MANUFACTURE OF COMPOSITE TUBE SPAR WING ASSEMBLY MANUFACTURING DEMONSTRATION UNITS WITH MATRIX REFLOW JOINTS

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ABSTRACT

The manufacturing process for a tubular spar wing assembly is presented with focus on a novel spar-to-skin bonding technique. Two manufacturing demonstration units (MDU) are described. Each MDU consisted of two tubular spars bonded to a skin panel. Both composite spars had the same laminate configuration but were manufactured by different methods. In this study, three of the four spars were created by using steel clamshell tooling. Plies were laid down onto two halves of the steel clamshell tools and then spliced together when the tools were closed together; next the plies were envelope-bagged to the steel tools and cured in the autoclave. The last spar was manufactured by wrapping plies around a wash-out mandrel, which was removed after cure. The wash-out process involves removing the tool by spraying pressurized water. The spars were bonded to a wing-skin panel in a secondary cure process. During the initial cures of the spar and skin panel, each of the surfaces that were to be bonded during the secondary process had an outer prepreg layer containing a higher epoxy volume fraction than typical prepreg plies. This epoxy was un-reacted during the initial cure. During the secondary cure, prepreg with additional hardener was added at the joint interface, along with a layer of adhesive. This bonding process resulted in a joint comparable to a co-cured assembly rather than a traditional adhesive bond. The two different MDUs had subtle variations in the secondary bonding process. Coordinate measurement machine (CMM) three-dimensional (3D) scans of the two MDUs revealed that the MDU that used an envelope bag during secondary cure was more warped than the MDU that had been bagged to a flat tool surface. Hardener rich ply orientation may have also played a role in level of warp observed in the MDUs.

Keywords: bonded joints, reflowable interface, polymer matrix composites
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1. INTRODUCTION

Adhesively bonded joints offer many advantages over traditionally fastened structures including faster assembly time, reduced stress concentrations, and reduced weight. However, even very minor amounts of contamination during the manufacturing process can result in weak and unreliable bonds [1]. Due to the possible variability in bond quality, certifying agencies such as the Federal Aviation Administration (FAA) typically require redundant load paths for civil

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transport aircraft to be certified. The latent cure, offset-stoichiometric, matrix-reflow composite bonding method [2] developed at NASA, known as AERoBOND, has been shown to enable more reliable, higher quality bonds than traditional adhesive bonds [3]. However, while the AERoBOND method has proven to be successful in coupon and sub-element level trials, it has yet to be proven for larger structures.

The NASA Advanced Air Transport Technology (AATT) project has considered the transonic truss-braced wing configuration to reduce fuel consumption and emissions in next generation commercial aircraft. Recently, AATT began design and manufacture of the Structural Wing Experiment Evaluating Truss-bracing 15-ft (SWEET-15) subscale truss-braced-wing test article. The SWEET-15 team identified AERoBOND as a strong candidate to include as a technology demonstrator on a 2.17-meter subassembly of its 4.6-meter (15-ft) subscale truss braced wing assembly. Prior to incorporating AERoBOND into the final SWEET-15 test article, multiple risk-reducing manufacturing demonstration units (MDU) were created. The detailed fabrication process of the MDUs is described herein.

The initial goal of the AERoBOND project was to achieve co-cure joint performance by using a secondary-bonding manufacturing process [4]. Problems arise for adhesive bonds due to material discontinuity at the joint interface—these discontinuities allow more susceptibility to defects and imperfections. Having matrix reflow in the secondary bonding process results in an assembly without a material discontinuity, and a more monolithic assembly is achieved compared to traditional adhesive bonding. Additionally, the AERoBOND curing process and matrix reflow are able to be monitored in-situ during the cure [5, 6], which can enable reduced inspection of the final part. The matrix reflow is enabled by including epoxy-rich (ER) prepreg at the joint interface of the parts to be bonded during the part primary cure. The parts then undergo a secondary cure during which hardener-rich (HR) prepreg is added between the parts at the joint interface. The unreacted epoxy from the primary cure then reflows and reacts with the extra hardener in the added HR prepreg. The matrix reflow process results in a continuous material across the material interface, which would not be the case with a traditional secondary bond.

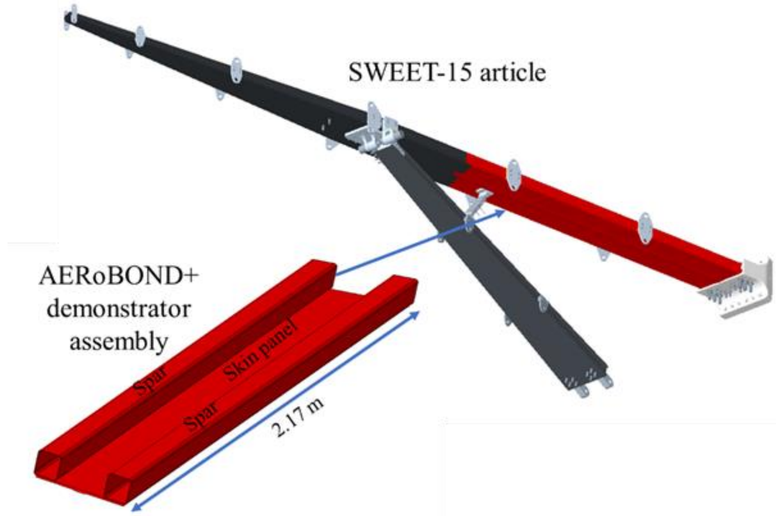
The standard AERoBOND process required tight spatial tolerances between the mating parts, making it less ideal particularly for parts with complex curvature. To make AERoBOND more applicable to parts with looser manufacturing tolerances, a hybrid approach, henceforth referred to as AERoBOND+ was developed [4]. The AERoBOND+ method involves the addition of an adhesive layer in between the HR prepreg plies that are added during the secondary bonding process. The AERoBOND+ formulation demonstrated comparable fracture toughness at the interface to both co-cured and conventional adhesively bonded joints [4].

