DOT/FAA/TC-25/19

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Assessment of Emerging Metallic Structures Technologies through Test and Analysis of Fuselage Structure: Design, Fabrication and Assembly of Advanced Fuselage Panels using Fiber Metal Laminate Materials

February 2026

Final report

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

From DOT F 1700.7 (8-72) Reproduction of completed page authorized

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-25/19		

4. Title and Subtitle Assessment of Emerging Metallic Structures Technologies through Test and Analysis of Fuselage Structure: Design, Fabrication and Assembly of Advanced Fuselage Panels using Fiber Metal Laminate Materials	5. Report Date February 2026 6. Performing Organization Code ANG-E281
7. Author(s) Paul Jonas, Ron Weddle, Matthew Webb	8. Performing Organization Report No.
9. Performing Organization Name and Address NIAR – FirePoint Innovations 1855 Innovations Blvd. Wichita, Kansas 67208	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Policy and Standards Division Technical Policy Branch, Airframe Section, AIR-622 2200 S 216th Street Des Moines, WA 98198 .	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

To effectively gauge the advancements in Emerging Metallic Structures Technologies (EMST), a collaborative effort involving Arconic, Embraer, the National Institute for Aviation Research (NIAR) and the Federal Aviation Administration (FAA) has been undertaken. This collaboration focuses on the development of a full-scale fuselage structure test article and coupon level testing to conduct damage tolerance investigations. These investigations leverage the FAA's Full-Scale Aircraft Structural Test Evaluation and Research (FASTER) facility and Structures and Materials Lab capabilities. The primary objective of this consortium is to assess the viability of integrating these cutting-edge materials into a full-scale aircraft fuselage structure. This follows the creation and testing of three initial test articles, which were instrumental in evaluating the crack growth and eventual structural failure.

The project has expanded to include the design, production, and assembly of two additional fuselage segment test articles, known as Panels 4 and 5. These panels are designed with a blend of aluminum alloys and Fiber Metal Laminates (FML) cobonded to a monolithic skin, forming hybrid skin structures. Conventional aluminum frames, shear ties, and stringers are joined using rivets to the hybrid skin structures. Panel 4 is distinguished by its bonded skin assembly, featuring an FML hybrid layup bonded to the skin under the stringers and frame/shear ties that enhances the structure's damage tolerance and residual strength performance. Panel 5 advances the design by decreasing the primary skin thickness from the 0.057 in. used in Panel 4 to 0.047 in., while the remainder of the structure is kept consistent.

The investigation concerning fatigue crack growth included coupon-level tests. These tests included scrutinizing small crack growth under broken stiffening elements in the presence of bondline voids (disbond) simulating Panel 4 construction.

This report comprehensively outlines the design, fabrication, and assembly procedures for Panels 4 and 5. It documents the various iterations, manufacturing techniques, and development of tooling that supports both the coupons and the full-scale test articles.

17. Key Words	18. Distribution Statement
Federal Aviation Administration (FAA), NIAR-FirePoint Innovations, Arconic, Embraer, Emerging Metallic Structures Technologies (EMST), Structural Integrity, Damage Tolerance, Weight Efficiency, Aircraft, Fuselages, Hybrid Materials, Fiber Metal Laminate (FML), Autoclave Bonding, Hydroforming, Chemical Milling, Waterjet Cutting, Tooling, Assembly, Coupon-level Test, Defect Installation, Fatigue Crack Growth, Aerospace Industry, Lightweight Materials, Durability Improvements, Cost-efficient Manufacturing Processes	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	80	

Acknowledgements

Developing a FML Hybrid fuselage structure required engineers and manufacturing staff at the National Institute for Aviation Research to use their extensive knowledge of composite and metal bond experience. The expertise of this team was essential in developing the design, manufacturing and tooling necessary for the program's success. It was pleasing to know that our assembly went together for the first time without any issues and the fit and finish was that of a well-established production process.

The NIAR work was centered out of the Advanced Machining and Prototyping Lab, led by Andy Jonas. The Engineering and Manufacturing Team, led by Matthew Webb, and the engineering Drawing Design drawing, led by Jeffery Briggs, were keys to the program's success. The team had to blend the multiple inputs of the consortium, with multiple design iterations and trade studies.

The manufacturing and tooling were led by Matthew Webb, and industry consultations by Ron Weddle.

The layup of the FML skin was led by Bret Brummer in the composite layup lab. In this lab, all the adhesive and composite cutting, kitting, and layup were developed and executed. Key members of the layup team included Samantha Bradley, Jacen Heafner, Blade Brasser, Arturo Garcia, Wee Jun Siow, Chung Weng Giam, and Chin Teng Tan. Their expertise in composite and metallic bonding proved to be very valuable.

The team would also like to recognize Dr. John Bakuckas for his efforts in coordinating the thoughts and process with the consortium. Through a biweekly coordination meeting the team was informed and allowed fruitful discussions.

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Acronyms

Acronym	Definition
AMP	NIAR - Advanced Manufacturing and Prototyping
ATLAS	NIAR - Advanced Technologies Lab
AURP	Association of University Research Parks
CAD	Computer-aided design
CNC	Computer numerical control
CTE	Coefficient of Thermal Expansion
CDR	Critical Design Review
EMST	Emerging Metallic Structures Technologies
FAA	Federal Aviation Administration
FAJ	Floor Assembly Jig
FASTER	Full-Scale Aircraft Structure Test Evaluation and Research Facility
FCG	Fatigue Crack Growth
FEA	Finite Element Analysis
FEM	Finite Element Method
FML	Fiber Metal Laminate
IML	Inside Mold Line
NDI	Non-Destructive Inspection
NIAR	National Institute for Aviation Research
OML	Outside Mold Line

Executive summary

A collaboration between the Federal Aviation Administration (FAA), Arconic, Embraer, and the National Institute for Aviation Research (NIAR) (referred to as the *team* in this report) focuses on the exploration of Emerging Metallic Structures Technologies (EMST) at the FAA's comprehensive Full-Scale Aircraft Structural Test Evaluation and Research (FASTER) and Structures and Materials Lab facility. This initiative is centered around gathering critical data from coupon level and full-scale fuselage panel tests to evaluate the influence of EMST on the resilience of aircraft structures. EMST concepts being tested include panels using advanced aluminum alloys and hybrid skin structures comprised of conventional alloys reinforced with Fiber Metal Laminates (FML) straps. These structures will be compared to a baseline conventional aluminum fuselage structure of a single-aisle transport category aircraft. For this project the team decided to evaluate a fuselage section located just before the wings on the upper section (crown) of the aircraft. This follow-on phase of the project describes the design, tooling, production, and assembly of Panels 4 and 5, employing the FML hybrid skin concept. Insights derived from this investigative study will validate improvements in both weight efficiency and structural integrity, thereby providing critical guidance for the integration of these emerging technologies and their potential impact on the design of future aircraft.

NIAR's role in this project was to provide design, fabrication and assembly support utilizing subject matter experts to supervise the project. This report captures the design, manufacturing, and assembly phases for coupons and Panels 4 and 5, chronicling the various developmental stages, production techniques, and the engineering of tooling that underpins the support of both the test specimens and the comprehensive test structures.

The data from the coupon and full-scale testing will be presented in other published reports.

1 Background—Emerging Metallic Structures Technologies program

Original equipment manufacturers (OEMs) are proposing new applications for using emerging metallic structures technologies (EMST) in safety-critical aircraft structures, such as fuselage structures. These applications have very limited or no prior in-service and certification experience. The primary technologies under consideration include aluminum–lithium (Al-Li), aluminum clad alloys, and hybrid construction using Fiber Metal Laminate (FML) reinforcement. Industry is interested in the use of these material systems due to the following benefits:

- In comparison to conventional alloys:
  - Weight savings due to higher strength-to-weight ratios
  - Improvements in other properties (e.g. fatigue and damage tolerance capabilities) resulting in reduced inspection burden and more efficient design
  - Improvements in corrosion resistance
- In comparison to composites:
  - Reduced supply chain challenges (e.g., flexibility and lead time)
  - Reduced fabrication cost.

At this point, the FAA has limited experience with certifying these material applications. We have not certified any applications of these materials in domestic aircraft, although the FAA was involved in two validation projects. Additionally, in this program the team is evaluating the use of materials in newer and more innovative ways, such as using FML as reinforcement to fuselage skins to optimize weight and maintenance schedules.

A basic understanding of the fatigue behavior and damage mechanisms is needed to determine appropriate methods to predict fatigue and damage tolerance capabilities to provide an appropriate level of safety. Examples of these considerations include 1) unique fatigue and cracking mechanisms in Al-Li alloys (e.g., a phenomenon-like eyebrow and interlaminar cracking observed in earlier research), and 2) inherent damage tolerance (DT) and damage containment capabilities in hybrid FML reinforced structure (e.g., crack arrestment features in FML-reinforced monolithic aluminum skins). The primary certification focus is on fatigue and

DT assessment of structures produced using the above EMST. FAA certification engineers need insights in these areas so that they can ask appropriate questions during certification and establish criteria for guidance material and policy. This information is also needed to address the recommendation from the Aviation Rulemaking Advisory Committee working group (TAMCSWG) to provide guidance on metal-bond structures in AC 25.571-1 or other policies.

2 Introduction

The aerospace industry is improving performance and cost efficiency through advanced materials and innovative manufacturing technologies. Significant progress in the aluminum sector includes the development of lightweight alloys (e.g. Al-Li), hybrid structures built from metals and composites. These new materials and hybrid structures are intended to enhance the damage-tolerance characteristics of aircraft structures when compared to the aluminum materials used in transport aircraft structures today. However, development of new materials and structural concepts often require rigorous testing for certification, making collaboration between regulators and industry crucial for successful implementation. The EMST program was established to gain a better understanding of the fatigue behavior and damage tolerance capabilities of these new materials and hybrid structures to ensure an appropriate level of safety is maintained. This report outlines the processes used to create the design, (section 3), produce tooling (section 4), install damage (section 5), fabricate detail parts (section 6) and assemble the full-scale fuselage test articles and test coupons (sections 7 and 8, respectively).

To support this effort, the FAA Structural Research Center, Embraer, and Arconic partnered with the National Institute for Aviation Research (NIAR). This phase of the EMST Project was focused on creating coupons and full-scale test articles using FML skin assemblies. Later, these will be tested to determine if the FML skin assemblies provide enhanced damage-tolerance characteristics when compared to conventional aluminum structure used today. To provide an assessment of advanced fuselage panels using FMLs, NIAR was tasked to develop the FML manufacturing processes and fabricate the coupons and full-scale skin assemblies. The coupons and fuselage panels were delivered to the FAA William Hughes Structural Test Center to be tested in the Full-Scale Aircraft Structural Test Evaluation and Research (FASTER). The FAA's FASTER facility will test various EMST approaches under simulated aircraft service conditions. Other reports will provide the results of those tests.

The EMST program consists of five fuselage panels of various designs and manufacturing approaches and one fuselage panel that represents the baseline configuration used in today's transport aircraft structure. The test results from each fuselage panel will be compared to each other and the baseline panel to incrementally understand the influence of new materials, designs, and manufacturing approaches (Tian, et al., 2023). Figure 1 outlines the EMST test panel design test matrix. This report provides information on the design, manufacturing and assembly of test Panels 4 and 5.

		Baseline	Advanced Density Reduction	Advanced Materials	FML Reinforced	FML Reinforced (Optimized for Weight)
Component	Skin	2524-T3 sheet	2060-T8E30 Al-Li sheet	2029-T3 sheet	2524-T3 sheet	2524-T3 sheet
	Stringer	7150-T77511 extrusions, riveted	2055-T84 Al-Li extrusions, riveted	2055-T84 Al-Li extrusions, riveted	7150-T77511 extrusions, with FML straps	7150-T77511 extrusions, with FML straps
	Frame	7075-T62 - shear tied, extruded, riveted	2099-T83 Al-Li integral extrusions , riveted	2099-T83 Al-Li integral extrusions, riveted	7075-T62 - shear tied, extruded with FML straps	7075-T62 - shear tied, extruded with FML straps
Schedule	Start	Oct-17	Jan - 19	June - 21	Sep - 24	July - 26
	Finish	Dec-18	May -21	Jan - 24	June – 26	Dec - 27

Figure 1. EMST test panel matrix

Panels 4 and 5 were designed to evaluate the effectiveness of using FML straps under the stiffening elements to improve crack growth resistance and overall residual panel strength (Heinimann & et al., 2007). The Panel 1 baseline design used a traditional chemically milled fuselage skin with built-up pads providing additional stiffness and strength for durability. Material was removed in the area between the stiffening elements, providing pocketed regions of the fuselage skin between the thicker pad-up areas required for fastening stringers and frames. In the Panel 4 and 5 hybrid designs, the fuselage skin did not have any chemically milled or machined skin pockets, and the 2-in. wide FML straps bonded to the skin served as the skin pad-up. Figure 2 and Figure 3 illustrate the hybrid FML reinforcement concept.

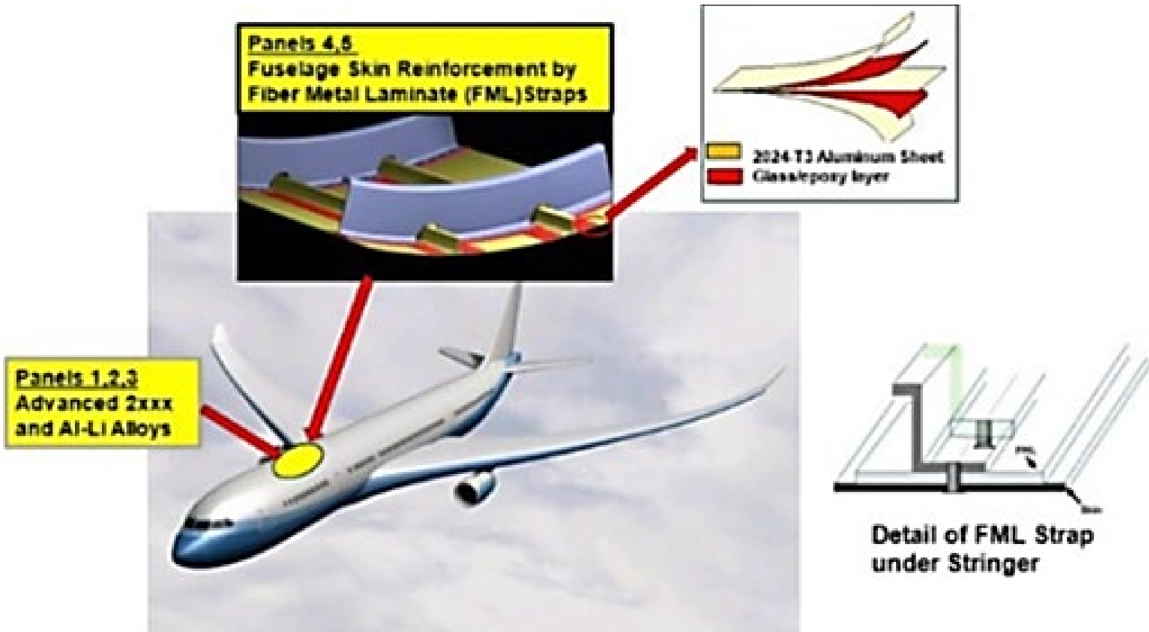


Figure 2. FML hybrid stiffened structure concept

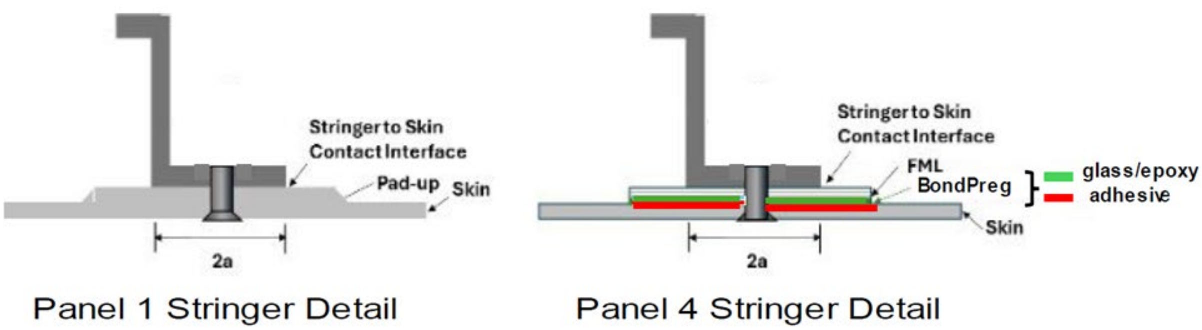


Figure 3. FML hybrid reinforcement detail

3 Design phase

3.1 Background

Computer-aided design (CAD) models for the Panel 1 design were provided by the FAA. The models formed the basis for the design effort accomplished by NIAR. The CAD files provided were uploaded into CATIA. From there, the NIAR engineering team created detailed drawings for the components, subassemblies, and assembly.

3.2 Proof-of-concept panels

Aluminum sheet bonding and fiber placement are well-established industry practices for skin fabrication with clearly defined parameters. However, the manufacturing of aluminum fiber laminate bonded skin assemblies raises concerns regarding the differences in the Coefficient of Thermal Expansion (CTE) among the components. This mismatch can induce internal stress when the assembly undergoes temperature changes. Variables in the design and construction include material thickness, ply orientation, and the use of film adhesive.

The design of the FML 2-in. wide strap layup for the Critical Design Review (CDR) Panel 4 concept design required that the 0.005-in. fiberglass plies ran continuously through the intersections of the frame and stringers. This additional buildup of the FML straps at each intersection raised concerns that the resulting layup thickness buildup would require “joggling” of the shear ties and/or stringers, which could increase cost and affect the interface and fit of the ribs and stringers. Specifically, the outer surface of the skin contour is controlled, but the inner surface of the skin panel visually reflects overlapping materials in the laminate, which could impact the attachment of riveted sheet metal details. Therefore, two different approaches to the stringer and frame crossover detail were developed for the FML straps by the EMST team to minimize or eliminate “joggling” considerations.

To investigate CTE issues, a conventional FML coupon panel consisting of a fiberglass/epoxy and aluminum lay-up was fabricated using a flat plate tool that simulated the planned design concept in only one direction. This panel exhibited adhesive squeeze-out like conventionally bonded aluminum structures but demonstrated a pronounced curvature due to the thermal expansion differences between the materials (see Figure 4 and Figure 5).

Figure 4. CTE bow

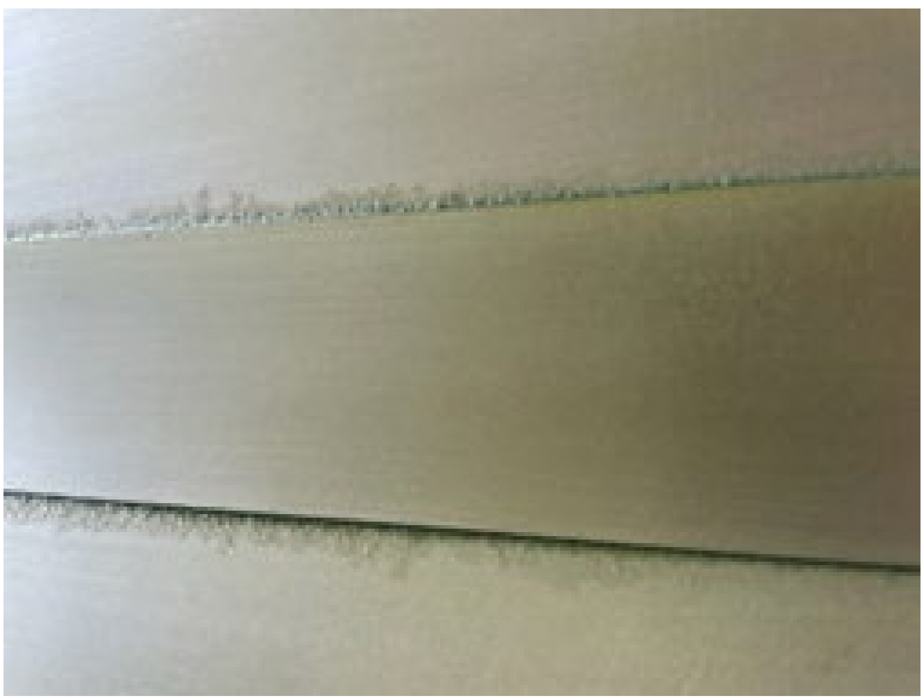


Figure 5. Bond flash (green)

New hydroformed shear ties were required for the panel design, raising concerns about the design of the inner skin mating surface. In conventional aircraft sheet metal design, joggles less than 0.032 in. are not typically tooled. To understand this issue, a prototype skin panel was designed and laid up in a bond tool contoured to the skin panel requirements. This prototype panel incorporated two bays of the fuselage structure so the team could understand how the cured layup and CTE would manifest itself in a three-dimensional representative structure. Post-cure, the prototype skin panel maintained its contour, with the inner surface revealing the lay-up locations for internal joggles. The transitions, while visible, were well below 0.032 in., allowing the shear ties to be fabricated with a smooth splined contour for the inner skin without joggles.

3.3 Coupon design and manufacturing

Reference Appendix C and D for detailed coupon information**.**

To develop structural data, a series of 13 coupons were designed, and a total of 22 coupons were fabricated. The coupon skins were made from alclad 2524-T3 aluminum, chemically milled on one side, targeting the Panel 1 skin pocket thickness of 0.059 in. for Panel 4 coupons and 0.059 in. in the pocket for Panel 1 coupons (final as-manufactured thicknesses are in Appendix C). All coupons were trimmed to 7.87 in. in width, 23.50 in. in length. All aluminum details associated with the coupon skin assemblies and the strap were trimmed, and pilot holes were drilled using a computer numerical control (CNC) waterjet. The details were then deburred and lightly sanded per industry standards. Each aluminum coupon detail used in the FML skin layup process was anodized with phosphoric acid and primed with water-based metal bond primer before the final layup and bonding process. An aluminum thin bar-shaped strap representing the Z-shaped stringer was sized using finite element method (FEM) on a detail-by-detail basis to match the specific skin midsurface stress intensities in the coupons with those in the Panel 1 or Panel 4 circumferential or longitudinal crack detail the coupon was simulating. This bar-shaped stringer made the coupon easier to grip compared to the actual complex stringer or frame/shear tie shape. This aluminum bar-shaped stinger was left in the bare condition. After the coupon FML-to-skin bond assembly was completed, the aluminum bar stringer was riveted without fay or fillet sealing.

