens. The reason for the larger scatter in CAI results for the precured face sheet specimens is not known. Despite the larger amount of scatter, it appears that the fiber waviness was not a contributor of the differences seen in CAI strength due to a 90° rotation.

3.3 Modulus Testing

The modulus of the sandwich structure was measured (using a line load instead of stress as with the CAI strength data) during each CAI test and a best fit line was drawn through the load-strain curve between 2000 and 4000 με. A sample load-strain curve from a CAI test is shown in figure 10.

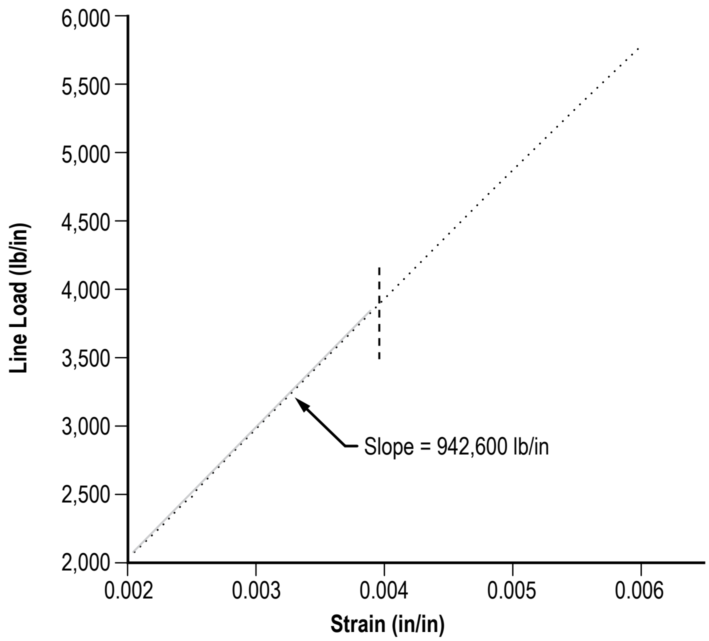


Figure 10. Sample line load-strain data from CAI tests.

When the gages are ‘far field’ from the damage, modulus measurements give the same results for notched and unnotched specimens.[3] The results are presented in table 2 and presented graphically in figure 11.

Note that more modulus measurement specimens were tested since some of the CAI specimens were taken to near failure and the test stopped before failure as part of another study examining the evolution of damage in a CAI specimen.

Table 2. Results of modulus measurements using line load.

Specimen Type	Specimens Tested	Average Compression Modulus (klb/in)
Precured Face Sheet in 0°	8	953±26
Precured Face Sheet in 90°	6	949±17
Co-cured Face Sheet in 0°	7	951±25
Co-cured Face Sheet in 90°	9	944±12