In addition to the use of AERoBOND+, the SWEET-15 team sought to employ tubular spars and integrally stiffened skin panels in the test article. Tubular spars enabled a ribless, multi-bay-like design to reduce part count and weight as compared to other explored designs. Integrally stiffened skin panels provide local reinforcement and can alleviate buckling concerns, while reducing the part count and removing the need for fasteners [7, 8]. For more details about the design process of the SWEET-15 article, the reader is referred to [9].

This paper is organized as follows. First, details are presented about the manufacturing processes used for the subcomponents involved in the MDUs, namely, the tubular spars and the integrally stiffened skin panel. Second, the manufacturing process required for the AERoBOND+ method is described in detail. Next, the specifics of and differences in the manufacturing process for each MDU are detailed. Finally, the resulting as-built MDUs are described, manufacturing distortions of each MDU are quantified by coordinate measuring machine (CMM) three-dimensional (3D) scan, and lessons learned about best manufacturing practices are shared.

2. METHODS

The SWEET-15 test-article assembly and the subassembly that were used to demonstrate the



AERoBOND+ process are shown in
Figure *1*. Highlighted in red is the 2.17-m long AERoBOND+ demonstrator subassembly which consists of two tubular spars that will be bonded to a skin panel. Two shorter, 0.61-m and 0.31-m MDUs of the same two-spars-bonded-to-skin-panel configuration were produced as a risk-reduction activity prior to manufacture of the AERoBOND+ demonstrator subassembly. The manufacturing details for the spar and skin-panel subcomponents used in the MDUs are detailed in the following sections, followed by detail of the secondary bonding processes used to create the bonded risk reduction MDUs and detail of the CMM 3D scan methodology.

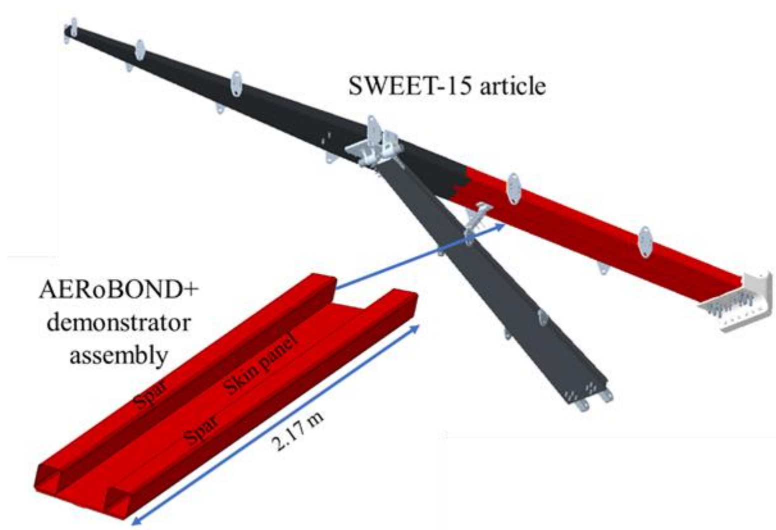


Figure 1. SWEET-15 article and AERoBOND+ demonstrator assembly.

2.1 Spar Manufacture

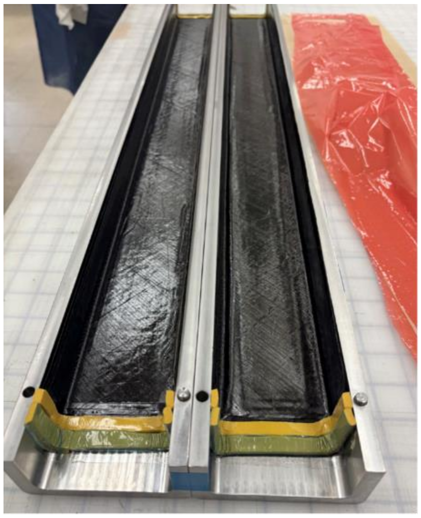
The spars were manufactured using two methods. Early test-article-manufacture plans used spars manufactured via clamshell molds that controlled the outer surfaces of the tubular spars. As the plans for the final assembly evolved, an alternate manufacturing plan using wash-out mandrels was selected to reduce risk associated with removing the full-size spars from the mold, while also allowing more distributed ply splices around the circumference of the spars.