The riveting was performed using a hydraulic squeeze mounted on a C-frame channel. The rivet size was validated using an industry-standard go/no-go gauge of the appropriate size. Multiple bond defects were introduced to the coupons consisting of Teflon film inserted between various layers of the FML layup, hand-sawed defects in rivet holes, and completely severed straps. Refer to the coupon drawings in Appendix C.

3.4 Critical Design Review Panels 4 and 5 concept and manufacturing plan

The design of Panel 1 served as the foundation for the concepts of Panels 4 and 5. Panel 1 consisted of a chemically milled 2524-T3 skin to 0.065 in. in the pad-up region and 0.059 in. in the pocketed region, resulting in 0.006-in. pad-ups at the locations of attaching structural elements. The skin was riveted to stringers made of 7150-T77511 aluminum extrusions, and 7075-T62 aluminum extrusions frames/shear ties were riveted to the skin. The longitudinal stringers were spaced 7 in. along the contour, while the frames/shear ties were spaced 20 in. apart on center. The overall test panel for all full-scaled articles measured 125 in. in length and 76 in. in vertical height, with a 74-in. radius of curvature. The frames were stretch-formed in the "0" condition to the desired contour, and then heat-treated to T-62. Then, the ends were milled. The stringers were Z-shaped aluminum extrusions.

In the CDR Panel 4 FML concept, the goal was to replace the Panel 1 pad-up regions with FML and keep the Panel 4 skin thickness the same as the pocketed skin thickness of Panel 1. Stringers, frames, and shear ties were kept the same as the baseline Panel 1. Loads were increased to compensate for the larger axial and hoop direction cross-section areas of Panel 4. Essentially, Panel 4 was the same as Panel 1 but with FML straps. The impact of the "crack bridging" damage tolerance feature of the bonded FML straps is demonstrated by comparing the crack growth performance of Panel 4 to Panel 1. In addition, Panel 4 demonstrates the cost impact of using the FML reinforcing staps. Finally, with no pocketing in the FML concept, thinner skins can be purchased and chemically milled pockets can be eliminated. However, the cladding must still be removed from the inner skin surface where the FML straps are bonded.

The Autoclave Bonded Skin assembly detail element design requirements are shown in Table 1.

Table 1. FML Autoclave Bonded Skin panel ply lay-up requirements

Element	**Thickness (inches) P 4**	**Thickness (inches) P 5**	**Material**	**Chemical Treatment**
Outer Skin	0.057	0.047	2524-T3 Aluminum Clad one side	Phosphoric Anodized and Bond Primed
Adhesive	0.005	0.005	FM 94(B.I.F.) M 03 Film 915	
Waffle Doubler	0.016	0.016	2024-T3 Bare aluminum sheet	Phosphoric Anodized and Bond Primed
Adhesive	0.005	0.005	FM 94(B.I.F.) M 03 Film 915	
0° Fiberglass	0.005	0.005	FM 94-27%-S-2GLASS-187-460	
90° Fiberglass	0.005	0.005	FM 94-27%-S-2GLASS-187-460	
Adhesive	0.005	0.005	FM 94(B.I.F) M 03 Film 915	
Waffle Doubler	0.016	0.016	2024-T3 Bare aluminum sheet	Phosphoric Anodized and Bond Primed
Total	**0.114**	**0.104**		

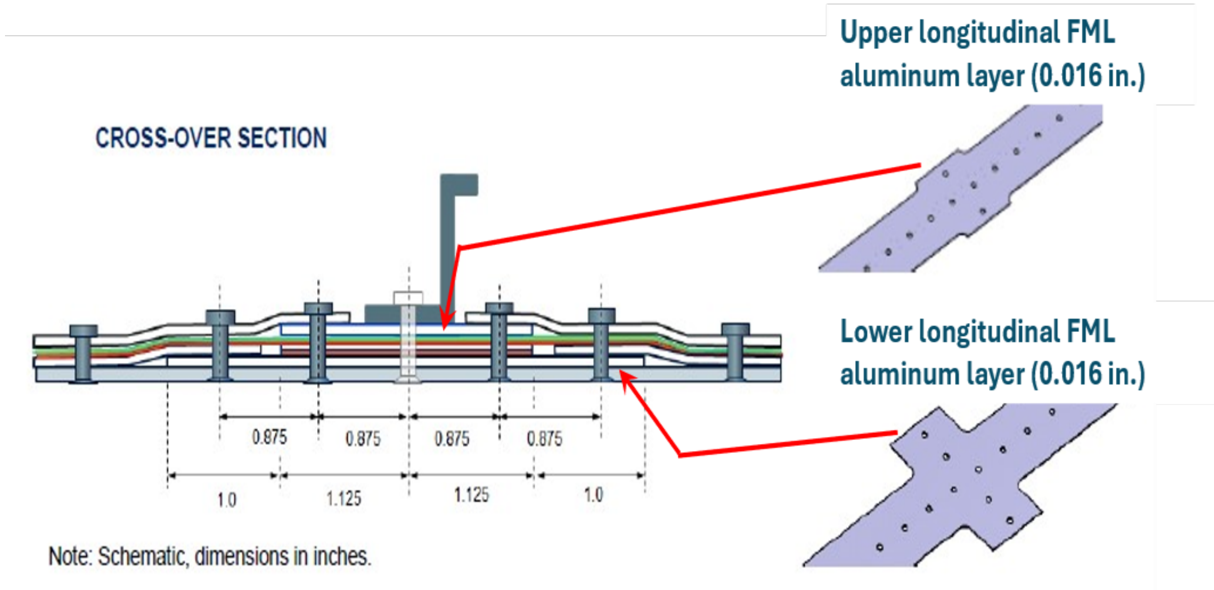


Figure 6. Circumferential view of stringer to frame crossover detail in panel

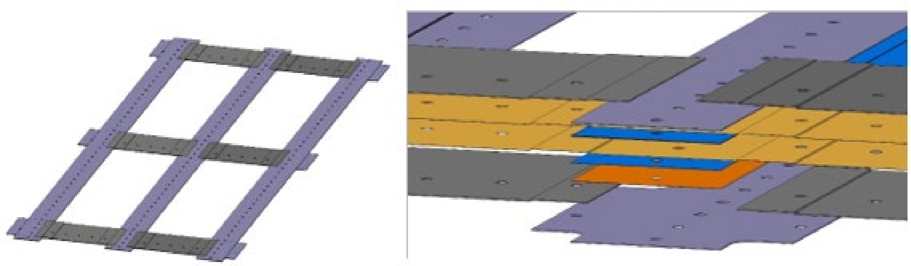


Figure 7. FML CDR Panel 4 concept showing local element overlaps

Figure 6 and Figure 7 show the the first option considered for the FML intersection detail at stringer and shear ties for CDR Panel 4. The continous fiberglass/epoxy plies pass through the intersection in both directions. As shown in Figure 6, the aluminum layers in the FML in the circumferential direction are lap-joined to the two longitudional cruciform-shaped aluminum layers in the FML strap, which runs continuously under the six frames along the panel length. Under the frames (between sringers), two shorter, constant cross-section aluminum layers in the circumferential direction are made individually and are lap-joined as shown in Figure 7. This concept required two additional fasteners in the shear tie to skin connection compared to the Panel 1 design. Along the stringer line there are two aluminum layers and two glass/epoxy plies between the frames and two aluminum layers and four glass/epoxy plies in the stringer to frame crossover area, which results in a 0.01-in. “bump” before any reduction is made due to autoclave consolidation. In this case, stringer “joggling” may or may not be needed in the crossover area.

A second approach was developed to fabricate two waffle doublers serving as the FML aluminum layers, which would eliminate the lap joints, as shown in Figure 8. From a manufacturing standpoint, the material wastage in creating this waffle doubler is greatly overshadowed by the cost of fabricating all the discrete FML circumferential aluminum layers under the frames between each stringer, including the nonvalue added steps of part marking, storing, and kitting. In addition, the layup process for the FML skin is much more tedious, requiring cutting the plies and laying them up individually, especially with the overlaps. The part count for the skin in Panel 4 to support the first approach increased from 1 part for Panel 1, to 216 in the original CDR Panel 4 option, and 113 in the final Panel 4 and Panel 5 approach, not counting the adhesive elements of the structure. (See Appendix A: CDR Panel 4 Concept vs Panel 4 and 5 Design Lay-up Comparison and Appendix B: Drawing list for Panel 4 and 5.) On the downside of the waffle doubler design approach, a very wide, thin 0.016-in. 2024-T3 aluminum waffle doubler sheet is not available as a product today. As a result, that configuration would require additional longitudinal splices.

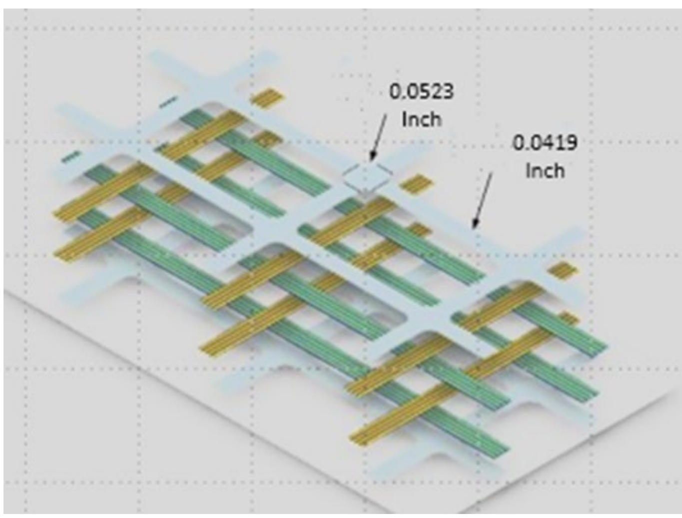


Figure 8. FML waffle panel layup

To demonstrate the feasibility of the waffle doubler approach chosen to manufacture Panel 4, a demonstration article was built to determine if the stringer/frame crossover areas or waffler doubler longitudinal splice areas would require joggling.

Conventional aircraft sheet metal construction, shear ties typically require joggling to facilitate the overlap of materials exceeding 0.032 in. However, the thickness buildup with the autoclave-cured FML was expected to fill any voids and fare out the transitions between the layers such that they meet this tooling standard for joggling. To refine the manufacturing process and validate the elimination of joggling the shear ties, a proof-of-concept skin assembly was fabricated before committing to dedicated test materials. This concept panel, measuring 45 in. wide by 73 in. long with a 74-in. radius, represented the design of the Panel 5 test panel center area; see Figure 9. The panel validated that the transitional overlaps were insignificant and that the rib clip design would align with the skin loft without joggles at the ends. The layup and processing of this skin assembly provided confidence in the manufacturing approaches developed for building Panels 4 and 5. It is important to note that the prototype panel did not undergo chemical processing for bonding or chemical milling for thickness, since it was only a manufacturing demonstrator.

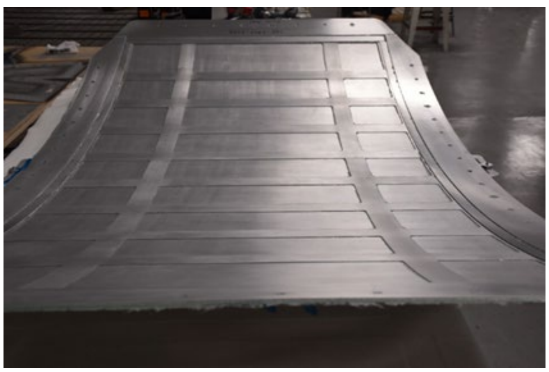


Figure 9. Prototype panel skin assembly

Additional improved design features in Panels 4 and 5 involved improving the frame reinforcement at the FASTER actuator load points. During the testing of Panel 3, the FAA experienced frame failure at the loading fixture attach point, resulting in frame cracking. To address this issue in Panels 4 and 5, two splices were designed, one for each side of the rib clip/channel, providing the bearing material for the fixture attach element. The splices were machined from 7075-T6 aluminum plates. The thickness of each machined splice was stepped down four times over the length of the joint to ensure uniform load transfer into the rib clip/channel structure. (See Appendix B for more details.)

Additionally, doublers were added to the exterior of the skin panels compared to the Panel 1 design in the areas common to the FASTER fixture loading points. The overall thickness of the doublers used in Panel 1 was increased by 25% to ensure proper transfer of higher loads and improve fatigue performance due to the large number of cycles in the Panel 4 and Panel 5 test plans. The doublers on the internal side of the skin were laid up and cured during the skin fabrication process, while the external doublers were cold-bonded to the exterior periphery of the skin prior to riveting the assembly.

The impact of drill wear during the drilling process and the potential risk of delamination in the FML laminate skin assembly were of concern. Drill wear and delamination were identified as concerns because the FML in the metal laminate skin detail was fabricated using a waterjet, which was utilized to trim the edges and drill all 2,142 #30 pilot holes required for subsequent assembly operations. Each #30 pilot hole was step-drilled to size and reamed to its final dimensions. Cutter wear was found to have minimal impact, and this procedure, combined with the step-drilling and final reaming process, proved highly effective in preventing delamination of the fiberglass plies.

3.5 Panel 4 and 5 design and manufacturing

The design objective of Panel 5 was to produce a lighter panel compared to Panel 4 while maintaining performance and reducing manufacturing labor. Weight reduction was to be achieved by decreasing Panel 1 skin thickness from 0.059 to 0.045 in. to match the weight of Panel 1 (note: after chemical milling the actual thickness is 0.046 in.). Manufacturing labor reductions were addressed by reducing the number of details in the skin assembly layup by adopting a waffle concept for the inner aluminum doublers of the FML. Appendix B details the weight analysis comparison. It is important to note that the manufactured Panel 4 and 5 both utilized the two-dimensional waffle construction for the FML aluminum layers, but due to a maximum 40 in. wide, 0.016 in. thick 2024-T3 sheet limitation, the waffle was spliced in the middle of the bay. The resulting steps due to the splices were insignificant such that no joggles or fillers were required to build the panel.

3.6 Manufacturing process development

Industry standard specifications for machining, waterjet cutting, drilling, chemical milling, stretching, rolling, chemical processing, layup of composite materials, and autoclave bonding were utilized in the fabrication process of Panels 4 and 5 and the test coupons. Special process development was focused on installing defect damage in the test articles. Special hand saws were fabricated to allow placing the defect in the center of the panel utilizing a selection of industry standard saws modified to allow for creating precise cuts.

4 Tooling

4.1 Background

The FAA supplied the fabrication and assembly tooling used for Panel 1 through 3 to NIAR. Appendix F: documents the tooling developed and used in the fabrication and assembly process. NIAR developed new and unique tools for the program, as described below.

4.2 Coupons

NIAR designed and fabricated tooling to support the assembly of the coupons and a special jaw assembly end effector, and edge clamps to facilitate their installation in the FAA test machine for crack growth testing. Special care was taken to provide shims for the jaws, ensuring the coupons were centered on the pulling axis and that the straps and skins were equally loaded. Due to the CTE-related bending of the coupons, special edge clamps were created for each side of the coupon to essentially straighten the coupon in the test fixture. A special drill fixture was developed to hold the coupon skin and strap in the correct location for rivet installation.

Given the flat nature of the coupons, no special tooling was required for the bonding process.

4.3 Skin assembly layup tooling

With the introduction of the FML, an aluminum layup tool was designed and fabricated. This tool was designed with ergonomics in mind to facilitate the layup process, featuring a low profile and incorporating the ability to rotate the tool surface for easy access. Additionally, the tool was designed to be easily disassembled for transportation purposes. It also included sufficient excess to facilitate bagging on the skin assembly, with adequate vacuum ports to ensure the application of uniform vacuums.

4.4 Hydroform tooling

The frame shear ties for Panels 4 and 5 were designed to provide the shear tie between the skin and the extruded frame element, incorporating necessary modifications to meet installation requirements at the skin and stringer locations. To facilitate fabrication, new aluminum hydro block forming tools were designed and manufactured.

4.5 Skin rolling and stretch tooling

Contour templets were fabricated via waterjet and used to validate the rolled and stretched contours. The original tool for stretching channel extrusion, which included the stretch tool and related snakes that matched the extrusion and desired radius of curvature, was provided to NIAR by the FAA. However, new stretch jaws were fabricated to interface with the machine and the extrusion being stretched.

Special attention was paid to the fit of the snake during frame stretching operations. The "snake" (see Figure 11) is a segmented rope consisting of nylon blocks attached to a wire rope which is stretched with the part to ensure that during the stretching operation the flanges or the part remain normal and do not buckle or warp.

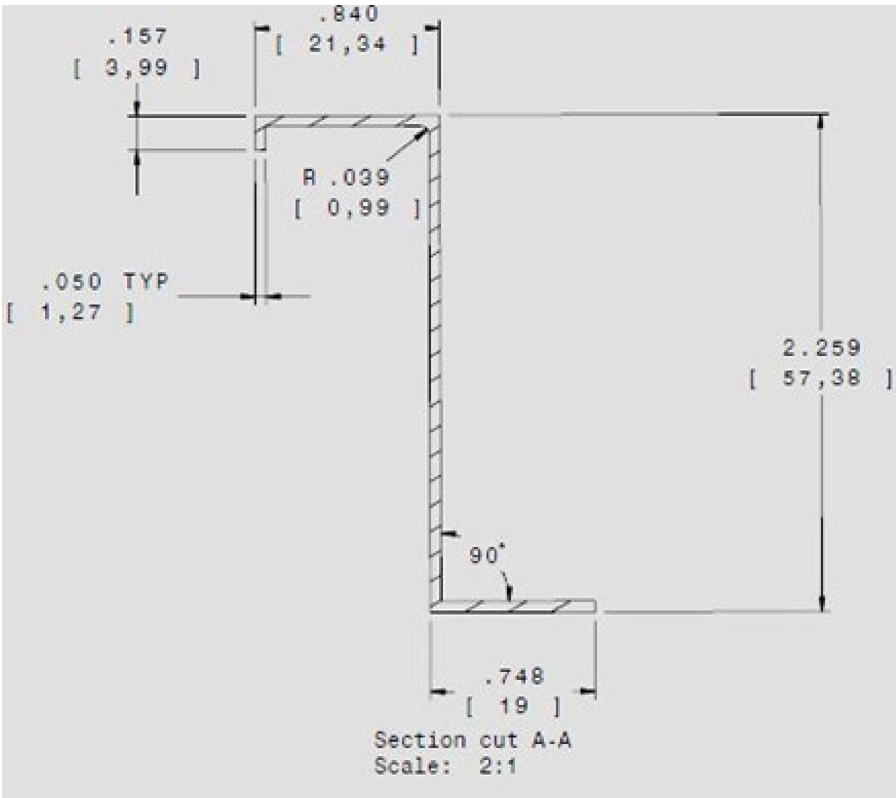


Figure 10. Frame cross-section

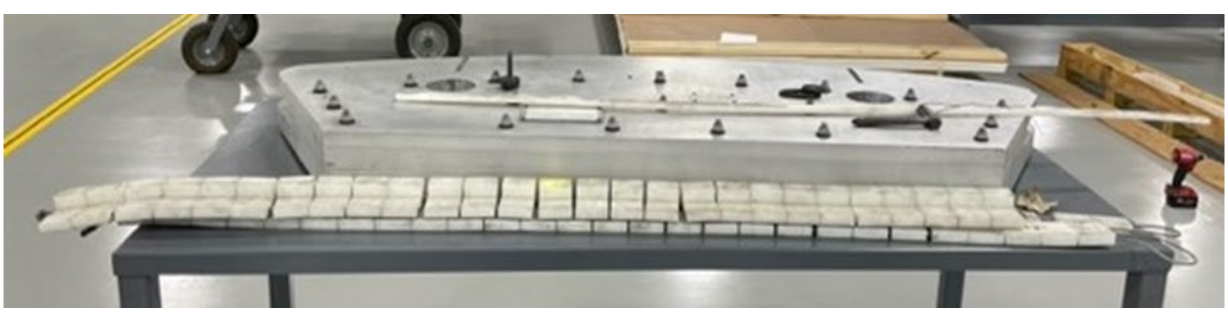


Figure 11. Frame stretch tooling (snake in foreground)

4.6 Assembly tooling

The assembly tooling provided by the FAA included skin drill fixtures and a Floor Assembly Jig (FAJ). The drill fixtures were essential for drilling the skin to add the common holes, which matched the FAA test fixture around the periphery of the skin panel. A special wood egg crate assembly tool was waterjet-fabricated and assembled to facilitate this process by allowing the skin panel to be supported from the underside and the drill fixtures to be pinned to the skin for back drilling. The external doublers were cold-bonded to the skin exterior using this fixture and coordinated tooling pins, straps, and edge clamps to supply pressure as the adhesive set up.

The FAJ was originally designed to use vacuum pads on contour fixtures to hold thin skin panels in place to maintain contour during assembly. Strategically placed jig pins were coordinated with the skin assembly and positioned around its periphery.

However, since the skin was rolled to contour templates, the vacuum was not used. The rigidity of the laminated skin facilitated its installation to the tool contour fixtures, and the skin was pinned to the FAJ and clamped at strategic locations to the contour fixtures.

5 Damage installation

The skin, stringer, and frame/shear tie damage definitions and locations were established by the team for Panels 4 and 5, along with the damage in the coupons, as defined in Appendix C and E. Due to the size of the coupons, small hand tools were used to make saw cuts to add defects that were representative of cracks in the skin of the assembly. However, it was a challenge to install the defects in the skins of Panels 4 and 5 due to the long reach required to make the saw cuts.

The initial skin defects were incorporated before the layup of the FML and adhesive. Once cured, the defects were cut through the FML laminate from the outside of the skin. Again, small hand tools and very fine jeweler’s saws were used.