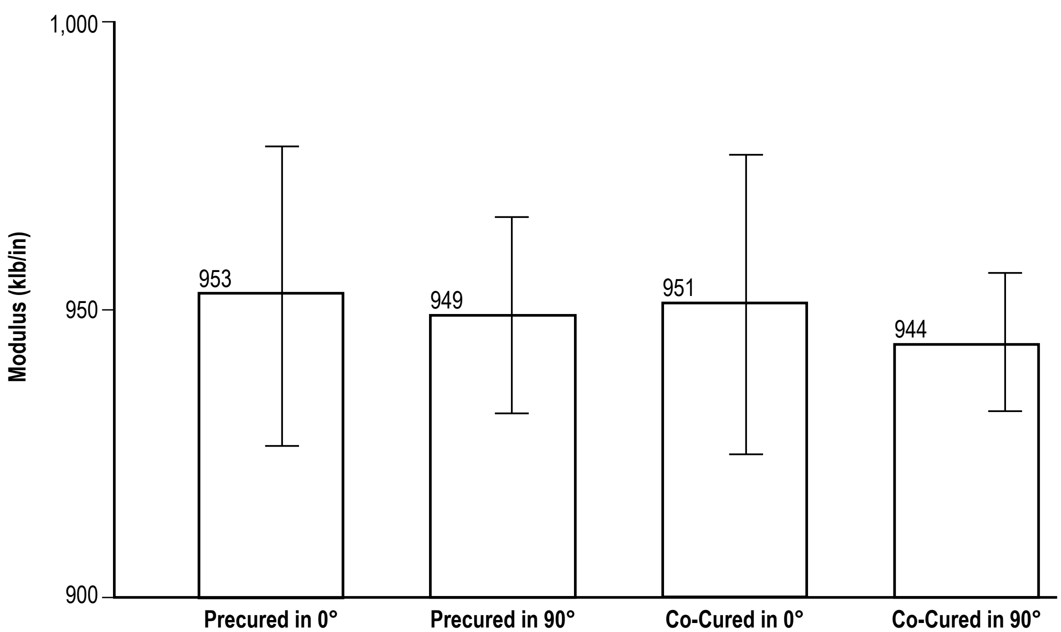


Figure 11. Graphic representation of modulus data of T1100/3960 face sheet specimens presented in table 2.

There appears to be no difference between specimens tested in the 0° versus 90° direction (an expected result) or in precured versus co-cured face sheets (not an expected result).

4. UNNOTCHED COMPRESSION STRENGTH OF FACE SHEETS

Although the PAF structure is being designed to damage tolerance criteria, (rendering undamaged strength moot), it was of interest to see if the fiber waviness of the co-cured specimens affected the undamaged compression strength of the face sheets to compare with the results in the 2008 study.[1] If the compression strength of sandwich structure is governed by the compression strength of the face sheets, as is assumed in this study since the direction of the core had no effect on CAI strength in a previous study,[2] then a direct measurement of the face sheets' compressive load carrying capabilities can be performed without impact damage. The best way to measure the compression strength of the as manufactured co-cured face sheets (with the inherent waviness) is to eliminate the honeycomb from the test method to preclude other failure modes involving the core and to maintain simplicity in specimen preparation and test technique. The technique used in this study to achieve this was to cut the face sheets off the aluminum honeycomb with a band saw (as shown in figure 12) and then abrade off any residual core material down to the adhesive layer that was used to join the face sheet to the honeycomb. Abrading off the adhesive down to the first carbon/epoxy ply was not feasible, since the core side surface was dimpled due to co-curing over the honeycomb and abrading this surface flat would have damaged carbon fibers. The resulting pair of face sheets were no longer symmetric due to this adhesive layer, which caused the face sheets to incur a curvature. A photograph of the face sheets of a specimen with the core removed is shown in figure 13.

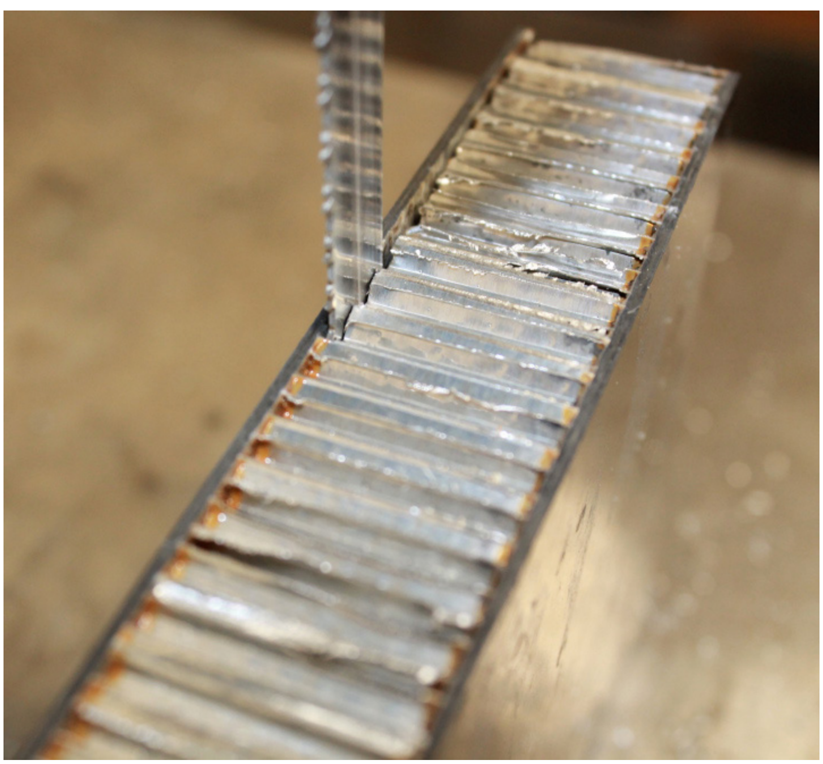


Figure 12. Photograph of face sheet removal from core.

