NASA/CR–2014-218149

PRSEUS Panel Fabrication Final Report

Kim A. Linton, Alexander Velicki, Krishna Hoffman, Patrick Thrash,
Robert Pickell, and Robert Turley
The Boeing Company, Huntington Beach, California

January 2014

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 443-757-5803

- Phone the NASA STI Information Desk at 443-757-5802

- Write to:
  STI Information Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076-1320

NASA/CR–2014-218149

PRSEUS Panel Fabrication Final Report

Kim A. Linton, Alexander Velicki, Krishna Hoffman, Patrick Thrash,
Robert Pickell, and Robert Turley
The Boeing Company, Huntington Beach, California

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Contract NNL13AA11C

January 2014

Acknowledgments

Acknowledgment is also made to the following individuals at NASA LaRC, Ms. Dawn Jegley, Mr. Marshall Rouse, and Mr. Andrew Lovejoy for their technical support.

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

FOREWORD

This document summarizes work performed by The Boeing Company, through its Boeing Research & Technology group located in Huntington Beach, California under the Environmentally Responsible Aviation (ERA) Project. This report documents the work that was performed to fabricate several large integrated stitched panels and associated hardware, which would ultimately be used to assemble a combined loads fuselage test section to validate the feasibility of a future Hybrid Wing Body (HWB) pressure cabin.

The NASA technical monitor was Dawn Jegley of the Structural Mechanics and Concepts Branch, NASA Langley Research Center.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

BHD	Bulkhead
CAPRI	Controlled Atmospheric Pressure Resin Infusion
DA	Determinate Assembly
DMS	Douglas Material Specification
ERA	Environmentally Responsible Aviation
HWB	Hybrid Wing Body
IML	Inner Moldline
MBB	Multi-Bay Box
NDI	Non Destructive Inspection
OML	Outer Moldline
PRSEUS	Pultruded Rod Stitched Efficient Unitized Structure
SoA	State of the Art

INTRODUCTION

NASA created the Environmentally Responsible Aviation (ERA) Project to explore and document the feasibility, benefits and technical risk of advanced vehicle configurations and enabling technologies that will reduce the impact of aviation on the environment. A critical aspect of this pursuit is the development of a lighter, more robust airframe that will enable the introduction of unconventional aircraft configurations that have higher lift to drag ratios, reduced drag, and lower community noise. The primary structural concept being developed under the ERA program in the Airframe Technology element is the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) concept.

The PRSEUS design and fabrication approach is a conscious progression away from conventional laminated and bonded assemblies toward larger one-piece panel designs with seamless transitions and damage-arrestment features such as stitch rows and tear straps. It is a new structural concept that integrates skin, stringer, frame and cap elements into a single large panel assembly in which all elements are stitched and cured together. The resulting structure is a novel solution for addressing the demanding out-of-plane loading requirements inherent in the flat sided pressure cabin of the Hybrid Wing Body (HWB) airplane.

The objective of the large multi-bay test article is to demonstrate that such a flat-sided structure is capable of withstanding bending and internal pressure loadings representative of a HWB aircraft. The test article was designed primarily of PRSEUS cover panels, pressure bulkheads and floor structures that can be assembled into a double deck test article that measures approximately 30-ft wide, by 14-ft tall, and 7-ft deep (Figure 1). In this contract, the crown, floor, both upper bulkheads, both lower bulkheads, both outer ribs, both upper center ribs and both lower center ribs were fabricated as well as all of the fittings (Figure 2) required to assemble the Multi-Bay Box (MBB). All of the hardware (fasteners) required to assemble the MBB was also purchased.

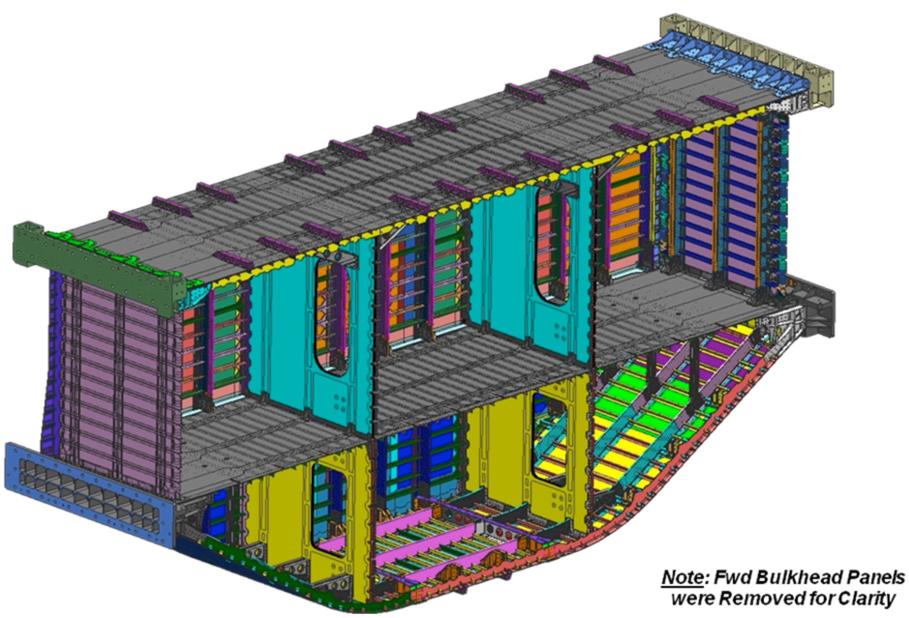

Figure 1. HWB Large-Scale Test Article Configuration

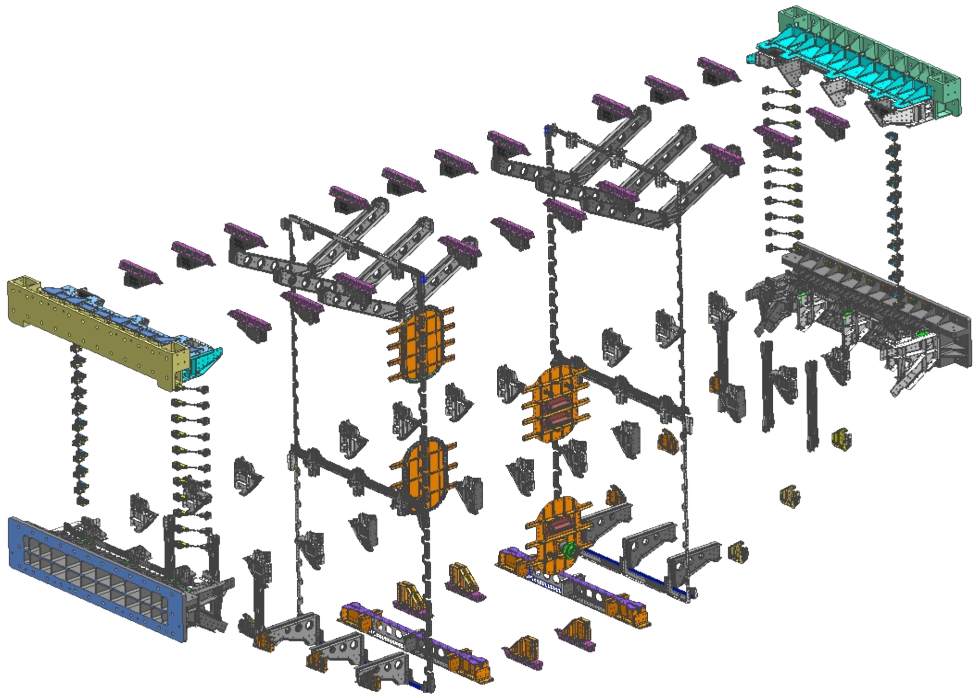

Figure 2. Metallic Fittings Required for the MBB Assembly

The work statement described within this report is a subset of a larger multi-year effort to design, fabricate, and test the Multi-Bay Box test article. The detail design, analysis and tool design for the MBB test article was completed under contract NNL04AA11B, task order NNL10AB00T in 2011. Tooling was procured under contract NNL04AA11B, task orders NNL10AB00T and NNL11AA68T. Acceptance and nonconformance reports for the panels delivered under this contract were submitted to NASA in June and September 2013 and are not included in this report.

1.0 Panel Fabrication

This new design and manufacturing concept exploits the unique processing advantages inherent in dry warp-knit fabrics and the superior out-of-plane strength afforded by stitched laminates to effectively carry structural loads in multiple directions. The basic panel geometry has 24-inch frame pitch and 6-inch stringer spacing, with 0.052-inch thick skins in the center of the panel and gradually increases the thickness to the ends where the concentrated loads will be introduced during testing of the MBB. The MBB test specimen requires 15 composite panels. This contract provided 12 of the 15 panels for the MBB.

1.1 Stringer Preform Fabrication

Stringer preforms were fabricated for the eight PRSEUS panels of the MBB test article. Nested flat patterns were cut from 55-inch wide DMS2436, Type 1, Class 72 warp/knit multi-axial carbon fiber fabric using a Gerber CNC ply cutting table. The individual flat patterns were subsequently folded over a steel leader wire and placed inside a large assembly fixture to stitch. A CNC gantry style lock stitch sewing machine was used to insert two seams of stitching into the stringer web using Vectran 1200d thread. The first stitching seam was positioned at the apex of the fillet at the base of the stringer bulb feature. The second stitch seam was located at the apex of the fillet for the web-to-flange radius. With the flanges still laid out flat and the bulb feature collapsed the stringer preform was placed inside a polyethylene bag. Pictures in Figure 3 through Figure 8 show the stringer subassembly process.

Figure 3. Nested Flat Patterns for Stringer Preforms CNC Cut from Multi-Axial Carbon Fiber Fabric