6 Detail parts fabrication

6.1 Skin assembly detail parts fabrication

The skin panel assembly aluminum materials were as follows:

- Skin: 0.071-in. initial thickness 2524-T3 aluminum sheet alclad on both surfaces
- External and internal panel edge doublers: 0.075-in. thick 2024-T3 bare aluminum sheet
- FML aluminum waffle doublers: 0.016-in. thick 2024-T3 bare aluminum sheet

NIAR used a CNC waterjet, which was utilized for trimming the sheet metal components necessary for the skin panel assembly, including drilling pilot holes required for subsequent assembly operations. Excess material was intentionally left on all sides of the components, requiring rolling to facilitate process. Tooling tabs were incorporated into the details where appropriate.

The skin detail was chemically milled on one side to achieve a finished thickness and subsequently rolled to a 74-in. radius. All skin components associated with the skin assembly, except for the 0.016-in. doubler details, were contoured by rolling. Metal contour templates, fabricated to match the desired radius, were employed to validate the final rolled shape.

In the post-processing phase, components required for the skin bond assembly underwent chemical cleaning, phosphoric acid anodizing, metal bond priming, and baking. Post-processing, the parts were individually bagged for protection and transportation.

6.2 Details of frame/shear tie and stringer

The rib and stringer details were fabricated from the following materials:

- Shear ties: 0.05-in. thick 2024-T3 aluminum sheet
- Shear tie doubler: 0.85-in thick 7075-T62 aluminum sheet
- Stringer clips: 0.05-in. thick 2024-T3 aluminum sheet
- Stringer: 7150-T7751 aluminum extrusion
- Frame: 7075 T62 aluminum extrusion

Flat pattern blanks for the hydroformed shear ties and stringer clips were CNC waterjet trimmed and drilled. The rib clips were hydroformed and deburred. The stringer clip was mechanically formed in a fabricated press. The stringers were cut to length and hand-trimmed on both ends. The frame extrusions were stretch-formed to contour in 0 condition, heat treated to T62, and CNC milled to length. The contour was three-dimensionally scanned to conform to the frame's contours. These sheet metal details were all hand-deburred but did not receive any further corrosion protection.

7 Panel assembly

7.1 Assembly process plan and quality documentation

The process plan developed for the assembly of Panel 3 was updated for Panel 4 and Panel 5 configurations. This updated document was also used for documenting the in-process quality control for the assembly as well.

7.2 Assembly process

The assembly tool provided by the FAA was placed on the assembly floor and leveled prior to loading the tool for the assembly process. A digital model of the FAJ was also created.

7.3 Skin panel lay-up

The lay-up tool was utilized for the lay-up of the skin and FML laminate and the subsequent autoclave curing process. The lay-up process was conducted at the NIAR – Composites & Structures lab followed with the autoclave curing at the NIAR – Advanced Technologies Lab (ATLAS) facility.

The FML fiber and adhesive detail part geometry was downloaded to a Gerber Prepreg Ply Cutter, which uses a knife cutter to cut out each lay-up detail. The details were marked and kitted to facilitate the lay-up sequence. Each ply detail was manually placed in the tool utilizing a visual aid for placement and alignment. The assembly was bagged, and vacuum was applied to debulk the individual plies, removing excess air between the layers of the assembly. Once all were in place, the entire skin assembly was covered with bleeder cloth and vacuum was applied, drawing out the air and locking the details in place for the autoclave cure cycle. The vacuum was checked throughout the process to ensure vacuum integrity was maintained. Figure 12 shows the prototype skin panel after lay-up. Once the cure process was completed, the tool and the skin were returned for debagging and Non-Destructive Inspection (NDI) of the skin panel assembly.

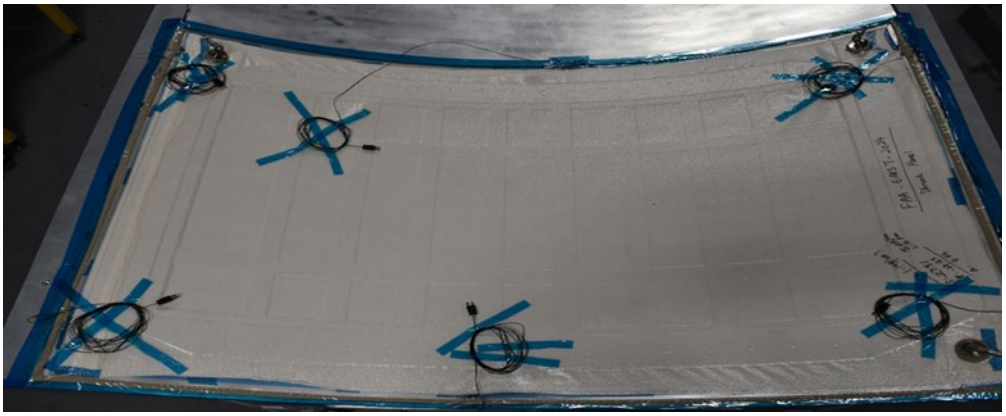


Figure 12. Prototype skin panel post-cure bagged with thermal couples taped down

A wood egg-crate tool was utilized to facilitate the back drilling of the skin edge doublers prior to the cold bond operation. The bonded skin assembly was placed on the tool concave side down. Then, the FAA-provided drill jigs were located, pinned and clamped to the skin assembly. After completion of this step, the fastener holes common to the skin doublers were then drilled in the skin assembly. Once the drilling operation was complete, the drill fixtures were removed, and the skin was deburred and cleaned. The skin assembly was placed back on the egg crate, and a thin layer of paste adhesive was applied to the skin at the doubler locations. The doublers were then pinned to the skin assembly and clamped for the room temperature curing process. Once cured, the excess adhesive was removed from the edges of the skin, and the doubler fastener holes were back-drilled through the doubler. The final step in this part of the process required drilling the fastener holes to their full size.

7.4 Panel assembly process

The completed skin bond assembly was placed in the FAJ utilizing the pin locations on the FAJ and the tooled tabs on the skin. When in place, the skin was clamped to the contour boards to ensure contour integrity.

The stringers were then located on the inside surface of the skin, utilizing the locaters on the assembly tool. Once located, the pilot holes were back-drilled from the skin into the stringers.

The same process was used for the stringer location and temporary attachment tools (Clecos) were used to locate all the shear ties clips and the shear tie clip channels.

After temporarily attaching the sheet metal details for the complete panel assembly, the locations of all detail components were verified. Once confirmed, the components were back-drilled using the pilot holes in the skin. They were then removed for deburring before being reassembled onto the skin panel. Fay surface sealant was not applied between the skin assembly and the attaching shear ties clips or stringer elements. The attaching rivets were not installed with wet sealant. While sealing is standard practice in aircraft assembly to maintain the pressure vessel integrity, it was omitted from the test articles and coupons to facilitate crack growth detection.

Rivets of the appropriate size were used to permanently attach the sheet metal details to each other and to the skin assembly. Care was taken to ensure they were properly bucked using go/no-go gauge and the depth checked to ensure head flushness.

8 Test coupon assembly

The test coupons consisted of an FML bonded skin panel assembly and a machined aluminum strap to simulate the stringer elements in the panel assembly. The coupon skin assembly was fabricated utilizing the same processes used for the skin assembly, except that a flat plate was utilized for the lay-up tool.

The assembly process utilized a fabricated drill fixture for drilling the coupon test fixture hole as well as the drilling and countersinking the holes by attaching the strap to the skin assembly. A C-Frame pneumatic riveter was used to squeeze the hand-installed rivets. Particular attention was paid to ensure proper riveting, but the size and head countersinking requirement were met by checking each fastener with go/no-go gauges.

9 Summary

The design and fabrication of Panel 4 and Panel 5 have evolved from the Panel 1 monolithic single-ply skins to a skin reinforced by bonded FML straps under stringers and frame/shear ties. This evolution aimed to enhance durability and damage tolerance while reducing weight and/or increasing inspection intervals. Each design evolution, however, has an increased manufacturing complexity and raised material and labor costs.

The primary cost increase from FML comes from the adhesive and pre-preg, with no measurable impact on tooling, manufacturing processes, or labor costs compared to conventional metal-bonded skins. Thinner-gauge purchased skins and the elimination of chemical milling or machining skin pockets offer some potential cost savings. The overall cost is expected to be significantly lower than that of fiber placement in composite materials.

The introduction of FML is expected to significantly improve the damage tolerance of the fuselage panel, offering opportunities for the designers to optimize their designs. In this program the baseline was the original Panel 1 design with its skin, stringers and frames/shear ties. In the

Panel 4 design, the panel skin/stringers and frame/shear ties were the same as Panel 1, and the 2/1 FML strap was bonded under the stringers and frame/shear ties. Thus, Panel 4 had a larger cross-sectional area and was much stronger. This design of Panel 4 was intentionally made to directly compare the performance improvement of the FML reinforcing straps. The loads applied by the FASTER test frame were increased to achieve the same far field stress as Panel 1(note: for the same far field crack driving stress, the FML bridges the crack, resulting in a lower stress intensity factor and hence longer crack lives in Panels 4 and 5). In the aircraft design process, the FML-reinforced skin panel would be optimized, and the weight could be similar to Panel 1 and result in longer inspection interval, or lighter while keeping the same inspection interval as Panel 1, or some combination. The goal for Panel 5 was to use the same stringers and frames/shear ties and reduce the skin thickness for additional information regarding how the FML would perform with a thinner skin gauge. Further weight reduction could be obtained in future panels by optimizing the stringers and frames/shear ties, but this was not an option for this program. Panels 4 and 5 will be loaded higher than Panel 1 to compensate for the respective weight increases to achieve the same undamaged skin stress during damage tolerance crack growth cyclic loading as Panel 1. This assumes that two different thickness skins with the same DA/DN properties would be expected to exhibit the same crack growth (not considering the thickness impact on pressure bulging or bending effects due to severed stringer and frame. In this case, the crack growth performance improvement of Panels 4 and 5 can be compared directly to Panel 1 (again assuming there is not a significant effect of skin thickness on DA/DN of the skins). The two options for a potential next set of panel tests could be:

- Optimize the skins, stringers and frames/shear ties to keep the FML concept the same as Panel 1. This goal is to validate the longer inspections measured in the current tests at equal skin stresses.
- Design the FML panels to reduce the panel weight compared to Panel 1. This would increase the stress levels in the FML reinforced panel, but the objective would be to maintain the same inspection cycles as Panel 1.

Other options could include a mix of these two options.

Differences in the CTE when bonding FML to aluminum were observed during the coupon bonding process using a flat plate tool. However, these differences were not significant enough in the skin panel manufacturing process, which used a tool with the desired contour, to require changes in tooling or assembly. The drilling and riveting processes used on the panel were identical to those used in drilling earlier metal laminate panels. Although the cured FML may impact drill tool life, the chips produced during drilling did not affect hole quality. No impact was observed on the riveting process. While the weight reduction observed between Panels 4 and 5 was less significant than anticipated, redesigning to reduce the number of detail parts in the FML layup process resulted in substantial manufacturing cost reductions associated with part count and significant labor hour savings. A sixth-generation design would further reduce detail part count by introducing increased waffling in the FML skins and potentially eliminating one FML skin ply, marking the next step in the evolution of FML reinforced skin panels.

10 References

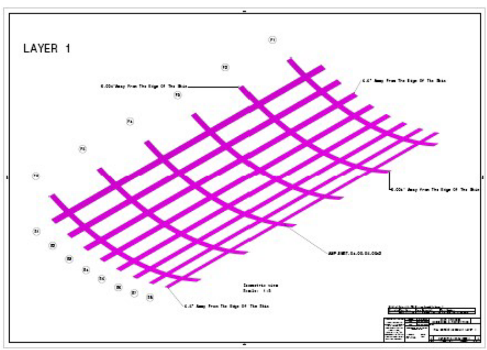
Heinimann, M., & et al. (2007). Validations of advanced metallic hybrid concepts with improved damage tolerance capabilities for next generation lower wing and fuselage applications. Naples, Italy.

Tian, Y., Stanley, D., Bukackas, Jr., J. G., Stonaker, K., Kulak, M., Sippel, W., . . . Chaves, C. E. (2023). Test and Analysis of Fuselage Structure to Assess Emerging Metallic Structures Technologies. *31st ICAF Symposium.* Delft, Netherlands.

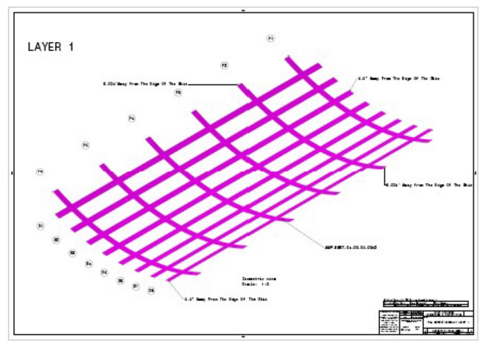
A Critical Design Review Panel 4 concept vs. Panel 4 and 5 design lay-up comparison

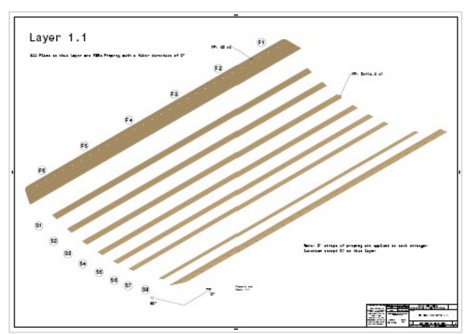
As discussed in paragraph 3 of this report, the following pictures compare the skin panel layup sequence for the initial panel skin assembly presented at the Panel 4 CDR compared to the final lay-up sequence used for Panels 4 and 5. The difference is the waffle doublers used in layers 2 and 7 of the final lay-up.

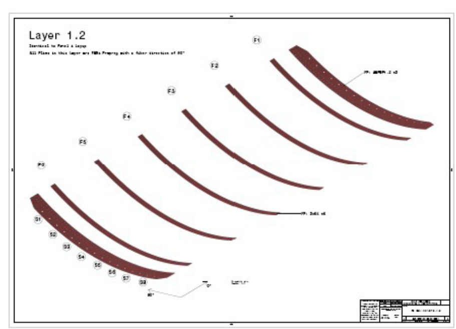
CDR Panel 4 Concept

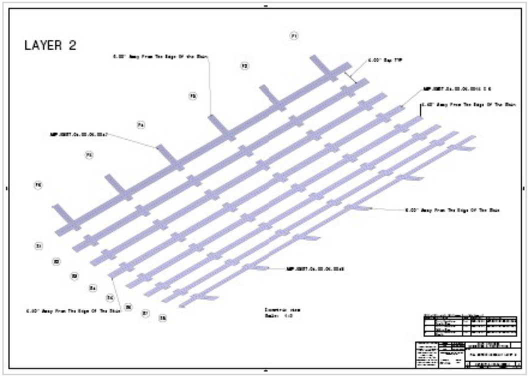


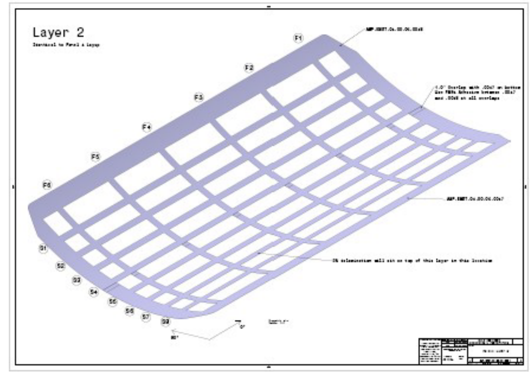
Panel 4 and 5 Design



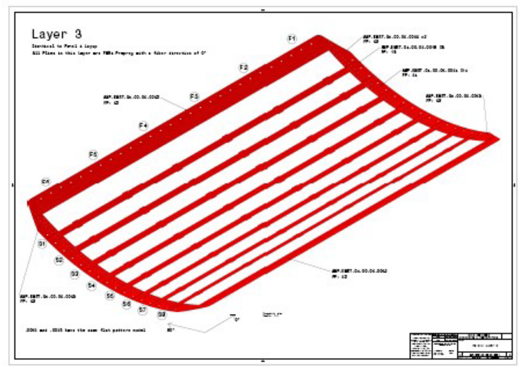





LAYER 2


Layer 2


LAYER 3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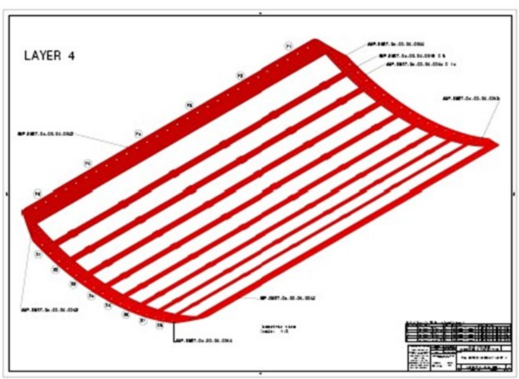
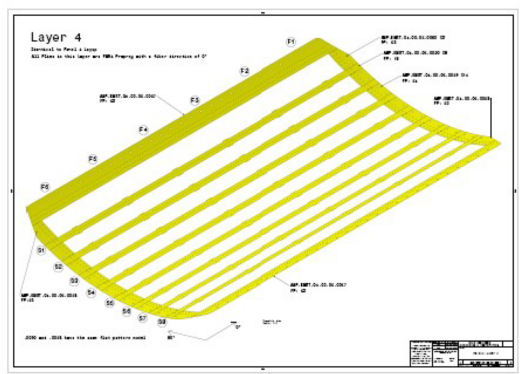
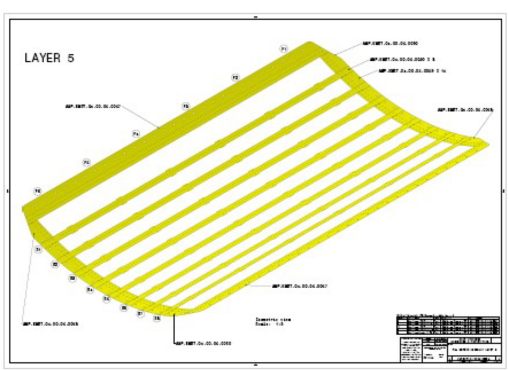
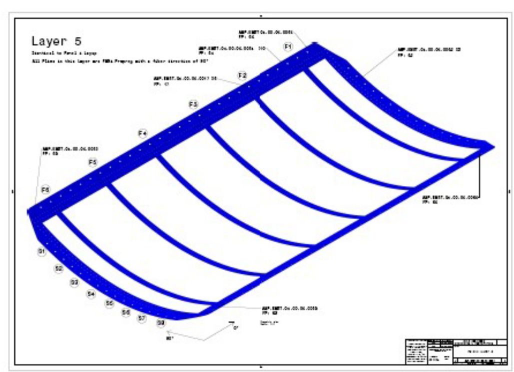
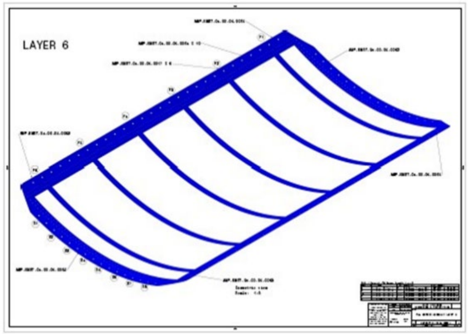
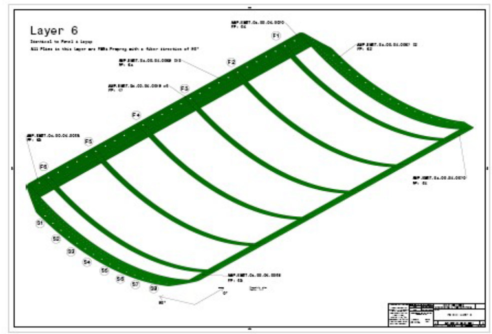

LAYER 4


Layer 4


LAYER 5


Layer 5


LAYER 6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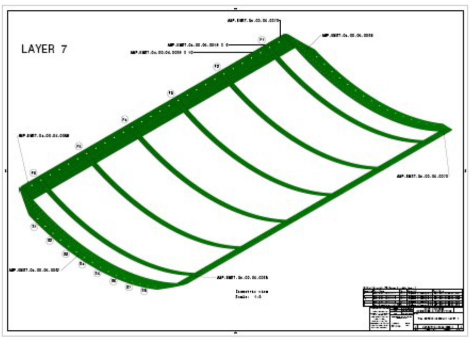
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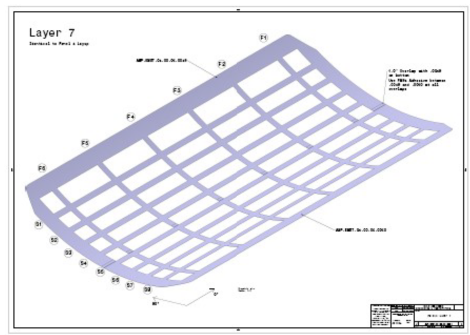
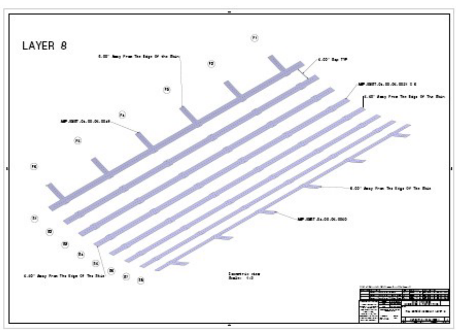

Layer 7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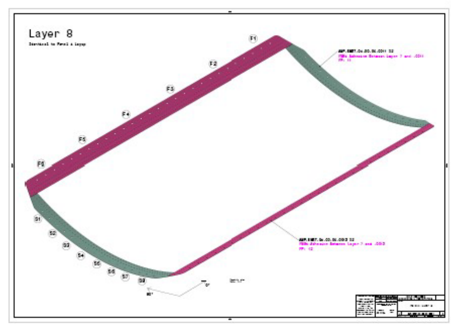
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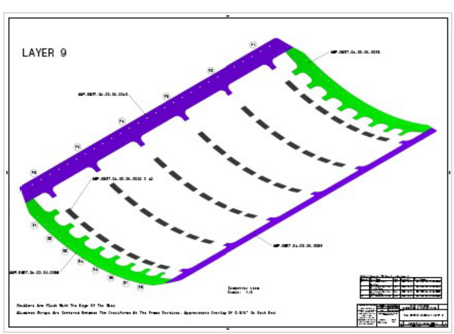
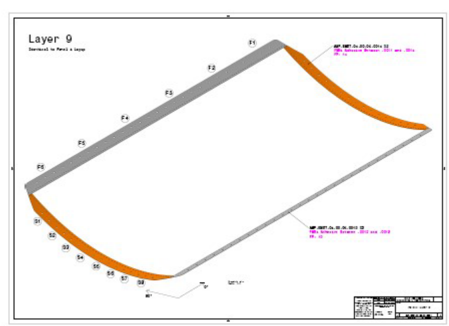
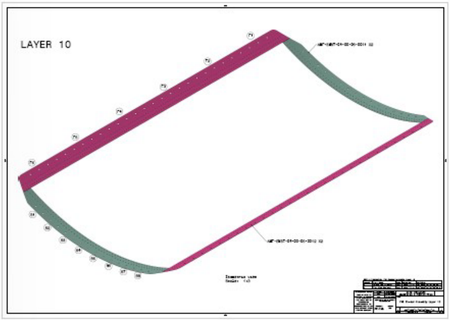
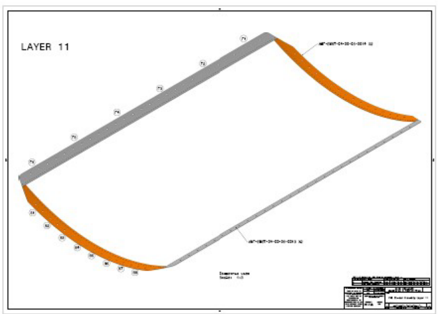

LAYER 9


Layer 9

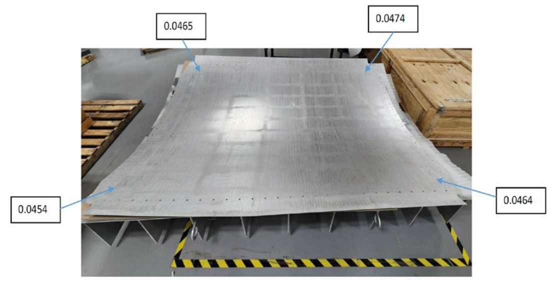

LAYER 10


LAYER 11

B Panel 4 and 5 test articles

B.1 Panel 4 and 5 skin thickness

Chem Milling Certification Measurement		
Panel 4		
Design	0.055	0.059
Actual	0.055	0.059
Actual Average		0.057
Panel 5		
Design	0.042	0.048
Actual	0.044	0.048
Actual Average		0.046



AMP Panel 5 Skin Thickness Measurements		
Measurement	**Location**	**Dimension**
1	LL	0.0454
2	UL	0.0465
3	UR	0.0474
4	LR	0.0464
Average		0.0464
Standard Deviation		0.000708431
Range		0.002
Variance		0.00000050187

B.2 Panel 4 and 5 drawing list

Bill of material explanation

The initial design for the CDR Panel 4 concept is shown in its drawing list on the left, utilized multiple small aluminum sheet details for the FML skin layup/bond assembly. These details were designed to overlap at each stringer/rib cross-section. However, this design was discarded to improve manufacturing efficiency. The updated design eliminates 104 individual sheet metal pieces, significantly reducing both fabrication and inventory costs and the labor required for placing each detail during the lay-up process. Panel 4 and 5 FML skin panels are identical except for the thickness of the skin detail. They share the same bill-of-material.