2.1.1 Clamshell tooling spar manufacture

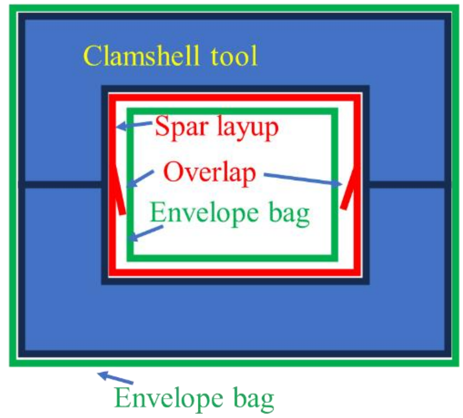
Metal clamshell tools were utilized for layup of the tubular spars and are shown in Figure 2 (a). The clamshell tool set consisted of an upper and lower clamshell. Plies were laid up inside of both the upper and lower clamshells. The upper clamshell had slightly longer plies that extended past the vertical walls of the tool and were meant to overlap with the laminate on the opposing tool. Upon closing the clamshell tools, this overlap region [Figure 2 (b)] of the upper plies was pressed into the plies on the lower tool. After layup, an envelope bag was created to apply pressure from within the center of the spars, pressing the layup onto the tool surface.

Prior to layup of the regular ply schedule on the lower clamshell tool, a unidirectional ER 0° ply, where 0° is aligned with the SWEET-15 spanwise direction, was laid down for post-joining to the skin panel using the AERoBOND+ process. Two separate spars were made with this clamshell process. The layup of the first spar used the Hexcel®[‡] IM7-8552 plain weave material, following the $[0°/90°, \pm45°]_{4s}$ layup schedule. The layup of the second spar used the IM7-8552 unidirectional material, following a $[0°/45°/90°/-45°]_{2s}$ layup schedule. The nominal thickness of the cured unidirectional IM7-8552 material was 0.18 mm and for the plain weave IM7-8552 the nominal ply thickness was 0.20 mm. The spars produced by the clamshell molds were 0.76 m in length and had a 7.62-cm x 7.62-cm box shape with 0.64-cm radius corners. The plain weave spar was later cut down in length into two 0.31-m long spars.

[‡] Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the hardware and materials used in this study. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified product is the best available.



(a)



(b)

Figure 2. (a) Metal clamshell tools and spar layup, (b) bagging method.

2.1.2 Wash-out tooling spar manufacture

One spar was fabricated using the wash-out tooling approach. Wash-out tooling is a general term for a tool made from ceramic sand or silica that can survive the cure process. Post-cure, the tooling can be washed away from inside of the cured composite part with cold tap water. Wash-out tooling allows a tooling surface that would otherwise be difficult to remove from the final cured part. This spar was laid up by hand around a wash-out mandrel as pictured in Figure *3* (a). Rotisserie-style tool handling allowed for ease of part rotation during layup as pictured in Figure 3 (b). The wash-out-tooling-produced-spar was of the same dimensions as the clamshell-tooling-produced-spars and used a $[0°/45°/90°/-45°]_{2s}$ layup of unidirectional IM7-8552. Unlike the clamshell-tooling-produced-spars that required the ER ply to be placed prior to the layup, with the wash-out-tooling-produced spar, the ER ply was placed on top of the final layup. The difference in sequence of the ER ply placement was due to the clamshell tools controlling the outside spar surface, whereas the wash-out tool spar controlled the inside spar surface, so the plies in general were placed in a different order. Afterward, an exterior vacuum bag was placed around the part as shown in Figure 3 (c).

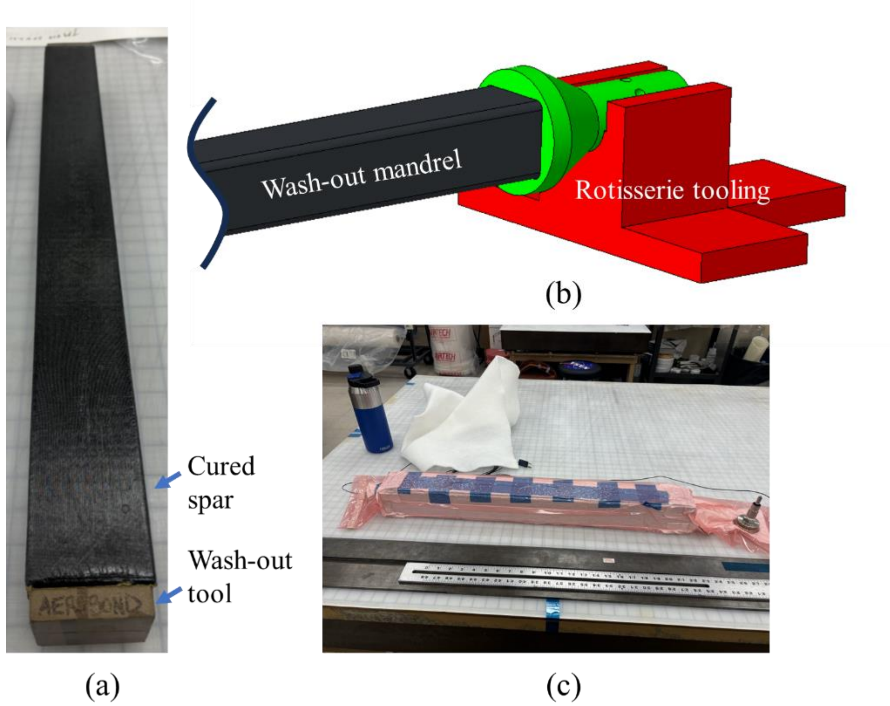


Figure 3. (a) Cured spar on wash-out tool, (b) rotisserie tooling for mandrel layup, (c) bagged spar and wash-out tool.

