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Repair of Sandwich Structure in Support of the Payload Adapter Fitting (PAF) Part II: Severe Damage Repair

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BVID	barely visible impact damage
PAF	payload adapter fitting
SLS	Space Launch System
TM	Technical Memorandum

TECHNICAL MEMORANDUM

REPAIR OF SANDWICH STRUCTURE IN SUPPORT OF THE PAYLOAD ADAPTER FITTING (PAF) PART II: SEVERE DAMAGE REPAIR

1. INTRODUCTION

As part of a program examining a Payload Adaptor Fitting (PAF) for NASA's Space Launch System (SLS), a repair study of impact damage and misdrilled holes in composite sandwich structure was undertaken.[1] In that study, it was shown that small holes and barely visible impact damage (BVID) could be repaired and all the measured undamaged in-plane compression strength recovered without removing the damaged material using a simple patch repair. It was noted that for more severe damage, either larger patches or removal of damage (or both) may be necessary to regain all of the measured undamaged compression strength. This Technical Memorandum (TM) presents the results of an experimental investigation into repair of more severely damaged sandwich structure than what was studied in reference 1.

At the beginning of this repair study, the PAF was baselined as a honeycomb sandwich structure with eight-ply quasi-isotropic carbon fiber reinforced epoxy face sheets. 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. Although the baseline configuration could change, the repair program presented herein is generic enough in nature such that it should apply to most sandwich configurations. The vast majority of load experienced by this structure will be in-plane compression; thus, this repair study concentrates on the in-plane compression strength of representative sandwich structure specimens. While launch vehicle hardware should be protected throughout its life on the ground, rogue events that may severely damage a part are still a possibility and thus repair techniques for such damage need to be identified.

In this study, an impact energy of about 16 ft•lb was used (by contrast, reference 1 used 2.4 ft•lb of impact energy). The repairs consisted of external patches and either leaving the damaged area in the sandwich structure or removing the damaged area and replacing with a plug of good material. In virtually all repairs reported in the open literature, the damaged area of sandwich panel has been removed and replaced with a plug of good material and either a scarf or patch repair then used.[2–8] Although it was found in reference 1 that for small impact damage, the damaged material need not be removed, and patch repairs could be used to recover all of the measured undamaged compression strength. For heavily damaged laminates, the damaged core may play a more important role in preventing premature inward buckling and subsequent collapse of the face sheet than in panels damaged by BVID. Scarf repairs were not attempted in this study, as they are not recommended for thin face sheet sandwich structure[2], and identical sandwich structure to what was used in this study was repaired using the scarf technique with poor results.[6]

2. SPECIMENS USED IN THIS STUDY

The sandwich structure used in this study was identical to that used to examine the repair of small damage and holes in the companion study[1] and consisted of 8-ply quasi-isotropic IM7/8552-1 carbon/epoxy face sheets with a layup of $[+45,90,-45,0]_S$ on each side of 1-inch-thick, 4.5-ft•lb^3-dense aluminum honeycomb. The core was oriented such that the L-direction aligned with the 0° fiber direction both of which aligned with the loading direction. An epoxy film adhesive (FM209-1M) was used between the core and face sheets, which were fiber placed and subsequently autoclave cured at 40 psi. The difference in specimens used in this study versus reference 1 was that they were larger (6-inches wide by 8-inches tall) and had the end potting and tabs reconfigured from the specimens in reference 1. The specimens needed to be larger since larger patches would be used. Uniform compression loading of the specimens was ensured by four strain gages that were placed on both sides and near both edges of the specimen to ensure even loading of each of the face sheets. The specimens were loaded to approximately 4,000 microstrain; and if one side (or end) was lower than the other by more than 10%, shims were placed under the side (or end) 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.

Removing the aluminum honeycomb core and inserting wood-end plugs (to help prevent end brooming) on these large specimens proved more difficult than on the smaller specimens used in reference 1 and premature breaks in the face sheets were initiating at the ends of the wooden inserts as sketched schematically in figure 1 leading to low compression strength values. Instead of removing honeycomb and inserting wood into the ends of specimens, a layer of epoxy paste adhesive was used to disrupt the original core as little as possible yet still prevent end brooming of the face sheets. To achieve this, the exposed core at the ends was crushed down about 0.25-inch and the space between the face sheets filled with epoxy paste adhesive. Carbon/epoxy tabs were bonded on, and the ends of the specimen were machined flat and parallel. This did succeed in eliminating end brooming but breaks along the top of the composite tabs that had been bonded onto the outside of the specimen (also to prevent end brooming) were occurring causing low compression strength values as shown schematically in figure 2.

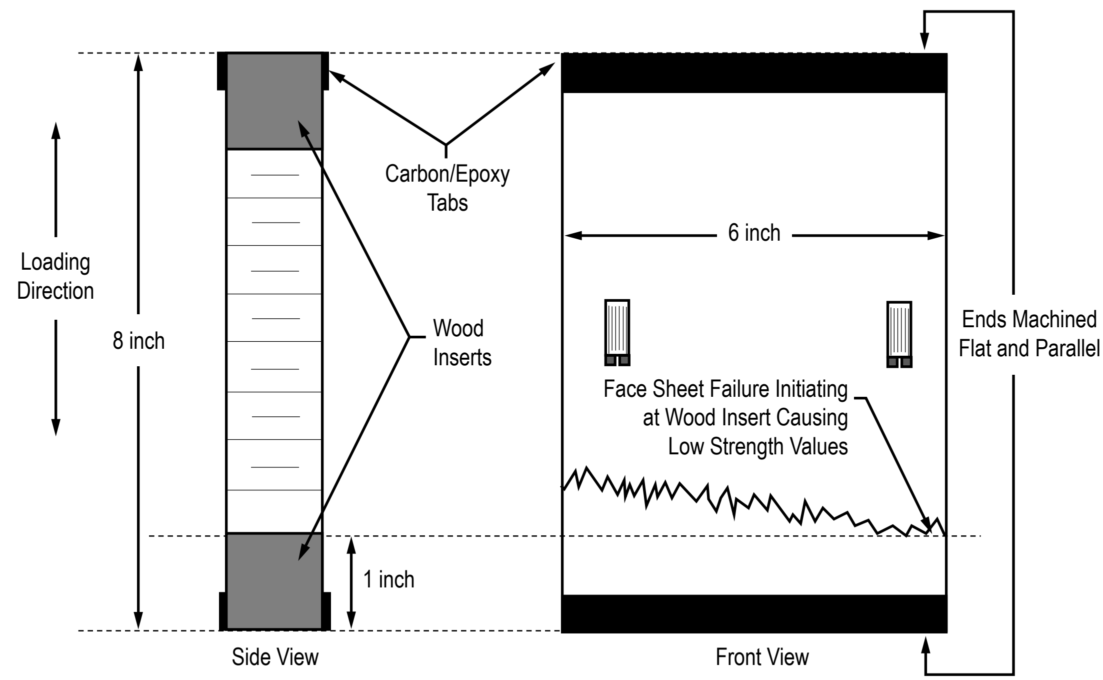


Figure 1. Schematic of wood inserts causing premature face sheet compression failures on larger test specimens.