The following table shows the Assembly Bill of Material for CDR Panel 4 concept along with both Panel 4 and 5, including part quantities for fabricated parts except as noted.

Table B- 1. CDR Panel 4 concept and Panel 4 and 5 bill of material

EMST CDR PANEL 4 CONCEPT VS Panel 4 and 5 Assembly BOM and Part Count (Excluding Fiber Laminate, Adhesive, and Rivets)								
	AMP - EMST CDR PANEL 4 CONCEPT - DRAWING LIST				AMP - EMST PANEL #4 and #5 DRAWING LIST (Waffle Doublers)			
INDEX	DWG No	Title	Assy	Skin Assy	DWG No	Title	Assy	Skin Assy
1	**AMP0001**	**PANEL ASSEMBLY**			**PANEL ASSEMBLY**	**PANEL ASSEMBLY**		
2	AMP-EMST-04-00-34-0000	INTERNAL SUPPORT ASSEMBLY			AMP-EMST-04-00-34-0000	INTERNAL SUPPORT ASSEMBLY		
7	AMP-EMST-04-00-34-0023	STRINGER	8		AMP-EMST-04-00-34-0023	STRINGER	8	
8	AMP-EMST-04-00-34-0024	YELLOW RIB CLIP	6		AMP-EMST-04-00-34-0024	YELLOW RIB CLIP	6	
9	AMP-EMST-04-00-34-0025	GREEN RIB CLIP	36		AMP-EMST-04-00-34-0025	GREEN RIB CLIP	36	
10	AMP-EMST-04-00-34-0026	ORANGE RIB CLIP	6		AMP-EMST-04-00-34-0026	ORANGE RIB CLIP	6	
11	AMP-EMST-04-00-34-0027	PURPLE RIB CLIP	6		AMP-EMST-04-00-34-0027	PURPLE RIB CLIP	6	
12	AMP-EMST-04-00-34-0028	FRAME	6		AMP-EMST-04-00-34-0028	FRAME	6	
13	AMP-EMST-04-00-34-0029	STIFFENER TAB	12		AMP-EMST-04-00-34-0029	STIFFENER TAB	12	
14	AMP-EMST-04-00-04-0000	PANEL 4 WITH EXTERNAL DOUBLERS			AMP-EMST-04-00-04-0000	PANEL 4 WITH EXTERNAL DOUBLERS		
15	AMP-EMST-04-00-04-0003	EXTERNAL DOUBLER ASSEMBLY			AMP-EMST-04-00-04-0003	EXTERNAL DOUBLER ASSEMBLY		
16	AMP-EMST-04-00-03-0000	EXTERNAL DOUBLER ASSEMBLY EXPLODED VIEW			AMP-EMST-04-00-03-0000	EXTERNAL DOUBLER ASSEMBLY EXPLODED VIEW		
17	AMP-EMST-04-00-03-0007	BOTTOM SALMON DOUBLER	2		AMP-EMST-04-00-03-0007	BOTTOM BLUE DOUBLER	2	
18	AMP-EMST-04-00-03-0008	BOTTOM BLUE DOUBLER	2		AMP-EMST-04-00-03-0008	BOTTOM SALMON DOUBLER	2	
19	AMP-EMST-04-00-03-0009	1ST BOTTOM DOUBLER FACING RIB CLIPS	1		AMP-EMST-04-00-03-0009	1ST BOTTOM DOUBLER FACING RIB CLIPS	1	
20	AMP-EMST-04-00-03-0010	2nd BOTTOM DOUBLER FACING FRAME	1		AMP-EMST-04-00-03-0010	2nd BOTTOM DOUBLER FACING FRAME	1	
21	AMP-EMST-04-00-03-0041	NEW LONG BOTTOM DOUBLER	2		AMP-EMST-04-00-03-0041	NEW LONG BOTTOM DOUBLER	2	
22	**AMP-EMST-04-00-05-0000**	FML BOND ASSEMBLY			**AMP-EMST-05-00-05-0000 Sht 1 of 14**	Panel Bond Assembly		
23	AMP-EMST-04-00-05-0000	FML BOND ASSEMBLY			AMP-EMST-05-00-05-0000 Sht 2 of 14	Panel Hot Bond Assembly		
24	AMP-EMST-04-00-05-0000-11	FML BOND ASSEMBLY LAYER 11			AMP-EMST-05-00-05-0000 Sht 13 of 14	Layer 9		
25	AMP-EMST-04-00-02-0013	TOP GRAY DOUBLER		2	AMP-EMST-04-00-02-0013	TOP GRAY DOUBLER		2
26	AMP-EMST-04-00-02-0014	ORANGE TOP DOUBLER		2	AMP-EMST-04-00-02-0014	ORANGE TOP DOUBLER		2
27	AMP-EMST-04-00-05-0000-10	FML BOND ASSEMBLY LAYER 10			AMP-EMST-05-00-05-0000 Sht 12 of 14	Layer 8		
28	AMP-EMST-04-00-03-0011	GREEN TOP DOUBLER		2	AMP-EMST-04-00-03-0011	GREEN TOP DOUBLER		2
29	AMP-EMST-04-00-02-0012	TOP PINK DOUBLER		2	AMP-EMST-04-00-02-0012	TOP PINK DOUBLER		2
30	AMP-EMST-04-00-05-0000-9	FML BOND ASSEMBLY LAYER 9						
31	AMP-EMST-04-00-05-0022	2ND ALUMINUM STRAP		42				
32	AMP-EMST-04-00-05-0038	2ND ADDED GREEN DOUBLER		2				
33	AMP-EMST-04-00-05-0039	2ND PURPLE DOUBLER YELLOW SIDE		1				
34	AMP-EMST-04-00-05-0040	2ND PURPLE DOUBLER PURPLE SIDE		1				
35	AMP-EMST-04-00-05-0000-8	FML BOND ASSEMBLY LAYER 8			AMP-EMST-05-00-05-0000 Sht 11 of 14	Layer 7		
36	AMP-EMST-04-00-05-0021	2ND CRUCIFORM MIDDLE		6				
37	AMP-EMST-04-00-05-0049	2ND CRUCIFORM YELLOW SIDE		1	AMP-EMST-04-00-05-0049	2ND CRUCIFORM YELLOW SIDE		1
38	AMP-EMST-04-00-05-0050	2ND CRUCIFORM PURPLE SIDE		1	AMP-EMST-04-00-05-0050	2ND CRUCIFORM PURPLE SIDE		1
39	AMP-EMST-04-00-05-0000-7	FML BOND ASSEMBLY LAYER 7			AMP-EMST-05-00-05-0000 Sht 10 of 14	Layer 6		
40	AMP-EMST-04-00-05-0019	2ND CIRCUMFERENTIAL FG		6	AMP-EMST-04-00-05-0019	2ND CIRCUMFERENTIAL FG		6
41	AMP-EMST-04-00-05-0067	2ND CIRC. FG PART 1		2	AMP-EMST-04-00-05-0067	2ND CIRC. FG PART 1		2
42	AMP-EMST-04-00-05-0068	2ND CIRC. FG PART 2		2	AMP-EMST-04-00-05-0068	2ND CIRC. FG PART 2		2
43	AMP-EMST-04-00-05-0069	2ND CIRC. FG PART 3		10	AMP-EMST-04-00-05-0069	2ND CIRC. FG PART 3		10
44	AMP-EMST-04-00-05-0070	2ND CIRC. FG PART 8		2	AMP-EMST-04-00-05-0070	2ND CIRC. FG PART 8		2
45	AMP-EMST-04-00-05-0000-6	FML BOND ASSEMBLY LAYER 6			AMP-EMST-05-00-05-0000 Sht 9of 14	Layer 5		
46	AMP-EMST-04-00-05-0017	1ST CIRCUMFERENTIAL FG		6	AMP-EMST-04-00-05-0017	1ST CIRCUMFERENTIAL FG		6
47	AMP-EMST-04-00-05-0062	1ST CIRC. FG PART 1		2	AMP-EMST-04-00-05-0062	1ST CIRC. FG PART 1		2
48	AMP-EMST-04-00-05-0063	1ST CIRC. FG PART 2		2	AMP-EMST-04-00-05-0063	1ST CIRC. FG PART 2		2
49	AMP-EMST-04-00-05-0064	1ST CIRC. FG PART 3		10	AMP-EMST-04-00-05-0064	1ST CIRC. FG PART 3		10
50	AMP-EMST-04-00-05-0065	1ST CIRC. FG PART 8		2	AMP-EMST-04-00-05-0065	1ST CIRC. FG PART 8		2
51	AMP-EMST-04-00-05-0000-5	FML BOND ASSEMBLY LAYER 5			AMP-EMST-05-00-05-0000 Sht 8 of 14	Layer 4		
52	AMP-EMST-04-00-05-0020	2ND LONGITUDIONAL FG		8	AMP-EMST-04-00-05-0020	2ND LONGITUDIONAL FG		8
53	AMP-EMST-04-00-05-0057	2ND LONG. PART 1		2	AMP-EMST-04-00-05-0057	2ND LONG. PART 1		2
54	AMP-EMST-04-00-05-0058	2ND LONG. PART 2		2	AMP-EMST-04-00-05-0058	2ND LONG. PART 2		2
55	AMP-EMST-04-00-05-0059	2ND LONG. PART 4		14	AMP-EMST-04-00-05-0059	2ND LONG. PART 4		14
56	AMP-EMST-04-00-05-0060	2ND LONG. PART 18		2	AMP-EMST-04-00-05-0060	2ND LONG. PART 18		2
57	AMP-EMST-04-00-05-0000-4	FML BOND ASSEMBLY LAYER 4			AMP-EMST-05-00-05-0000 Sht 7 of 14	Layer 3		
58	AMP-EMST-04-00-05-0018	1ST LONGITUDINAL FG		8	AMP-EMST-04-00-05-0018	1ST LONGITUDINAL FG		8
59	AMP-EMST-04-00-05-0052	1ST LONG. FG PART 1		2	AMP-EMST-04-00-05-0052	1ST LONG. FG PART 1		2
60	AMP-EMST-04-00-05-0053	1ST LONG. FG PART 2		2	AMP-EMST-04-00-05-0053	1ST LONG. FG PART 2		2
61	AMP-EMST-04-00-05-0054	1ST LONG.FG PART 4		14	AMP-EMST-04-00-05-0054	1ST LONG.FG PART 4		14
62	AMP-EMST-04-00-05-0055	1ST LONG.FG PART 18		2	AMP-EMST-04-00-05-0055	1ST LONG.FG PART 18		2
63	AMP-EMST-04-00-05-0000-3	FML BOND ASSEMBLY LAYER 3						
64	AMP-EMST-04-00-05-0016	1ST ALUMINUM STRAP		42				
65	AMP-EMST-04-00-05-0035	1ST ADDED GREEN DOUBLER		2				
66	AMP-EMST-04-00-05-0036	1ST PURPLE DOUBLER YELLOW SIDE		1				
67	AMP-EMST-04-00-05-0037	1ST PURPLE DOUBLER PURPLE SIDE		1				
68	AMP-EMST-04-00-05-0000-2	FML BOND ASSEMBLY LAYER 2			AMP-EMST-05-00-05-0000 Sht 6 of 14	Layer 2		
69	AMP-EMST-04-00-05-0015	FIRST CRUCIFORM MIDDLE		6				
70	AMP-EMST-04-00-05-0047	FIRST CRUCIFORM YELLOW SIDE		1	AMP-EMST-04-00-05-0047	FIRST CRUCIFORM YELLOW SIDE		1
71	AMP-EMST-04-00-05-0048	FIRST CRUCIFORM PURPLE SIDE		1	AMP-EMST-04-00-05-0048	FIRST CRUCIFORM PURPLE SIDE		1
72								
73					AMP-EMST-05-00-05-0000 Sht 5 of 14	Layer 1.2 FM94 Prepreg fiber direction 90° AMP-BP 5.1.2		
74	AMP-EMST-04-00-05-0000-1	FML BOND ASSEMBLY LAYER 1			AMP-EMST-05-00-05-0000-Sht 4 of 14	Layer 1.1 FM94 Prepreg fiber direction 0° AMP-BP 5.1.1		
75	AMP-EMST-04-00-05-0042	SKIN PREPREG			AMP-EMST-05-00-05-0000 Sht 3 of 14	Layer 1.0 FM94 Adhesive AMP-BP 5.1.0		
76	AMP-EMST-04-00-00-0000	SKIN		1	AMP-EMST-04-00-00-0000	SKIN		1
77								
78	**Stiffening details (Stringer, Rib Clips etc.)**		**88**		**Stiffening details (Stringer, Rib Clips etc.)**		**88**	
79	**Skin Assembly including external doublers**			**217**	**Skin Assembly including external doublers**			**113**
80	**Total Detail Part Numbers**			**305**	**Total Detail Part Numbers**			**201**

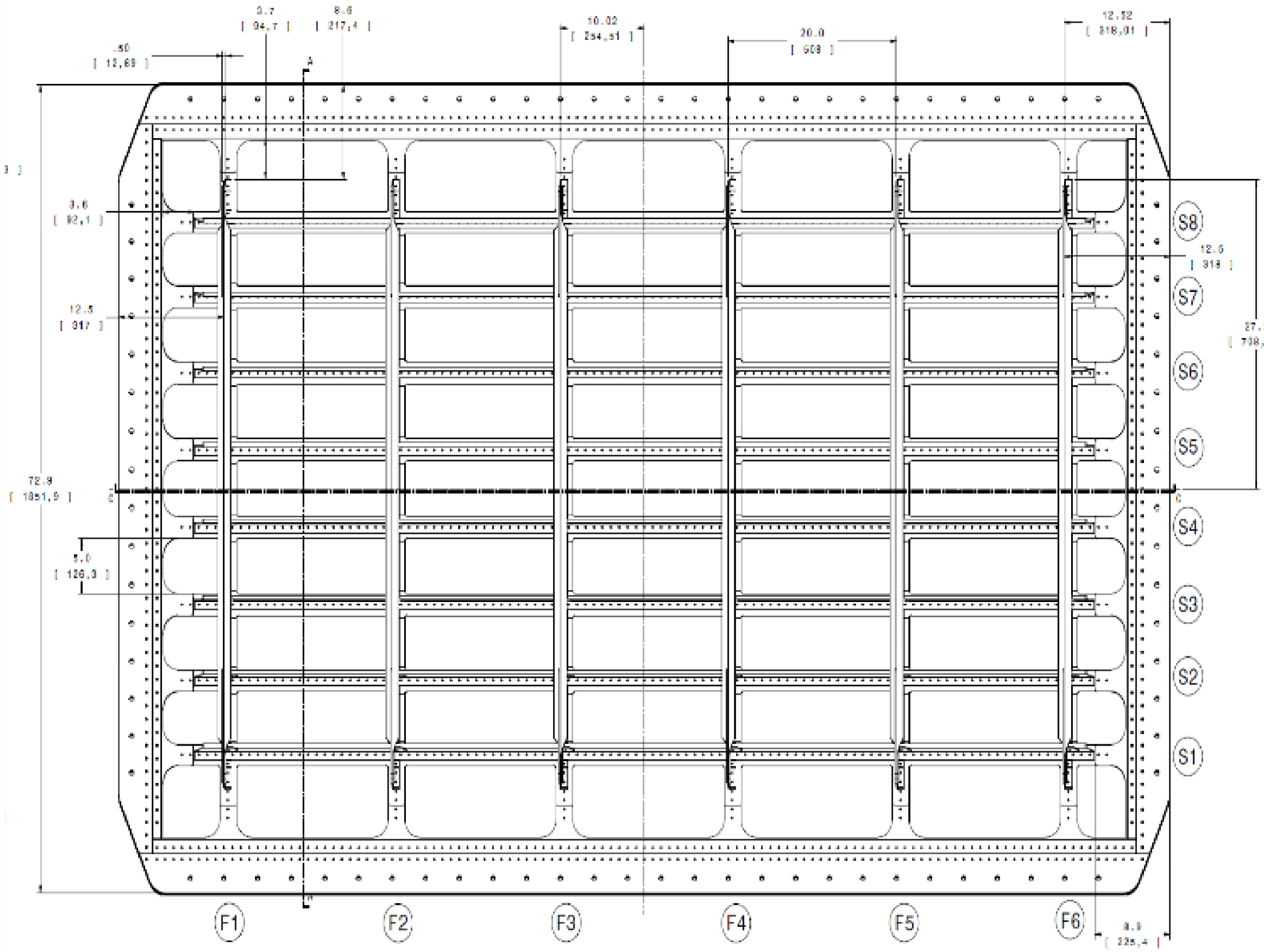


Figure B- 1. Panel 4 and 5 geometry

Table B- 2. Rivet requirements

Panel 4 & 5 Rivet Requirments	
Rivet	**Quantity**
NAS1097AD5-6	28
NAS1097AD5-7	1048
NAS1097AD5-12	48
NAS1097AD6-9	230
NAS1097AD6-10	230
NAS1097AD6-11	2
NAS1097AD6-12	2
NAS1097AD8-12	102
NAS1097AD8-16	114
MS20470AD5-6	498
MS20470AD5-7	72
MS20470AD5-8	334
MS20470AD5-9	12
MS20470AD5-10	72
Total	2792