2.2 Skin Panel Manufacture

Two skin panels were laid up by automated fiber placement (AFP) using the Integrated Structural Assembly of Advanced Composites (ISAAC) robot at NASA Langley Research Center [10]. Stiffener plies were staggered and interleaved through the skin plies. The panel had the layup of $[[90°/(90°/0°)_2/0°/(90°/0°)_2/\text{-}45°/(90°/0°)_2/45°/(90°/0°)_2]_2]_s$ where the $(90°/0°)_2$ groupings are integral stiffener plies only, and do not cover the entire panel acreage. The panel dimensions were 40.64 cm x 71.12 cm with two integral stiffeners along the shorter dimension and one along the longer dimension (Figure 4). The integral stiffeners were interleaved during the layup of the panel. The material used for the skin panel was IM7-8552 0.25-in.-wide tow-preg.

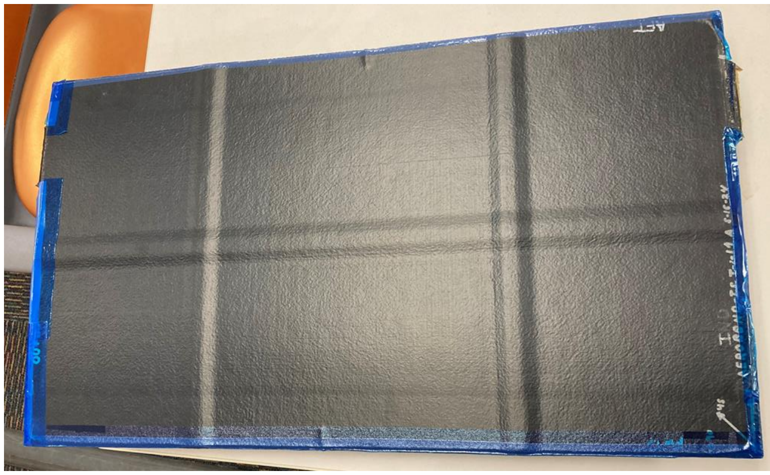


Figure 4. Integrally stiffened panel.

Special care was required to add the ER plies required for the AERoBOND+ process to the skin panel. To fabricate the first skin panel, first the ER plies were placed on the layup or mold surface, and then plies were placed on top of the ER plies using a robotic AFP process. During the AFP layup over the ER plies, the ER plies had more tackiness than the tow-preg used to create the regular plies. The additional tackiness in the ER plies resulted in frequent adhesion of the ER plies to the AFP roller that is used to press down the new course of prepreg to the laminate, resulting in distortion of the ER plies. While the ER ply tackiness issue and distortion were able to be dealt with during the layup process, and the part was successfully manufactured, the second skin panel was manufactured differently to avoid delay in the manufacturing process.

During manufacture of the second panel, peel-ply was placed on the layup surface prior to placing the laminate via AFP. This peel-ply was approximately the thickness of the ER plies and was used as a placeholder for the ER plies. Prior to cure of the skin panel, the panel was flipped upside-down onto a caul plate to support the integral stiffeners and the peel-ply was removed by hand and manually replaced with ER plies. After the addition of the ER plies, the panel was flipped back over with the ER plies on the tooling surface and the part was bagged and cured.

Special care was required during the bagging and curing for the integrally stiffened panels to ensure that the stiffeners did not distort under autoclave pressure. A matched caul plate was used to distribute pressure on the panel and maintain the desired shape of the integral stiffeners. The matched caul plate was made from silicone that was poured directly onto a bagged skin panel and cured in place. Then, a second vacuum bag was attached the caul plate to outside of the first vacuum bag. By curing the caul plate in place on top of the integrally stiffened panel, the shapes of the integral stiffeners were preserved.

2.3 Secondary Bonding Process

The AERoBOND+ process was used to bond the two spars to the panel. The layup for the AERoBOND+ process consisted of two layers of Syensqo® (formerly Solvay®) FM209-1U adhesive sandwiched between two layers of HR prepreg. These four layers were placed in between the mating parts as shown in Figure 5 (a). The partially cured ER ply was part of the initial layup of the separate parts that had already been cured, whereas the HR plies and adhesive were uncured and added prior to the secondary cure. Using lessons learned from the first MDU (subsequently referred to as MDU 1), custom 3D-printed spacing tools were used during MDU 2 to set spar spacing and alignment indicators were carefully added in marker to ensure appropriate placement of the spars on the skin panel [Figure *5* (b)]. Finally, adhesive fillets were placed in the corners where the spars meet the skin panel [Figure 5 (c)] prior to bagging and secondary cure.