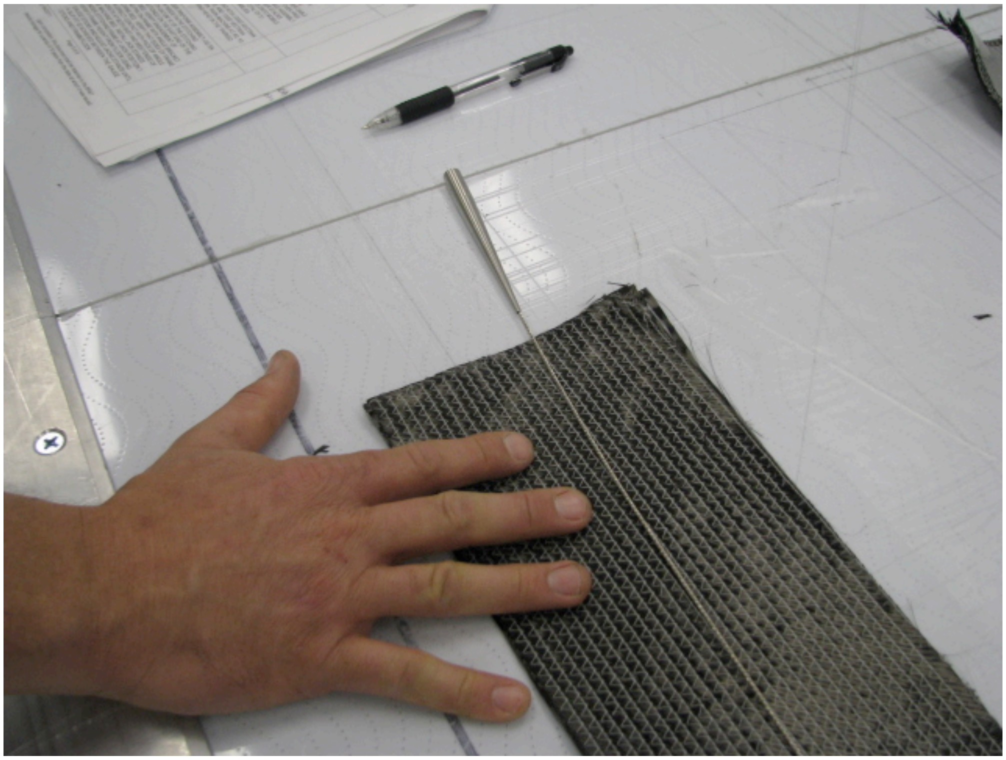

Figure 4. Leader Wire with Adapter Positioned Over Stringer Flat Pattern

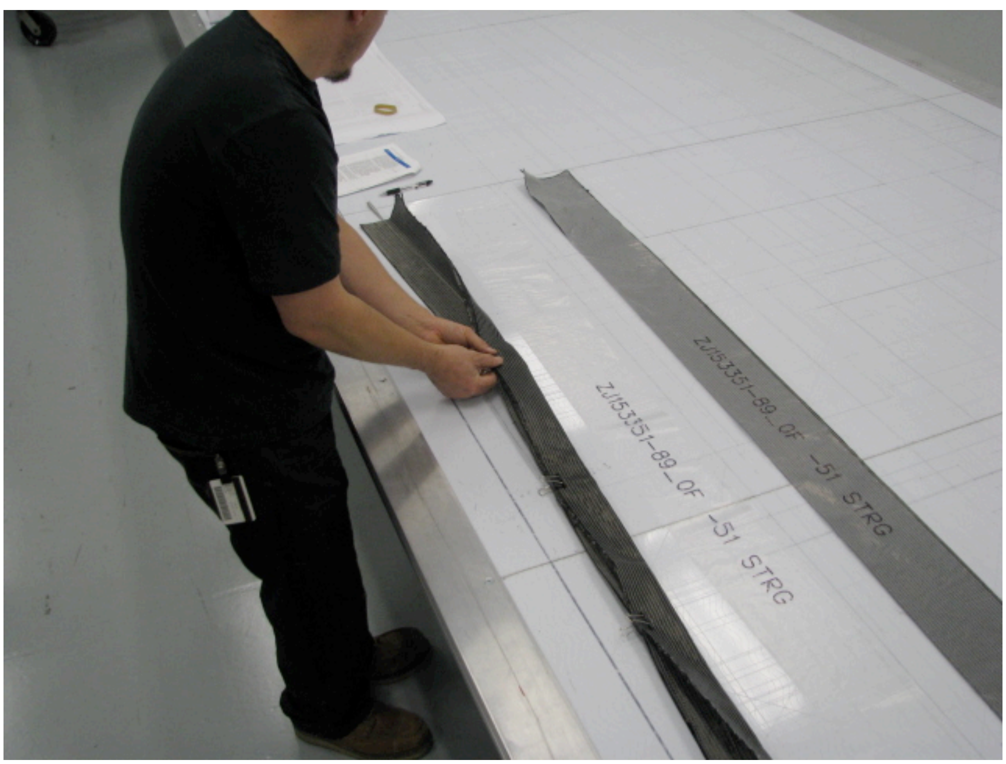

Figure 5. Stringer Flat Pattern Folded Over Leader Wire

Figure 6. Stringer Preform on Gantry Style Sewing Machine

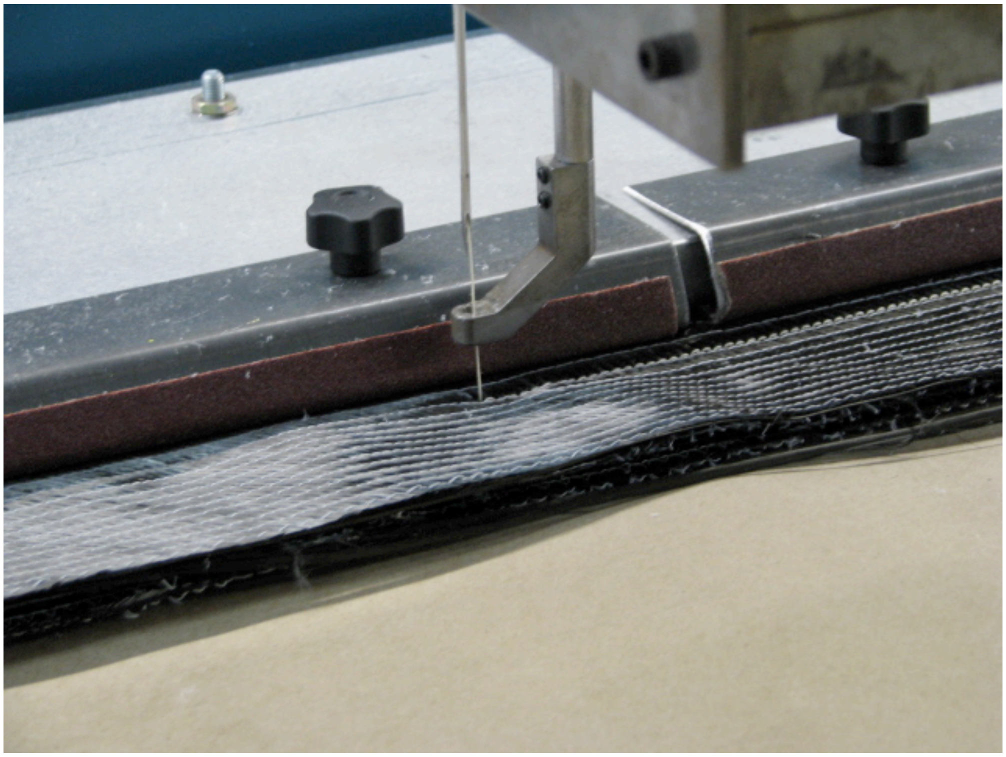

Figure 7. Insertion of Stitch Seam into Stringer Web

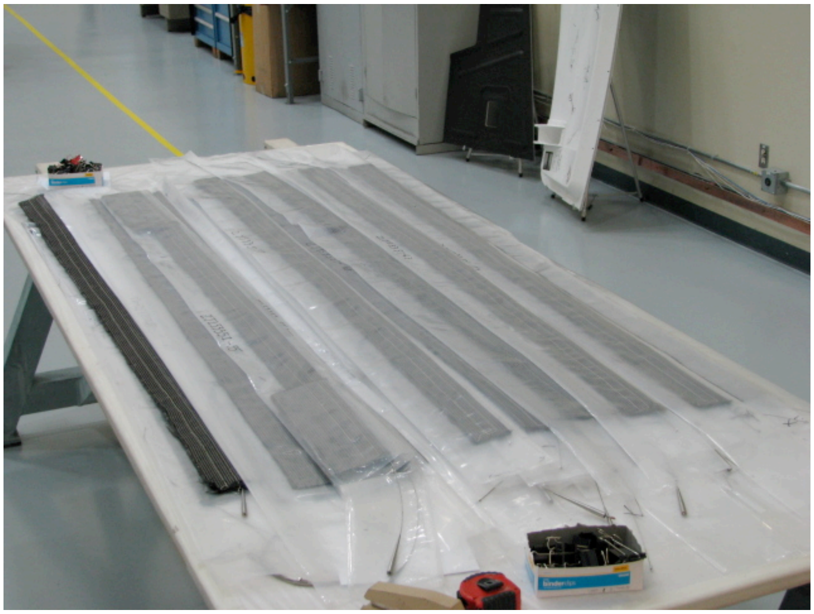

Figure 8. Completed Stringer Preforms with Leader Wire in a Poly Bag

1.2 Cap Fabrication

Preforms for the cap components were produced in a similar fashion to the stringer details. Net flat pattern ply stack details were cut from 55-inch and 99-inch width multi-axial carbon fiber fabric (Figure 9) and placed inside a rectangular stitching frame located over the open bed of a gantry style stitching machine. The first stitch row at the base of the cap web goggled up to account for the additional thickness of the stringer flange and tear strap. All of the remaining stitches were all straight and parallel spaced ½-inch apart (Figure 10).

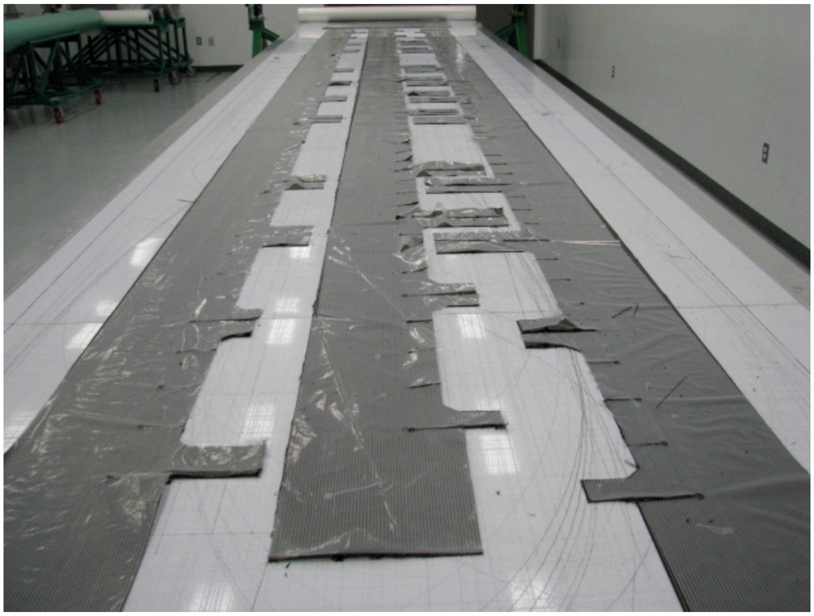

Figure 9. Nested Flat Patterns for Crown Panel Cap Preform

Figure 10. Stitching of Crown Panel Cap Web on the Gantry Sewing Machine

1.3 Pultruded Rod Preparation

The PRSEUS panels of the MBB test article utilized a pultruded carbon fiber epoxy rod in the top of the bulb shaped stringers. The rod is pre-cured and subsequently bonded to the carbon fabric of the stringer surrounding it in-situ with resin infusion processing of the panel dry fiber preform. The pultruded rods were manufactured by Lawrie Technologies in Girard, PA. using Applied Poleramic Inc. PUL6 epoxy resin system and standard modulus GRAFIL 34-700WD carbon fibers. Preparation of the rod began with a post-cure cycle in an oven at 350°F for two hours. The rods were then cut to length using an abrasive cut-off wheel mounted on a portable power tool. The fillet feature was then abrasively removed from approximately 0.5 inches at the end of the rod to enable insertion of the rod into pockets created at the top of the stringer preform. A hole was drilled axially in one end of the rod and a nylon set screw installed for subsequent attachment of an adapter to connect the rod to the metal wire leader inside the stringer preform. The outer surface of the rod was prepared via grit blasting and rinsed with deionized water. A water break test was then performed to verify the surface was properly prepared for bonding. The rods were dried inside an oven and subsequently wrapped in craft paper to minimize moisture absorption. The prepared rods were ultimately packaged inside a heat sealed poly bag and forwarded to the panel preform assembly jig for installation into the stringer preforms. Pictures in Figure 11 through Figure 15 depict the key steps in the process.

Figure 11. Rough Cutting of a Pultruded Carbon Fiber Epoxy Rod to Length

Figure 12. Removal of Fillet Feature from End of Rod Using Abrasive Sanding Disk

Figure 13. Drilling of Rod End to Accept Nylon Set Screw for Mounting of Leader Wire Adapter

Figure 14. Grit Blasting of Rod to Prepare Outer Surface for Bonding

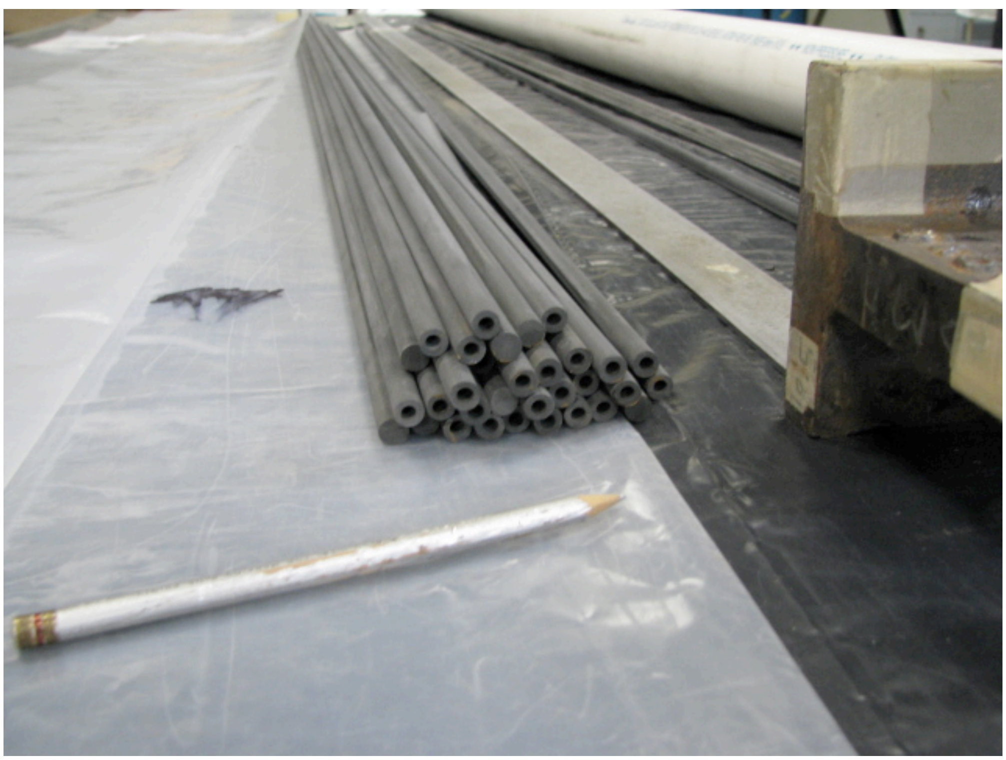

Figure 15. Prepared Rods Ready for Deionized Water Rinse and Water Break Test

1.4 Frame Fabrication

From the outset of the program, it was well understood that maintaining the dimensional stability of the Rohacell foam over its 30-ft length in the shop air assembly environment would be difficult. To mitigate this concern, a 30-ft test piece was conditioned, machined and then delivered back to Boeing where it was dimensionally inspected to verify that the new machining and handling processes developed for these details would in fact produce a part with the intended dimensional tolerances. Once this was accomplished, several key aspects of the new approach that differed from conventional foam machining practices were identified. They were documented in the overall foam core procurement package that would be completed by the Evonik Company.

Prior to machining, the foam blanks were conditioned in ambient shop air for four weeks at the Stitching Center at Huntington Beach to stabilize their moisture content. They were then shipped to Evonik in Alabama for the shaping operations before being sent back to Boeing in environmentally controlled bags (Figure 16).

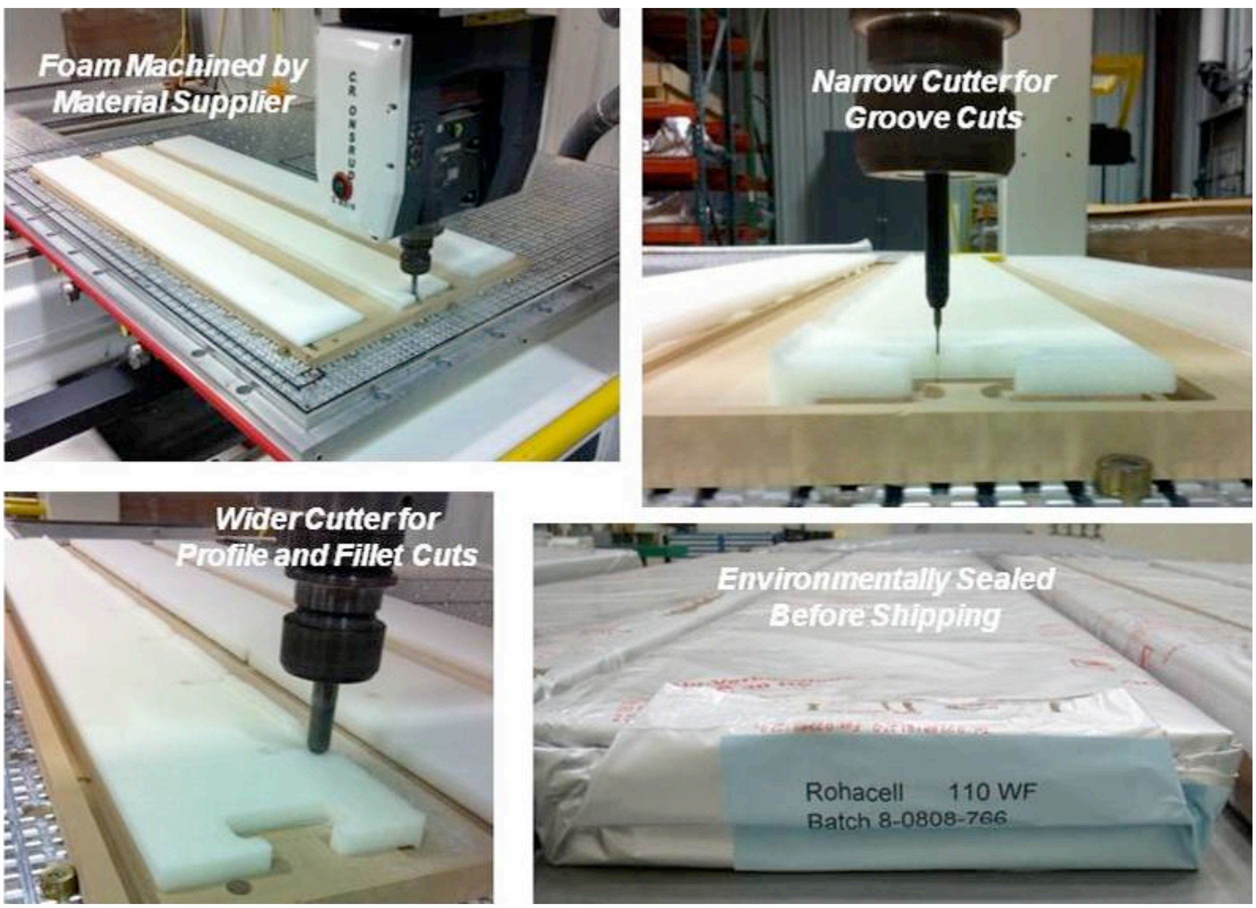

Figure 16. Foam Core Details are N/C Machined and then Stored in Controlled Packaging

Solid fiberglass core details were used at all fitting locations to react the clamp-up forces created by the fasteners. These details were purchased from a local vendor and then joined with the foam core pieces to create the frame core subassemblies (Figure 17). The details were located and checked by a tooling template with pins placed at each stringer key hole location. The template also served as a bonding jig.

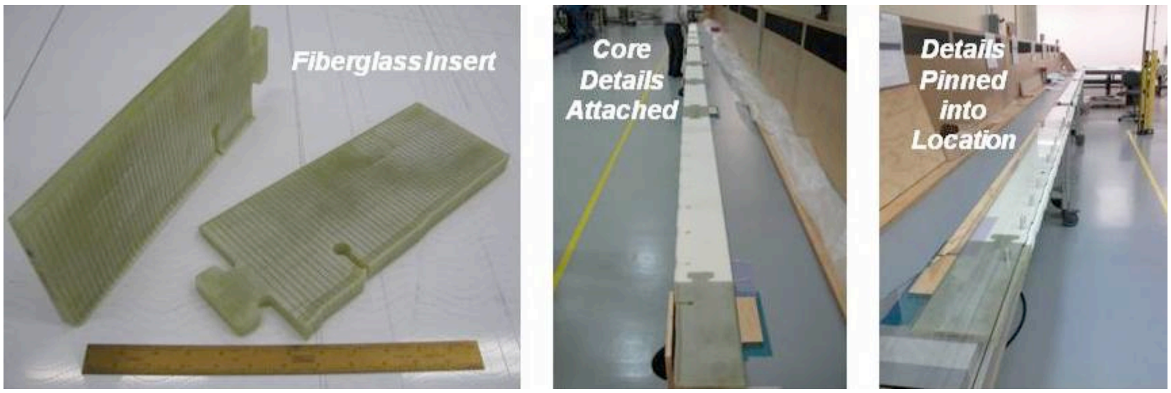

Figure 17. Frame Core Details are Located Using an Assembly Template

It was during this rigging step, the dimensional tolerance between the stringer key holes in the foam was discovered to be out of tolerance on a cumulative basis, so that the last cutout at either end of the 30-ft section was off by as much as 0.25-inch (Figure 18). After a thorough review with the vendor, it was discovered that the machining feed rates and cutting sequence were modified (without notifying Boeing) to reduce the overall machining time. These changes resulted in excessive foam growth that was not present in the original process check-out test article.