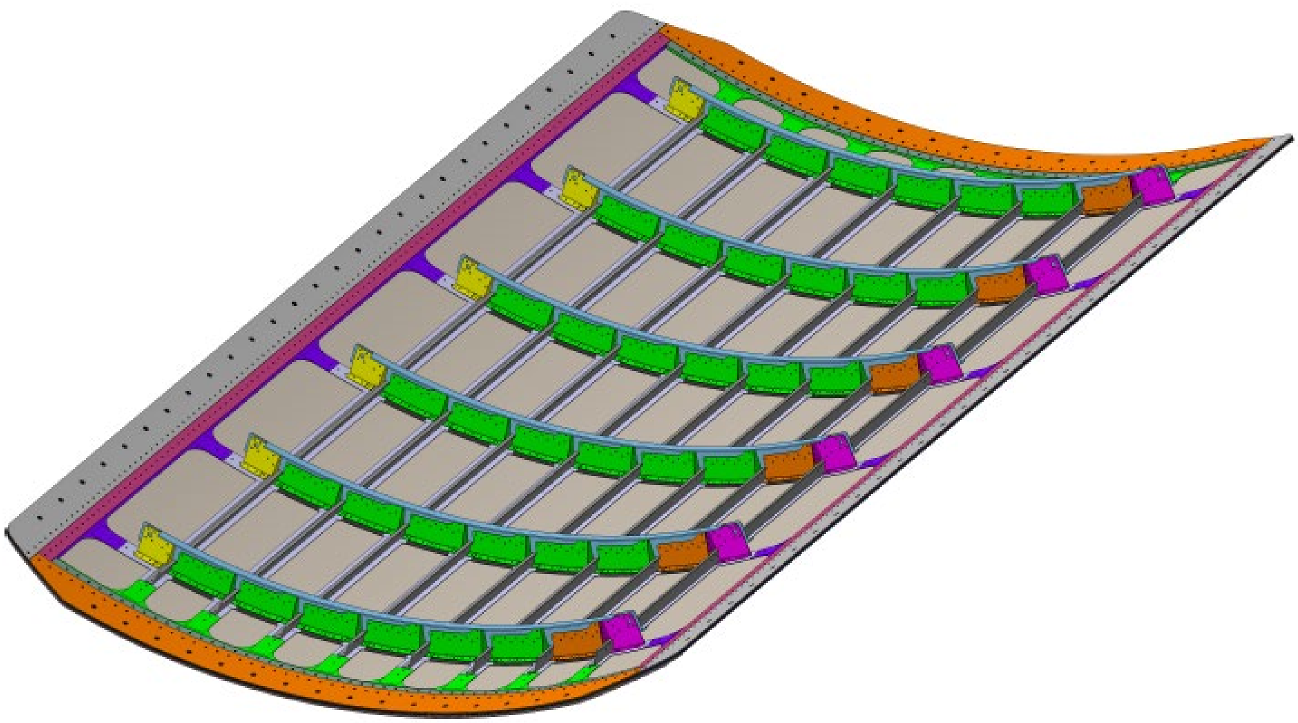


Figure B- 2. Panel CATIA model — interior frame structure

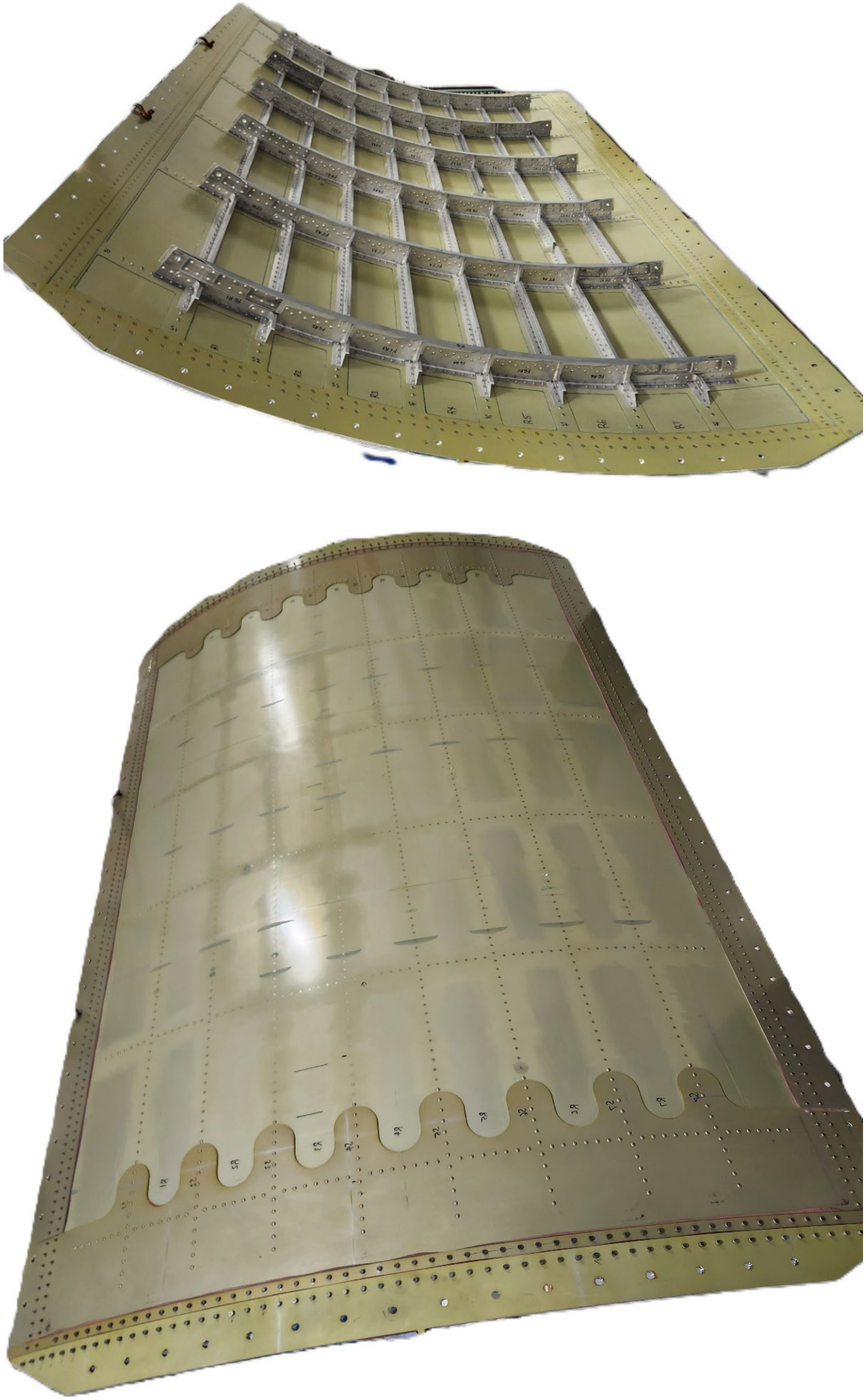


Figure B- 3. Internal and external view of completed panel assembly

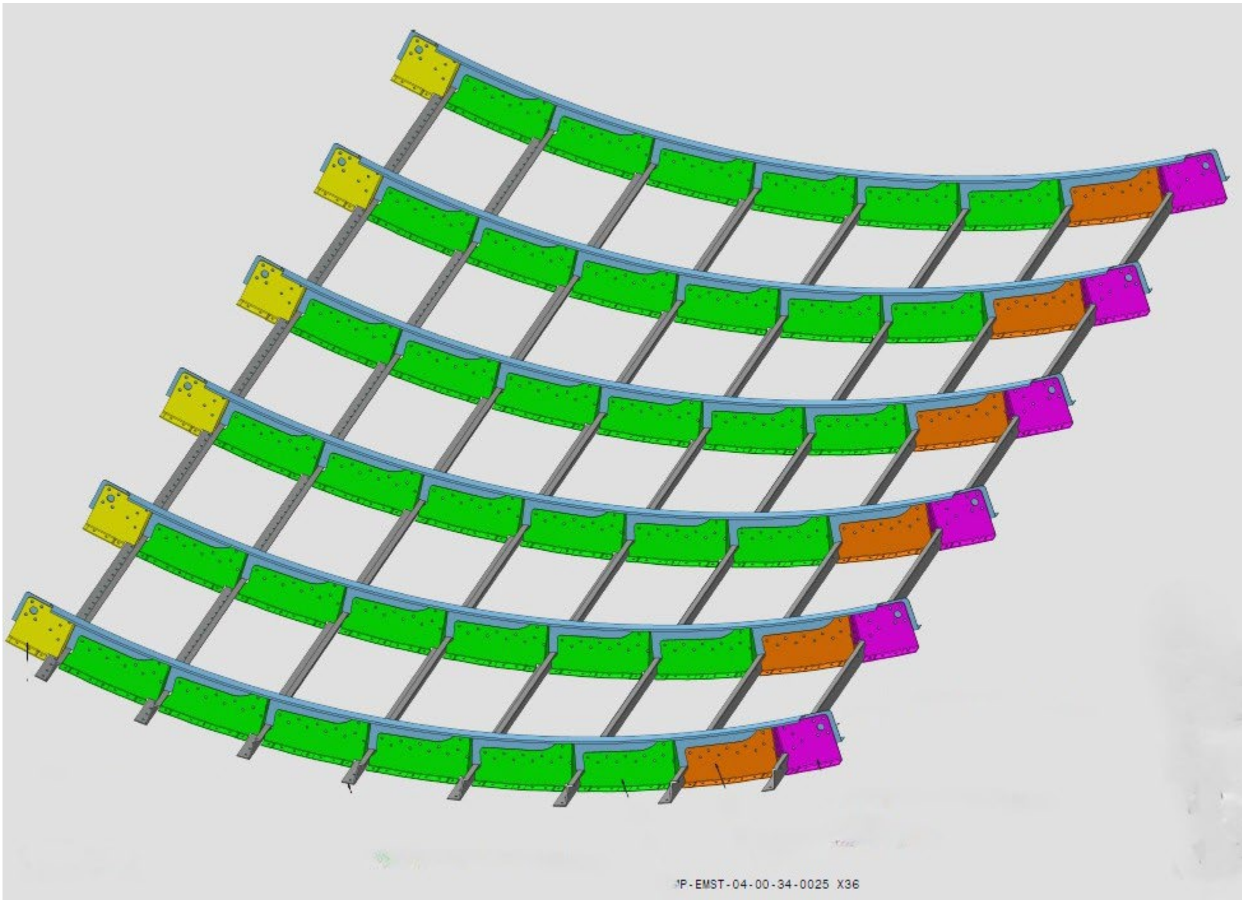


Figure B- 4. CATIA model of the panel interior frame structure

B.3 Panel Weight Analysis

During the design phase for Panel 5, a weight analysis was conducted on the skin assembly to assess the impact of reducing the number of plies on the overall weight of the assembly. The analysis focused on a single 20-in. by 7-in. bay within the skin panel, as illustrated in Figure B-5. This specific area was chosen because the reinforced sections outside the designated region, which are thicker to accommodate internal structure attachments, were excluded from the analysis. These reinforced areas were not considered as a part of the riveted structure.

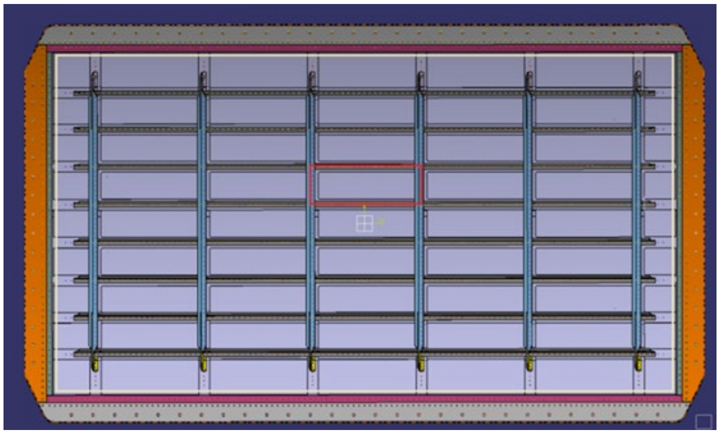
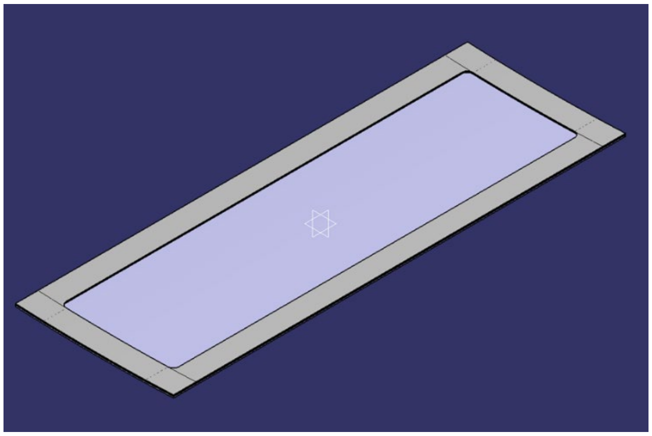


Figure B- 5. Panel skin section showing analysis area in the red rectangle

Panel 4



Panel 4 section	
Component	Weight
Skin	0.768
Adhesive	0.01
Prepreg 1.1	0.014
Prepreg 1.2	0.005
Lower Cruciform	0.078
1st Long Prepreg	0.014
2nd Long Prepreg	0.014
1st Circ prepreg	0.005
2nd Circ Prepreg	0.005
Upper Cruciform	0.078
Total Weight	0.991

Figure B- 6. Closeup of the analysis area

Panel 5: 0.050-in. thick skin and 0.016-in. thick cruciform

Panel 5 with the 0.016-in. thick cruciform has the same construction as Panel 4 with 0.050-in. thick skin, as opposed to the 0.056-in. thick Panel 4 skin.

Panel 5 section	0.016 cruciforms
Component	Weight
Skin (0.050)	0.685
Adhesive	0.01
Prepreg 1.1	0.014
Prepreg 1.2	0.005
Lower Cruciform	0.078
1st Long Prepreg	0.014
2nd Long Prepreg	0.014
1st Circ prepreg	0.005
2nd Circ Prepreg	0.005
Upper Cruciform	0.078
Total Weight	0.908

Panel 5: 0.050-in. thick skin and 0.012-in. thick cruciform

Panel 5 with 0.012-in. thick cruciform has the same construction as Panel 4 with a 0.050-in. thick skin.

Panel 5 section	0.012 cruciforms
Component	Weight
Skin (0.050)	0.685
Adhesive	0.01
Prepreg 1.1	0.014
Prepreg 1.2	0.005
Lower Cruciform	0.059
1st Long Prepreg	0.014
2nd Long Prepreg	0.014
1st Circ prepreg	0.005
2nd Circ Prepreg	0.005
Upper Cruciform	0.059
Total Weight	0.87

Panel 5: 0.045-in. thick skin and 0.016-in. thick cruciform

Panel 5 with 0.016-in. thick cruciform has the same construction as Panel 4, with a 0.045-in. thick skin opposed to the 0.056-in. thick Panel 4 skin.

Panel 5 section	0.016 cruciforms
Component	Weight
Skin (0.045)	0.617
Adhesive	0.01
Prepreg 1.1	0.014
Prepreg 1.2	0.005
Lower Cruciform	0.078
1st Long Prepreg	0.014
2nd Long Prepreg	0.014
1st Circ prepreg	0.005
2nd Circ Prepreg	0.005
Upper Cruciform	0.078
Total Weight	0.8404

Panel 5: 0.045-in. thick skin and 0.012 in. thick cruciform

Panel 5 with 0.012-in. thick cruciform is the same construction as Panel 4 with a 0.045-in. thick skin and 0.012-in. thick cruciform.

Panel 5 section	0.012 cruciforms
Component	Weight
Skin (0.045)	0.617
Adhesive	0.01
Prepreg 1.1	0.014
Prepreg 1.2	0.005
Lower Cruciform	0.059
1st Long Prepreg	0.014
2nd Long Prepreg	0.014
1st Circ prepreg	0.005
2nd Circ Prepreg	0.005
Upper Cruciform	0.059
Total Weight	0.8024

Skin weight comparison: Panel 1 monolithic skin vs Panel 4 laminate vs. Panel 5 alternative laminates

Because the original Panel 1 skin, stringers, and frames/shear ties were used, there was a weight increase in Panel 4 compared to Panel 1. The goal for Panel 5 was to use the same thickness of stringers and frames/shear ties and reduce the skin thickness to make the total weight the same as Panel 1 (skin thickness around 0.045 in.). Further weight reduction could be obtained in future panels by optimizing the stringers and frames/shear ties, but this was not an option for this program. However, due to the variability inherent in the chemical milling process, the final thickness of Panel 4's skin was 0.057 in. vs. the 0.046-in. thickness of Panel 5. However, Panels 4 and 5 will be loaded higher to compensate for any respective weight increases to achieve the same undamaged far field skin stress during damage tolerance crack growth cyclic loading (two different thickness skins with the same DA/DN properties and the same stress intensity factor from the far field stress would be expected to exhibit the same crack growth, assuming secondary effects of building and bending are ignored). In this case the crack growth performance improvement of Panels 4 and 5 can be compared directly to Panel 1. Since Panels 4 and 5 are tested to the same cyclic far field stresses any inspection life improvement in Panels 4 or 5 would be a rough indicator of the weight savings potential. The options for a potential next set of panel tests would be to optimize the skins, stringers, and frames/shear ties to keep the FML concept the same weight as Panel 1 and validate the longer inspections measured in the current tests at equal skin stresses, or design the FML panels to reduce the panel weight compared to Panel 1 which increases the stress levels in the FML reinforced panel with the goal to maintain the same inspection cycles as Panel 1. Other options could include a mix of these two options.

			P1 Comparison	
Panel Section	Weight	Difference	Difference	Percentage
1	0.826	0	0	100.00%
4	0.991	0.165	0.165	119.98%
5(0.050, 0.016)	0.908	-0.083	0.082	109.93%
5(0.050, 0.012)	0.87	-0.038	0.044	105.33%
5(0.045, 0.016)	0.8404	-0.0296	0.0144	101.74%
5(0.045, 0.012)	0.8024	-0.038	-0.0236	97.14%

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Prototype skin assembly layup

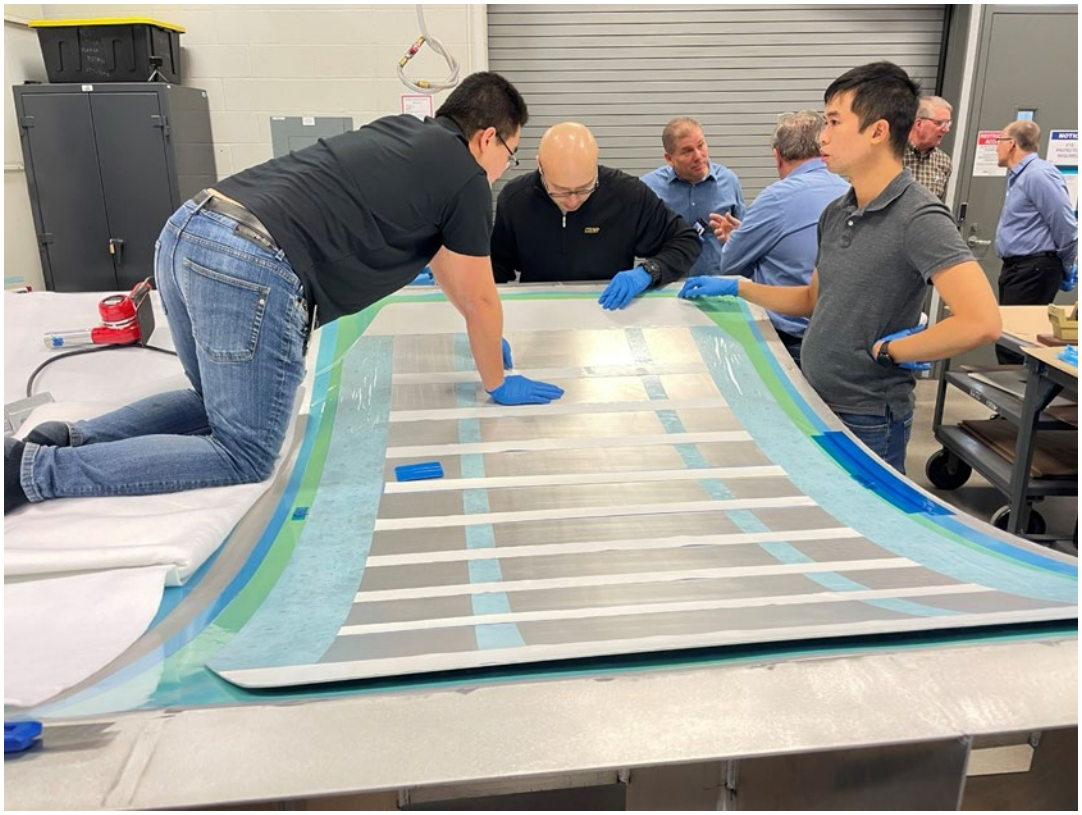


Figure B- 7. Prototype panel lay-up

Figure B- 8. Waffle skin details

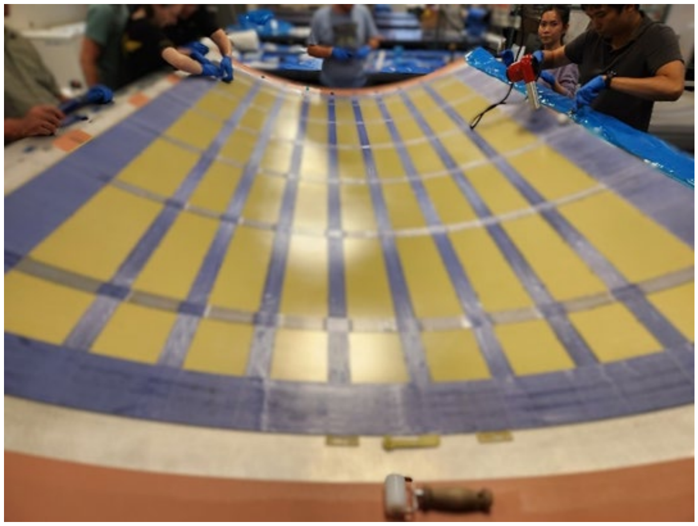


Figure B- 9. FML lay-up on waffle skin

Panel assembly

Figure B- 10. Completed assembly in the FAJ

Figure B- 11. Panel assembly work in progress showing how frames were attached

Figure B- 12. Close-up of the frame locator fixture

Figure B- 13. Installed frame assembly and details with locator

Panel frame redesign to facilitate test load application

The FAA experienced frame failure as shown in Figure B- 14 and requested a redesign of the frame attachments.

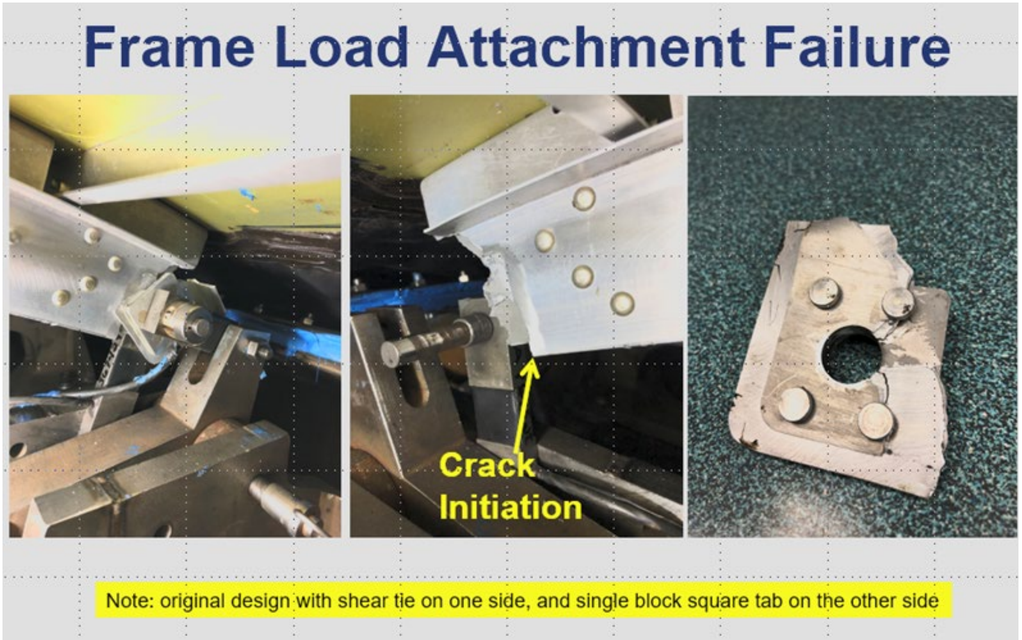


Figure B- 14. Frame load attachment failure

Multiple design concepts were investigated, resulting in replacing the sheet metal joint with two machined fittings and two bearing pads that distributed the load over the frame structure through thickness step-downs, as shown below.