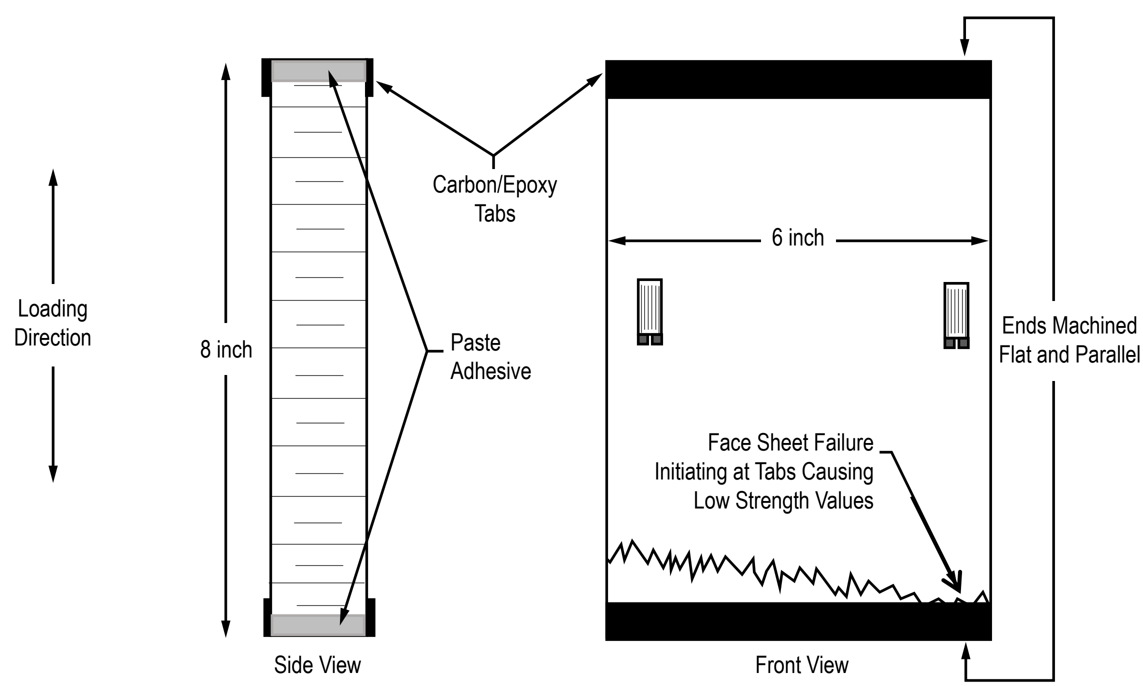


Figure 2. Schematic of carbon/epoxy tabs causing premature face sheet compression failures.

To avoid this problem the tabs were ‘bow tie’ shaped to eliminate the line load stress concentration running across the width of the specimen at the top edges of the tabs. A schematic of the new test specimen with the bow tie tabs is shown schematically in figure 3. This improved the measured undamaged compression strength to values at or above those measured in the smaller specimens as presented in reference 1.

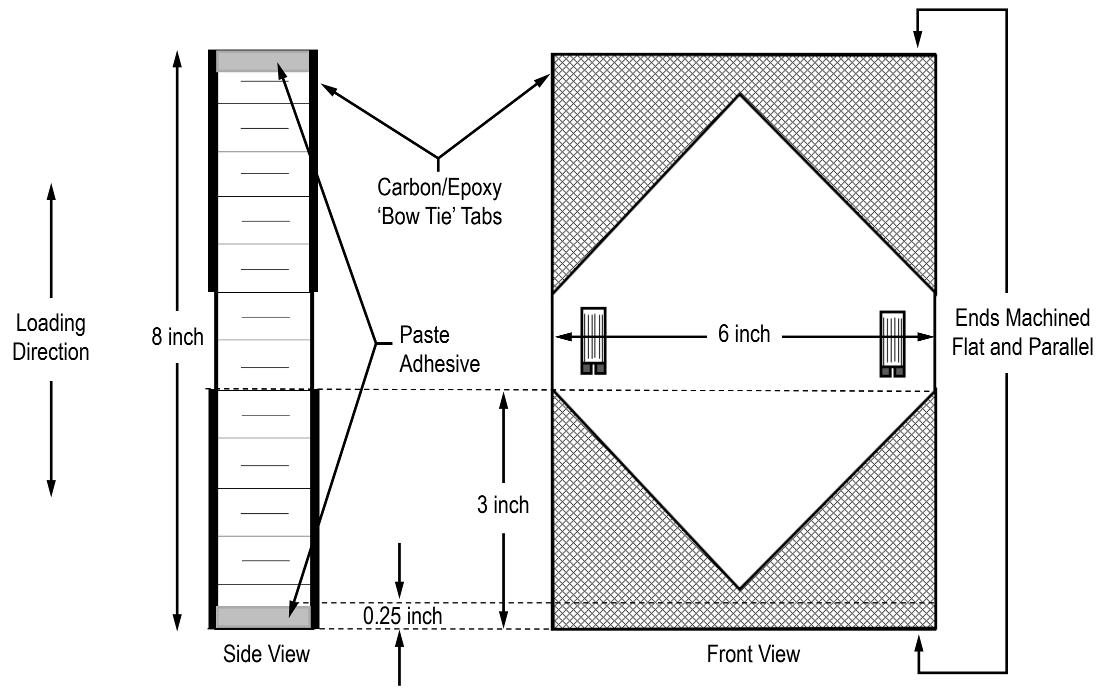


Figure 3. Schematic of specimens used in this study.

2.1 Determining Undamaged Compression Strength

In order to establish a baseline against which to compare the repaired specimens, the undamaged compression strength of five of the specimens of the type shown in figure 3 were measured. It should be noted that in reference 1 it was shown that the upper limit of this strength value should be about 98.2 ksi based on the compression strength of the as-manufactured face sheets that were tested without the core (assuming face sheet failure is the only failure mechanism of the sandwich structure). Achieving this value is unlikely since alternate failure modes and interactions between these failure modes, particularly face sheet wrinkling, are now present with the core being part of the structure. The compression strength results of the five undamaged specimens are presented in table 1. As can be seen, getting the full 98.2 ksi compression strength from the face sheets was not achieved. The average measured compression strength result of 88.8 ± 1.3 ksi obtained for these specimens is higher than the average compression strength (78.1 ksi) of identical sandwich structure tested with smaller specimens in reference 1. The higher average compression strength values achieved for the larger specimens used in this study is probably due to eliminating the wood inserts and using larger tabs as mentioned earlier. The different average compression strength results obtained between the two types of specimens highlight the difficulty in testing undamaged sandwich structure in that the strength values attained are highly dependent on the test specimen and test methodology, thus the term 'measured' undamaged strength that is used throughout this TM instead of undamaged strength since a 'true' or 'correct' undamaged compression strength does not exist (a range of values can be legitimately measured depending on the specimen preparation and test methodology). Further examination of this and its implications are beyond the scope of this study and will not be addressed further in this TM. A typical failed specimen that had no impact damage is shown in figure 4.

Table 1. Results of compression testing of undamaged sandwich structure used in this study.