With all of the foam details delivered, the decision was made to remove slices of the core to bring the stringer locations back into tolerance. Although the number of slices differed from frame to frame, typically about a dozen slices were required to achieve drawing tolerances on the longer frame subassemblies. All of the frame details were reworked in this fashion and then bonded back together to maintain the proper stringer key hole spacing.

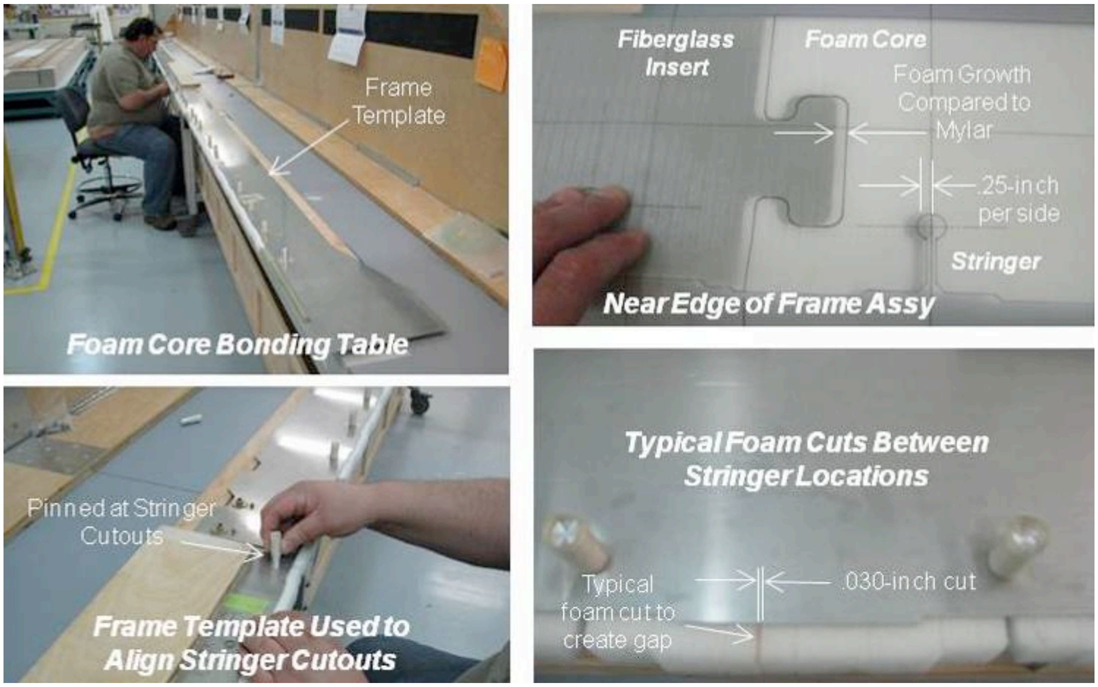

Figure 18. Foam Core Rework was Required to Bring the Stringer Key Hole Locations within Tolerance

The final step in completing the core subassemblies was the addition of local web doublers that were placed into machined recesses on both sides of the core (Figure 19). This was the first time this feature was used in a panel and is the result of the high stress concentrations apparent around the key hole feature in the FEM analysis at some locations. Adding web doublers during the core assembly sequence was straight-forward and did not present any problems. These doublers were only added to the crown and keel panel frames.

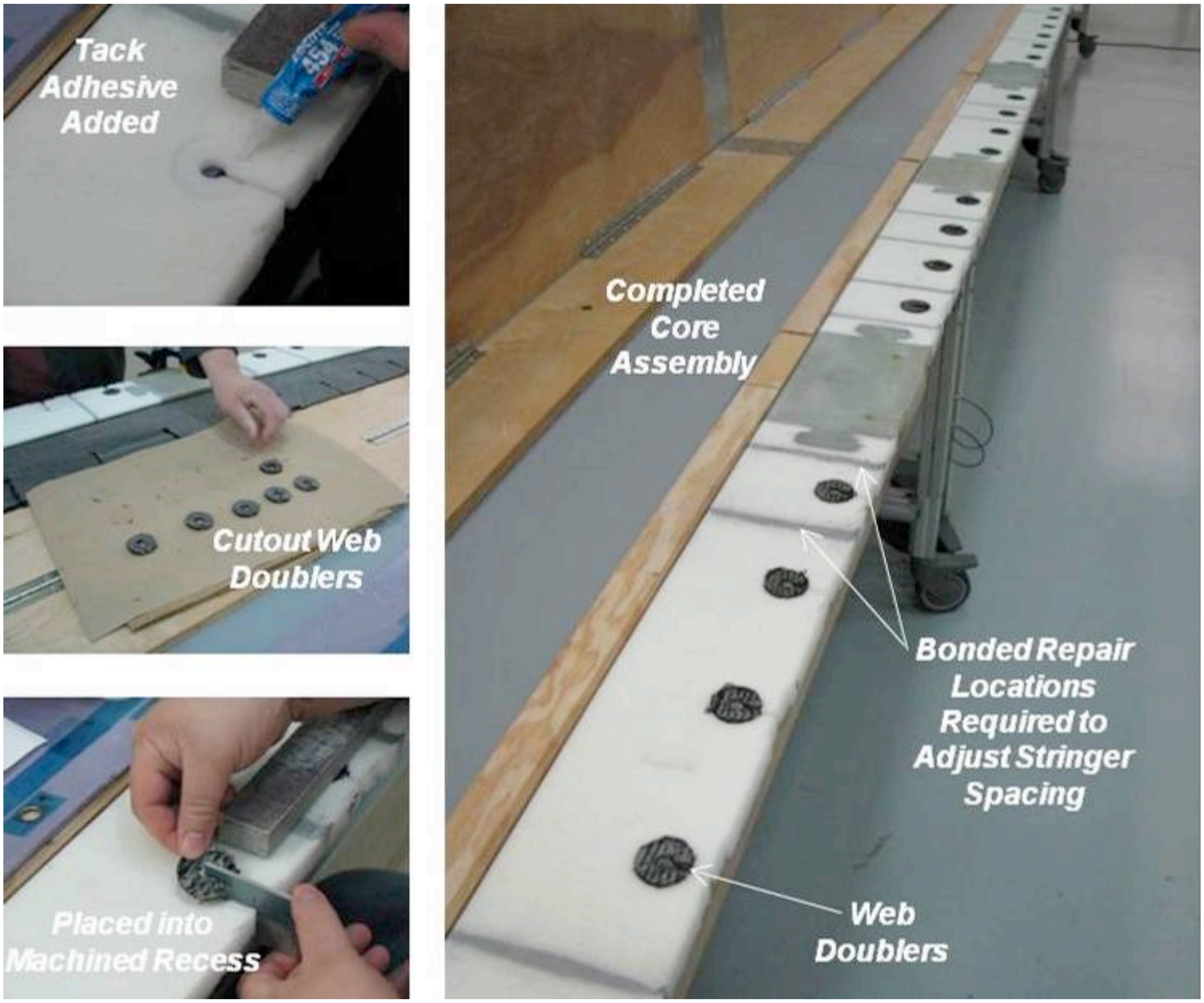

Figure 19. Frame Web Doublers Added at Rod Pass-Through Locations

Next, the pre-cut warp-knit fabric was rolled out onto bonded core subassembly and then stapled into place (Figure 20). A wooden frame assembly tool was used to locate the fabric relative to the core, and then used to flip the frame over to attach the fabric on the other face.

Figure 20. Wooden Assembly Tool Used to Attach Fabric to Foam Core

When the final face was stapled in place, the tool was rotated into the vertical position and then the completed frame assembly was lifted from the tool and placed in a storage box (Figure 21) until it would be needed for the preform assembly operation.

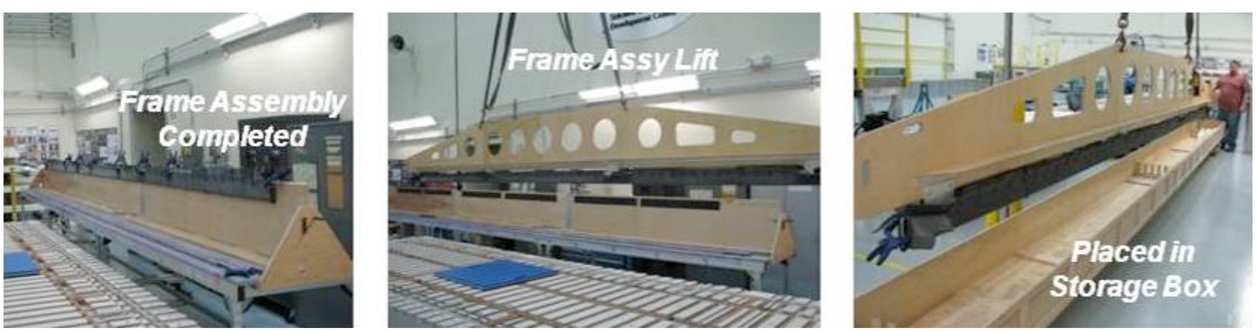

Figure 21. Completed Frame Lifted from the Frame Assembly Tool

1.5 Crown Panel

The 55-inch wide warp-knit multi-axial dry carbon fiber fabric, which is delivered on cardboard support tubes to Boeing, was rolled out by hand onto the table cutting surface. A plotter program was then executed and the nested flat patterns for the skin, doublers and tear straps were cut out of the fabric. Once cut, the individual pieces of material were then removed from the cutting table and organized into kits for their respective components. The stringer, frame and cap subassemblies along with the precut fabric (Figure 22) were all delivered to the large preform assembly and stitching tool.

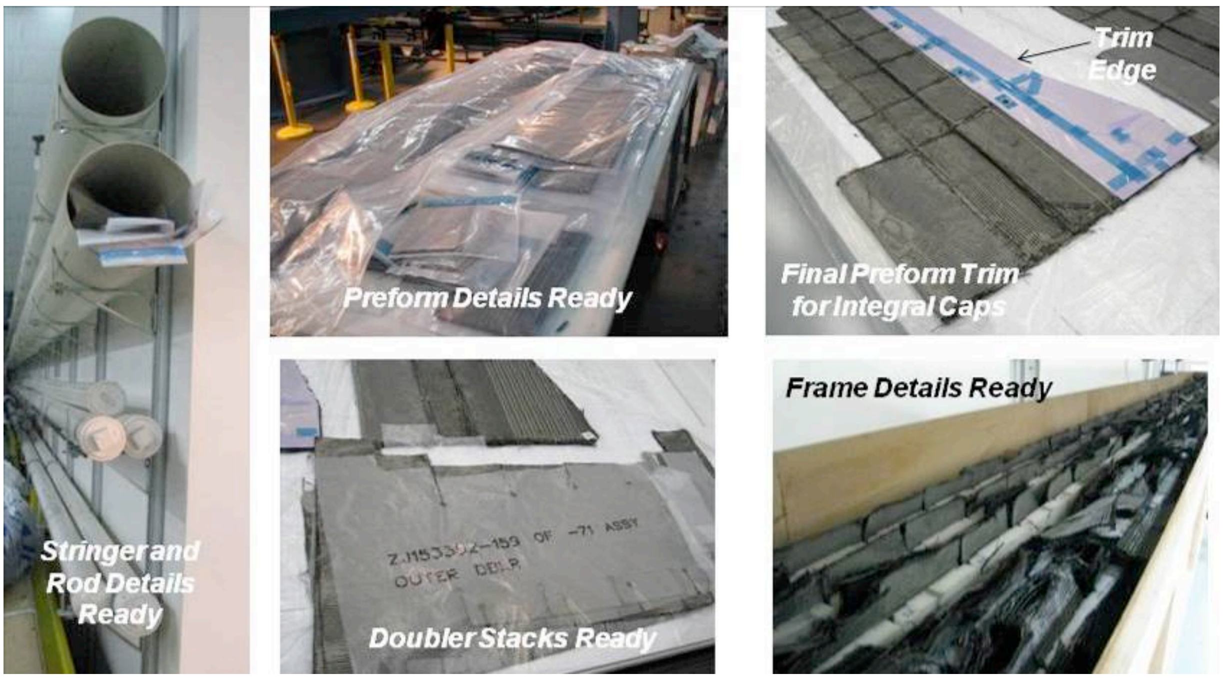

Figure 22. Panel Preform Details Prior to Assembly

The preform assembly takes place in the stitching tool. The tool is a collection of wooden frame elements and foam blocks that is used to hold the dry fabric details in position when the preform was stitched together. The tooling elements were accurately N/C machined details that were indexed to a common steel base. The details were designed to fall away from the base when the tool is rotated to place the preform onto the cure tool. Each panel configuration requires a specific block set to accommodate the differences in panel design features. The initial set up for the crown panel configuration is shown in Figure 23 as it nears completion and checkout.

Figure 23. Crown Panel Stitch Tool Preparation and Checkout

Once the stitch tool was assembled and covered with a thin fiberglass layer to support the fabric backside during stitching, the crown panel preform details were loaded into their respective holding slots (Figure 24).

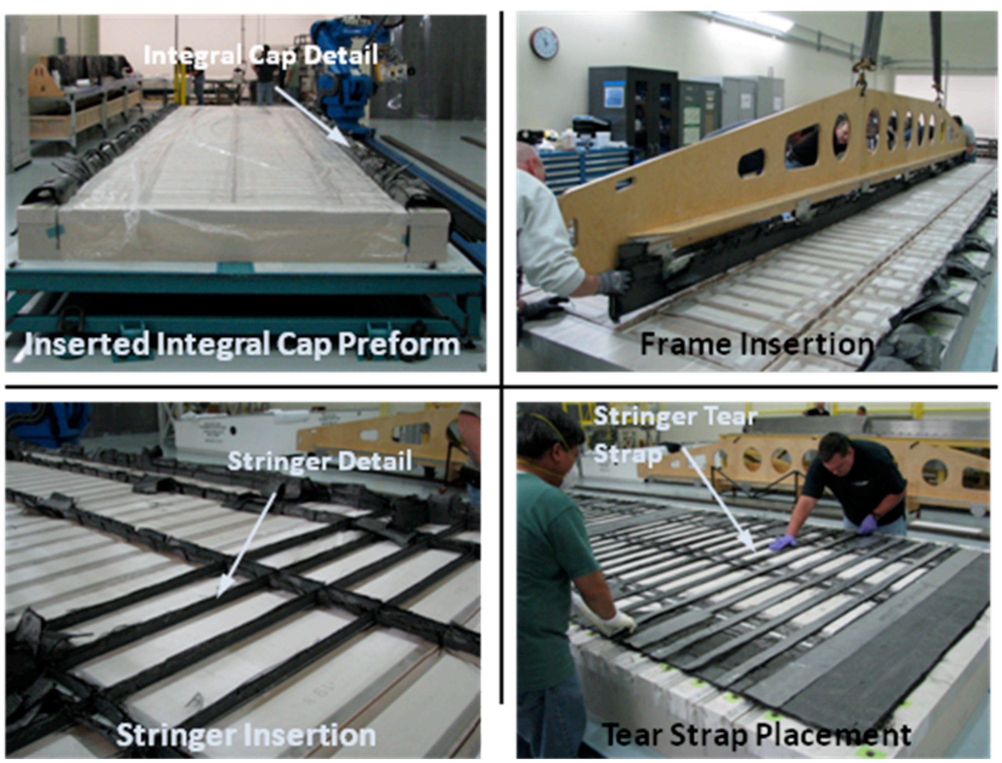

Figure 24. Loading Preform Details into Stitching Tool

The frames were installed into the assembly tool first by simply dropping the frame subassemblies into the corresponding slot for each frame station with the top of the frame facing down. Next, the stringers were installed in between the wood picture frames. Using the wire leaders, full size carbon rods were then pulled through the stringers. As the rod passed through the stringer, the fabric surrounding the rod, expanded forming the bulb feature at the top of the stringer section. In addition, the carbon fiber rod had now locked the stringer into the foam core of each frame web. The stringer and frame flanges were formed next by folding the web plies flat against the assembly tool. Strips of fabric making up the stringer and frame bases (or tear straps) were then placed over the flattened flanges. Then the skin ply stacks were positioned over the entire assembly.