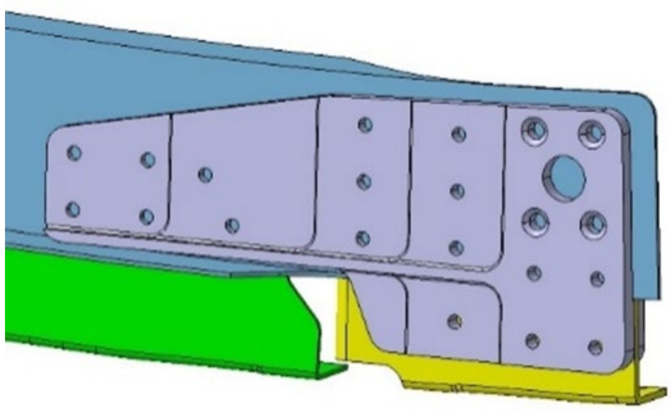


Figure B- 15. CATIA model, right-hand side

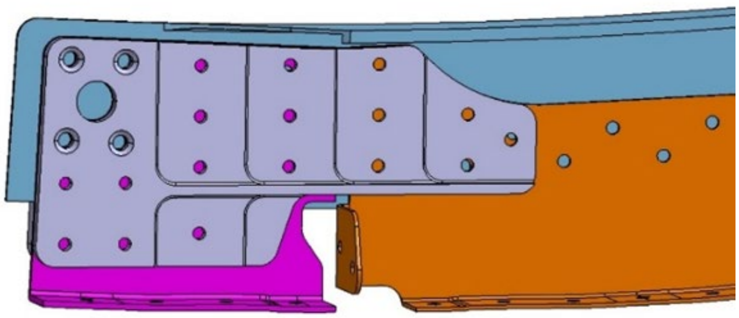


Figure B- 16. CATIA model, left-hand side

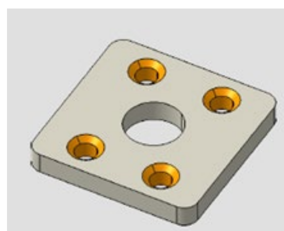


Figure B- 17. Bearing Block 2 location

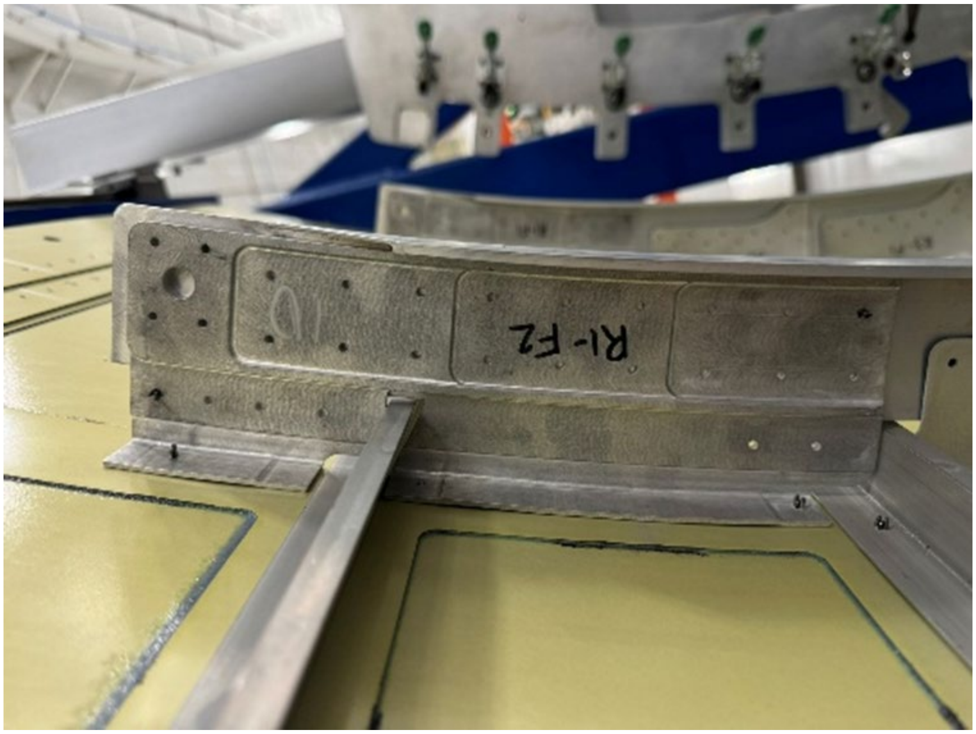


Figure B- 18. Close-up of machined fitting without bearing block

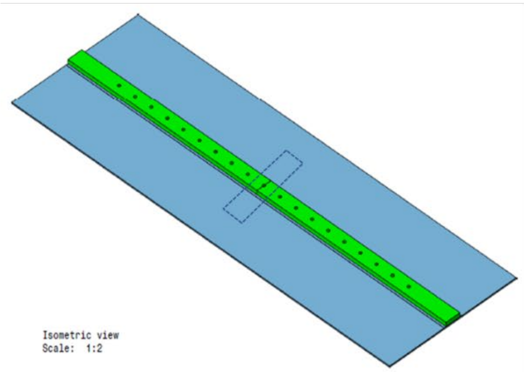
C Coupon design and damage locations

AMP Coupon Assembly and Manufacturing Plan Details														
Description				Damage					Geometrical Requirements					
Coupon	Panel Style	Direction	Quantity	Delam Size	Delam Location	Stringer/Frame Flange	FML	Skin	Skin Thickness	Bonding method	FML Thickness	Strap Thickness	Coupon Thickness	Rivet Length
A	1	Longitudinal	4	NA	NA	Cut	NA	0.256	0.065	NA	NA	0.079	0.144	-6
B1BP	4	Longitudinal	2	1	Skin-BP	Cut	0.3	0.256	0.057	BondPreg	0.042	0.125	0.234	-8
B2BP	4	Longitudinal	2	1	Skin-BP	Cut	0.3	0.256	0.057	BondPreg	0.042	0.125	0.234	-8
B3BP	4	Longitudinal	2	0	NA	Cut	0.3	0.256	0.057	BondPreg	0.042	0.125	0.234	-8
B4BP	4	Longitudinal	2	0	NA	Cut	0.3	0.256	0.057	BondPreg	0.042	0.125	0.234	-8
C1	4	Longitudinal	2	23.5	No Bondpreg	Cut	0.3	0.256	0.057	NA	0.042	0.125	0.234	-8
C2	4	Longitudinal	2	23.5	No Bondpreg	Cut	0.3	0.256	0.057	NA	0.042	0.125	0.234	-8
F1BASE	1	Circumferential	1	NA	NA	Cut	NA	0.256	0.065	NA	NA	0.134	0.199	-7
F2BASE	1	Circumferential	1	NA	NA	Cut	NA	0.256	0.065	NA	NA	0.134	0.199	-7
F1BP	4	Circumferential	1	NA	NA	Cut	0.3	0.256	0.057	BondPreg	0.042	0.098	0.207	-7
F2BP	4	Circumferential	1	NA	NA	Cut	0.3	0.256	0.057	BondPreg	0.042	0.098	0.207	-7
F3BP	4	Circumferential	1	0	NA	Cut	0.3	0.256	0.057	BondPreg	0.042	0.098	0.207	-7
F4BP	4	Circumferential	1	0	NA	Cut	0.3	0.256	0.057	BondPreg	0.042	0.098	0.207	-7

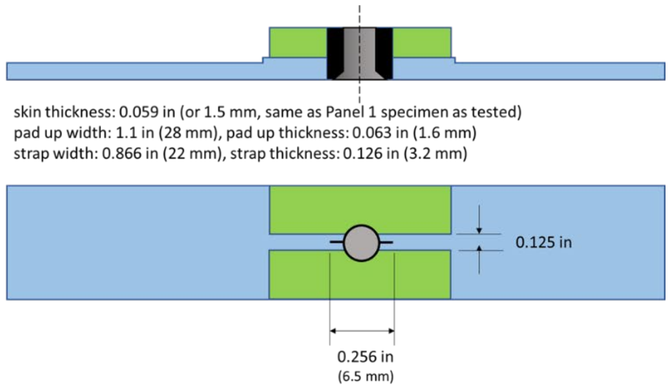
Coupon Layup Stack up			
	Layers		
Strap			**9**
FML	**Cruciform 2**		**8**
	Prepreg 2		**7**
	Prepreg 1		**6**
	Cruciform 1		**5**
Bondpreg (BP)	**Prepreg**		**4**
	Adhesive		**3**
Delamination			**2**
Skin			**1**

Coupons:	
Rivet	**Quantity**
NAS1097A	88
NAS1097A	132
NAS1097A	264
Total	484

GROUP A (4 Specimens)



Detail View



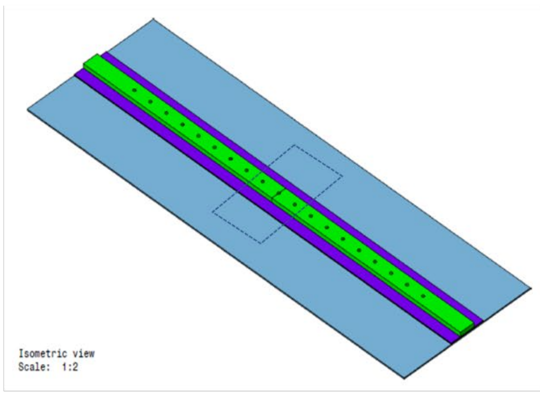
GROUP A - Baseline - Stringer Panel 1

			Initial damage		
	ID	delamination	stringer flange	FML	Skin
Panel 1 Mid-stringer Simulation Circumferential Crack Constant Amplitude Loading	A1	N.A.	severed	N.A.	0.05 in.
	A2	N.A.	severed	N.A.	0.05 in.

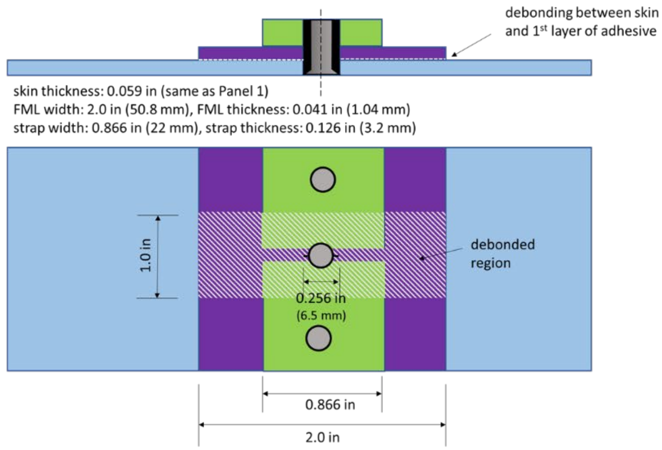
			Initial damage		
	ID	delamination	stringer flange	FML	Skin
Panel 1 Mid-stringer Simulation Circumferential Crack Spectrum Loading	A3-S	N.A.	severed	N.A.	0.05 in.

Coupon A - Layup Stack up						
Layers				Material	T - Inches	T - MM
2	Strap			2024 T3 Aluminum	0.079	2.0066
1	Skin			2524 T3 Aluminum	0.065	1.651
				Total Layup Thickness	0.144	3.6576

GROUP B – Bond Preg (8 Specimens)



Detail View



GROUP B - Bond Preg - Stringer Panel 4

			Initial damage		
	ID	delamination	stringer flange	FML	Skin
Panel 4 - BondPreg Bonded Mid Stringer FML Simulation Test - Circumferential Crack Under FML Strap with 1.0 in. Delamination C.A. Loading	B1BP-CA B2BP-CA	1.0 in.	severed	0.05 in.	0.05 in.
	B3BP-CA B4BP-CA	0.0 in.	severed	0.05 in.	0.05 in.

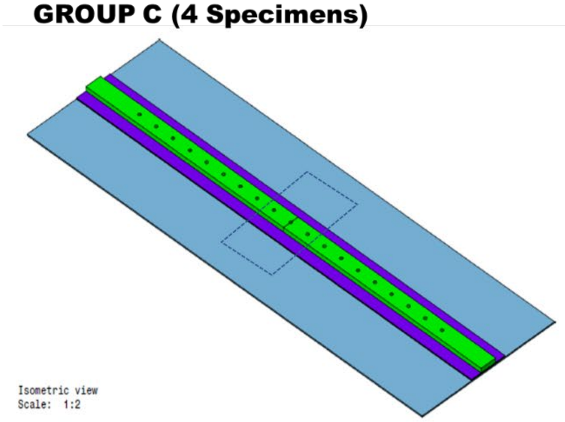
			Initial damage		
	ID	delamination	stringer flange	FML	Skin
Panel 4 - BondPreg Bonded Mid Stringer FML Simulation Test - Circumferential Crack Under FML Strap with 1.0 in. Delamination Spectrum Loading	B1BP-S B2BP-S	1.0 in.	severed	0.05 in.	0.05 in.
	B3BP-S B4BP-S	0.0 in.	severed	0.05 in.	0.05 in.

Coupon B1-B2BP - Layup Stack up

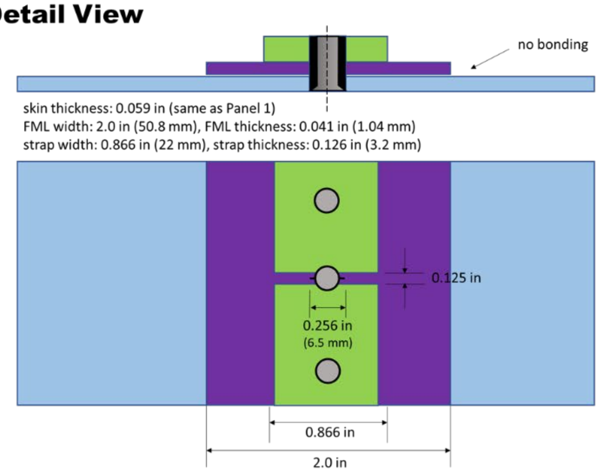
Layers				Material	T - Inches	T - MM
9	Strap			2024 T3 Aluminum	0.125	3.175
8	FML	Cruciform 2		2024 T3 Aluminum	0.016	0.4064
7		Prepreg 2		FM94 Prepreg	0.005	0.127
6		Prepreg 1		FM94 Prepreg	0.005	0.127
5		Cruciform 1		2024 T3 Aluminum	0.016	0.4064
4	Bondpreg (BP)	Prepreg		FM94 Prepreg	0.005	0.127
3		Adhesive		FM94 Adhesive	0.005	0.127
2	Delamination			PTFE Skived Teflon Sheet	0.0005	0.0127
1	Skin			2524 T3 Aluminum	0.057	1.4478
				Total Layup Thickness	0.2345	5.9563

Coupon B3-B4BP - Layup Stack up						
Layers				**Material**	**T - Inches**	**T - MM**
8	Strap			2024 T3 Aluminum	0.125	3.175
7	FML	Cruciform 2		2024 T3 Aluminum	0.016	0.4064
6		Prepreg 2		FM94 Prepreg	0.005	0.127
5		Prepreg 1		FM94 Prepreg	0.005	0.127
4		Cruciform 1		2024 T3 Aluminum	0.016	0.4064
3	Bondpreg (BP)	Prepreg		FM94 Prepreg	0.005	0.127
2		Adhesive		FM94 Adhesive	0.005	0.127
1	Skin			2524 T3 Aluminum	0.057	1.4478
				Total Layup Thickness	0.234	5.9436

GROUP C (4 Specimens)



Detail View



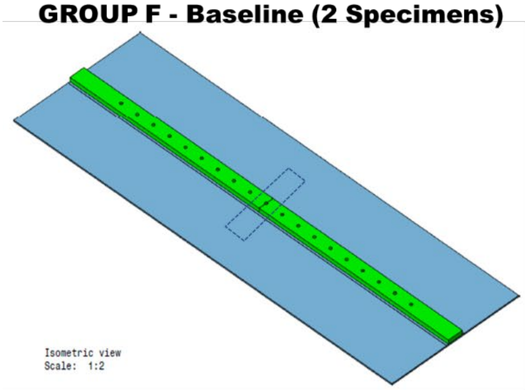
GROUP C - No Bonding - Stringer Panel 4

			Initial damage		
	ID	delamination	stringer flange	FML	Skin
Panel 4 - Mid Stringer FML Simulation Test - Circumferential Crack Under FML Strap	C1-CA C2-CA	riveted only	severed	0.05 in.	0.05 in.

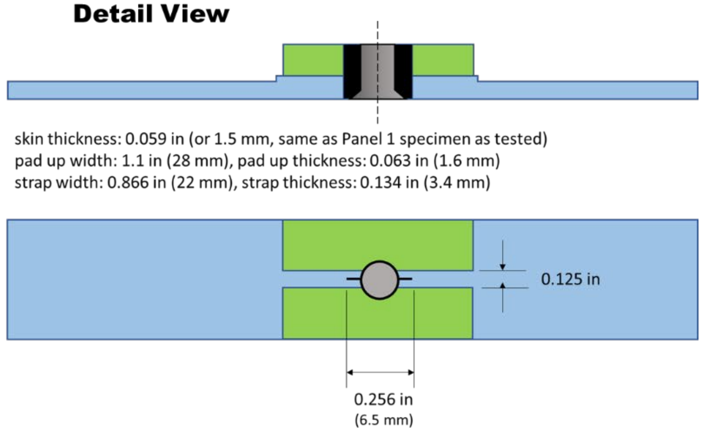
			Initial damage		
	ID	delamination	stringer flange	FML	Skin
Panel 4 - Mid Stringer FML Simulation Test - Circumferential Crack Under FML Strap	C1-S C2-S	riveted only	severed	0.05 in.	0.05 in.

Coupon C1 & C2 - Layup Stack up						
Layers				**Material**	**T - Inches**	**T - MM**
7	Strap			2024 T3 Aluminum	0.125	3.175
6	FML	Cruciform 2		2024 T3 Aluminum	0.016	0.4064
5		Prepreg 2		FM94 Prepreg	0.005	0.127
4		Prepreg 1		FM94 Prepreg	0.005	0.127
3		Cruciform 1		2024 T3 Aluminum	0.016	0.4064
2	Delamination			PTFE Skived Teflon Sheet	0.0005	0.0127
1	Skin			2524 T3 Aluminum	0.057	1.4478
				Total Layup Thickness	0.2245	5.7023

GROUP F - Baseline (2 Specimens)



Detail View

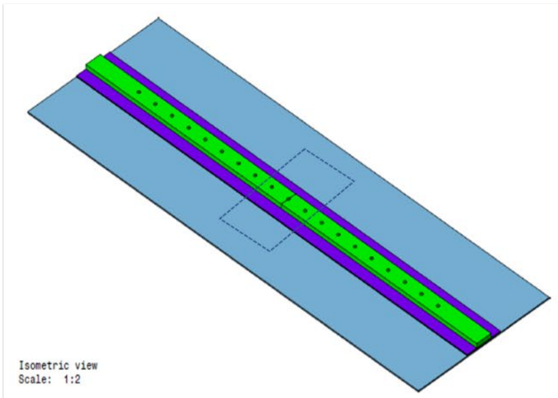


GROUP F - Baseline Frame Panel 1

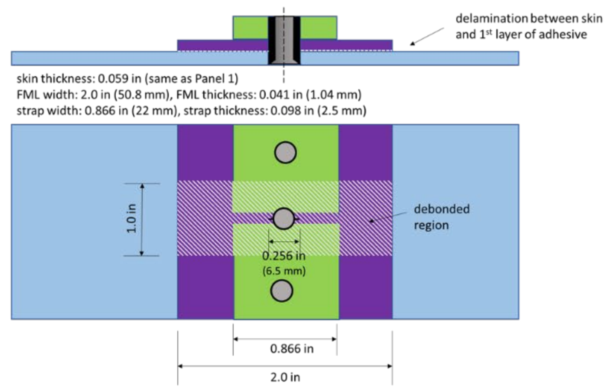
			Initial damage		
	ID	delamination	frame flange	FML	Skin
Panel 1 - Baseline Mid Frame Simulation Test -Longitudinal Crack C.A. Loading	F1BASE-CA F2BASE-CA	N.A	severed	N.A	0.05 in.

Coupon F1 -F2 BASE Layup Stack up						
Layers				**Material**	**T - Inches**	**T - MM**
9	**Strap**			**2024 T3 Aluminum**	**0.098**	**2.4892**
8	**FML**	**Cruciform 2**		**2024 T3 Aluminum**	**0.016**	**0.4064**
7		**Prepreg 2**		**FM94 Prepreg**	**0.005**	**0.127**
6		**Prepreg 1**		**FM94 Prepreg**	**0.005**	**0.127**
5		**Cruciform 1**		**2024 T3 Aluminum**	**0.016**	**0.4064**
4	**Bondpreg (BP)**	**Prepreg**		**FM94 Prepreg**	**0.005**	**0.127**
3		**Adhesive**		**FM94 Adhesive**	**0.005**	**0.127**
2	**Delamination**			**PTFE Skived Teflon Sheet**	**0.0005**	**0.0127**
1	**Skin**			**2524 T3 Aluminum**	**0.057**	**1.4478**
				Total Layup Thickness	**0.2075**	**5.2705**

GROUP F – Bond Preg (2 Specimens)



Detail View



GROUP F - Bond Preg - Frame Panel 4

			Initial damage		
	ID	delamination	frame flange	FML	Skin
Panel 4 - BondPreg Bonded Mid Frame FML Simulation Test -Longitudinal Crack Under FML Strap with 1.0 in. or 0.0 in. Delamination	F1BP-CA F2BP-CA	1.0 in.	severed	0.05 in.	0.05 in.
	F3BP-CA F4BP-CA	0 in.	severed	0.05 in.	0.05 in.