Specimen #	Stress at Failure (ksi)
Undamaged-1	87.4
Undamaged-2	88.3
Undamaged-3	89.7
Undamaged-4	87.8
Undamaged-5	90.6
Average	**88.8 ± 1.3**

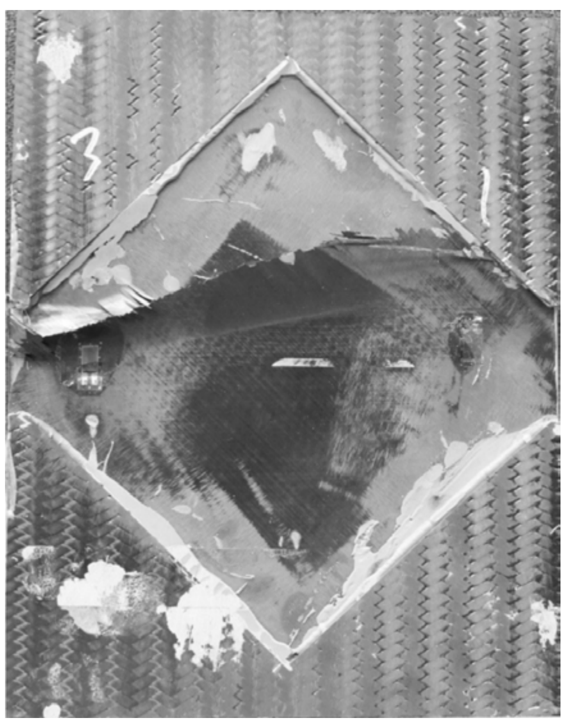


Figure 4. Photograph of failed undamaged specimen of the type used in this study.

2.2 Damaged Specimens

Specimens in this study were impacted with about 16 ft•lb of energy with a 0.5-inch diameter impactor (for comparison, ref. 1 used 2.4 ft•lb). This impact severity level was near the upper limit of the small drop tower used in this study and caused complete penetration of the impacted face sheet. A photograph of damage caused due to a 16.2 ft•lb impact, along with its thermography signature, is shown in figure 5. A cross section through the impact zone is shown in figure 6.

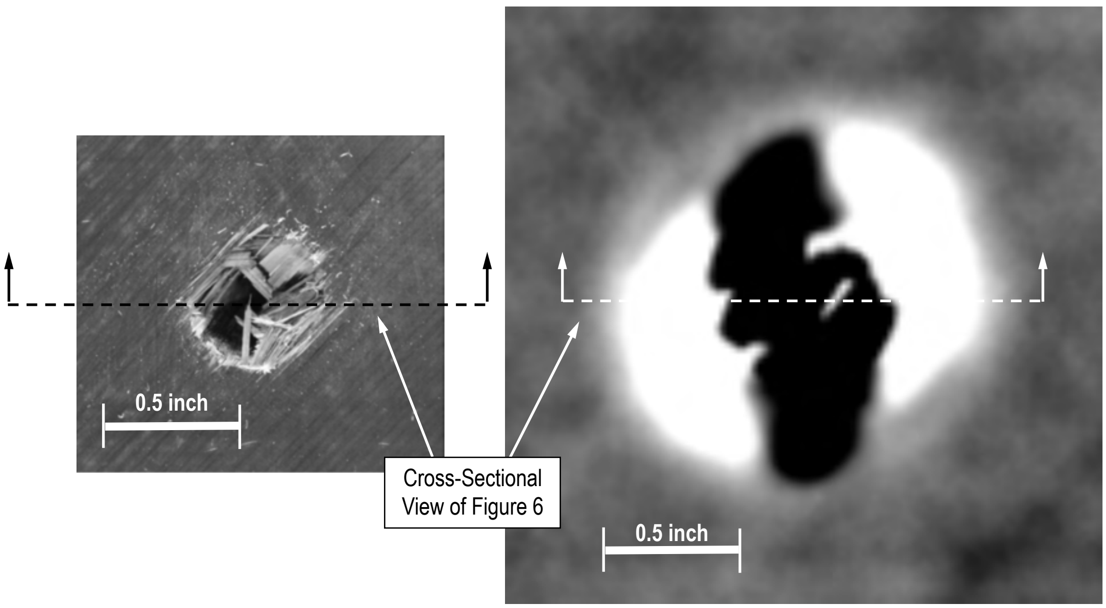


Figure 5. Sandwich specimen impacted with 16.2 ft•lb: (a) photograph and (b) thermography image. Location of cross-section in figure 6 indicated on both images.

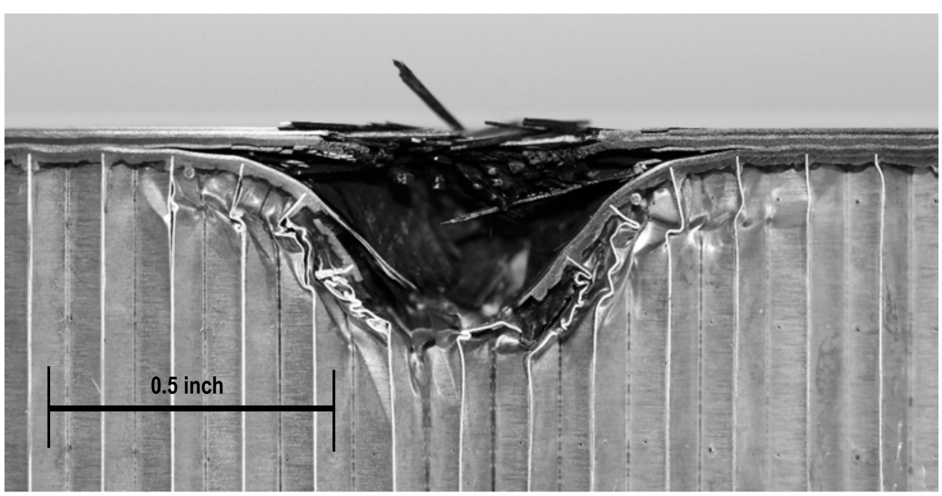


Figure 6. Cross-section photograph of 16.2 ft•lb level impact on sandwich structure used in this study. View shown indicated on photographs in figure 5.

Compression strength results of two specimens tested with this severity of impact damage are presented in table 2. As expected, all failures were through the impact damage zone. More specimens were not tested since this value is of little practical use for this study and the specimens were saved for the repair portion of this study.

Table 2. Measured compression strength of impacted specimens.

Specimen	Impact Energy (ft•lb)	Dent Depth (in)	Compression Strength (ksi)
Damaged-1	16.0	Puncture	45.7
Damaged-2	16.0	Puncture	43.8
		Average	**44.8**

3. REPAIR

3.1 Specimens With No Damage Removal

Since in an earlier study[1] it was found that the average compression strength measured for undamaged specimens could be regained for small impact damage without removing the damage, the first attempts at repair of large damage were attempted without removing the damage. The damage was filled as much as possible with epoxy paste adhesive and then sanded smooth to give the patch a flat surface to adhere to. This was found necessary in reference 1 in order to avoid the patch draping into the damage during cure. The patches in this study were larger than those used in reference 1 and had the same layup as the parent laminate ($[45/90/-45/0]_S$). The unidirectional pre-preg used to make the patches was an out-of-autoclave IM7/5320-1 carbon/epoxy which has about the same compression modulus and strength as the parent material (IM7/8552-1) since the same fiber is used. FM 209-1M film adhesive was used between the patches and the specimens to aid in adhesion of the patch to the specimen. The plies of the patches where made successively smaller by 0.25 inch per ply to minimize edge effects. The patches where circular with an outermost diameter of 4 inches (innermost diameter of 2.5 inches). The two centermost 0° plies were both the same size (3.25 inches). A schematic of this repair technique is shown in figure 7. The patches where placed at the center of the specimen over the filled damage area and the specimen was then vacuum bagged and placed in a programmable oven for cure of the patch (figure 8). The results of four specimens repaired as shown schematically in figure 7 are presented in table 3.