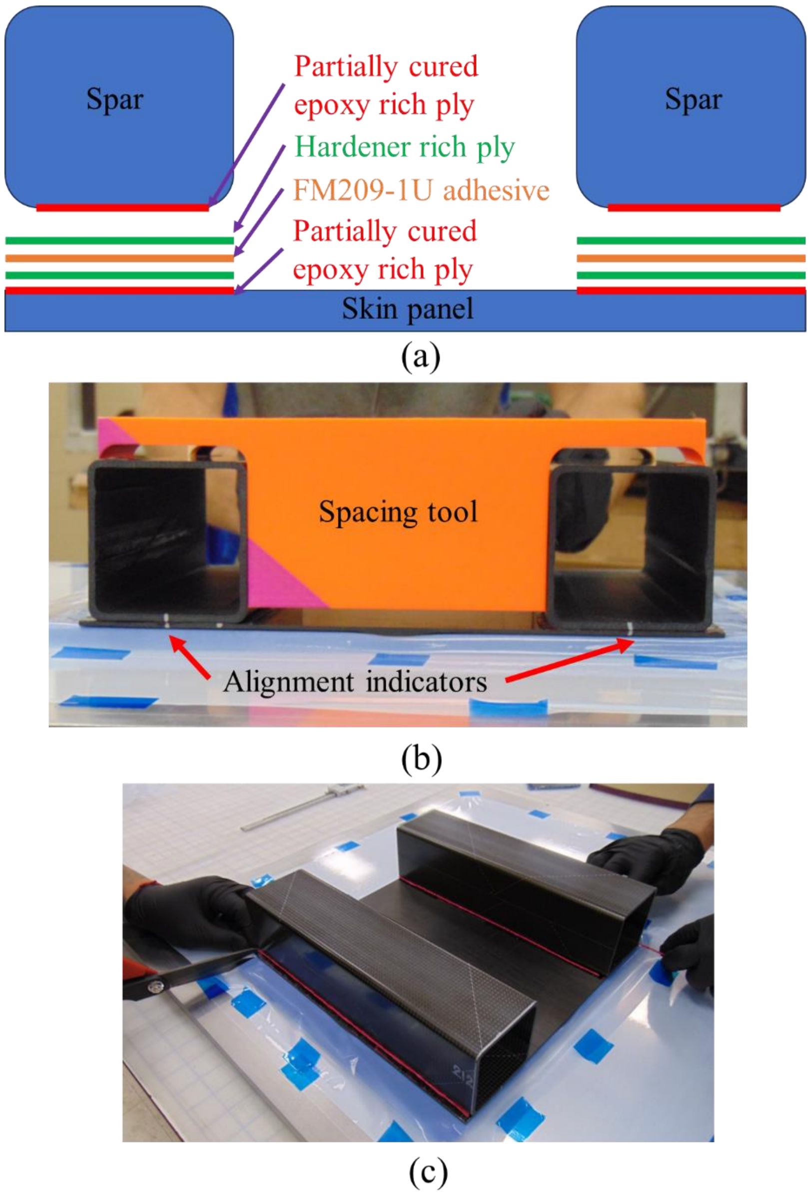


Figure 5. (a) AERoBOND+ layup scheme, (b) alignment tooling and features, (c) adhesive fillets (red).

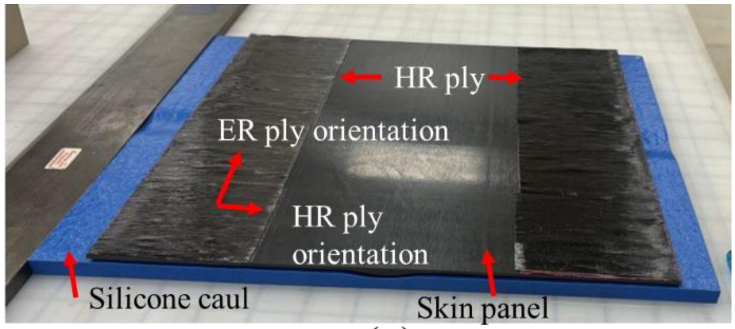
2.4 First Manufacturing Demonstration Unit

MDU 1 was created using the wash-out tooling spar and the unidirectional layup clamshell tooling spar. MDU 1 was 71.12-m long and 40.64-cm wide. For MDU 1, the skin panel extended 5.72 cm past the edges of the spars, as shown in Figure 6. The wash-out mandrel was left inside of the spar for the secondary bonding process. The HR plies were placed with the fibers in the same direction as the fibers of the ER plies, along the length of the spar. For the secondary cure of MDU 1, an envelope bag was created around the assembly.

Figure 6. MDU 1 spar side.

2.5 Second Manufacturing Demonstration Unit

MDU 2 was created by cutting the plain weave clamshell-tooling-produced spar in half to have two 0.31-m long spars to bond to a shorter 0.31-m x 0.31-m wide skin panel. In this case, the fibers of the HR plies were placed perpendicular to the fibers in the ER plies to reduce part warpage, as shown in Figure 7 (a). Instead of placing a HR ply on each mating subcomponent, the HR ply, adhesive, and HR ply stack was placed onto the skin panel, so that the spars could be placed onto the skin panel without the added complexity of having uncured plies on both mating surfaces. Additionally, instead of the envelope bag used in MDU 1, for MDU 2, the assembly was bagged to a tool surface as shown in Figure *7* (b). Due to the integral stiffeners on the part, the caul plate with the print of the integral stiffeners was placed in between the assembly and the tool surface.