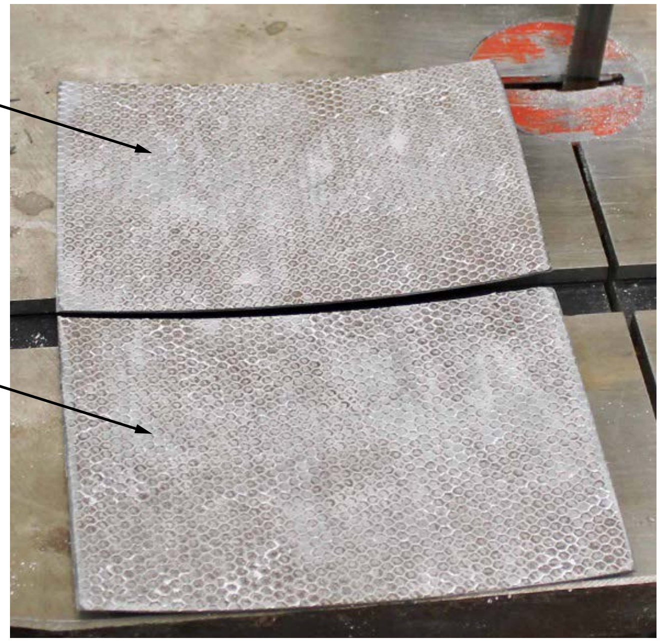


Figure 13. Photograph of face sheets after removal of core. Note curvature of face sheets after core removal.

To regain symmetry and provide a flat specimen that could be compression tested, the two halves were bonded with concave sides together using EA 9394 epoxy paste adhesive and placed in a platen press until the paste adhesive cured. After the paste adhesive cured, the resulting flat panel was machined into specimens to be tested by a combined loading compression (CLC) method similar to ASTM D6641. The specimen edges were not machined further after the saw cut and the ends were machined parallel to one another within 0.001-in. This method of CLC preparation has been shown to give good compression strength results.[4] A CLC specimen made of two face sheets is shown in figure 14 and a magnified view of the edge of each of the four types of CLC specimens are shown in figure 15. The paste adhesive (which has small aluminum particles as filler) and remnants of core that could not be removed without damaging carbon fibers are noted in the top figure.

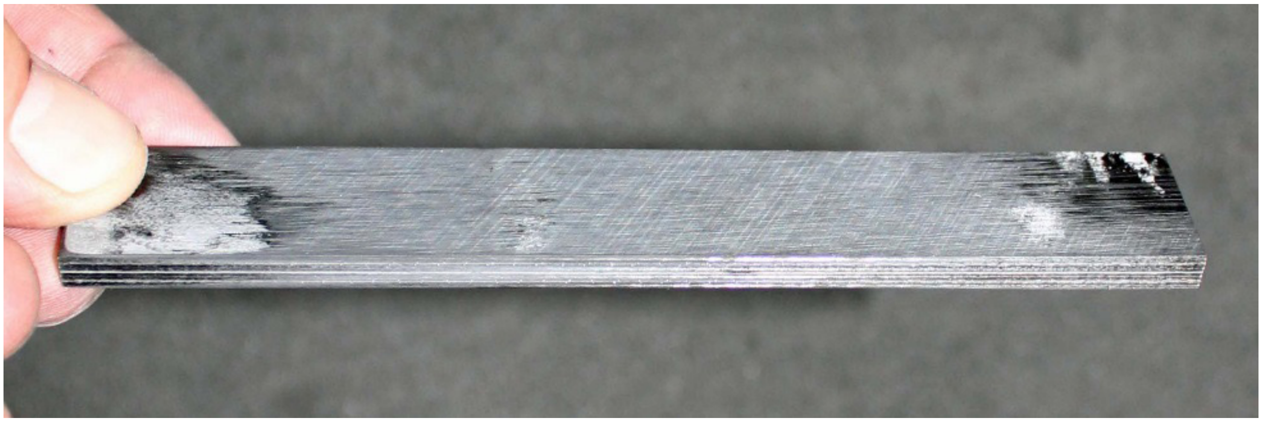


Figure 14. Photograph of CLC test specimen made from two face sheets bonded together after core removal.