Finally, using one-sided stitching technology, the two needle system was used to form a modified chain stitch. The industrial robot arm gives the end effector six degrees of freedom for stitching in 3-D space. The initial seams were inserted into the preform to attach the frame and stringer flanges to the skin (Figure 25).

Figure 25. Single-Sided Stitching of Crown Panel Preform Started

After stitching of the preform was completed (Figure 26), it was transferred to an outer mold line (OML) cure tool for resin infusion processing. This was accomplished by strapping the dry preform to the preform assembly tool so it could be inverted without dropping the preform. Once the preform was flipped (Figure 27) and positioned over the cure tool (Figure 28), the straps were removed and the steel base was lifted off.

Figure 26. Completed Crown Panel Preform Stitching

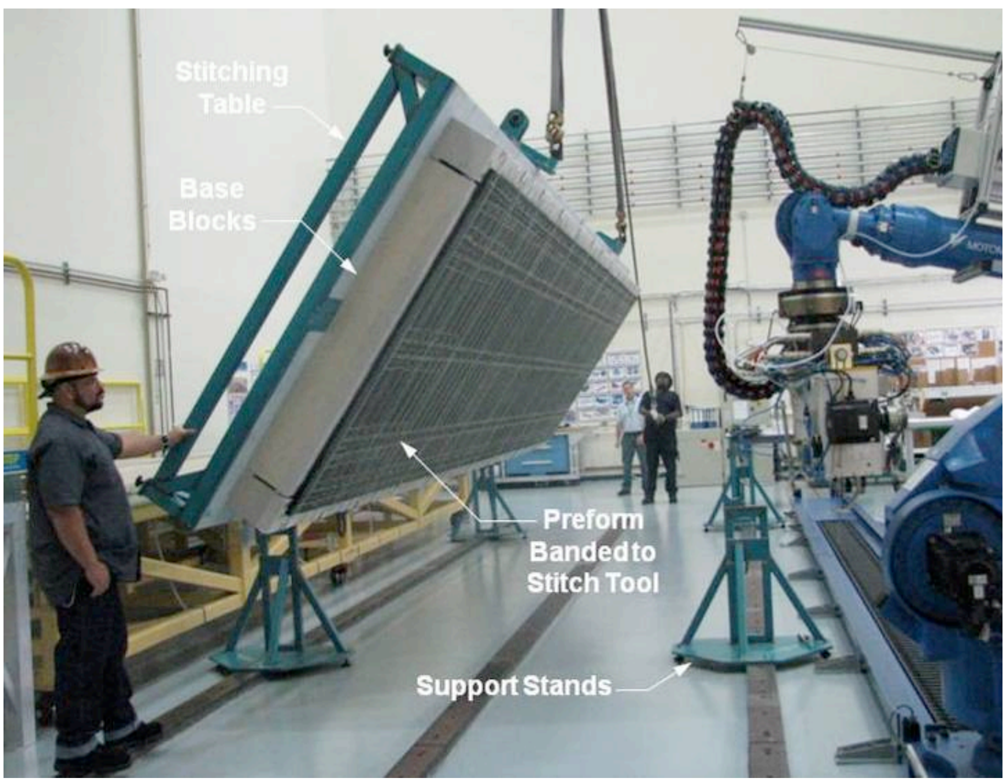

Figure 27. Stitch Tool Rotation with Preform

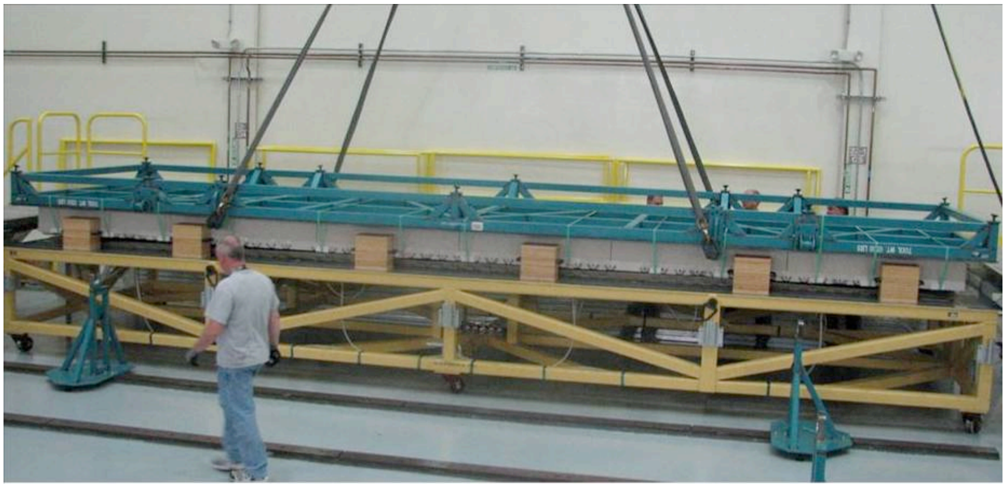

Figure 28. Stitch Tool and Preform Placed onto Cure Tool

With the steel base detached, access to the foam blocks and wood picture frame details was now possible. All of the foam blocks and wood frames were easily removed and concerns that the one-piece wood frames might be locked into the preform were not realized. The relative flexibility of the stitched preform was adequate to release the wood frame details without having to pull the rods out. Once these tooling details were removed (Figure 29), only the self-supporting preform remained on the cure tool (Figure 30).

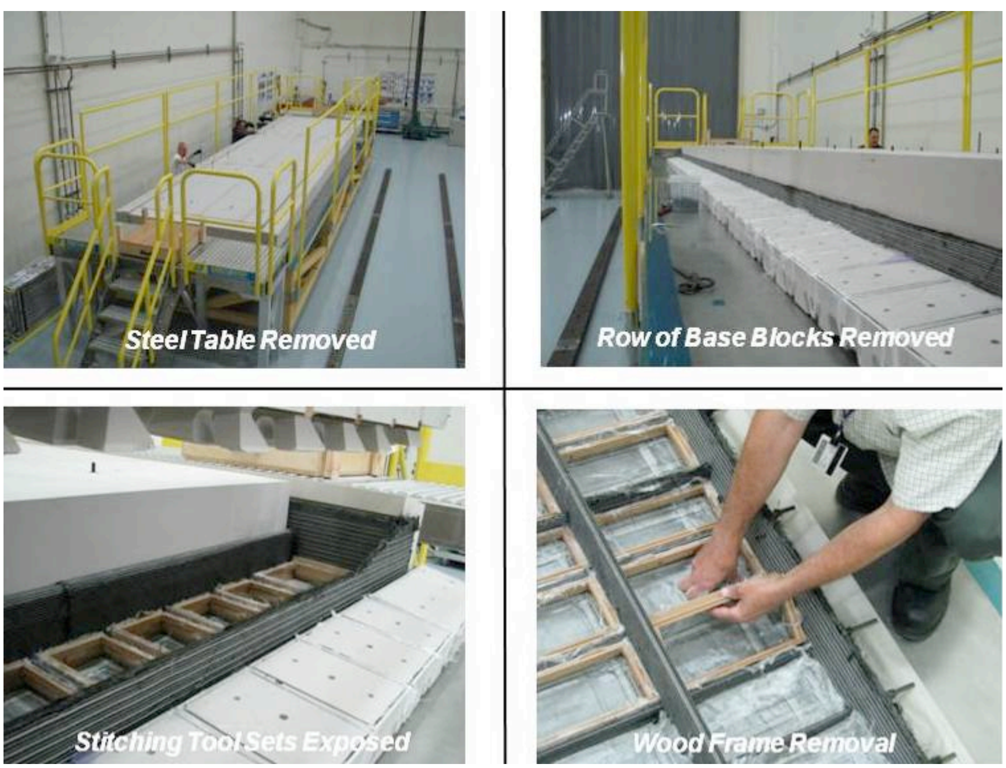

Figure 29. Removal of Stitch Tool Foam Blocks and Wood Frame Tooling Details

Figure 30. Self-Supporting Crown Panel Preform Placed on the Cure Tool

The preform was then prepared for resin infusion and cure cycle processing. The first step was to install all of the IML cure tool details onto the preform (Figure 31). Then peel ply (beige colored material in the photos) layers were added to eliminate resin ridges caused by the pleated vacuum bagging system. Location paddles and forming plates were used to accurately position frame and integral cap feature stations. Frame cap covers were used to maintain frame straightness. Silicone bagging aids were added to the stringers to reduce vacuum bag elongation in the sharp corners. The rigged cure tool with all of these IML cure tool details is shown in Figure 32 for the crown panel.

Figure 31. Preform Preparation on Cure Tool

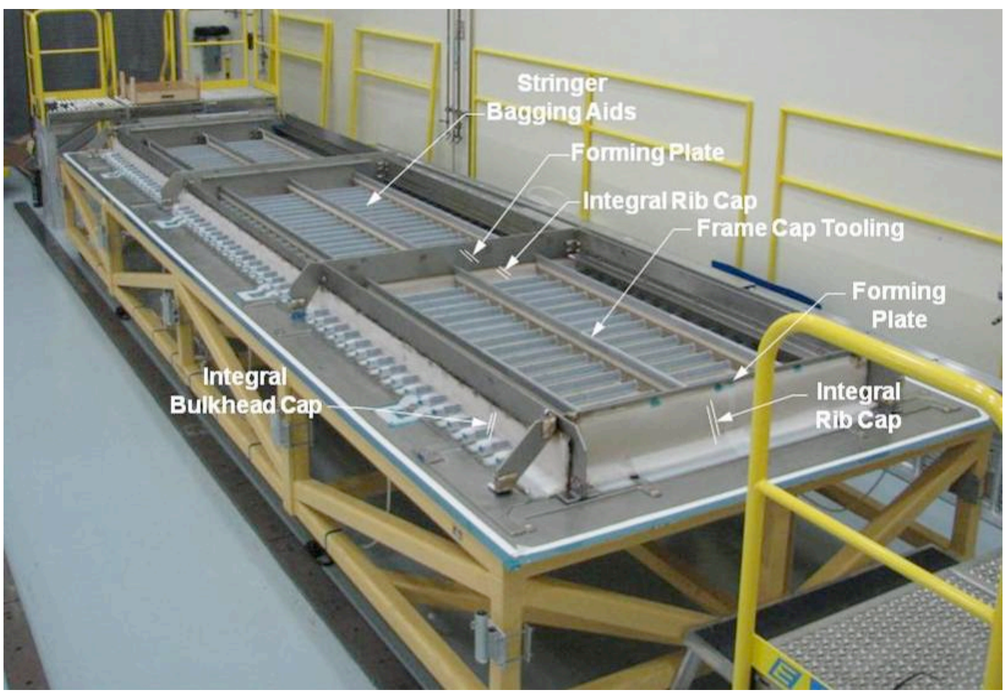

Figure 32. Under Bag IML Tool Details Located

A two bag system is used to seal vacuum the part against the tool. First the primary pleated nylon vacuum bag is draped over the preform, pleated and then sealed down against the OML tool (Figure 33). A secondary textured vacuum bag (green bag in Figure 34) was also added to provide a level of safety should any leaks develop in the primary bag.

Figure 33. Pleating Operation for Primary Bag Installation

Figure 34. Secondary Bag is added to Maintain Vacuum Integrity during Infusion and Cure

After successfully passing a vacuum check, the bagged part was then transported from the Stitching Center to the oven. (Figure 35)

Figure 35. Part is Transferred and Loaded into Oven

The 3-D preform was infused using CAPRI process. The resin was a Hexcel two-component amine cured epoxy system known as HEXFLOW VRM34. Resin infusion processing took place with the preform held in a cure tool, which was the only hard tooling required. The preform was infused and cured out. An automated machine was used to prepare and handle the resin (Figure 36). With this machine, the resin and hardener components were kept separated until just prior to entering the part mold fill line. The two components, resin and hardener, were automatically degassed, metered, mixed, and delivered on demand to the mold at the predefined temperature and pressure. The time that the mixed material was at elevated temperature within the machine was reduced to mere seconds, and more importantly, the volume of mixed material is minimized to reduce the chance of an adverse exothermic reaction and clean up time.

Figure 36. Automated Infusion Equipment Used for Resin Infusion

Upon completion of the initial cure, the infused part was removed from the oven (Figure 37) where the bagging materials and resin lines could easily be removed to expose the IML surface of the part and the IML cure tool details (Figure 38). The vertical standing IML tooling plates were then broken away to expose the final cured interior surface of the part. The cured part was then placed back in the oven for the final 350°F free-standing post-cure cycle.

Figure 37. Infusion and Initial Cure Completed

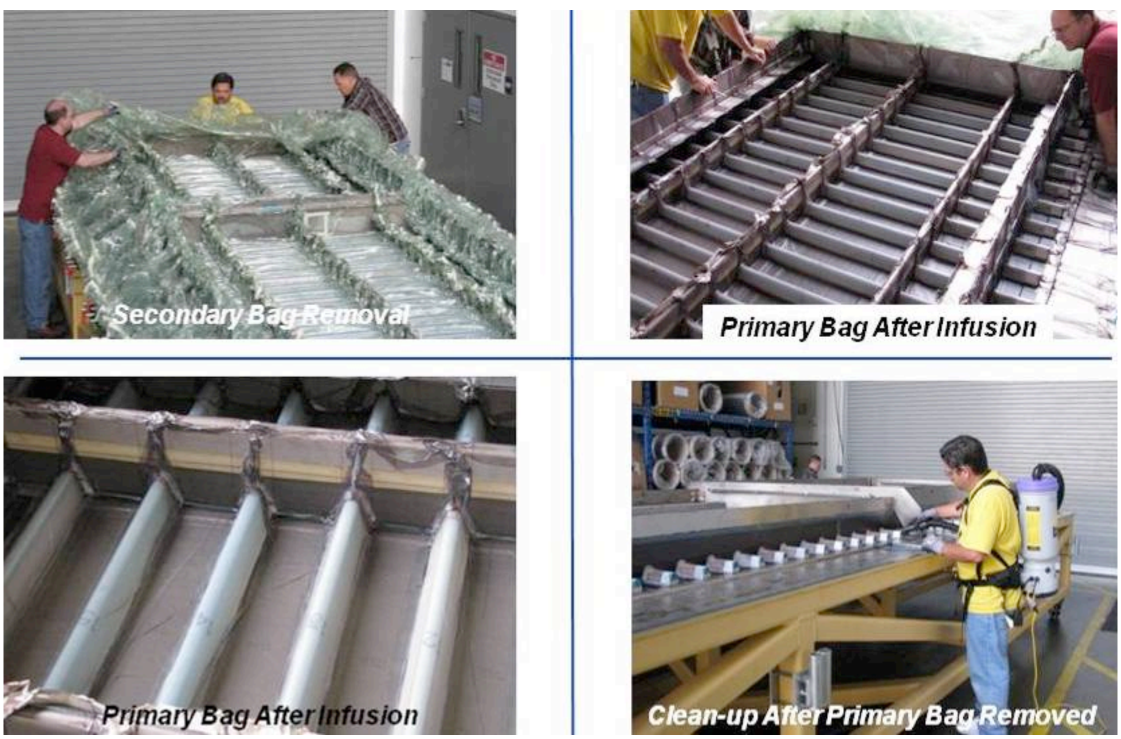

Figure 38. Bag and Tool Removal Prior to Post Cure

The final cured crown panel is shown in Figure 39. Generally, all aspects of the design approach, tooling concepts, and processing elements worked as expected to produce a useable panel for the test article. Considering the panel size and complexity, along with the simultaneous introduction of new concepts for the IML cure tools, it was encouraging that the first panel off the tool was successfully infused and cured without major complications that would preclude its use, or lead to major tool modifications or process changes on subsequent panels.