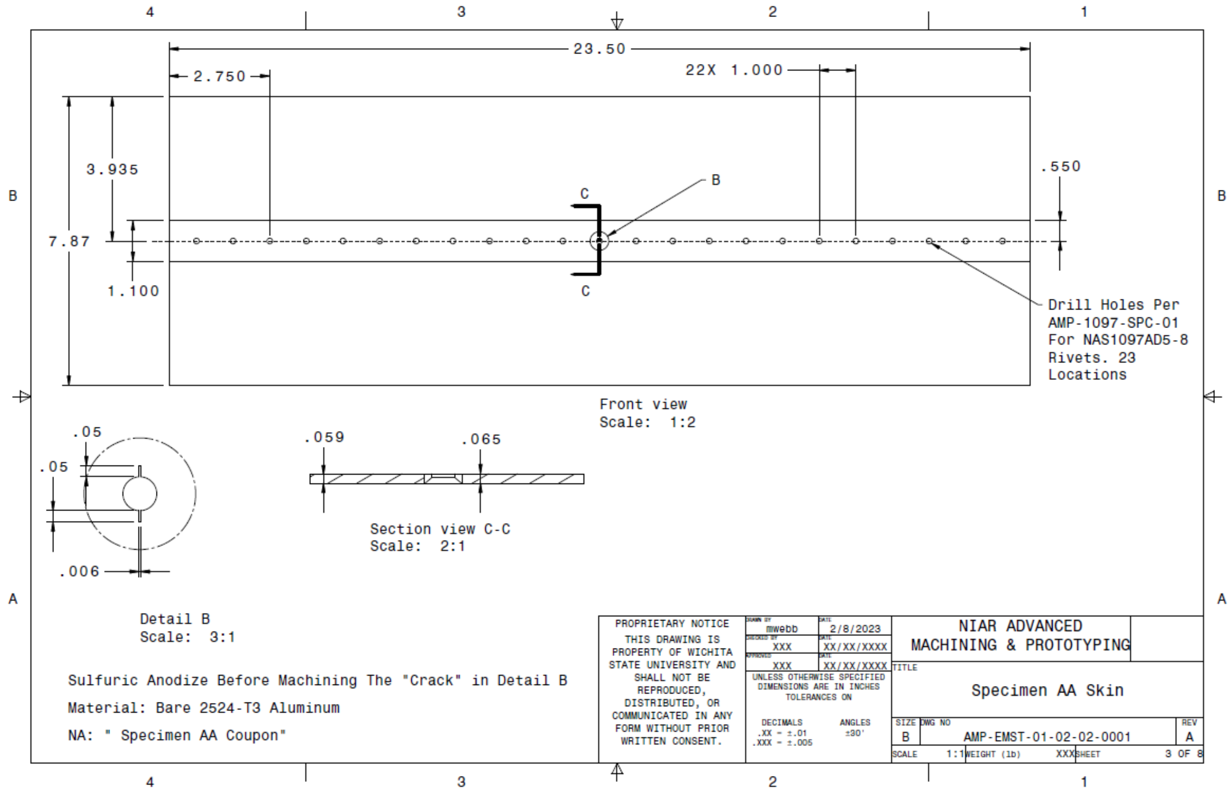
Coupon F1 - F2BP- Layup Stack up

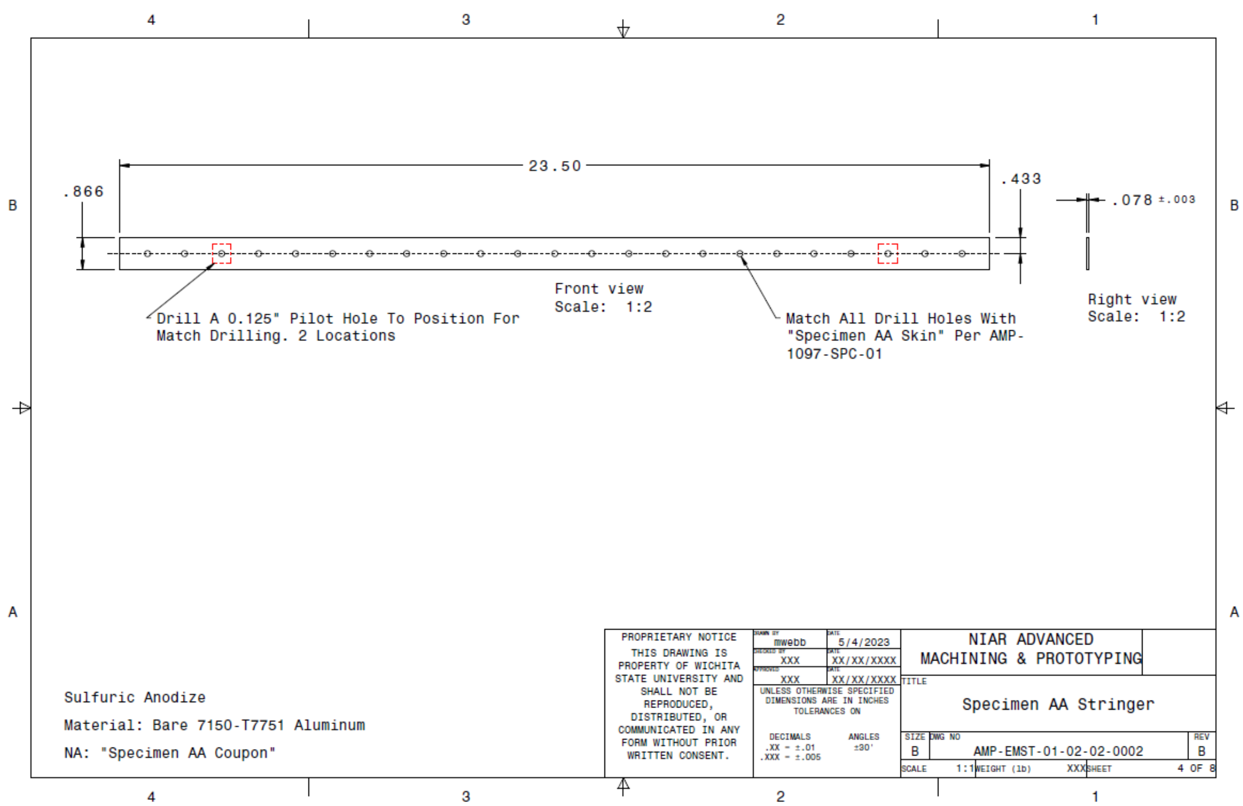
Layers				Material	T - Inches	T - MM
9	Strap			2024 T3 Aluminum	0.098	2.4892
8	FML	Cruciform 2		2024 T3 Aluminum	0.016	0.4064
7		Prepreg 2		FM94 Prepreg	0.005	0.127
6		Prepreg 1		FM94 Prepreg	0.005	0.127
5		Cruciform 1		2024 T3 Aluminum	0.016	0.4064
4	Bondpreg (BP)	Prepreg		FM94 Prepreg	0.005	0.127
3		Adhesive		FM94 Adhesive	0.005	0.127
2	Delamination			PTFE Skived Teflon Sheet	0.0005	0.0127
1	Skin			2524 T3 Aluminum	0.057	1.4478
				Total Layup Thickness	0.2075	5.2705

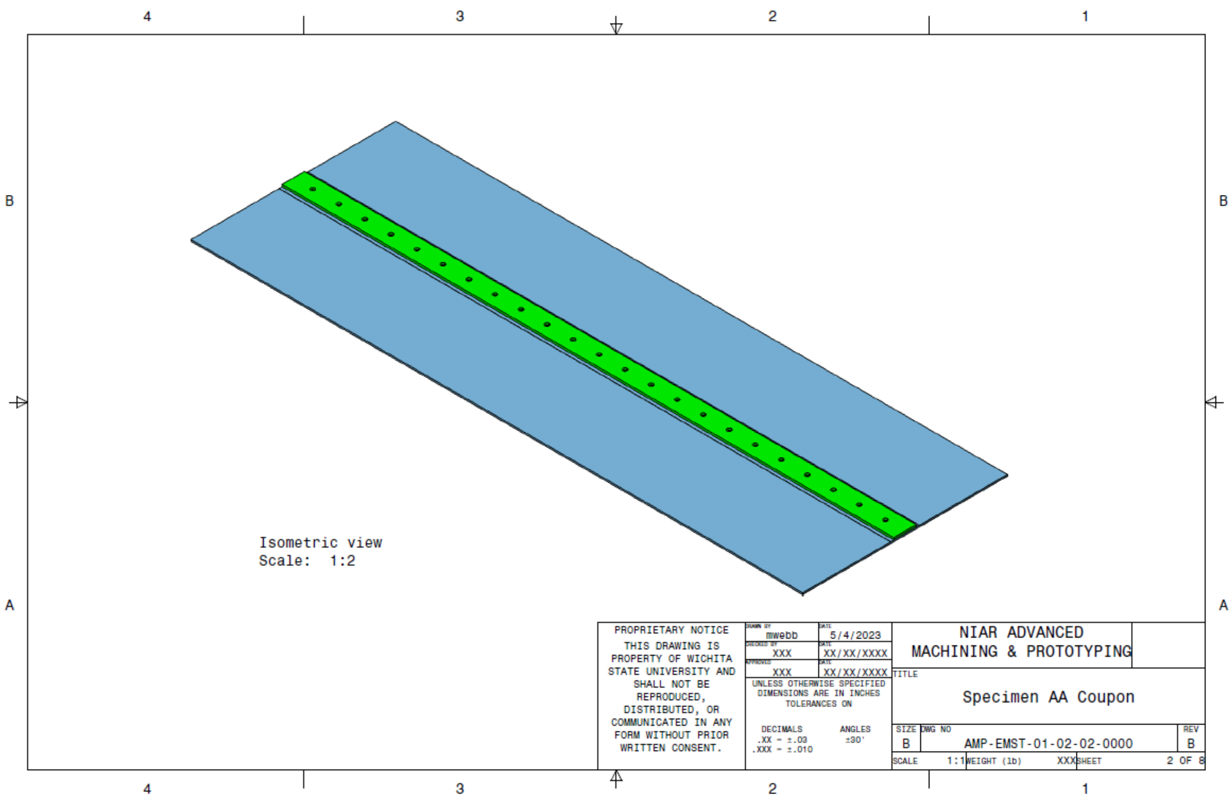
Coupon F3 - F4BP- Layup Stack up

Layers				Material	T - Inches	T - MM
8	Strap			2024 T3 Aluminum	0.098	2.4892
7	FML	Cruciform 2		2024 T3 Aluminum	0.016	0.4064
6		Prepreg 2		FM94 Prepreg	0.005	0.127
5		Prepreg 1		FM94 Prepreg	0.005	0.127
4		Cruciform 1		2024 T3 Aluminum	0.016	0.4064
3	Bondpreg (BP)	Prepreg		FM94 Prepreg	0.005	0.127
2		Adhesive		FM94 Adhesive	0.005	0.127
1	Skin			2524 T3 Aluminum	0.057	1.4478
				Total Layup Thickness	0.207	5.2578

Coupon geometry (Typical)






Isometric view
Scale: 1:2
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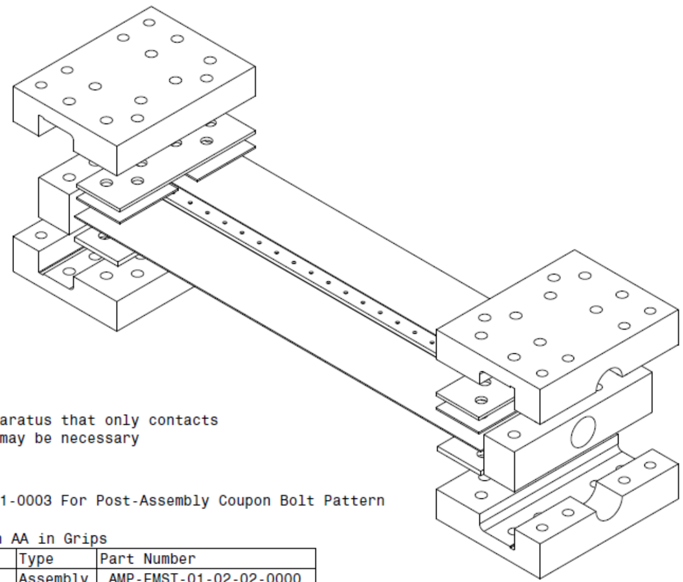
mwebb
5/4/2023
XXX
XX/XX/XXXX
XXX
XX/XX/XXXX
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON
DECIMALS
.XX = ±.03
.XXX = ±.010
ANGLES
±30'
NIAR ADVANCED MACHINING & PROTOTYPING
TITLE
Specimen AA Coupon
SIZE
DWG NO
REV
B
AMP-EMST-01-02-02-0000
B
SCALE
1:1
WEIGHT (lb)
XXX
SHEET
2 OF 8

4 3 2 1

B



Isometric view
Scale: 1:3

Use of an Anti-Buckling Aparatus that only contacts the edges of the specimen may be necessary

Note: See AMP-EMST-04-01-01-0003 For Post-Assembly Coupon Bolt Pattern

A

Bill of Material: Specimen AA in Grips

Quantity	Part Name	Type	Part Number
1	Specimen AA	Assembly	AMP-EMST-01-02-02-0000
2	Specimen A Rear Spacer	Part	AMP-EMST-04-01-03-2275
4	Specimen A Spacers	Part	AMP-EMST-04-01-02-0820
4	Jaw	Part	AMP-EMST-04-01-01-0001
2	Grip Bar	Part	AMP-EMST-04-01-01-0002
2	Specimen A Front Spacer	Part	AMP-EMST-04-01-03-1520

DRAWN BY mwebb DATE 5/4/2023
CHECKED BY XXX DATE XX/XX/XXXX
APPROVED XXX DATE XX/XX/XXXX

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON
DECIMALS .XX = ±.01 .XXX = ±.005
ANGLES ±30'

NIAR ADVANCED MACHINING & PROTOTYPING

TITLE Specimen AA Coupon In Grips

SIZE B DWG NO AMP-EMST-01-02-02-0000 REV B

SCALE 1:1 WEIGHT (lb) XXX SHEET 5 OF 8

4 3 2 1

D Coupon and grip tooling drawing list

Table D- 1. Coupon and grip drawing list

EMST Coupon Drawing Number, Material, and Quanty Information						
Coupon	**Drawing Number**	**Description**	**Material**	**Part Qty**	**Assembly Qty**	**Test Setup Qty**
A	AMP-EMST-01-02-01-0000				4	1
A	AMP-EMST-01-02-01-0001	Skin	2524-T3	1		
A	AMP-EMST-01-02-01-0002	Stringer	7150-T775	1		
			Total	2	4	1
B	AMP-EMST-04-02-01-0000				8	1
B	AMP-EMST-04-02-01-0001	Skin	2524-T3	1		
B	AMP-EMST-04-02-01-0002	Stringer	7150-T775	1		
B	AMP-EMST-04-02-01-0003	Aluminum Straps	2024-T3	2		
B	AMP-EMST-04-02-01-0004	GL-Epoxy	Gl-Epoxy	2		
			Total	6	8	1
C	AMP-EMST-04-02-03-0000				4	1
C	AMP-EMST-04-02-03-0001	Skin	2524-T3	1		
C	AMP-EMST-04-02-03-0002	Stringer	7150-T775	1		
C	AMP-EMST-04-02-03-0003	Aluminum Straps	2024-T3	2		
C	AMP-EMST-04-02-03-0004	GL-Epoxy	Gl-Epoxy	2		
			Total	6	4	1
F	AMP-EMST-05-02-01-0000				6	1
F	AMP-EMST-05-02-01-0001	Skin	2524-T3	1		
F	AMP-EMST-05-02-01-0004	Top Cruciform	2024-T3	1		
F	AMP-EMST-05-02-01-0005	Bottom Cruciform	2024-T3	1		
F	AMP-EMST-05-02-01-0008	Circ Fiberglass	Gl-Epoxy	2		
F	AMP-EMST-05-02-01-0009	Long Fiberglass	Gl-Epoxy	2		
F	AMP-EMST-05-02-01-0010	Prepreg	FM94	1		
			Total	8	6	1
Total Coupon Part Count				22	22	4

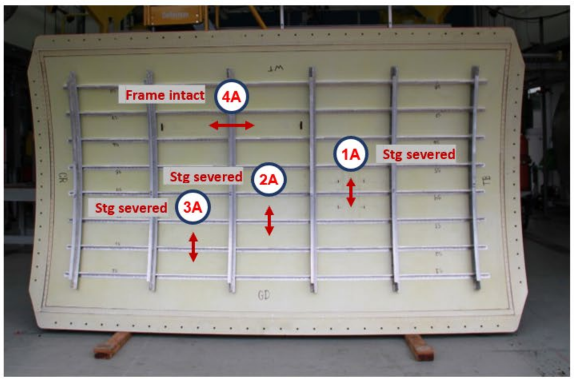
Coupon Test Holding Fixture Drawing List						
Tool	**Drawing Number**	**Description**	**Material**	**Part Qty**	**Assembly Qty**	**Test Setup Qty**
Grips	AMP-EMST-04-01-01-0000				1	1
	AMP-EMST-04-01-01-0001	Jaw	17-4 SS	4		
	AMP-EMST-04-01-01-0002	Loading Bar	17-4 SS	2		
	91273A675	0.5" Bolt	18-8 SS	10		
	98017A209	0.5" Washer	18-8 SS	20		
	90762A136	0.5" Nut	18-8 SS	10		
	91273A641	0.375" Bolt	18-8 SS	1		
	98017A199	0.375" Washer	18-8 SS	2		
	90762A127	0.375" Nut	18-8 SS	1		
			Total	50	1	1
Coupon Spacers	**Drawing Number**	**Description**	**Material**	**Part Qty**	**Assembly Qty**	**Test Setup Qty**
A Spacers	AMP-EMST-04-01-02-0195	Spacers	2024-T3	4		4
	AMP-EMST-04-01-03-0385	Front Spacer	2024-T3	2		2
	AMP-EMST-04-01-03-2275	Rear Spacer	2024-T3	2		2
B Spacers	AMP-EMST-04-01-02-2360	Spacers	2024-T3	4		4
	AMP-EMST-04-01-03-2360	Rear Spacer	2024-T3	2		2
C Spacers	AMP-EMST-04-01-02-2310	Spacers	2024-T3	4		4
	AMP-EMST-04-01-03-0050	Front Spacer	2024-T3	2		2
	AMP-EMST-04-01-03-2360	Rear Spacer	2024-T3			Duplicate
F Spacers	AMP-EMST-04-01-02-2360	Spacers	2024-T3	4		4
	AMP-EMST-04-01-03-2360	Rear Spacer	2024-T3	2		2
			Total	26	0	26
Anti-Buckling Bar	**Drawing Number**	**Description**	**Material**	**Part Qty**	**Assembly Qty**	**Test Setup Qty**
	AMP-EMST-04-01-04-0000				2	2
	AMP-EMST-04-01-04-0001	Bar	AL	1		
	AMP-EMST-04-01-04-0002	Stiffener	AL	1		
	AMP-EMST-04-01-04-0003	Grips	Teflon	2		
	90732A340	Thumb Screw	Steel	7		
			Total	11	2	2
Total Coupon Test Holding Fixture				87	3	29

E Skin panel damage definition

E.1 Panel 4 damage scenarios

March 14, 2024

Panel 4 Damage Scenarios



(*) Direct comparison with previous panels

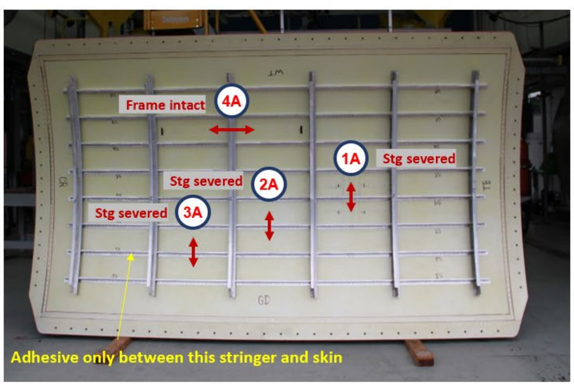
(**) Crack size adjusted to match previous panels scenarios for Phase 2

SCENARIO	Initial Skin Flaw Size (2a)	Delamination (between skin and FML)
1A	1.3 in (*) (33 mm)	1 in (25.4 mm)
2A	0.7 in (16.7 mm)	1 in (25.4 mm)
3A	0.36 in (9 mm)	20 in (508 mm)
4A (Phase 1)	1.50 in (38.1 mm)	1 in (25.4 mm)
4A (Phase 2)	> 2 in (*)(**) (> 50.8 mm)	n/a

0.256” crack on FML in all scenarios

E.2 Panel 5 damage scenarios

Panel 5 Damage Scenarios



(*) Direct comparison with previous panels

(**) Crack size adjusted to match previous panels scenarios for Phase 2

SCENARIO	Initial Flaw Size (2a)	Delamination (between skin and FML except 3A)
1A	1.3 in (*) (33 mm)	1 in (25.4 mm)
2A	0.7 in (16.7 mm)	1 in (25.4 mm)
3A	0.7 in (16.7 mm)	1 in (25.4 mm)
4A (Phase 1)	1.50 in (38.1 mm)	1 in (25.4 mm)
4A (Phase 2)	> 2 in (*)(**) (> 50.8 mm)	n/a

0.256” crack on FML in all scenarios
3A stringer bonded with adhesive instead of BondPreg
3A delamination between the 1st Al and 1st fiber glass layer

F Tooling

F.1 Tooling used and fabricated in support of the project

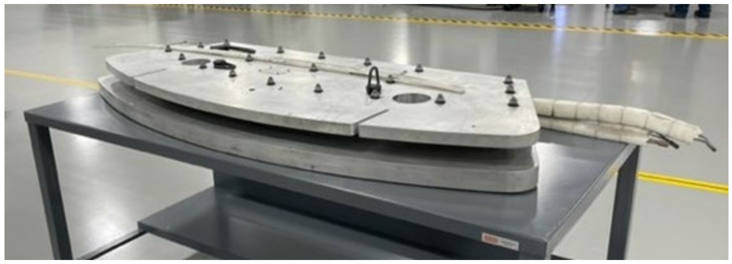
FAA EMST FAJ: The FAA provided the FAJ used in previous panel assemblies for this project. The assembly tool was inspected, installed, and releveled at the NIAR Advanced Machining and Prototyping (AMP) facility.