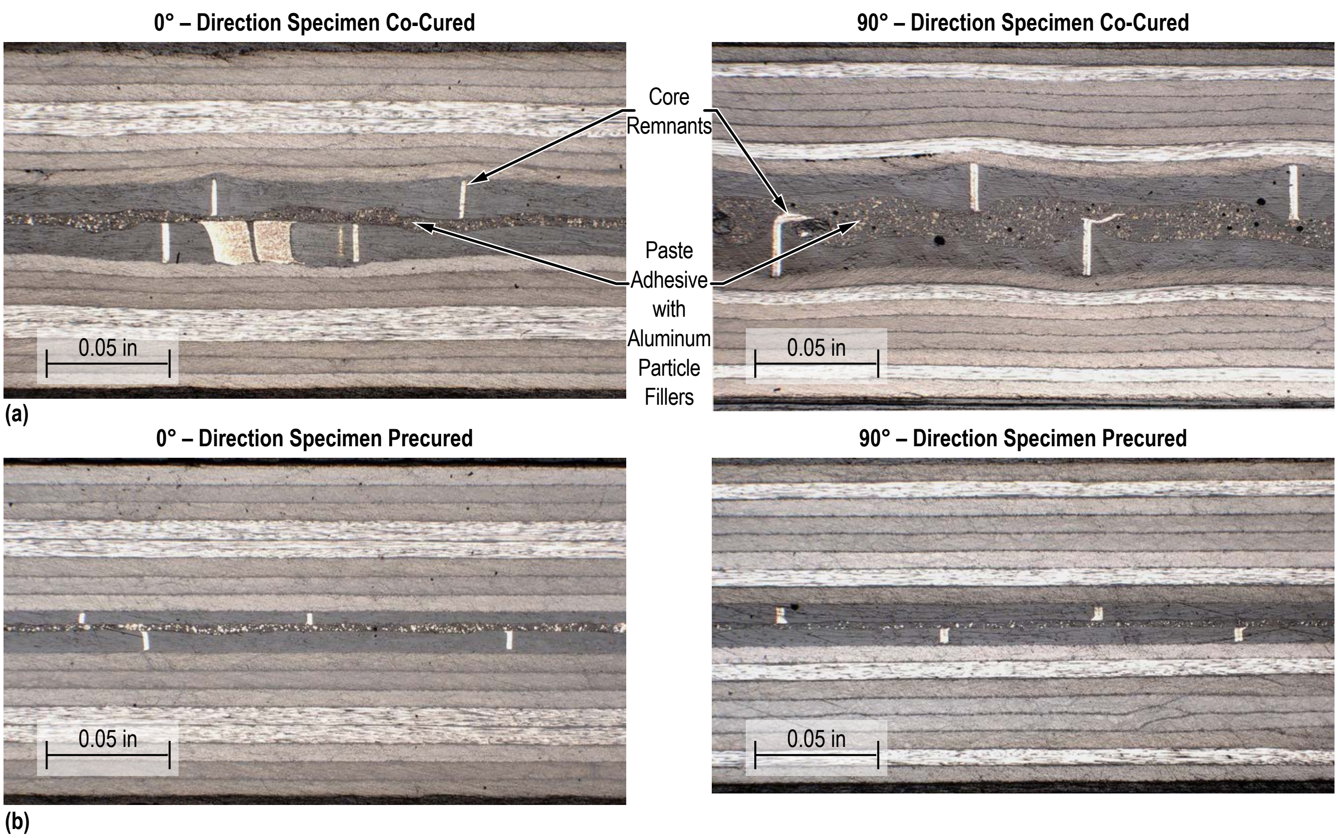


Figure 15. Magnified view of edge of CLC test specimens made from two face sheets bonded together after core removal. (a) Co-cured specimens and (b) precured specimens.

The compression strength results for the specimens tested are presented in table 3. The paste adhesive does add some load carrying capabilities, but the layer is thin, and stiffness is low in comparison to the thickness and stiffness of the face sheets cut from the sandwich specimens.The load carrying contribution of the adhesive is not included in the stress calculations thus biasing the compression strength values to a slightly higher value than would be measured if the paste adhesive were infinitely thin.