Figure 39. Final Cured Crown Panel Read for Edge Machining

All of the internal panel features were fabricated within drawing tolerances. The frame and stringer quality was good - straightness and resin penetration. The integral cap features at the center rib stations were also straight and perpendicular as intended, and the fillet radii shaped by the vertical plate edges was accurately formed and located. Going into the first-article fabrication, the quality of the integral cap features around the panel's perimeter was the largest concern due to the increased cap thickness/bulk, density of the stitching through the web, and unbalanced stack architectures on the interior versus the exterior sides of the cap web. How this unique combination of physical characteristics would influence the perpendicularity of the cap web would not be readily apparent until the first part came off the tool and the relative warping of the caps could be assessed.

Visual inspection of the caps, along with some simple hand measurements, indicated that the caps are molded accurately and that excessive amounts of shimming will not be required during panel joining.

Although no rework will be required on the IML features of the panel, there was a problem encountered on the OML side of the panel. Once the peel layer was removed, it was immediately apparent that a rectangular pattern of grooves had been molded into the OML surface of the panel. Since the grid pattern matched the splice locations of the perforated plates, the problem was quickly diagnosed as an interference problem at the perforated plate splices (a layer of perforated plates is inserted between the cure tool and preform to prevent the carbon fabric from imprinting into the flow media which results in a roughly textured OML surface).

Unlike prior PRSEUS panel infusions, this was the first time an Invar cure tool was used. With panels almost 30-ft long, the mismatch in thermal growth between a steel cure tool and carbon fiber part would have created out of tolerance panels. During fabrication of the crown panel, a mark-off pattern occurred on the OML surface of the part during the infusion and cure cycle. This was caused by the edges of the perforated caul sheets that are placed between the preform and cure tool. Driven by thermal expansion, the sheets pressed together and then dug into the preform during the cure cycle to mold a permanent groove in the OML surface of the part. (Figure 40), their relative locations and groove depths are called out in Figure 41.

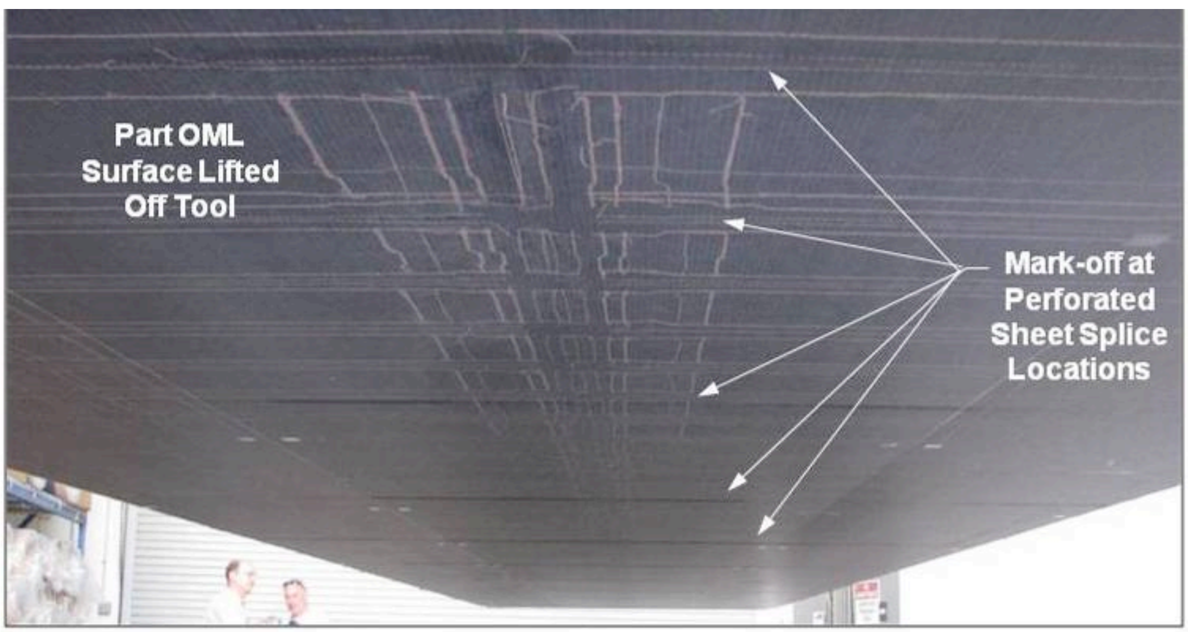

Figure 40. Thermal Expansion of Caul Sheets Caused Mark-off on the Crown Panel OML

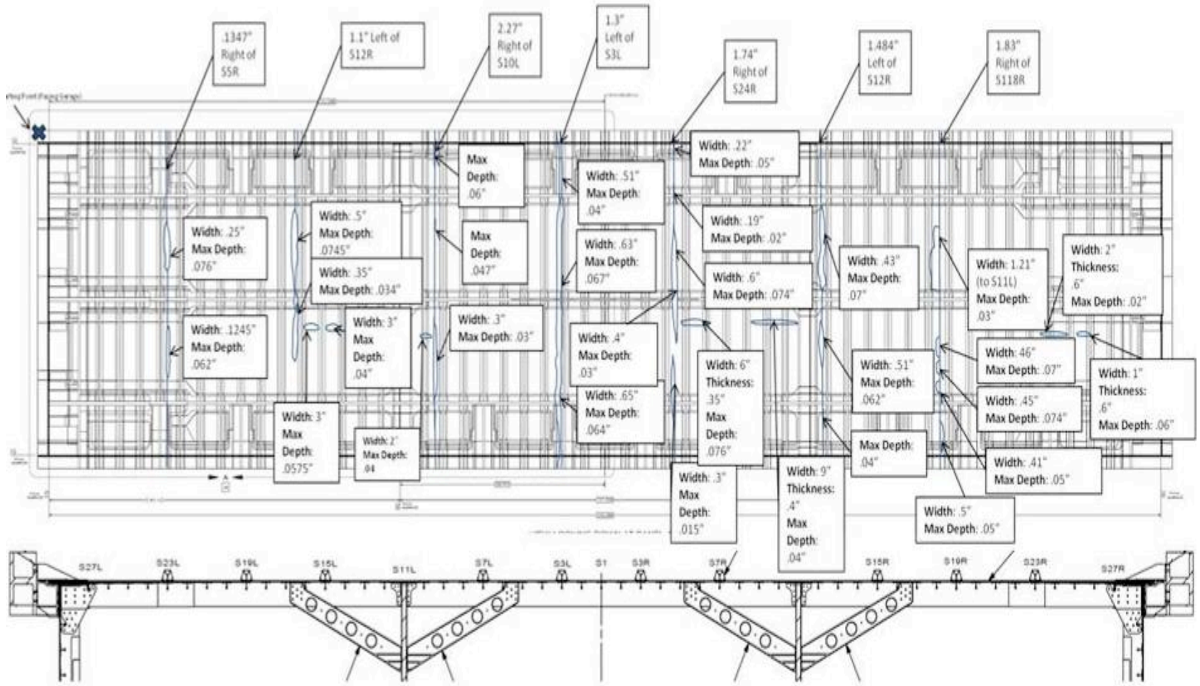

Figure 41. Schematic of Groove Location and Depth Measurements

Since the resulting pattern matched the edges of the individual caul sheets, it was quickly determined that the difference in thermal expansion between the low-carbon steel perforated sheets and the Invar cure tool caused the interference. In addition to the mark-off, permanently buckled regions occurred in the caul sheets themselves along the spliced edges indicating that the sheets had grown during the cure cycle and caused permanent deformations in the regions with the smallest gaps between the sheets (Figure 42). On subsequent panel infusions, this problem was resolved by increasing the spacing between the caul sheets which eliminated the interference condition that led to the grooves in the first panel (Figure 66).

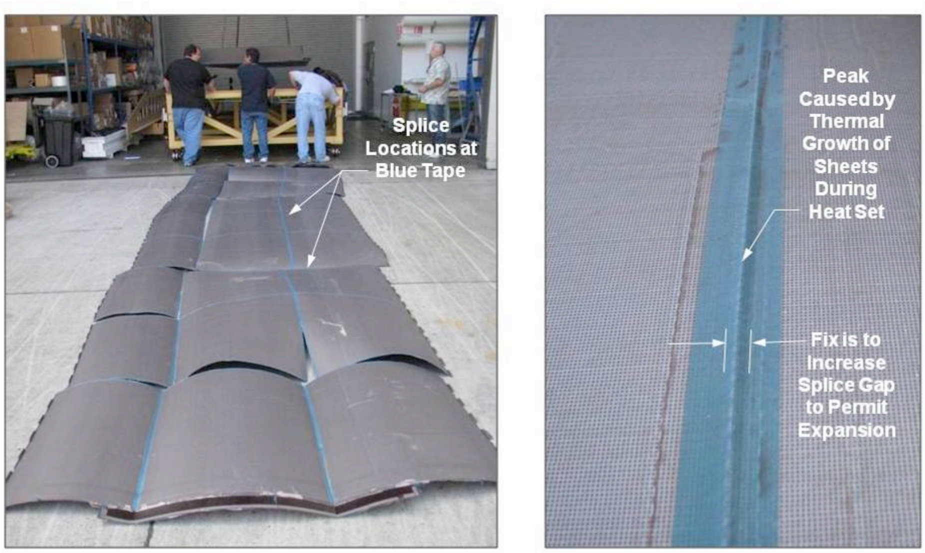

Figure 42. Perforated Caul Sheets from Crown Panel Infusion (Revised for Subsequent Panels)

Rather than build a new crown panel, a decision was made to repair it. To accomplish this, the grooves were filled in with a rigid adhesive/filler and then sanded flush, while the repair technique and validation approach outlined in Figure 43 was developed. This basic repair methodology and process control was first developed and tested at the coupon level. In addition to validating the repair approach, the testing also generated repair allowables that were used to write margins for the repaired panel condition on the Multi-bay Box test article.

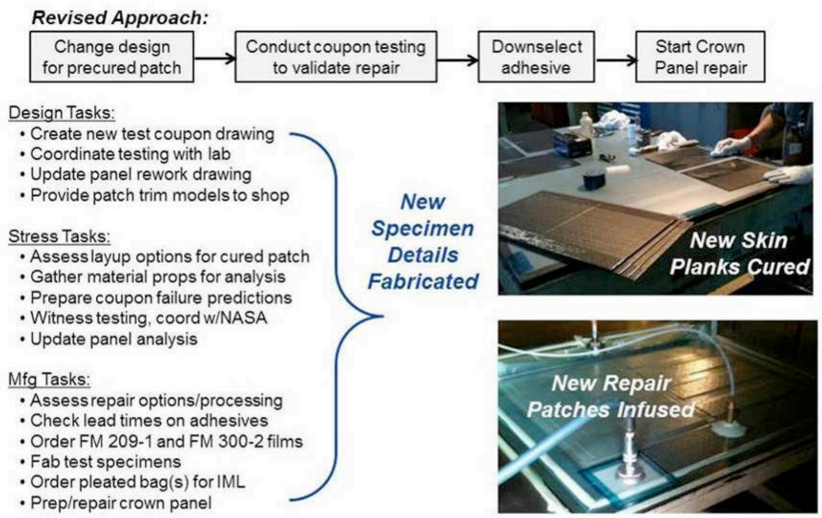

Figure 43. Repair Technique and Validation Approach

Initially two different repair approaches were considered before down selecting a pre-cured bonded patch approach where the patches would be built up using thinner 2-ply warp-knit fabric stacks to replace the missing load path across the grooves. The "equivalent" stack architecture used to replicate the basic Class 72 skin stack is depicted in Figure 44. This basic four stack lay-up of DMS 2436 Class 75/76 stacks is used in the skin regions of the repair and then was locally doubled up to eight layers at the frame intersections.

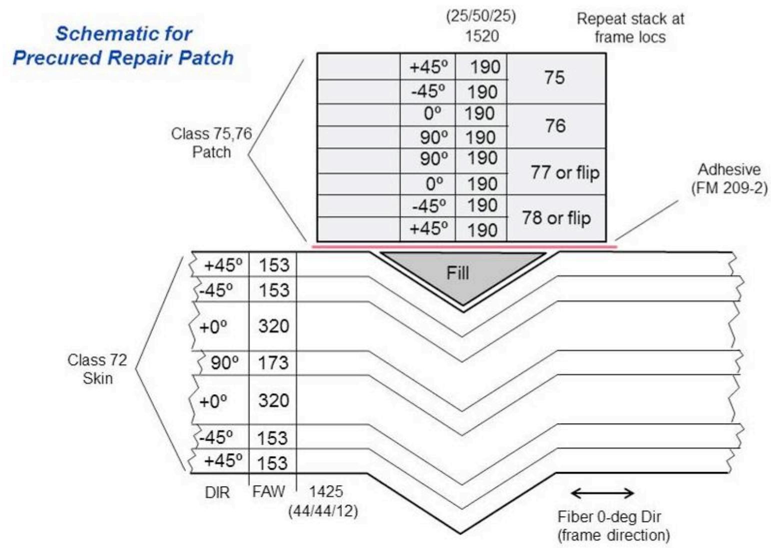

Figure 44. Repair Patch Laminate Architecture Created Using Warp-Knit Fabrics

The primary design objective of the repair patch was to maintain a minimum taper ratio while providing an adequate overlap across the groove. Based on an FEM investigation of the load transfer across the patch, it was determined that a minimum patch width of at least 4-inches would be needed. This result drove the specimen cross-section design depicted in Figure 45.

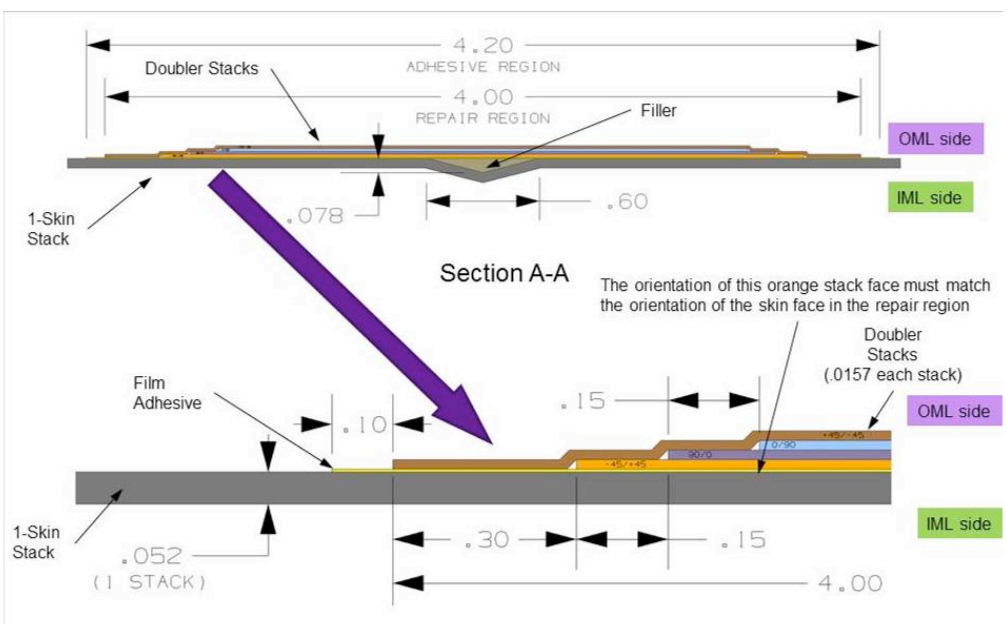

Figure 45. Precured Patch Overlap and Edge Taper Dimensions

The coupon specimens were fabricated and tested under tension and 4-point bending loads to simulate the critical conditions for the crown panel (Figure 46). In both cases, as expected, a classic first-ply failure separation occurred between the outer +/- 45-deg layers of the skin stack at a far-field strain averaging 0.0085 in/in, which exceeded the notched tension design allowable used to design the crown panel.