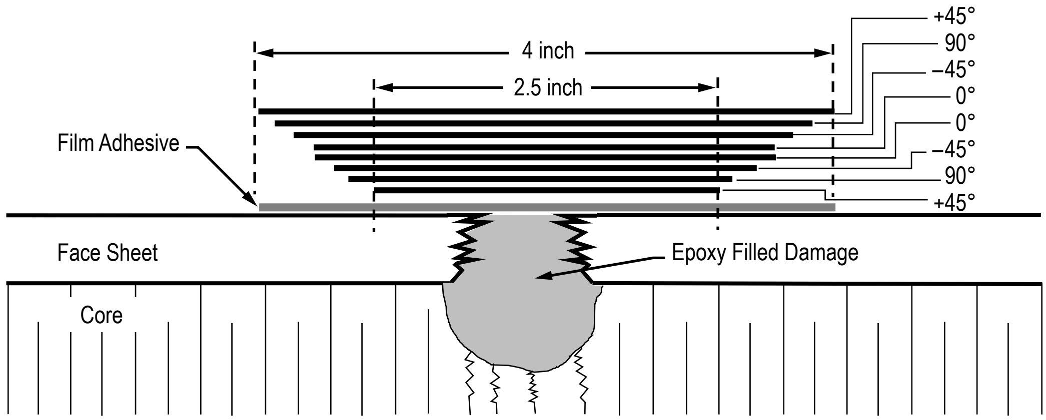


Figure 7. Schematic of repair without removing damage.

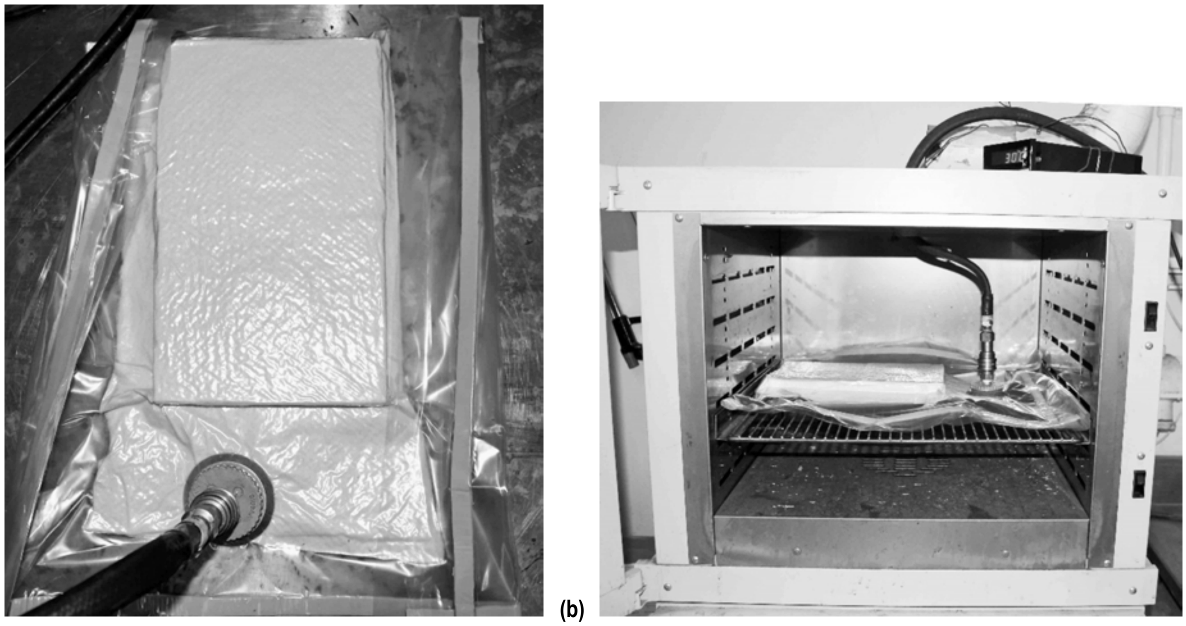


Figure 8. Photographs showing vacuum bagged: (a) repaired specimen and (b) specimen in oven to be cured.

Table 3. Compression strength results of patch repaired specimens without damage removal.

Specimen	Impact Energy (ft-lbs)	Compression Strength (ksi)	Failure Mode
Repair-1	16.1	70.3	Through patch
Repair-2	16.1	68.8	Through patch
Repair-3	16.1	78.4	Through patch
Repair-4	16.1	71.2	Through patch
	Average	**72.2 ± 4.3**	

A typical failure of these specimens is shown in figure 9 where it can be seen that the failure was through the center of the patch. The average repaired compression strength value of 72.2 ksi (81% of the measured undamaged compression strength) is well above the unrepaired average compression strength of 44.8 ksi, but it is desirable to come closer to the average 88.8 ksi value of the undamaged specimens. As shown in the following section, this was attempted by removing the damaged material rather than leaving it in place. Although small damage was repaired without removing the damaged material such that all of the compression strength was regained in a previous study[1], it was postulated that the damage levels being used in this study were too severe to simply leave the damage in place.

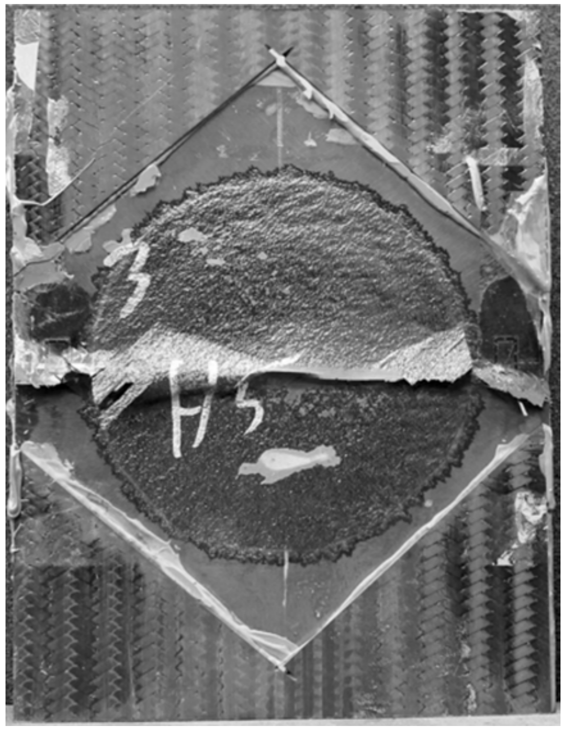
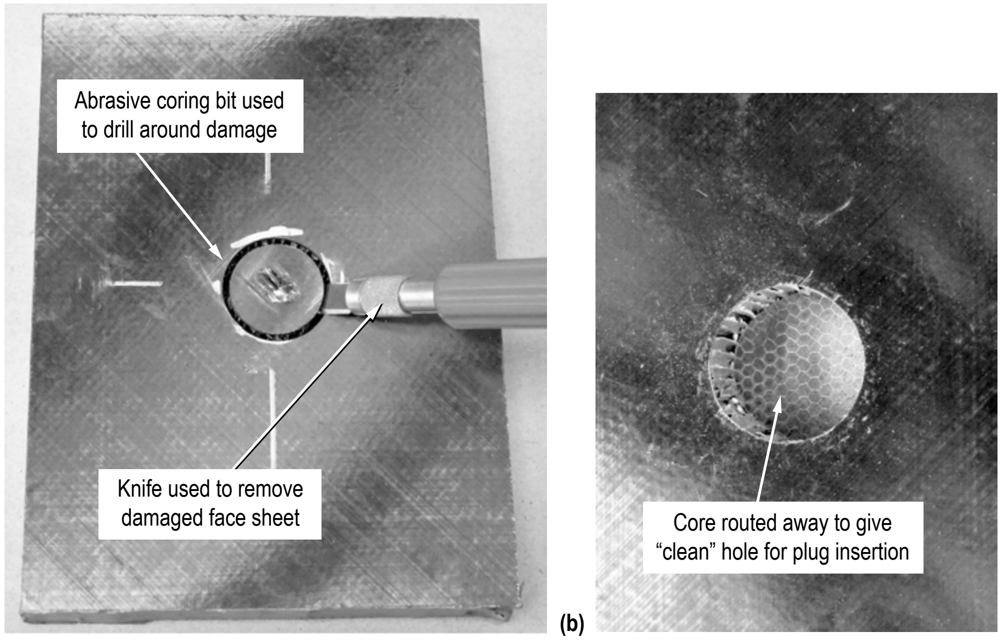