Table 3. Results of compression strength measurements using line load.

Specimen Type	Specimens Tested	Average Compression Strength (lb/in)
Precured Face Sheet in 0°	6	11,741±251
Precured Face Sheet in 90°	6	11,350±372
Co-cured Face Sheet in 0°	6	12,090±462
Co-cured Face Sheet in 90°	6	10,278±679

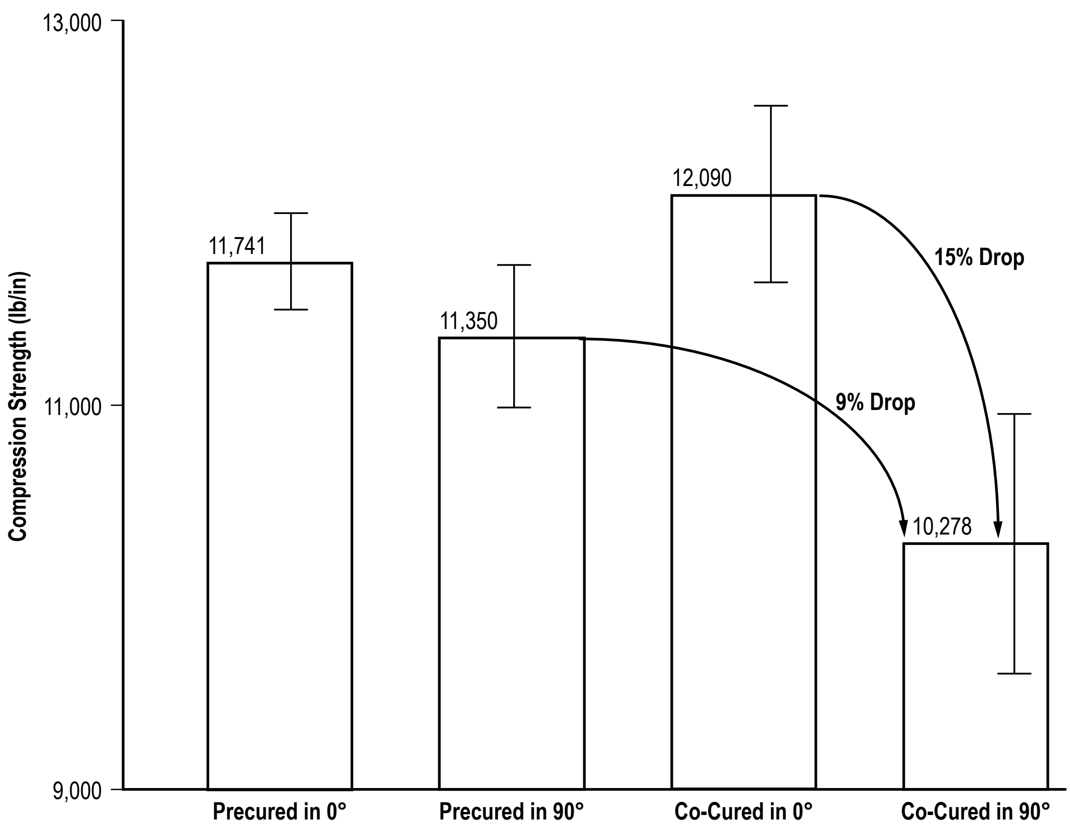


Figure 16. Graphic representation of compression strength data of undamaged face sheet specimens presented in table 3.

The results show that, when undamaged, only the co-cured face sheet sandwich structure is significantly affected by the 90° rotation (a 15% drop with no overlap of standard deviation). If the precured face sheet sandwich structure is affected by the 90° rotation, it is small and well within scatter. When tested with the 0° plies at the center of the face sheets, the precured and co-cured face sheet structure had about the same compression strength. However, when the 0° plies were one ply from the surface of the laminate, the co-cured face sheet specimens did see a 9 % drop in strength.

Although of more academic interest, the cause of the drop in undamaged strength of the co-cured face sheets with 0° plies near the surface was examined. This was accomplished via 'interrupted' testing in which the test is stopped just before failure and the evolution of damage interrogated by either destructive or non-destructive techniques (or both).