(a)

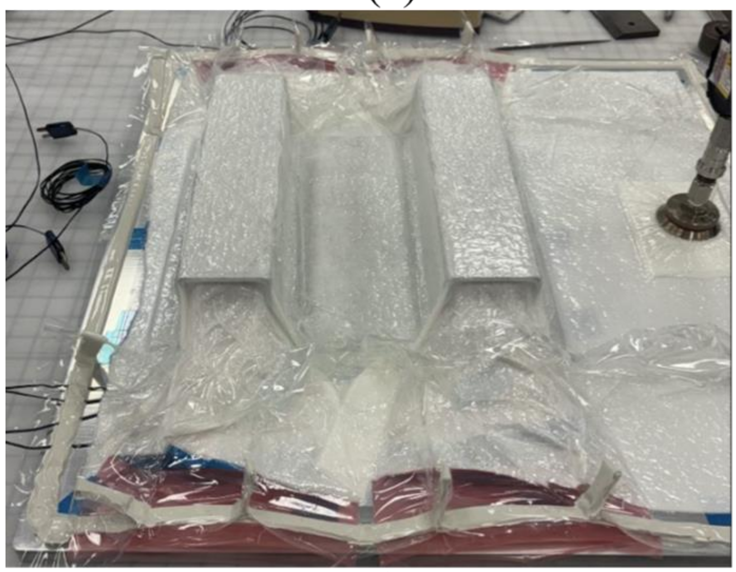

(b)

Figure 7. (a) HR plies on MDU 2 skin panel, (b) bagged MDU 2 assembly.

2.6 3D Scanning via Coordinate Measuring Machine

In order to assess whether warping occurred during the secondary cure of each MDU, a coordinate measuring machine (CMM) was used to 3D map the surface of the skin panel in each assembly. To assess flatness, a selected surface area was used to calculate a theoretical plane based on root-mean-square (RMS) values. This plane served as a baseline for a 3D comparison image, providing both statistical values and a visual representation of deviations. The plane was defined based on the panel surface but excluded the integral stiffener surfaces.

3. RESULTS

3.1 First Manufacturing Demonstration Unit (MDU 1)

The final assembly produced for MDU 1 is shown in Figure 8 (a). Warping of the part was observed. As seen in the 3D scan of MDU1 [Figure 8 (b)], severe out of plane deviation occurred near the edges of the part, with a difference in out-of-plane location of as much as -8.0 mm as compared to the reference plane. The distortion may be attributed to the vacuum bagging layup scheme, which may have allowed the part to develop nonuniform pressure during cure, and the coefficient of thermal expansion (CTE) of the fibers of the HR plies causing warpage during cure.

Typical properties of CTE for unidirectional carbon reinforced epoxy composites are 1.35e-6 1/°C in the longitudinal direction and 3.61e-5 1/°C in the transverse direction. As the CTE is significantly higher in the transverse direction, and warpage was observed primarily transverse to the HR plies, it was believed that by orienting the HR plies transverse to their original orientation, warpage could be reduced. For these reasons, MDU 2 was produced with the HR plies in an alternate orientation, as well as with the assembly bagged to a flat tool as opposed to using an envelope bag.