Figure 9. Photograph of compression failure of patch repaired specimen without removing damage.

3.2 Specimens With Damage Removed and Replaced With Good Material

In order to ascertain if removing and replacing severely damaged areas with good material would help compression strength retention when using a patch repair technique, the damaged areas were cored out and removed from the specimen and replaced with undamaged plugs of material. Simply filling in the damage is acceptable to recover in-plane compression strength for small damage and holes as was shown in reference 1, but the core remains damaged and may be needed to support the repaired face sheet when more severe damage exists. Thus, replacing the damaged core with plugs of undamaged material was examined.

An abrasive coring bit of 1.5-inch diameter was used to cut a circle around the damage zone on the impacted face sheet. This size was sufficient to remove all of the damaged material as measured by thermography and cross-sectional examinations of damage. The typical damage zone was a circular area of 1.3-inch diameter (see fig. 5). The coring was continued through the honeycomb until the back face sheet was reached. A knife was then used to cut off the damaged face sheet (fig. 10a). The core that remained was removed with a router bit resulting in a 1.5-inch diameter hole through the specimen down to the back face sheet (fig. 10b).



(a) (b)

Figure 10. Technique of removing damage zone from impact damaged specimen.

Plugs of 1.4-inch diameter consisting of one face sheet and full thickness of core were cut from similar sandwich structure (fig. 11a) for placement into the 1.5-inch diameter hole that resulted after the damage zone had been removed. These plugs where placed such that the core and face sheet aligned with the parent sandwich structure. An epoxy paste adhesive was liberally applied both in the hole and to the outside of the plug before insertion. The excess paste adhesive that came out of the ring between the plug and parent material when the plug was pushed in was removed and the plug left to cure in place. Once cured the surface was abraded smooth and the patch was ready to be applied (fig. 11b).

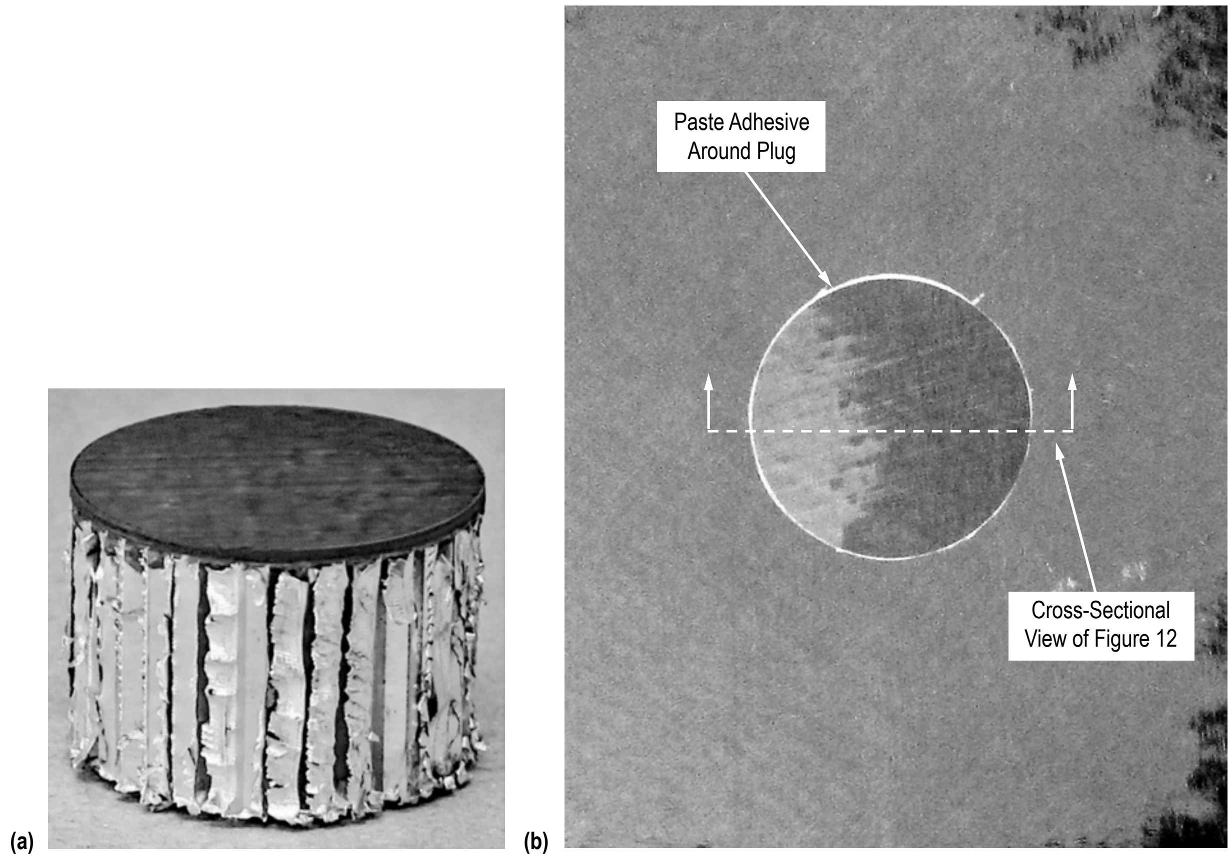


Figure 11. Photograph of: (a) plug and (b) plug inserted in specimen. Location of cross section in figure 12 indicated on image on right.

The patches used for these specimens were similar in size and layup to those used in section 3.1 of this TM, however, the carbon/epoxy prepreg used to make these patches was IM7/TC350 since no additional IM7/5320-1 material was available. This material also had similar modulus and strength as the parent material (IM7/8552-1) since the fiber is the same. A few variations on patch size were attempted and are noted in the text that follows. Cross-sectional photographs (one overall and one detailed) of a repaired specimen with pertinent features noted is shown in figure 12. Note that the patch has some porosity in it despite efforts to produce void-free laminates. Four specimens were repaired with patches identical in layup and size to figure 7, and table 4 presents the compression strength result of these four plug repaired specimens. A fifth specimen used a slightly larger patch but its results are included with these. A photograph of failed specimen Plug-4 is shown in figure 13 to give the reader an idea of what is meant by a break 'under patch through repaired area'. This type failure is indicative of the patch not carrying enough load to bypass the damage zone and fail within the patch. It was at first thought that end brooming would be the dominant failure mode since the first two specimens failed in this manner and a redesign of the specimens would be in order after the first two tests, however the next two (and all subsequent tests) did not fail by end brooming. No explanation for this is known. The failure mode is noted for the specimens however using postmortem inspection to identify how these specimens actually failed can be difficult since the failures of these specimens was so sudden and violent. Some of the damage seen after failure may be attributed to the shock wave that the specimens experience upon failure.