4.1 Interrupted Testing of Undamaged Face Sheets

Some of the CLC specimens used to determine the undamaged compression strength in the previous section were tested to about 95% of the average failure load, or until an audible 'pop' was heard at which point the test was stopped. For all of the 90° specimens, an audible sound was heard before failure. For all of the 0° specimens, failure was sudden and catastrophic with no sounds until ultimate failure.

Table 4. Results of interrupted testing of undamaged face sheet specimens.

Specimen Type–ID	Load/Width at Which Test Stopped (lb/in)	% of Failure Load	Comments
Precured in 0°–1	11,168	95	No sound
Precured in 0°–2	11,154	95	No sound
Precured in 0°–3	11,161	95	No Sound
Precured in 0°–4	11,305	96	No sound
Precured in 0°–5	11,138	95	Specimen failed
Precured in 0°–6	11,154	95	No sound
Precured in 90°–1	9,114	80	Audible sound
Precured in 90°–2	9,797	86	Audible sound
Precured in 90°–3	9,834	87	Audible sound
Precured in 90°–4	9,787	86	Audible sound
Precured in 90°–5	8,686	77	Audible sound
Precured in 90°–6	8,743	77	Audible sound
Co-cured in 0°–1	11,498	95	No sound
Co-cured in 0°–2	11,382	94	No sound
Co-cured in 0°–3	11,626	96	No sound
Co-cured in 0°–4	10,669	88	Specimen failed
Co-cured in 0°–5	11,537	95	No sound
Co-cured in 0°–6	10,969	91	Specimen failed
Co-cured in 90°–1	8,843	86	Audible sound
Co-cured in 90°–2	9,527	93	Audible sound
Co-cured in 90°–3	8,868	86	Audible sound
Co-cured in 90°–4	9,614	94	Audible sound
Co-cured in 90°–5	9,794	95	Audible sound
Co-cured in 90°–6	8,233	80	Audible sound

All of the 90° specimens (both precured and co-cured) had a visible crack across the specimen width at (or near) one of the ends of the gage section where the clamping block ends. A picture of these cracks is shown for both precured and co-cured specimens in figure 17. Note that the failure zones are 2.5 in from the specimen ends which is at the edge of the clamping block.