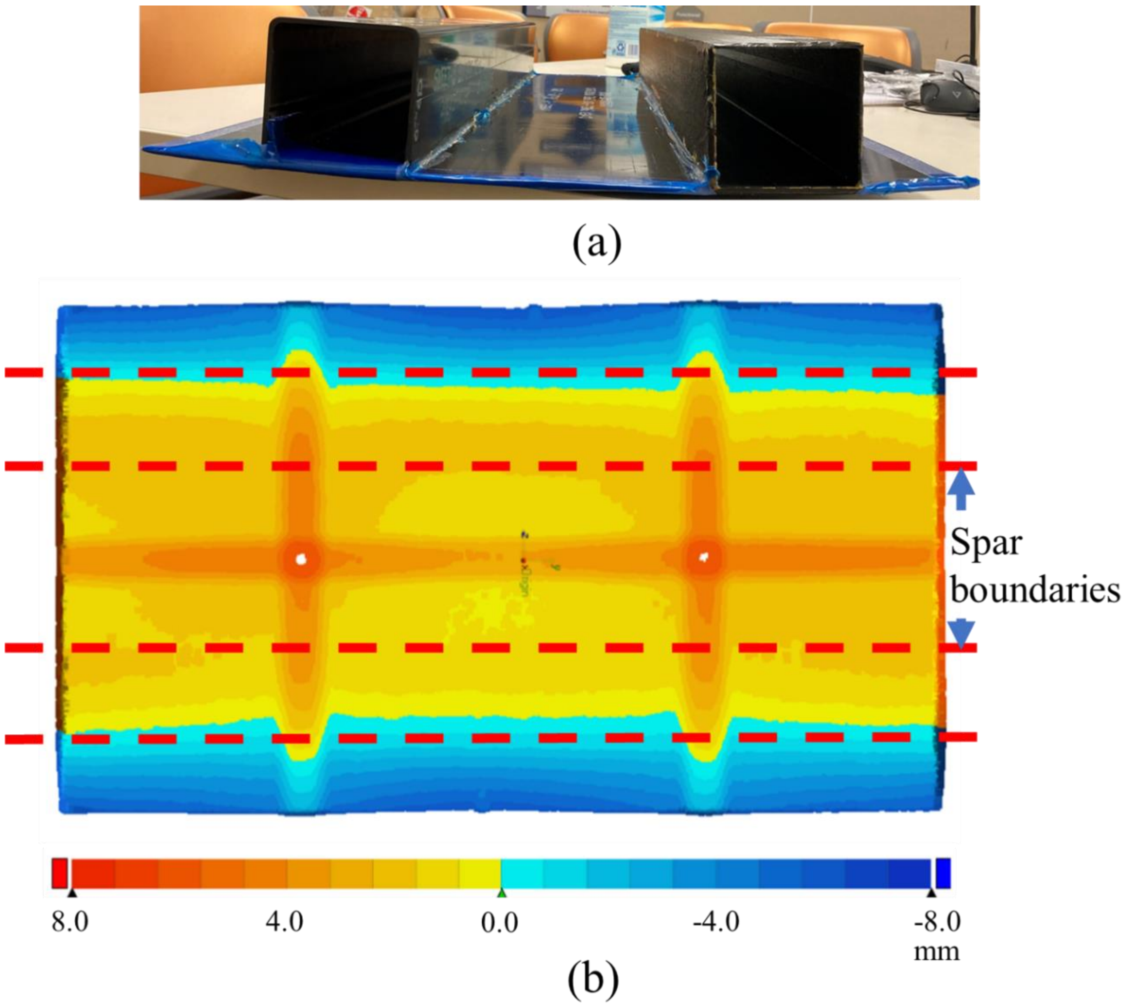
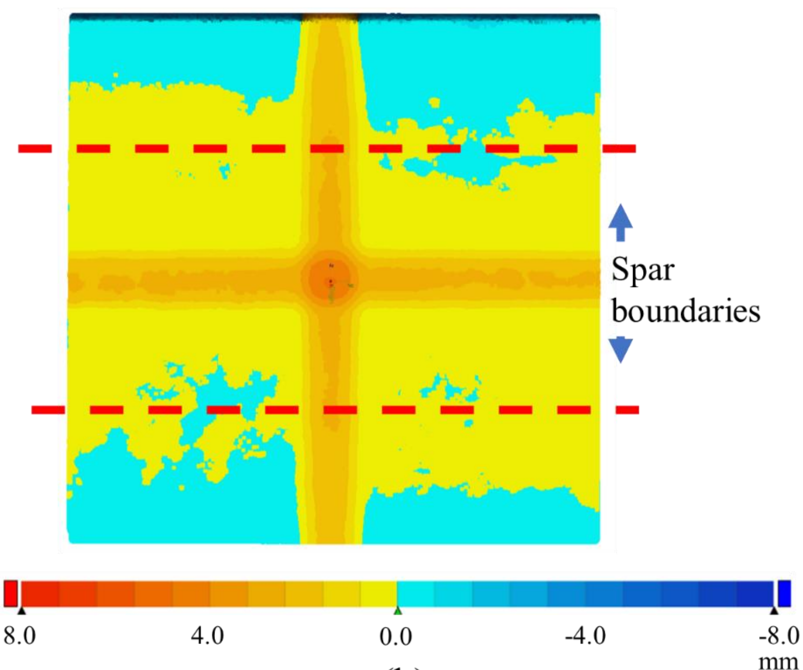


Figure 8. (a) As built MDU 1, (b) deviation from reference plane as obtained via CMM scan of MDU 1.

3.2 Second Manufacturing Demonstration Unit

The final assembly produced for MDU 2 is shown in Figu (a). No significant warping was visible to the naked eye. The CMM scan [Figu (b)] of the part revealed minimal part warping of MDU 2 as evident by significantly lower minima in deviation as compared with MDU 1 [Figure *8* (b)]. Out-of-plane deviation from plane surface at the edge of the part did not exceed 0.8 mm in MDU 2. Additionally, the total RMS distance to the theoretical plane for the entire surface was 1.01 mm for MDU 2, significantly smaller than the RMS value of 2.57 mm as observed for MDU 1. However, the integral stiffeners contributed to the RMS in both MDUs, as these portions of the scan were included in RMS calculation. Additionally, it is important to note that MDU 1 had portions of skin panel that extended past the spar boundaries and MDU 2 did not. This additional overhanging skin panel would not have been part of the final part and due to the curvature between the spars observed on MDU 1, the overhanging portion would be oriented more steeply out of plane and thus this additional portion of the skin panel on MDU 1 may also have contributed to the higher RMS value observed.

(a)



(b)

Figure 9. (a) As built MDU 2, (b) deviation from reference plane as obtained via CMM scan of MDU 2.

4. DISCUSSION AND CONCLUSIONS

In this work, multiple subcomponents were manufactured and bonded together via the AERoBOND+ process. The first manufacturing trial was deemed unsuccessful due to excessive part warping; however, part warpage was greatly reduced in the second manufacturing trial, and the manufacturing technique was deemed to be acceptable for the upcoming SWEET-15 test article fabrication. The part warpage was reduced by bagging the assembly to a tool surface instead of using an envelope bag, and by changing the orientation of the HR plies.