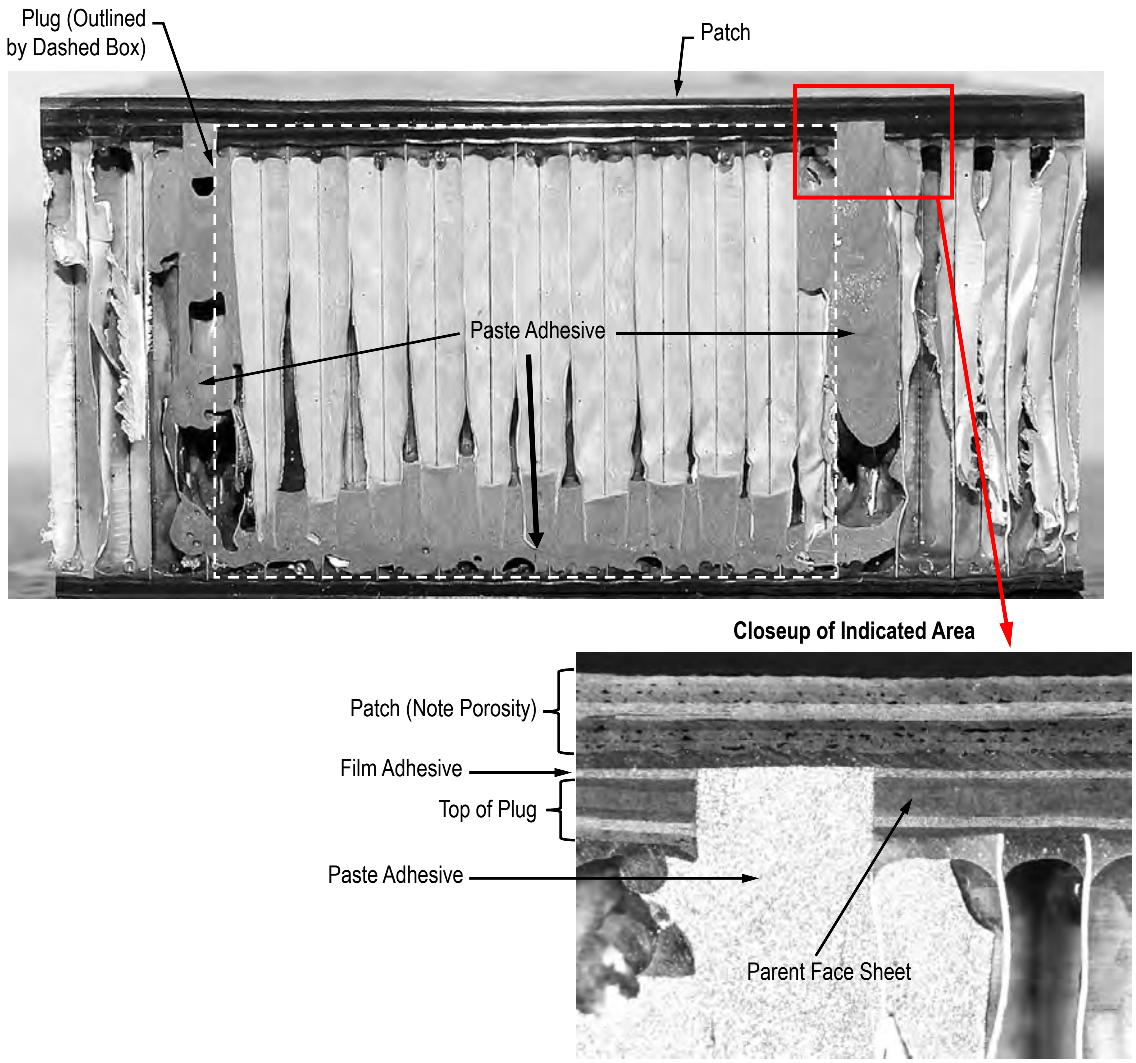


Figure 12. Cross section of repaired specimen with damage removed and replaced with plug of good material.

Table 4. Compression strength results of repaired specimens with damage removed and plug inserted.

Specimen	Patch size (in)	Compression Strength (ksi)	Failure Mode
Plug-1	4	88.6	End broom
Plug-2	4	78.9	End broom
Plug-3	4	79.9	Through patch
Plug-4	4	79.3	Under patch through repaired area
Plug-5	4.25	88.5	Under patch below repaired area
	Average	**83.0 ± 5.0**	

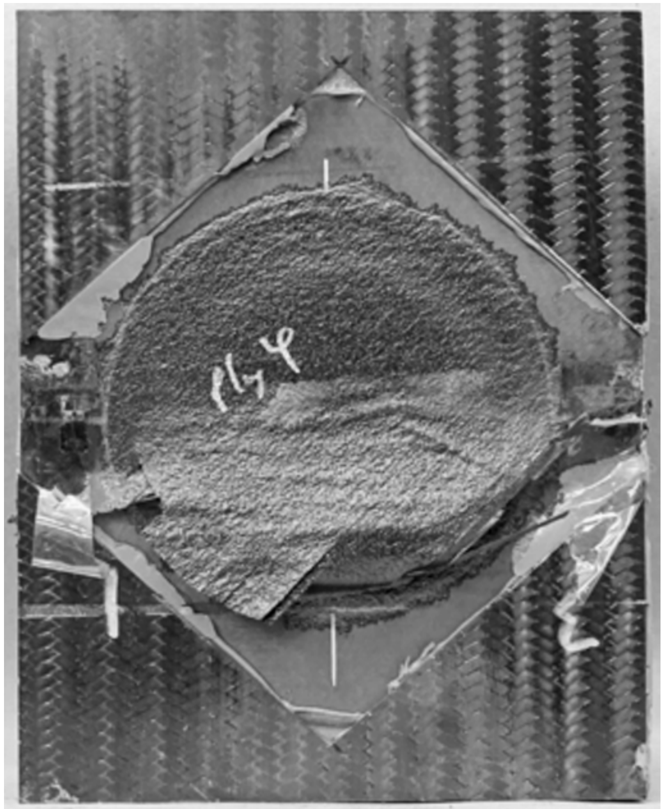


Figure 13. Photograph of ‘plug-4’ failure showing failure mostly under the patch and not through the patch as seen in figure 9.

The average value of 83 ksi is an improvement over the 72.2 ksi achieved for the repaired specimen without removing the damage indicating that, unlike small damage and holes, the damaged core may need to be replaced for more severe damage if more compression strength is required of the sandwich structure.

Next bigger patches were tested in an effort to get the average compression strength even closer to the measured 88.8 ksi average compression strength of undamaged specimens. The size and layup of these patches are shown in figure 14.