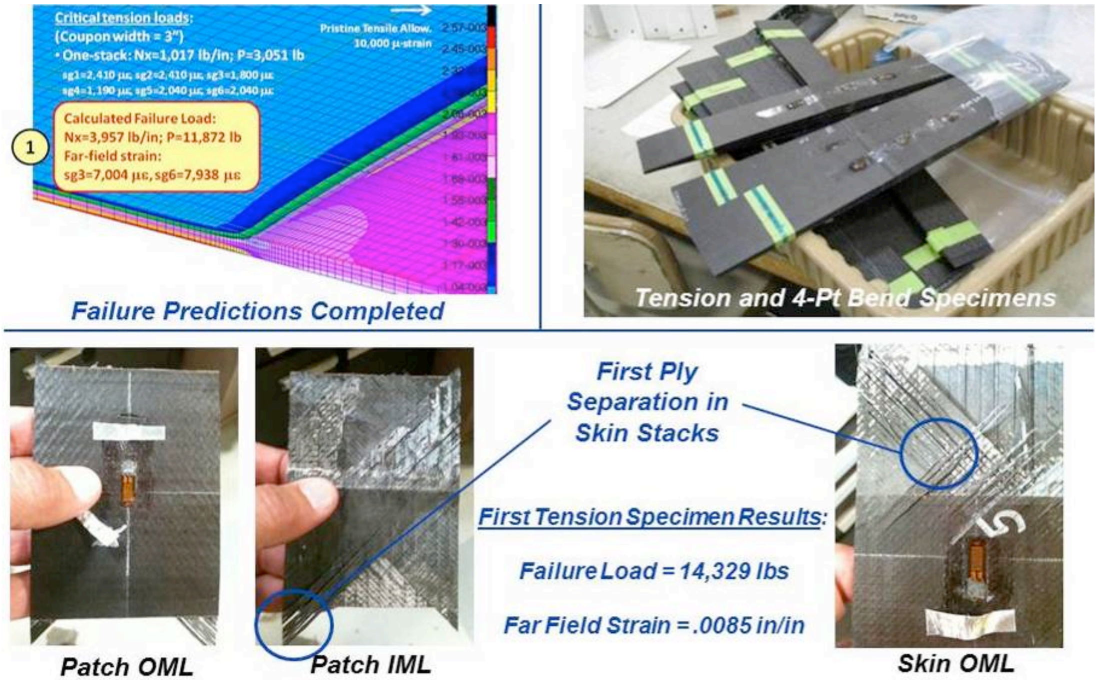

Figure 46. Coupon Testing Used to Validate Repair Design and Processes

With the repair design validated by analysis and test, the approach was scaled up for the crown panel repair. In addition to being larger than the coupons, the minimum width of the patches was also increased to six inches to match the stringer spacing on the crown panel. This facilitated maintaining a minimum 2- inch overlap (measured from the groove centerline to the patch edge), while still being able to position the patch edges over skin build-ups in the stringer flange and tear strap regions. The in-process lay-up of the repair patch dry fabric is shown in Figure 47.

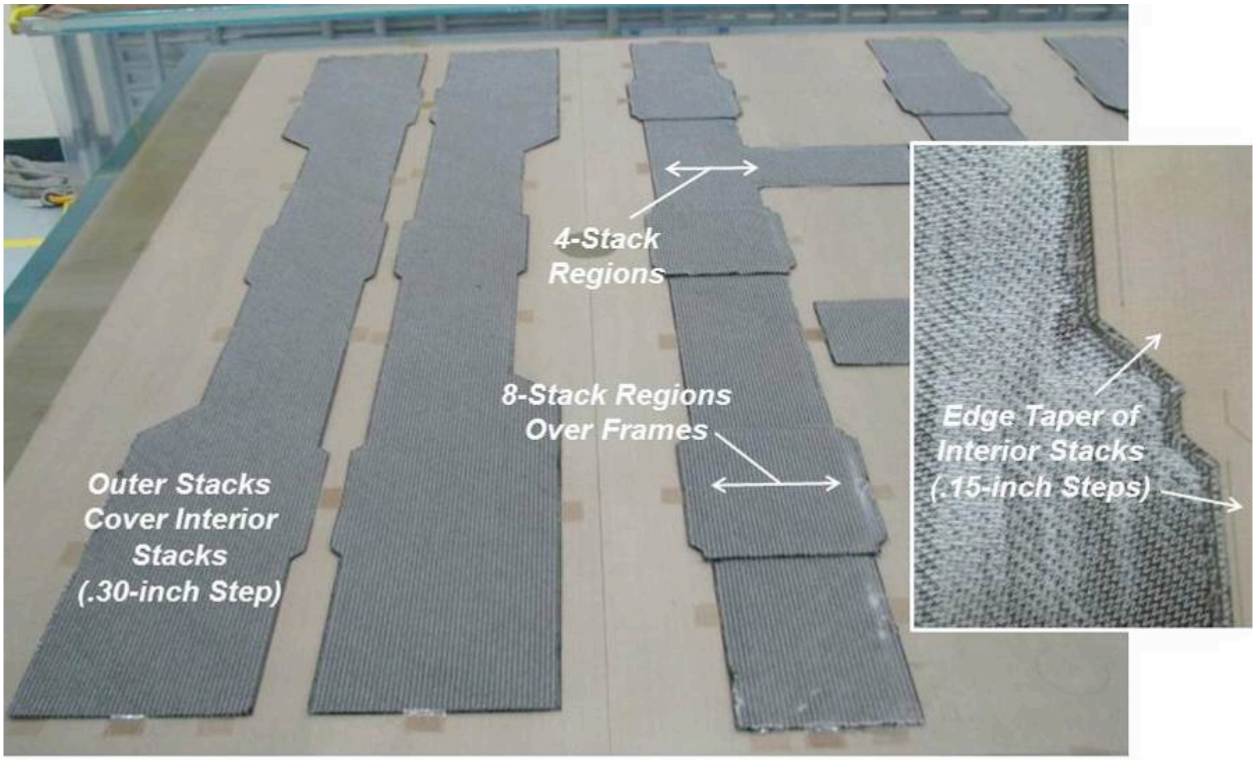

Figure 47. Dry Fabric Lay-up Used to Create Precured Patches

Once the patches were infused and cured in the oven, small bleed holes were mechanically drilled approximately 2-inches apart (to vent trapped air during bonding), and then an FM-209 film adhesive was applied to the back side of the patch (Figure 48).

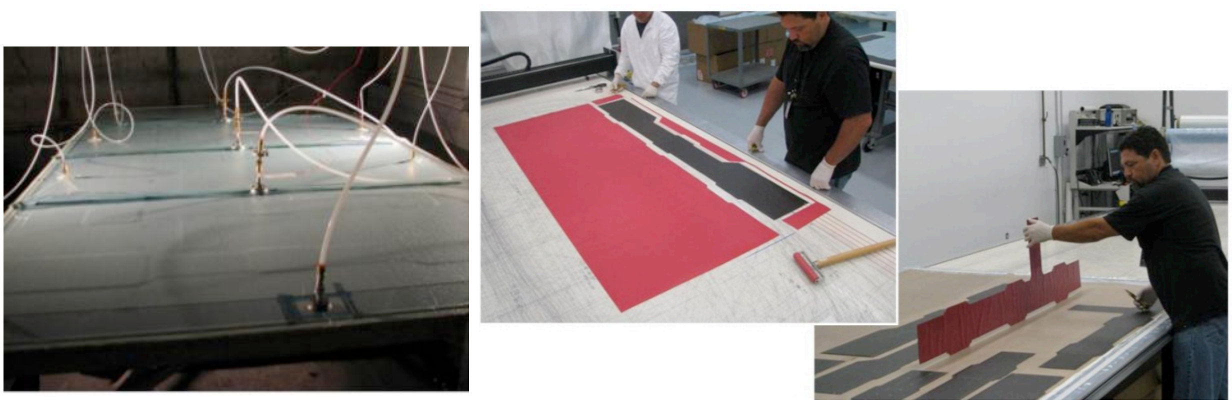

Figure 48. Patches were Infused and Cured in an Oven and then an Adhesive Layer was Applied

Simultaneously, the crown panel OML surface was prepared by filling in the grooves, sanding them flush, grit blasting the bonding regions, and then conducting water-break tests to verify the prepared surface condition. (Figure 49 & Figure 50)

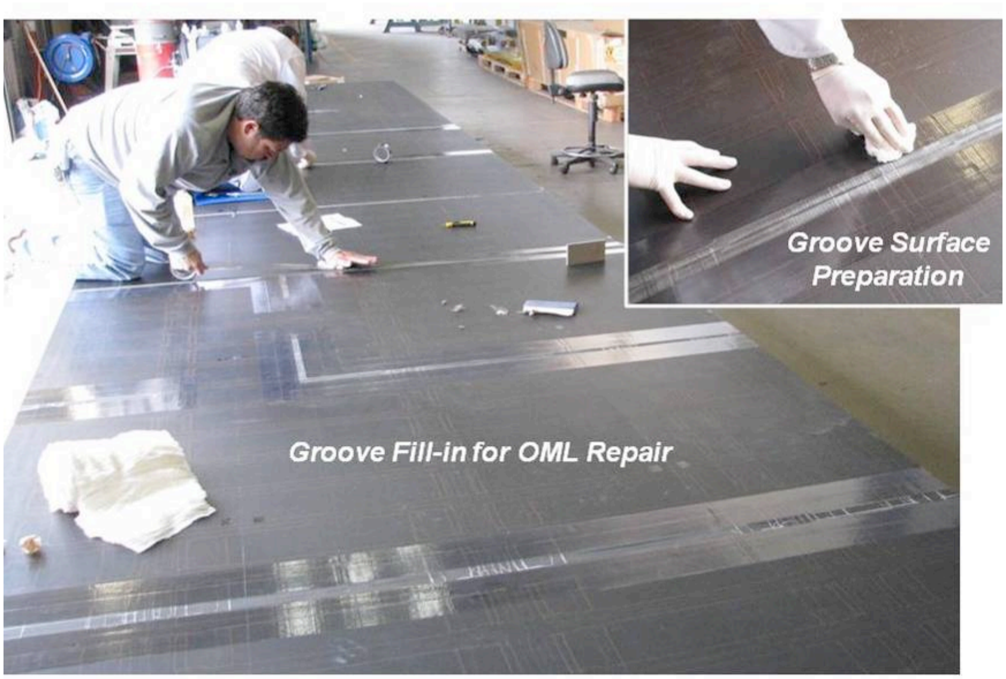

Figure 49. Crown Panel OML Surface Prepared for Repair

Figure 50. Bonding Surfaces were Readied for Repair Patches

The prepared patches were then located into position, taped along the edges to secure them, and marked to aid in finding the bleed holes after the bonding cycle (Figure 51). The panel was then flipped over onto the cure tool and vacuum bagged (Figure 52).

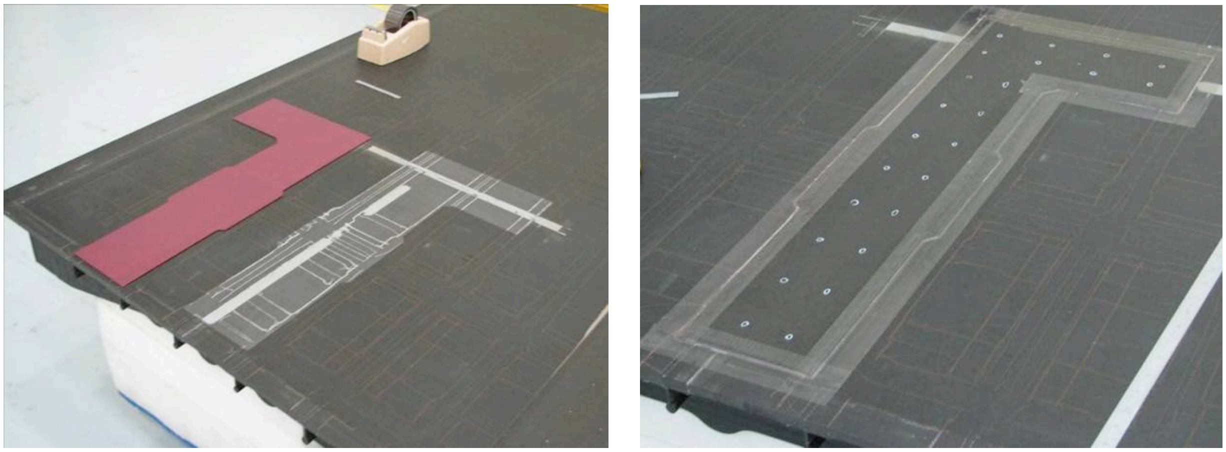

Figure 51. Precured Repair Patches were Taped into Position Prior to Applying the Vacuum Bag

Figure 52. Bagged Crown Panel with IML-side Up and Repair Patches Taped to the OML

To minimize thermal distortion and out-gassing during the bonding operation, the combination of an FM-209 adhesive and a 250ºF cure cycle was used. The processing parameters were identical to those used for the test coupons and no abnormal conditions were encountered. The post-bond inspection of the patch edges and bleed holes showed normal adhesive wet-out without any indications of voids or trapped air beneath the patches. (Figure 53)

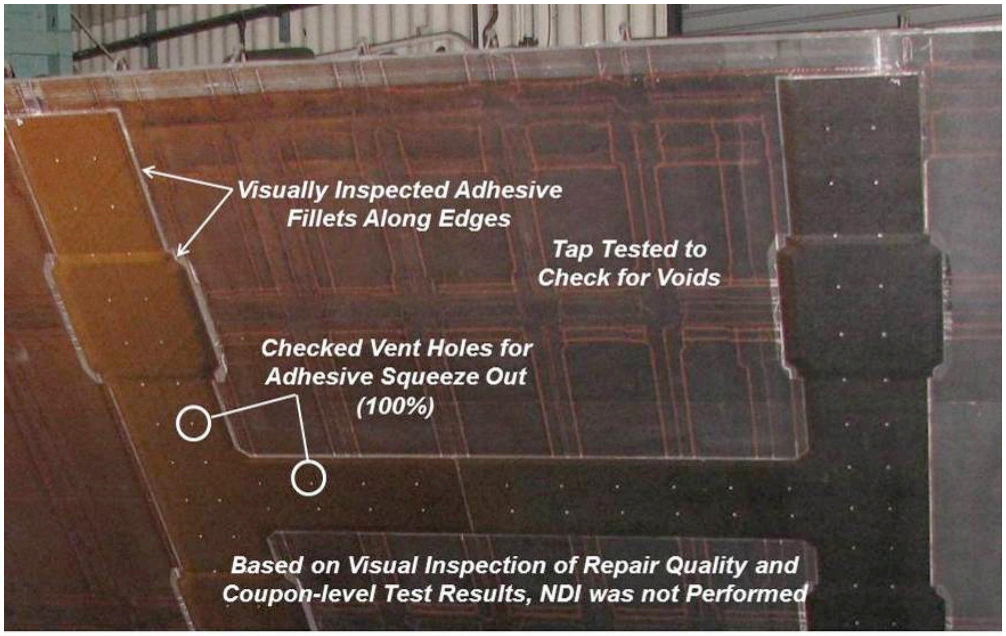

Figure 53. Region of Bonded Repair Patches Shown on OML

Due to the large variation in geometric complexity of the internal structure covered by the patches, the use of common inspection techniques via pre-sampled reference standards was not practical, therefore no ultrasonic non destructive inspection was performed. The repair was bought-off based on using the same process control standards as the test coupons, visual inspection of the adhesive wet-out, tap testing of the completed repair, and ultimately the favorable results of the coupon test effort. The repaired panel was then delivered to the assembly site (Figure 54).