This tooling was designed to hold the panel and position riveted components during the final panel assembly. However, Panels 4 and 5 feature longitudinal external doublers that interfere with the curved vacuum pads. Clearance adjustments were necessary to ensure the panel aligned with the correct profile.

While the FAJ functions effectively, loading and unloading the panel can be challenging due to its recessed design. Introducing locating features outside the panel may provide benefits, given the large acceptable tolerance on the 0.5-in. loading holes used to orient and position the panel in the tool. External tabs could serve as an improved alternative, facilitating component positioning during the layup procedure.

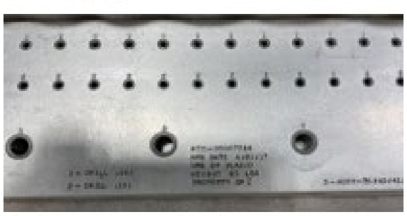
F.2 Frame stretch fixture and jaws

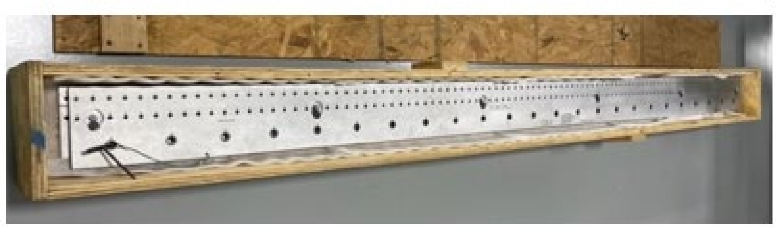
The FAA furnished the frame stretch tool and the supporting nylon snakes used in fabrication of the rib frame details. New stretch jaws were designed and fabricated to facilitate adaptation to the specific stretch machine.



F.3 Drill fixtures

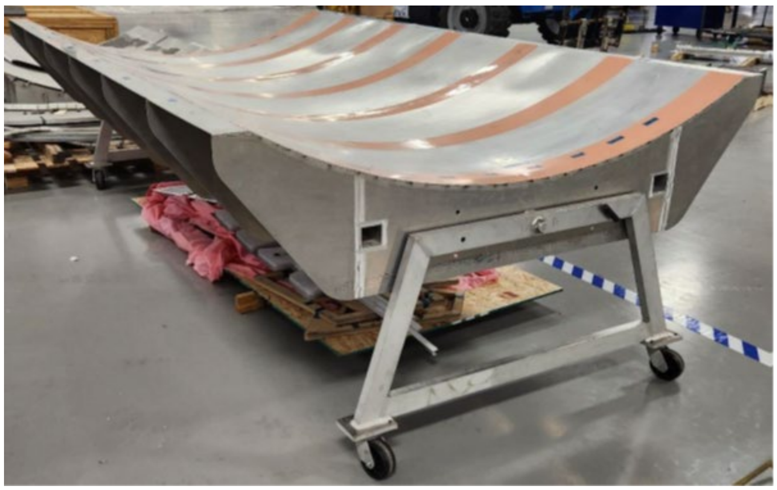
Several drill fixtures we provided by the FAA to facilitate drilling the skin panels to coordinate attachment to the FAA test fixture.





F.4 Skin assembly lay-up/bonding tool

The tooling for Panel 4 and 5 was designed to control the panel's form and ensure bag integrity during the cure cycle and transport between facilities. The lay-up surface consisted of 0.063-in. sheets, which were shaped to conform to the profile created by the supporting structure. Additionally, the tool was designed to tilt, facilitating the lay-up process, and featured vacuum ports around the perimeter.

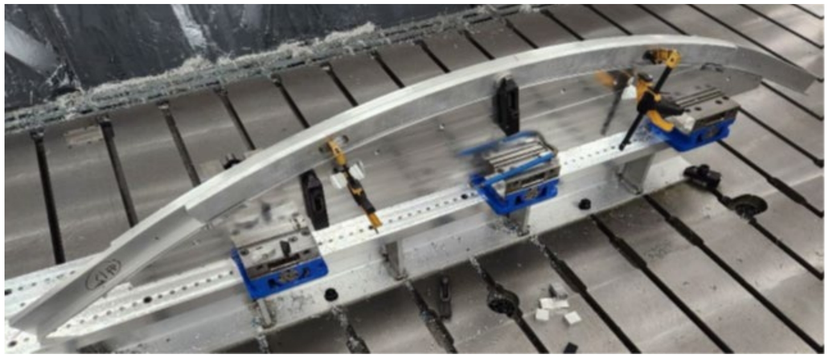


This approach was selected due to the CTE compatibility between the tool and the aluminum skin material. The tool’s lightweight design enabled easy transportation. However, weld seams caused distortion and leaks, which were resolved using Toolwrite (orange) material over the weld joints.

Although manufacturing the lay-up surface from one continuous sheet was evaluated, it was not completed due to availability of sheet material and time constraints. This method is recommended for future tooling projects. Enhancements such as adding locking casters and shortening the legs by a few inches would improve the design. While the built-in vacuum ports were not utilized, bag surface ports proved effective for each lay-up and cure cycle.

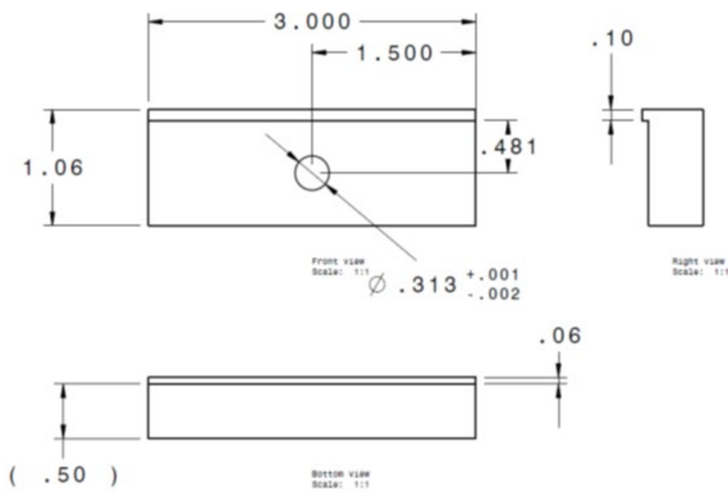
F.5 Numerical control mill fixture

This fixture is used to hold the frames in a final contour rigidly during the machining of the stretch-formed frames. Adequate clamping locations and force so that the part does not shift during milling as well as clearance for tools and holders.



F.6 Stringer drill fixture

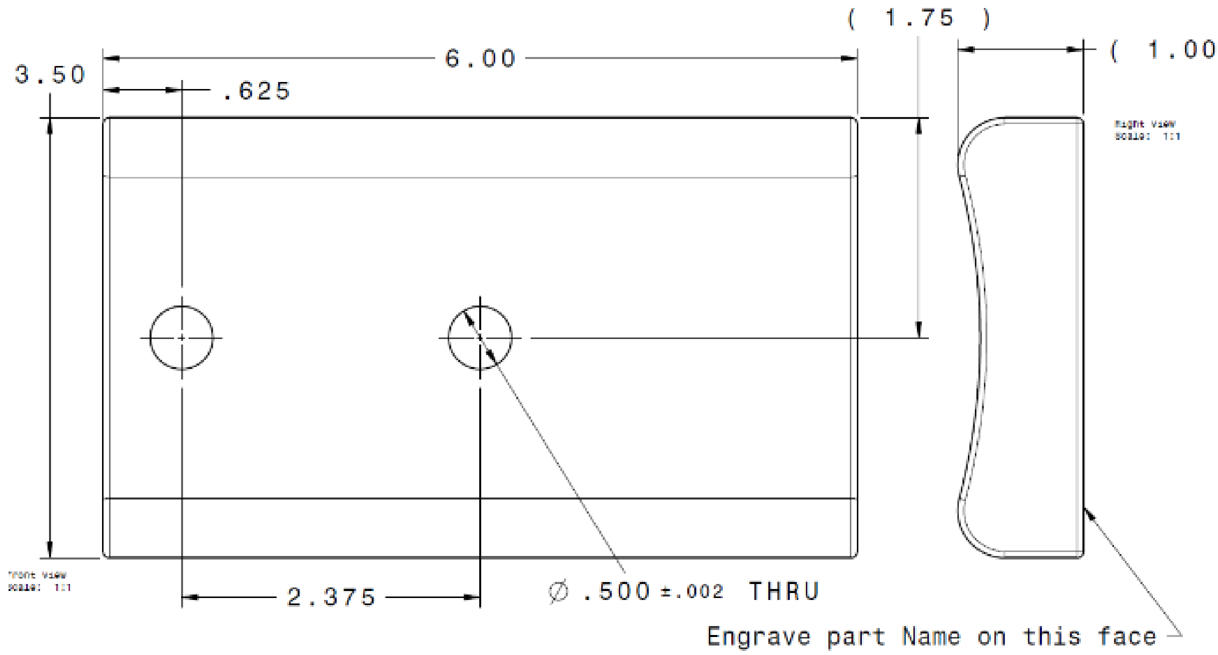
This tooling was developed to pilot holes in the stringers at the correct edge offset so that the stringer would be properly located during the assembly process. The lip locates the hole relative to the edge of the stringer and the end holes when lined up flush with each end of the stringer. There is a 0.125-in. drill busing press-fit into the 5/16-in. hole.



F.7 Skin drill fixture

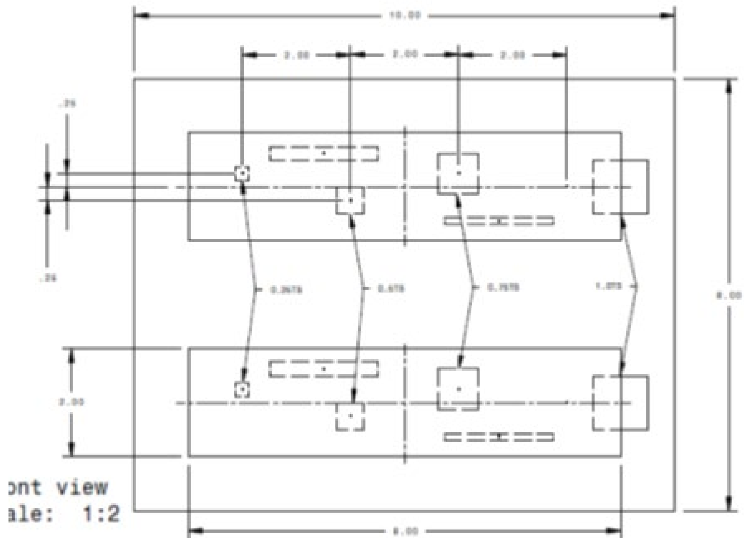
The skin panels were routed, and all pilot holes were water jet-drilled while in the flat condition, adhering to the design specifications of the previous test article skins. This tooling was developed to drill full-sized holes perpendicular to the contoured skin surface, accommodating drill bushings of various required sizes.

When aligned longitudinally with the panel on the outer surface of the skin, the tool enabled precise drilling of holes perpendicular to the skin. This design provided a simple yet accurate method to drill hundreds of holes in the skin panel. However, maintaining alignment with the drill during operations proved challenging, leading to difficulties and multiple broken drill bits.



F.8 Non-Destructive Inspection coupons

This tooling was designed to establish NDI criteria and methodologies for both coupons and skin bond assembly. The tool consists of a panel with two pad-up regions, constructed in the same manner as skin panel. Teflon delaminations of varying sizes are embedded at different layers within the panel. This configuration enables the NDI inspector to calibrate their equipment effectively, ensuring that the panel bonds comply with specification requirements. Two versions were fabricated, one as shown with square Teflon shapes and one with round.



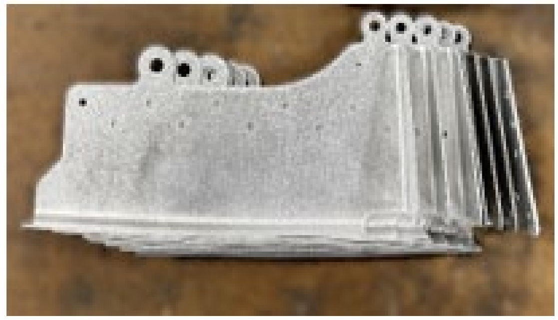
F.9 Contoured bench dolly

This tooling was designed to hold the panel's outside-mold-line (OML) in contour during the cold bonding of external doublers or other operations from the OML side. The top surface was engineered with the correct radius and equipped with stabilizing legs to allow the tooling to stand unassisted.

Clamp points were incorporated to maintain the panel's contour during the cold bonding of exterior doublers to the skin assembly. These also facilitated coordination with external drill bars used to transfer the FAA test fixture coordinating holes. The tooling board was waterjet cut, ensuring a rigid and cost-effective solution.

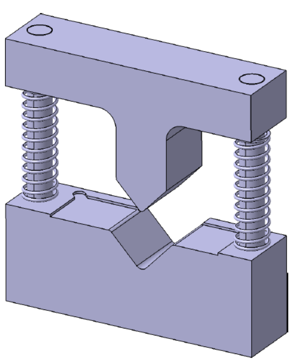
F.10 Rib clip hydroforming dies

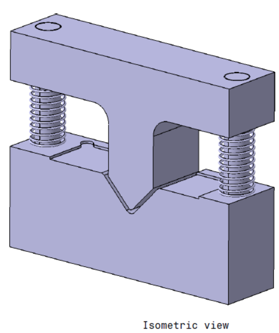
Aluminum hydroforming blocks were developed for hydroforming the rib clips from blank water jetted flat patterns. Correct forming radius and bend angles were developed to account for material springback.



F.11 Stringer clip form block

This tooling was designed to bend aluminum stringer clip flat patterns into their final shape while ensuring consistent part positioning during the bending process. The inclusion of two locating edges on the setting face and sprung guide rods provided consistency and precision throughout the procedure.



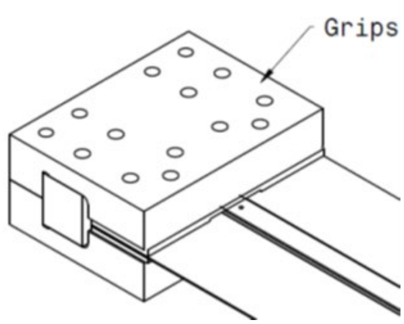


F.12 Coupon assembly tooling

This tooling was designed to consistently assemble EMST coupons by locating the stringer to the skin, clamping both components flat, and incorporating a drill jig to accurately match-drill the required hole pattern. After drilling, the tooling also clamps the coupons flat and provides support during the riveting process. Additionally, it includes necessary adjustments to accommodate various coupon component sizes.

F.13 Load cell coupon gripping components

These components were developed to securely grip the EMST coupons during FAA fatigue testing. A single grip was designed, with interchangeable shims specifically designed to fit each as-built coupon configuration. The grip jaws were knurled, and the shims were grit-blasted to 120 grit. Individual shims were fabricated for each panel configuration to aid in clamping the coupons during assembly.



F.14 Crack initiation profile cutting tool

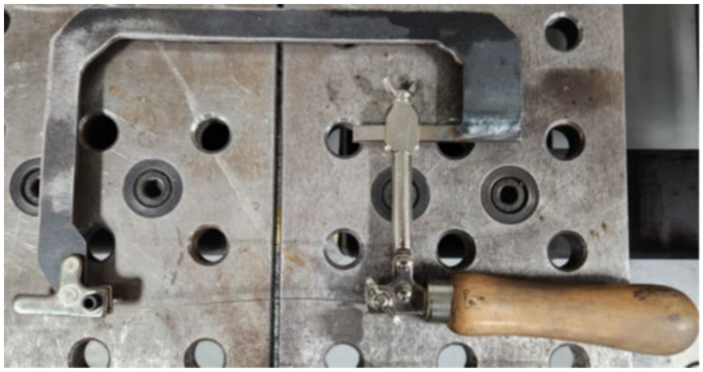
This tooling was developed to saw crack initiation profiles effectively. The cutter was designed to function as a very fine cutoff wheel, enabling the precise cuts required from one side. It utilized a specialized mandrel to hold readily available jeweler’s circular saw blades, which provided the thinness and strength needed to cut through FML.

To maximize the effectiveness of the tool, cuts had to be made wider due to its radius, as opposed to the square profiles used in previous designs. When paired with a small amount of Boelube, the tool performed excellently on a Dremel platform.

However, the tool proved less effective for shorter cuts (under 0.7 in.), as it could not cut through the FML without exceeding the required crack length. Additionally, it was unable to produce square-cut ends, which had to be manually finished using a jeweler’s saw blade.

F.15 Crack initiation profile saw tool

This tool was developed to saw the crack initiation profile in the coupons. It features a modified standard coping saw with a deeper throat, enabling access to the center of the coupons for crack initiation sawing. The tool utilizes the same jeweler’s saw blades that are employed to “square” the crack ends on full-size panels, ensuring an equivalent starting crack tip for both coupons and full panels. As a modification of a standard tool, it effectively cuts through FML. However, consistent use requires practice to achieve optimal results.



F.16 Tooling list

Table F- 1. Tools supplied by FAA/Arconic

TOOLS SUPPLIED BY FAA/ ARCONIC		
TOOL NUMBER	TOOL CODE	DESCRIPTION
ATC-05007200	FAJ	ASSY JIG
ATC-05007255	NCMF	NC MILL FIXTURE
ATC-05007257	NCMF	NC MILL FIXTURE
ATC-05007257	STFB Part 1	STRETCH FORM BLOCK
ATC-05007257	STFB Part 2	STRETCH FORM BLOCK (INSERT)

Table F- 2. New tooling fabricated by NIAR

NEW TOOLING FABRICATED BY NIAR
DESCRIPTION
CONTOURED BENCH DOLLY
COUPON ASSEMBLY TOOLING:
CRACK INITIATION PROFILE CUTTING TOOL
CRACK INITIATION PROFILE SAW TOOL
FRAME NC MILL FIXTURE
LOAD CELL COUPON GRIPPING COMPONENTS
METAL BOND TOOL
NC PROGRAMS
NDI COUPONS
RIB CLIP HYDROFORMING BLOCK:
SKIN ASSEMBLY LAY-UP/BONDING TOOL
SKIN DRILL FIXTURE
STRETCH FORM JAWS
STRINGER CLIP FORM BLOCK
STRINGER DRILL FIXTURE

G Organizational support overview

G.1 Wichita State University

Wichita State University in Kansas has been recognized by the Association of University Research Parks (AURP) with the 2023 Emerging Research Park Award for its Innovation Campus. This award acknowledges the campus's exceptional ecosystem, which fosters technological development, creates high-paying jobs, and contributes to the region's economic health.

The Innovation Campus, initially envisioned in 2012, has transformed an underutilized area of the university into a state-of-the-art research hub. Over the past decade, it has evolved into 120 acres of cutting-edge research facilities, collaborative partnerships, and educational opportunities.

The campus collaborates with more than 50 partner businesses, including notable names like Dassault Systèmes, Deloitte's Smart Factory @ Wichita, NetApp, Airbus, Spirit AeroSystems, Textron Aviation, and the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF). Students work alongside industry professionals, gaining hands-on experience while contributing to real-world projects.

Key features of the Innovation Campus include research and testing labs, the Hub for Advanced Manufacturing Research, the Digital Research and Transformation Hub (home to WSU's National Institute for Research and Digital Transformation), the Frank W. Barton School of Business, and the Advanced Virtual Engineering and Testing Labs.

This transformation from an underutilized area to a thriving research hub demonstrates the power of vision, determination, and strategic planning.

G.2 National Institute for Aviation Research

The National Institute for Aviation Research (NIAR), established at Wichita State University in 1985, serves as a hub for cutting-edge research and development in the aerospace industry. Focused on meeting the needs of the "Air Capital of the World," NIAR has expanded to multiple sites across the city of Wichita.

NIAR is globally recognized for its expertise in critical areas of aerospace R&D, including composites, advanced materials, digital twin, and advanced manufacturing technologies such as automated and additive manufacturing. The research efforts have contributed to Wichita State University ranking fourth among all U.S. universities in aeronautical R&D expenditures, with a strong focus on industry funding.

With a substantial $240 million annual budget, a staff of 1,400, and 12 million square feet of laboratory and office space spread across six locations in Wichita, NIAR is a powerhouse in aerospace research. NIAR's areas of expertise span from advanced machining and prototyping to wind tunnel testing, making it a vital player in advancing aerospace technology and innovation allowing it to provide research, design, testing, certification, and training to aviation manufacturing industries and government agencies, including the U.S. Department of Defense.

G.3 FirePoint Innovations

FirePoint is an independent non-profit organization sponsored by Wichita State University and supported by NIAR. FirePoint plays a pivotal role in advancing aerospace technology. Its mission is to facilitate joint technology development, transfer, and commercialization between U.S. government entities, universities, and both traditional and non-traditional industries. FirePoint focuses on supporting educational, commercial, and workforce development to drive innovation and collaboration across critical modernization priorities. Through initiatives that foster collaboration, partnerships, and STEM workforce development, FirePoint contributes to ensuring readiness and superiority in the multidomain research and development areas is serves.

G.4 Advanced Manufacturing and Prototyping

NIAR's Advanced Machining and Prototyping Lab, is an advanced engineering, prototyping, and manufacturing facility that specializes in turnkey solutions, complex tool design, high-speed machining, and advanced quality control. With a 90,000-square-foot lab, AMP focuses on manufacturing high-precision machined components for the aerospace and defense industries. By achieving AS 9100 and ISO 9001:2015 certifications, AMP reinforces its reputation as a key player in advancing aerospace innovation. The facility's expertise spans from advanced machining and prototyping, and additive manufacturing providing critical research, design, certification, and training services to aviation manufacturers and government agencies.