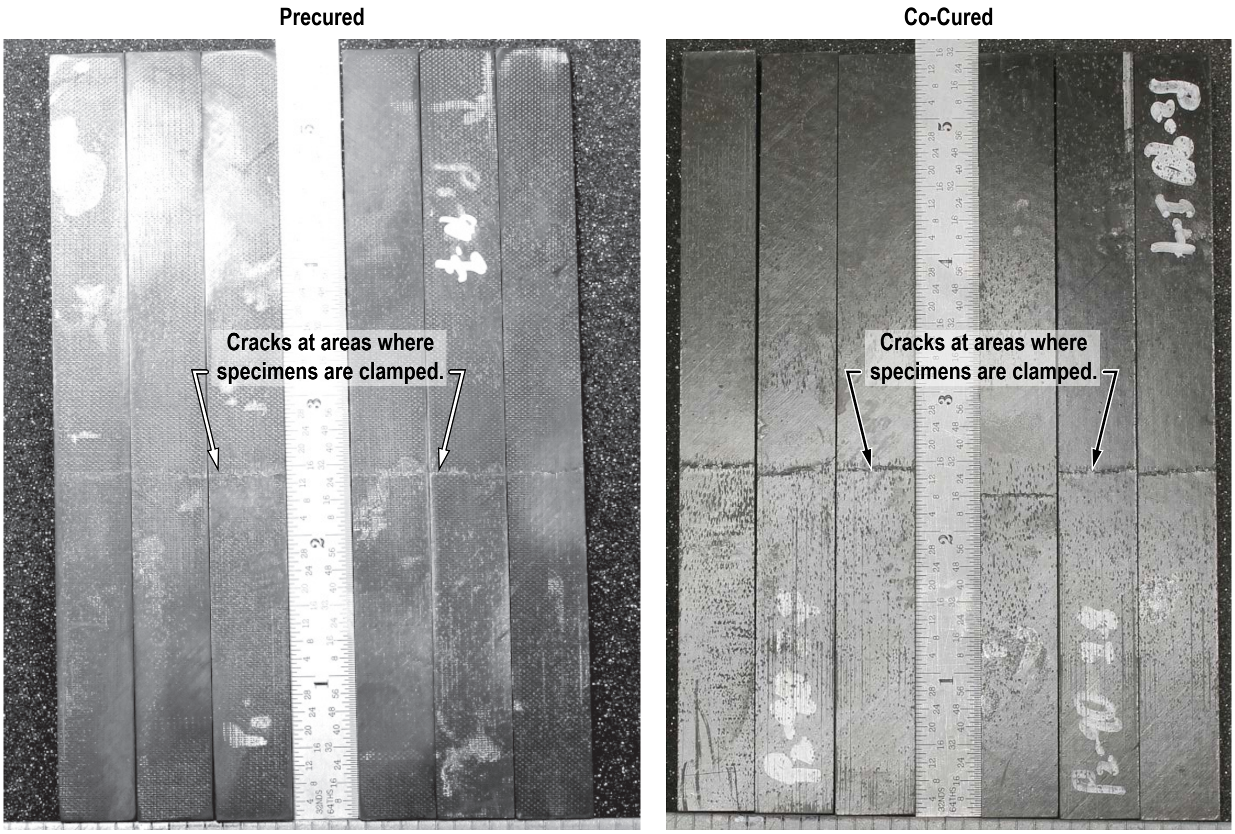


Figure 17. Photograph of 90° CLC specimens stopped after first audible sound but before specimen failure.

These specimens were then polished on their edges and the failure zone examined. For the 90° specimens the pre-failure consisted of the outermost 0° ply microbuckling for both the precured and co-cured specimens, as shown in figure 18, with the only notable difference being the load at which the test was stopped (generally lower load for co-cured specimens). It can be seen in these photographs how the buckling causes the outer +45° ply to ‘break out’ (split) which causes the visible cracks seen in figure 17.

It is theorized that for the 90° specimens, the outermost load-bearing ply need only break through one ply to buckle, whereas the innermost ply need break through one ply plus the adhesive layer between the core and face sheet. For the 0° specimens, the load bearing plies must break through 3 plies to buckle (see fig. 1).

It is also theorized that the co-cured 90° specimens failed at a lower load since the ‘wavy’ innermost 0° ply probably has a lower modulus and thus carries slightly less load than the straighter outermost 0° plies, putting these fibers under higher stress.

The 0° specimens showed no predamage indicating explosive failure, it is assumed, when the two center 0° plies begin to buckle.