Figure 54. Completed Bonded Repair Patches on Crown Panel OML

1.6 Floor Panel Fabrication

The floor panel design is similar to the crown panel except that it does not have the integral cap features at the forward and aft edges. As such, the preform was built on the common stitching table, but required some new foam blocks and wooden frames for the edges that were specifically developed for the floor panel configuration. The preform details were loaded into the tool and stitched in the same manner as the crown panel described earlier before being flipped onto the cure tool, where the internal foam blocks and wooden frames could be removed to reveal the self-supporting dry carbon fabric preform (Figure 55).

Figure 55. Completed Floor Panel Stitched Preform

The preform was then positioned onto the cure tool and located by the IML tooling details around the perimeter. The vertically positioned IML cure plates were placed underneath the bag to form the smooth tooled surfaces on the integral cap features (Figure 56). The remaining IML cure tool details, silicon rubber bagging aids and aluminum channels on frame caps were also added (Figure 57).

Figure 56. Integral Cap Tooling Plate Installation

Figure 57. Bagging Aids on Frames and Stringers

Once these details were positioned, the bagging operation was started. Due to the problems encountered in the crown panel vacuum bagging sequence, where numerous leaks were detected in both the primary and secondary bags, that ultimately led to replacing both bags and starting over with a new sheet of bagging film, a revamped bagging handling approach was developed in conjunction with the bagging film supplier (AirTech) that was first tried on the floor panel bags.

The first step in the new process was to receive the bagging film from the supplier in a rolled and fully moisture-saturated condition, rather than the loosely controlled folded state where high stress concentrations at the double-folded corners were becoming initiation sites for bag cracking. In addition to having the vendor initially steam treat the bags, tighter control of the bag moisture content was also maintained during transport, storage, and the pleating operation on the shop floor. The first new precondition bag and packaging packing system received is shown on the cutting table in Figure 58 prior to use.

Figure 58. New Pre-Conditioned Vacuum Bag Delivery Packaging

Next, two lanyards were added at the edges of the tool to help the bag clear the IML tooling plates as it was unfurled onto the cure tool (Figure 59). Both changes were helpful in reducing the trauma inflicted on the bagging film by the previous method of unfolding, dragging, and pleating the bag across the part and tooling surfaces. Ideally in a production scenario, the vacuum bags should arrive in a pre-pleated, rolled-up state, and packaged in an environmentally-controlled bag media that maintains the high moisture content needed to maximize the workability of the bagging film.

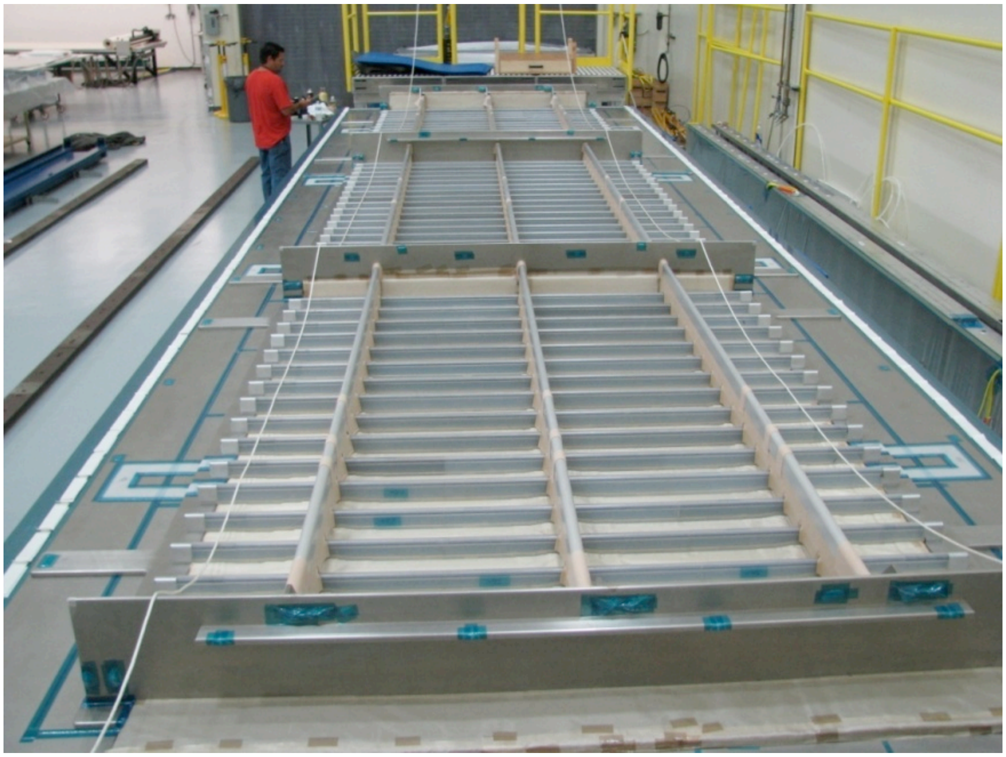

Figure 59. Added Lanyards to Support Bag During Unrolling Operation

Although the emphasis on the new approach focused on changes to the bag conditioning and handling procedures, it also became apparent that the on-tool pleating process was creating damage sites that could later develop as leak paths as the bag was cycled during subsequent leak checks (and again potentially during the heat-up cycles and additional leak checks in the oven).

After leaks were detected in the primary bag after a heat cycle, it was also determined that the damage sites were being created as the bag was pulled across the tool to start the pleating operation (i.e. as it was dragged across the top corners of the vertical forming plates shown in Figure 60). After closely inspecting the tool edges, it was clear that the sharp edge at the corners of the vertical plates were not adequately broken per the drawing general note and that further hand filing was required to eliminate the sharp edges that were puncturing and/or weakening the vacuum bags.

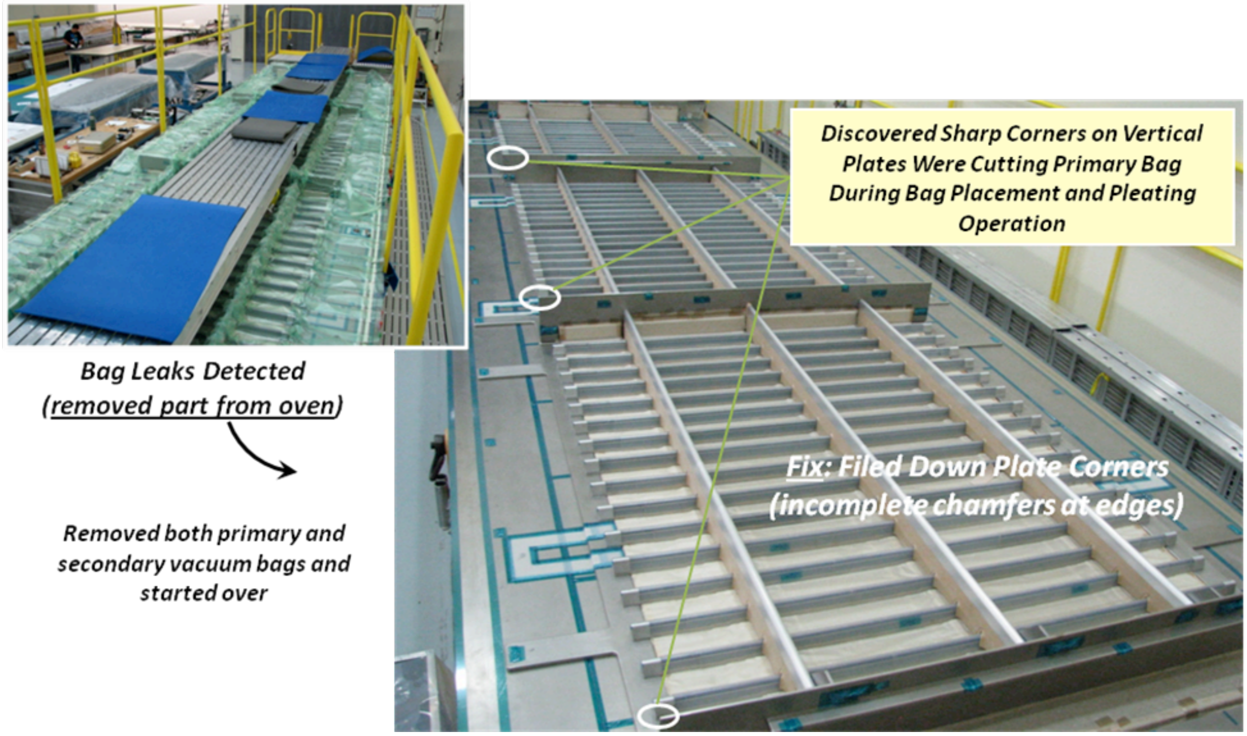

Figure 60. IML Vertical Plate Corners were Tearing the Bagging Film

Once the tool benching was completed and the preform was re-bagged with new primary and secondary vacuum bags, it easily passed the vacuum checks without further leaks (Figure 61 and Figure 62). The floor panel was then placed back in the oven and cured without incident (Figure 63 and Figure 64).

Figure 61. Primary Bag Installed and Leak Checked

Figure 62. Secondary Bag Installed and Leak Checked

Figure 63. Floor Panel Preform Placed in Oven Ready for Heat-up, Infusion, and Cure

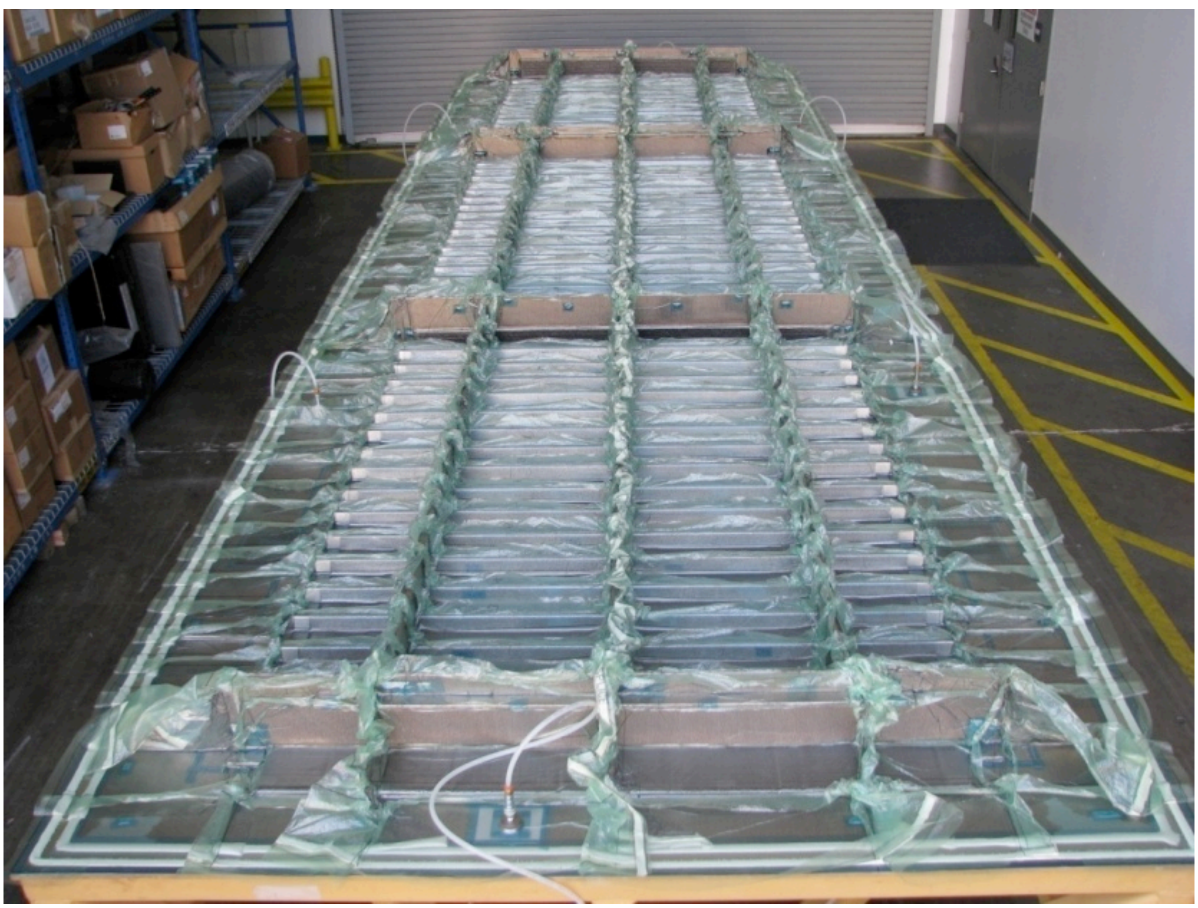

Figure 64. Post Cured Part Prior to Bag Removal

As the bagging problems were eliminated, the other key focus on the floor panel fabrication task was fixing the perforated plate gaps that caused the grooving condition on the crown panel. After running some subscale infusion tests to determine the optimum gap conditions for the perforated plates, the nominal gap used for the floor panel infusion was increased to 0.017-inch which solved the problem.

The resulting floor panel (Figure 65) had high quality IML features and did not have any of the grooves or excessive mark-off (Figure 66) that was prevalent on the crown panel. The cured floor panel was inspected and then placed in storage until the edge trim operation could be scheduled at the machining vendor.

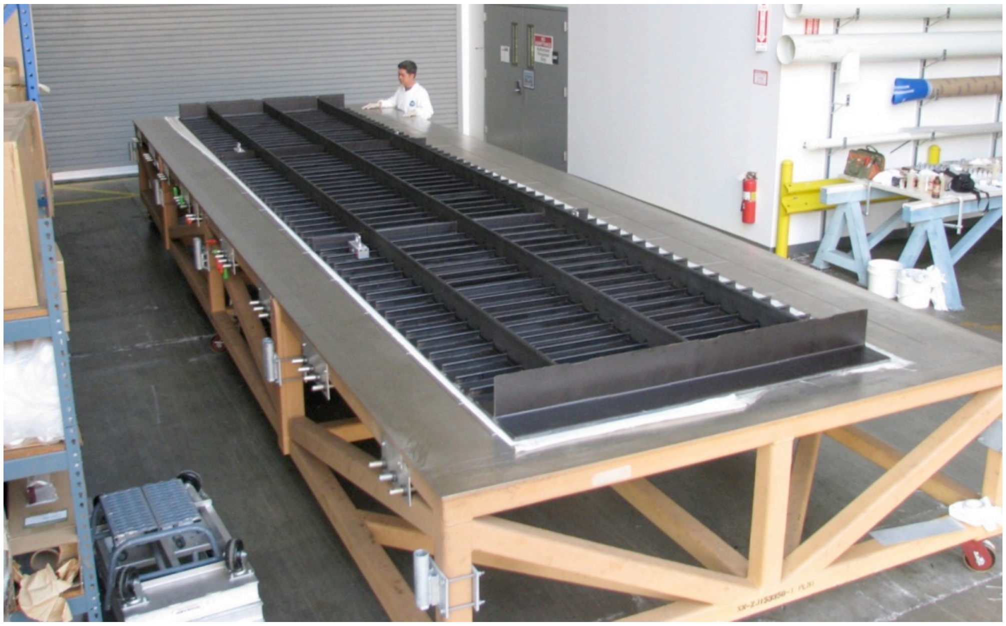

Figure 65. Cured Floor Panel

Figure 66. Floor Panel IML and OML Cured Part Surfaces

1.7 Outer Rib Panel Fabrication

Due to their smaller size and reduced complexity, the two outer rib panels provided an excellent opportunity to demonstrate the process improvements based on the lessons learned with the crown and floor panels. Once the reworked frame elements were loaded in the stitching tool (Figure 67), the remaining details came together quickly (Figure 68), and the stitching (Figure 69) was completed ahead of schedule.