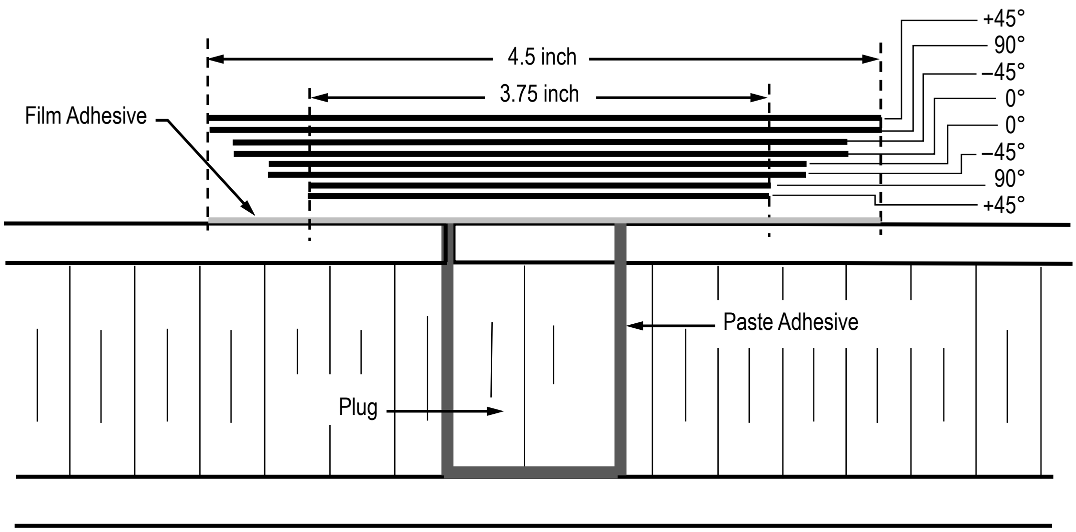


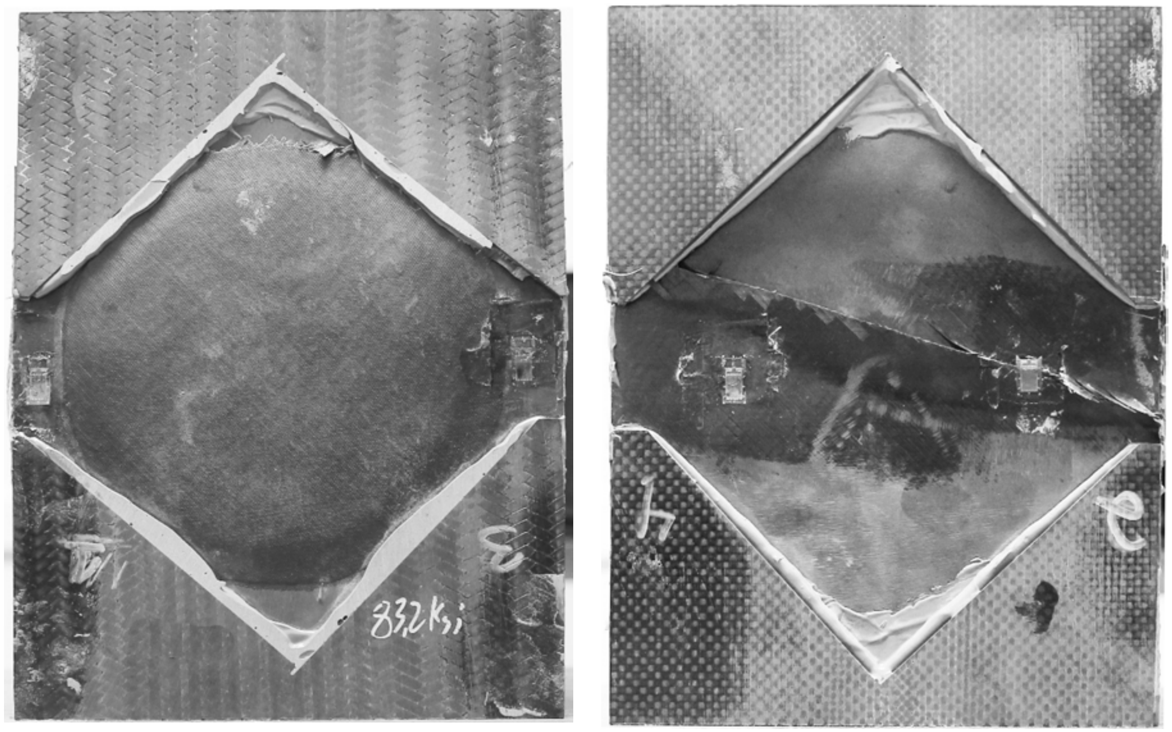
Figure 14. Schematic of plug repair using largest patches.

Results of five specimens tested with the largest patches are presented in table 5. These results indicated no additional increase in repaired compression strength over the smaller patches tested and it was concluded that about the most compression strength that could be regained using the plug repair technique in this study was on average about 93% of the average undamaged compression strength of 88.8 ksi.

Table 5. Compression strength results of repaired specimens with damage removed and plug inserted using largest patches.

Specimen	Compression Strength (ksi)	Failure Mode
Large Patch-1	88.1	Broke on unrepaired side
Large Patch-2	85.7	Broke on unrepaired side
Large Patch-3	76.9	Broke in patch
Large Patch-4	83.2	Broke on unrepaired side
Large Patch-5	78.7	Broke at top of patch
Average	**82.5 ± 4.7**	

Figure 15 shows a failure of the unrepaired side of the specimen which occurred in 3 of the 5 specimens. The compression strength values of these are higher than the other 2 but this failure mode could not be consistently achieved.



Front (Repaired Side)

Back (Undamaged-Unrepaired Side)

Figure 15. Photograph of large patch specimen failure showing failure on unrepaired face.

3.3 Specimens With Repair Patches of Woven Cloth (Fabric) Prepreg

A series of repair techniques using patches made of woven cloth prepreg instead of unidirectional prepreg were attempted. This was done since working with woven material is a little easier than working with unidirectional tape. For this series of tests, the plug replacement technique was utilized.

The prepreg cloth material used for the patches was T650/5320 plain weave fabric. This fiber is different that the fiber used throughout the rest of this study (IM7) and has about 14% less compression modulus. As a first attempt a simple quasi-isotropic layup $[+45/-45_f, 0/90_f]_S$ (subscript f denoting one ply of fabric) of the patch was used with an outer diameter of 4 in. A schematic of this layup is shown in figure 16.

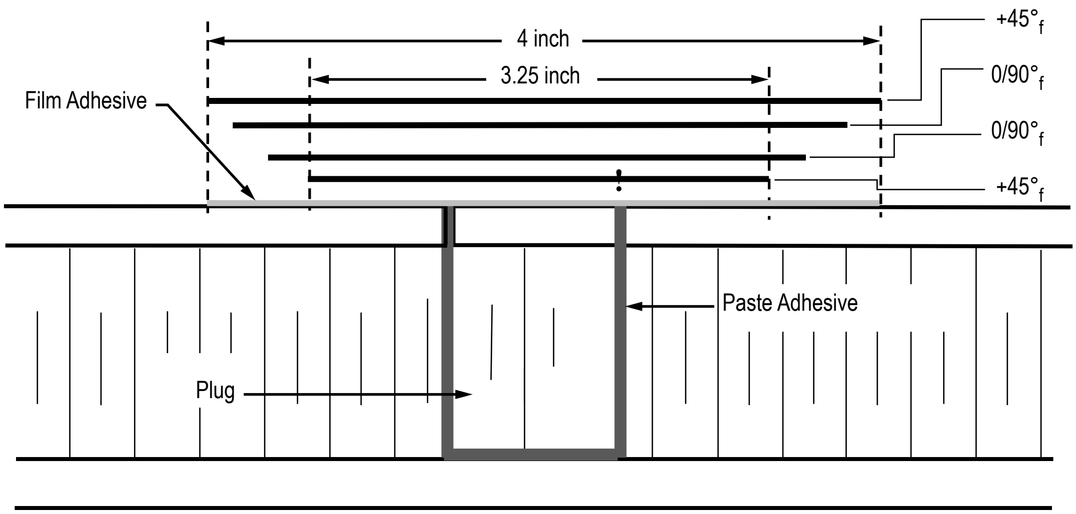


Figure 16. Schematic of plug repair using patches of woven cloth prepreg.