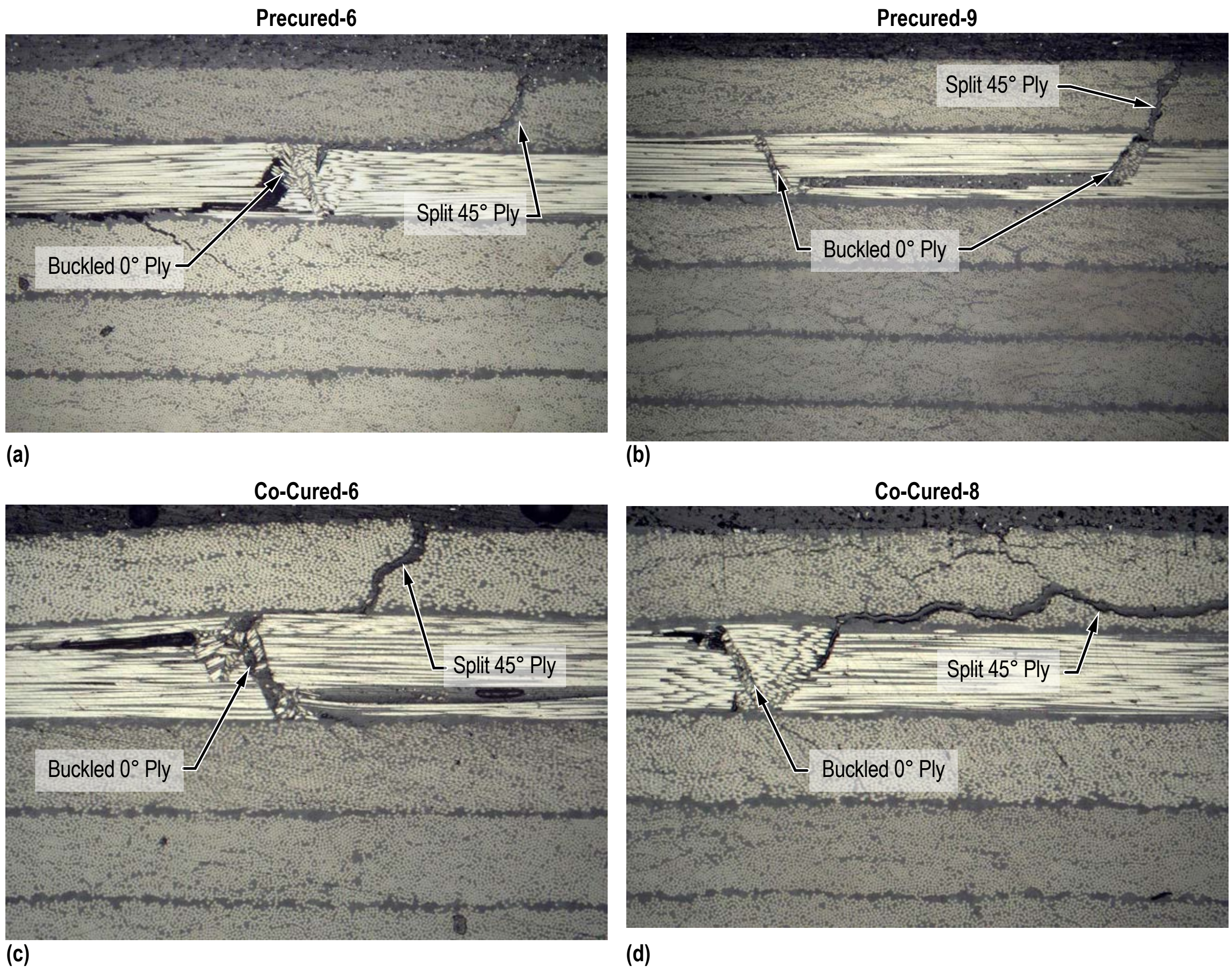


Figure 18. Photomicrographs of buckled fibers in 90° CLC specimens stopped after first audible sound but before specimen failure.

CONCLUSIONS

Some of the conclusions that can be drawn from this study are:

- There was no difference in CAI strength for a precured face sheet versus a co-cured face sheet when using aluminum core with a cell size of 0.125 in. A larger cell size may produce different results.
- For both the precured and co-cured face sheet specimens, a layup of $[-45/90/+45/0]_S$ had a higher average CAI strength than specimens with a layup of $[+45/0/-45/90]_S$. Thus, a generic CAI allowable for a quasi-isotropic laminate may not be valid but it depends on the direction of testing.
- There is no difference in modulus for a precured face sheet versus a co-cured face sheet when using aluminum core with a cell size of 0.125 in. A larger cell size may produce different results.
- Using the core and face sheet material specific to this study, the undamaged compression strength is the same for precured and co-cured face sheet sandwich structure when the 0° plies are at the center of each face sheet (0° specimens). If the 0° plies are one ply away from the surfaces of the face sheet (90° specimens), then the precured face sheet sandwich structure has a higher undamaged compression strength. The cause of this, as ascertained from interrupted testing, was theorized to be the waviness of the innermost 0° plies on the 90° co-cured specimens carrying less load and causing the outermost 0° ply on the co-cured specimens to be overloaded sooner than equivalent co-cured laminates in which there is no wavy ply.

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14. ABSTRACT
This study presents experimental results of compression after impact (CAI) and stiffness testing of aluminum honeycomb core sandwich structure with quasi-isotropic face sheets that have either been co-cured or precured (and then bonded to the core in a secondary operation). The co-cured face sheets contain some ply waviness whereas the precured face sheets did not. The effect of this waviness was ascertained for two important design parameters for the Space Launch System (SLS) Payload Adapter Fitting (PAF); compressive modulus and CAI strength. It was found that there was no effect on the modulus between co-cured and precured face sheets using the material and processes in this study. In addition, there was no difference in CAI strength behavior between the co-cured and precured face sheet.

15. SUBJECT TERMS
sandwich structure, damage tolerance, compression after impact (CAI) strength, co-cure, ply waviness, quasi-isotropic stacking sequence

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