For composites, the thermal expansion is greater perpendicular to the fiber direction than in the fiber direction, as such, it was hypothesized that by changing the orientation of the HR plies, warping would be less likely to occur, as the fibers would be oriented perpendicular to the stiff box spars. There are implications to changing the HR ply orientation that mean additional changes will be necessary during manufacture of the final test article. The first implication is that the AERoBOND+ properties used for design of test article were taken from data in which the ER and HR plies were oriented in the same direction; no test data exists for a latent cure bond with the HR and ER plies oriented 90° to each other. Another possible implication is that the bond could be weaker with the HR and ER plies orthogonal to each other, as during matrix reflow, the fibers within the plies will not be able to nest together due to the orthogonal orientation and this could result in a weaker bond. To mitigate these concerns, the final test article will have both the HR and ER plies oriented along the width of the assembly.

One hypothesis about why the difference in bagging process may have been the main contributor to the warpage in the first MDU is that during the new bonding step, the lack of pressure on the skin panel outside of the spars during the autoclave process, coupled with the part being near the glass transition temperature during the cure of the HR plies and matrix reflow, allowed the parts to take on a new shape during the secondary cure. In order to de-couple the bagging effects from the hardener ply orientation, additional studies will be needed, however, due to the success of the second MDU that did not use an envelope bag, an envelope bag will not be used to fabricate the final test article.

Additional lessons were learned about the use of the wash-out tooling. While the wash-out tooling was not removed prior to the secondary cure step in this trial, it was learned that the presence of the wash-out tooling made it more difficult to ultrasonic testing (UT) scan the spar for quality assurance. Therefore, to enable better inspection of the spars, the wash-out tooling will be removed prior to the secondary cure in which the spars are bonded to the skin panel.

Several other manufacturing lessons were learned. First, placing a stack of HR ply, adhesive and HR ply onto the skin panel, and finally the spars (as done in MDU 2) was much easier than the method used in MDU 1 in which an HR ply was placed on both mating components before placing the spar on top of the skin panel. Additionally, difficulty in placing prepreg via AFP over top of the ER plies was observed, when compared to layup of the panel via AFP followed by placement of the ER plies after flipping the panel upside-down.

These manufacturing trials were deemed to be a successful risk mitigation in moving forward with the use of AERoBOND+ on the SWEET-15 assembly. While excessive warping issues were observed in MDU 1, these issues were able to be resolved as proved by the successful manufacture of MDU 2 as quantified by the significant reduction in RMS observed from CMM 3D scans.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Larson, R., Bergan, A., Leone, F., Kravchenko, O.G.: Influence of stochastic adhesive porosity and material variability on failure behavior of adhesively bonded composite sandwich joints. Compos. Struct. 306, 116608 (2023). https://doi.org/10.1016/j.compstruct.2022.116608
2. Palmieri, F.L., Hudson, T.B., Smith, A.J., Cano, R.J., Kang, J.H., Lin, Y., Abbott, L.J., Clifford, B., Barnett, I.J., Connell, J.W.: Latent cure epoxy resins for reliable joints in secondary-bonded composite structures. Compos. Part B Eng. 231, 109603 (2022). https://doi.org/10.1016/j.compositesb.2021.109603
3. Smith, A.J., Salem, J.A., Hudson, T.B., Palmieri, F.L.: Interlaminar mechanical performance of latent-cure epoxy joints. Compos. Part B Eng. 255, 110567 (2023). https://doi.org/10.1016/j.compositesb.2023.110567
4. Hudson, T.B., Smith, A.J., McWeeney, N.J., Dolph, C.T., Kang, J.H., Cano, R.J., Palmieri, F.L.: Offset-stoichiometric reflowable composite bonding method with adhesive for mitigating strict faying surface tolerances. Compos. Struct. 351, 118636 (2025). https://doi.org/10.1016/j.compstruct.2024.118636
5. Hudson, T.B., Smith, A.J., Cano, R.J., Kang, J.H., Lin, Y., Palmieri, F.L.: In-situ inspection of reflowable-interface composite joints during cure in an autoclave. In: AIAA Paper 2021-1773. Presented at AIAA Scitech Forum. Virtual Event (January 11-21, 2021)
6. Hudson, T.B., Baro, F., Smith, A.J., Kang, J.H., Cano, R.J., Palmieri, F.L.: Ultrasonic inspection during autoclave cure of reflowable-interface composite joints. J. Compos. Mater. 57, 3515–3528 (2023). https://doi.org/10.1177/00219983231188173
7. Cardona, A.M., Jegley, D.C., Lovejoy, A.E.: Manufacturing trials of integrally stiffened composite panels using automated fiber placement. Presented at the SAMPE Conference & Exhibition, Seattle, WA (April 17-20, 2023)
8. Cardona, A.M., Anderson, E.K., Simmons, L., Larson, R.A., Mason, B.H., Tury, J.: Manufacturing of aircraft structures using composite tailoring techniques. Presented at the SAMPE Conference and Exhibition, Indianapolis, Indiana (May 19-22, 2025)
9. Mason, B., Anderson, E., Cardona, A., Jutte, C., Larson, R.: Structural sizing of a tow-steered truss-braced wing box test article. AIAA Paper 2025-0637. Presented at the AIAA Scitech 2025 Forum , Orlando, FL (January 6-10, 2025)
10. NASA ISAAC Fact Sheet, FS-2016-12-273, 2021