Testing of two specimens gave compression strength values of 67.6 and 68.3 ksi with the failure zones being under the patch (the patch was still intact after failure). A photograph of one of these failed specimens is shown in figure 17. The relatively low values and fact that the failure was under the patch was attributed to the woven material having a lower modulus than the parent material (and thus not carrying enough load, putting too much load into the damaged material). The parent sandwich structure has a face sheet modulus of 8.3 Msi while the woven quasi-isotropic patch had a calculated value of about 7.2 Msi. A few different layups were attempted to match the stiffness of the parent material so that equal strain would be carried by the patch and the surrounding good material.

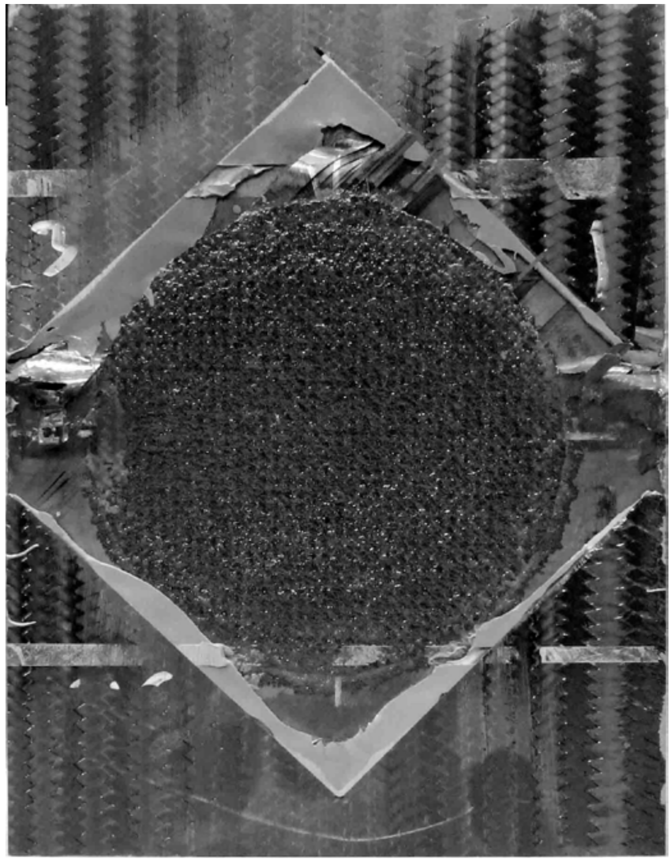


Figure 17. Failure of repaired specimen with quasi-isotropic layup of fabric repair patch. Note failure zone is under patch.

Next, the patch was made stiffer by adding an extra 0/90 ply such that the layup was $[+45/-45_f, 0/90_f, 0/90_f, 0/90_f, +45/-45_f]$, which has a modulus of 7.9 Msi. Two specimens tested with this slightly stiffer patch gave compression strengths of 76.9 and 74.2 ksi which was an improvement over the less stiff fabric repair patch and the failure zone was mostly through the patch. In order to try to reach around the 83 ksi compression strength values achieved by the unidirectional tape, yet another 0/90 ply was added such that the layup was $[+45/-45_f, 0/90_f, 0/90_f, 0/90_f, +45/-45_f]$ which has a modulus of 8.3 Msi which matches that of the face sheet. This specimen gave a compression strength of 76.9 ksi and failed mostly through the patch. Another 0/90 ply was added to the patch of the next specimen (modulus of patch now 8.6 Msi) and the compression strength was measured at 70 ksi with the failure being through the patch. As a final test a four-ply all 0/90 patch (modulus of 10.0 Msi) was used and the measured compression strength was 73.1 with the failure being through the patch as expected due to the high stiffness of the patch which causes the patch to carry excess load. A summary of the compression strength results of the fabric patch specimens is given in table 6.

Table 6. Summary of fabric patch repaired specimens.

Specimen	Patch Lay-Up	Patch Stiffness (Msi)	Patch Thickness (in)	Failure Stress (ksi)	Failure Zone
Cloth-1	$[+45/-45_f,0/90_f]_S$	7.2	0.032	67.6	Under patch
Cloth-2	$[+45/-45_f,0/90_f]_S$	7.2	0.032	68.3	Under patch
Cloth-3	$[+45/-45_f,0/90_f,0/90_f,0/90_f,+45/-45_f]$	7.9	0.040	76.9	Across top of patch
Cloth-4	$[+45/-45_f,0/90_f,0/90_f,0/90_f,+45/-45_f]$	7.9	0.040	74.2	Through patch center
Cloth-5	$[+45/-45_f,0/90_f,0/90]_S$	8.3	0.048	76.9	Through patch center
Cloth-6	$[+45/-45_f,0/90_f,0/90_f,0/90_f, 0/90_f, 0/90_f, +45/-45_f]$	8.6	0.056	70.0	Through patch center
Cloth-7	$[0/90_f,0/90_f,0/90_f, 0/90_f]$	10.0	0.032	73.1	Through patch center

Using cloth prepreg instead of unidirectional prepreg did give higher compression strengths than no repair, but even the highest compression strength values were a little lower than the average strength value of repairs using the unidirectional prepreg.

4. SUMMARY AND CONCLUSIONS

The measured undamaged compression strength of sandwich structure is more a test of the test specimen and testing methodology than a representation of its actual structural compressive load carrying capability. This indicates that allowables for compression strength of undamaged sandwich structure are not a true material property since sandwich structure is not a 'material,' and allowables cannot be established. This conclusion has more important implications that are beyond the scope of this study and will be addressed in a separate TM.

In reference 1 it was found that the damaged material need not be excised and replaced with good material in sandwich structure with small impact damage and holes to regain all of the measured undamaged compression strength. For severe impact damage examined in this study, only 81% of the compression strength could be recovered if damage is not removed and replaced. Replacing the damage with a plug of good material was shown to maximize compression strength, with only about 93% of the average measured compression strength being recovered in the specimens tested in this study.

Patches made from unidirectional prepreg tape yielded repaired specimens with higher average compression strength than patches made from woven cloth prepreg although good strength recovery could be obtained with the patches made from woven cloth prepreg.

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14. ABSTRACT
This Technical Memorandum presents results from a repair study on sandwich structure supporting Payload Adaptor Fitting for Space Launch System. A previous study found all measured in-plane compression strength could be regained for sandwich structure with small-impact-damage patch repair without removing damaged material. Sandwich structure with more severe damage was examined. Using patch repair like in the previous study, about 81% of measured undamaged compression strength could be regained without removing damaged material, and about 93% of average measured undamaged compression strength could be regained if damaged area was removed and replaced with a plug of good material.

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