Figure 67. Outer Rib Preform Assembly – Frame Installation

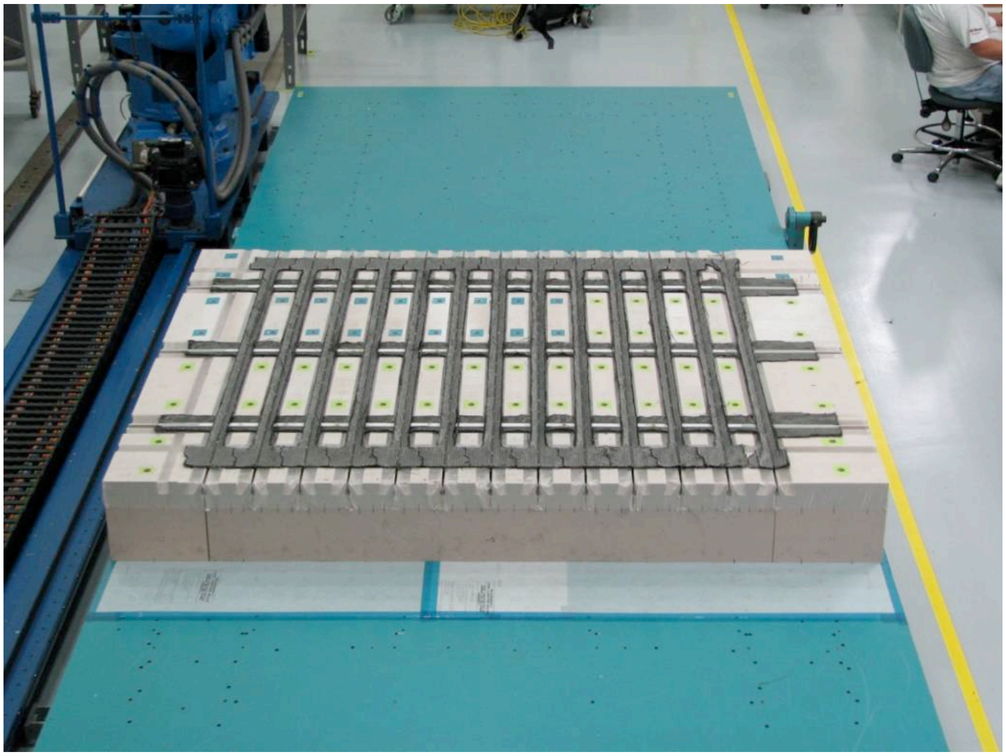

Figure 68. Outer Rib Preform Assembly – Frames and Stringers Installed

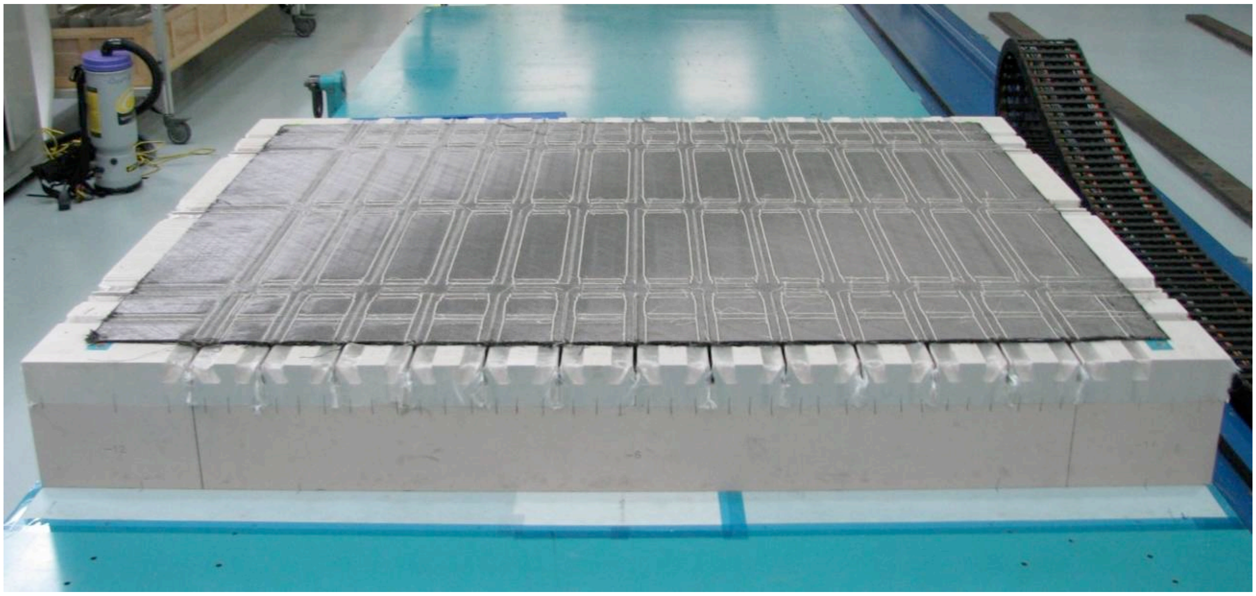

Figure 69. Outer Rib Preform Assembly – Stitching Complete

The first stitched preform was then set aside until the cure tool could be cleaned and rigged with the IML tooling details. Meanwhile, the stitching tool details for the second outer rib panel were quickly reassembled and the second preform was brought together and stitched. The two completed dry preforms are shown together in Figure 70.

Figure 70. Two Outer Rib Preforms were Fabricated Simultaneously

Once the cure tool was ready, the first preform was loaded into position so the IML cure tool details could be positioned (Figure 71). It was then covered with the primary and secondary bags using the newly developed bagging procedures, and then vacuum checked (Figure 72).

Figure 71. IML Tooling Placed on Preform

Figure 72. Bagged Outer Rib Panel During Vacuum Check

The bagging improvements were immediately apparent and repeated on both panels. Neither panel leaked during any of the vacuum checks. This single improvement had a substantial impact on reducing the processing schedule for the outer rib panels, shaving 2-3 weeks off the span time. Both panels were infused and cured in a two week period without any defects. The IML and OML surfaces for outer rib panel #1 are shown in Figure 73, and outer rib panel #2 in Figure 74. The cured panels were trimmed to their final shape (Figure 75). A completed outer rib is shown in Figure 76 and Figure 77.

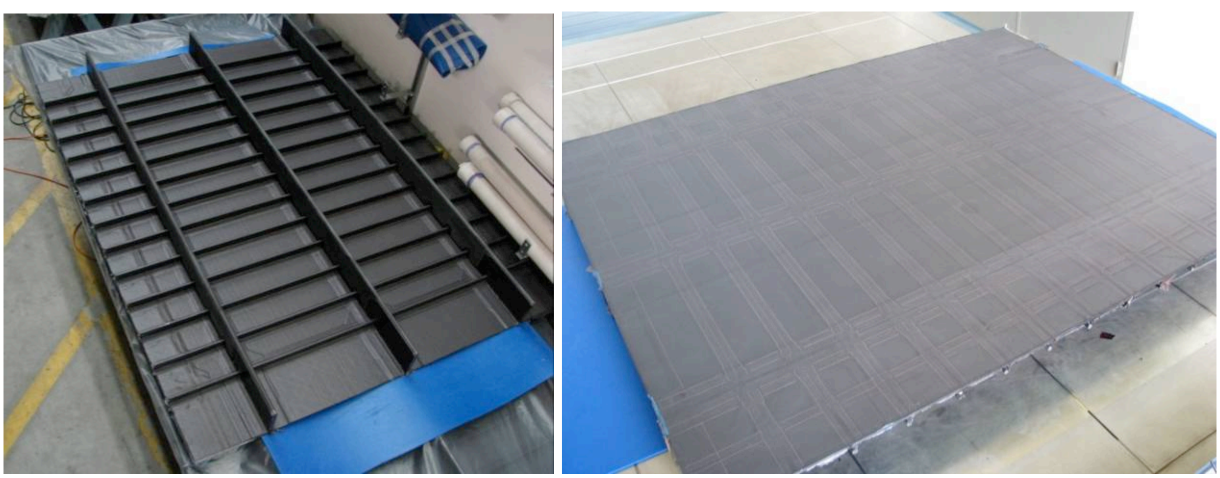

Figure 73. First Untrimmed Cured Outer Rib Panel - IML and OML Surfaces

Figure 74. Second Untrimmed Cured Outer Rib Panel - IML and OML Surface

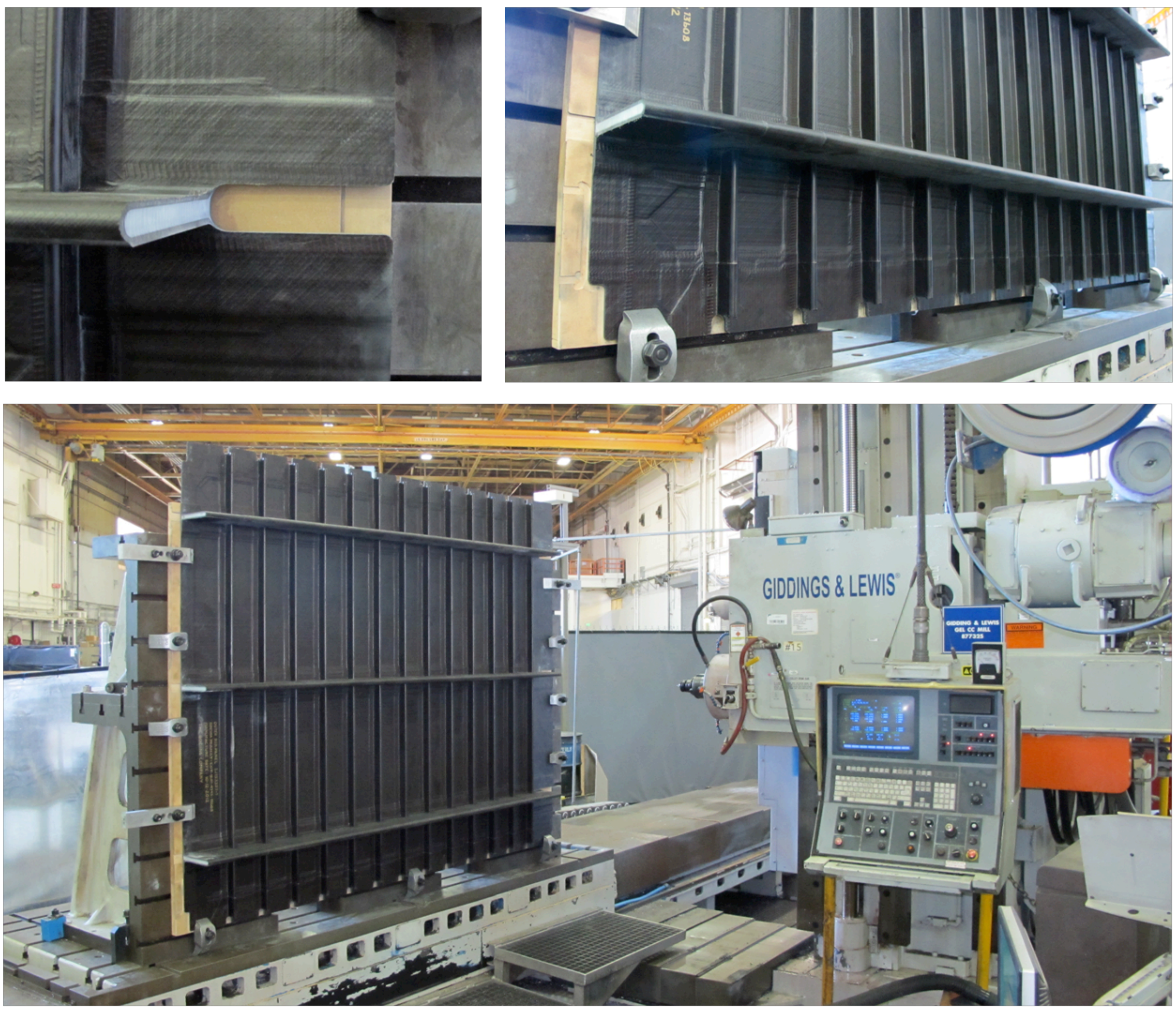

Figure 75. Trimming the Outer Rib Panel

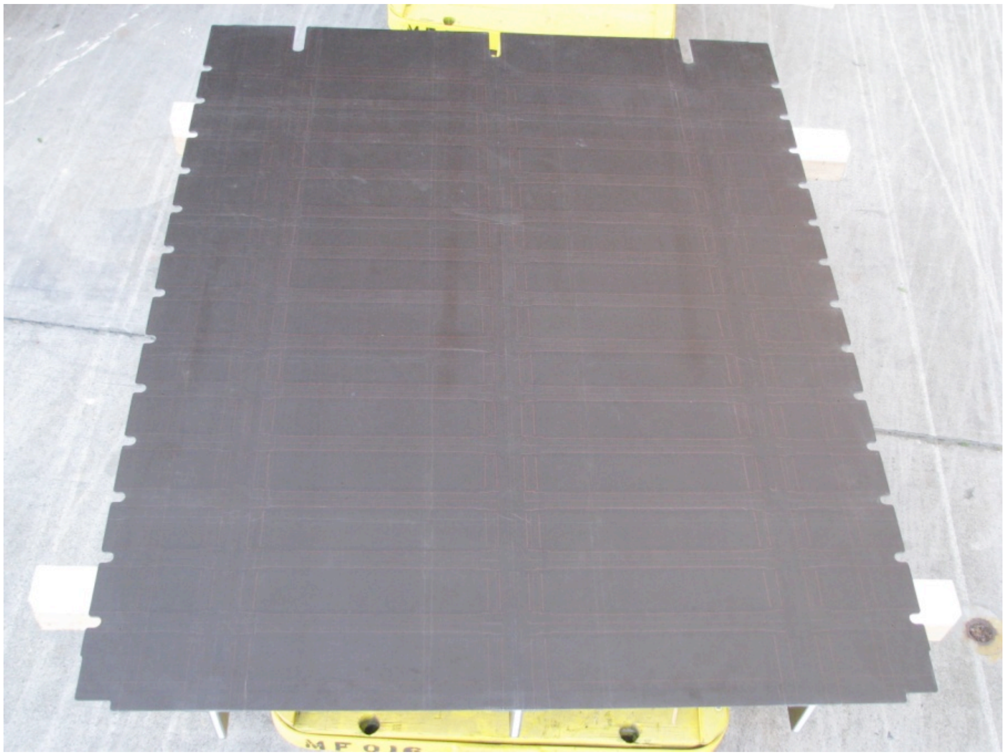

Figure 76. Finished Outer Rib Panel – OML Surfaces

Figure 77. Finished Outer Rib Panel – IML Surfaces

1.8 Upper Bulkhead Panel Fabrication

Having demonstrated the improved fabrication process on the outer rib panels, the focus once again returned to the largest of the 30-ft panels. The primary difference between this panel and the crown and floor panels that were previously fabricated is that the frame and stringer elements are now rotated 90 degrees, so that the stringers are running lengthwise in the 30-ft direction rather than transversely as in the prior panels (which substantially increases the length of the stringer rod pull). Even though the frame elements are shorter now, they still required foam core reworking to adjust the stringer spacing. The gray spliced regions in the core are evident in the photograph in Figure 78, showing four lines where the core was cut and then glued back together before being assembled into the frame detail.

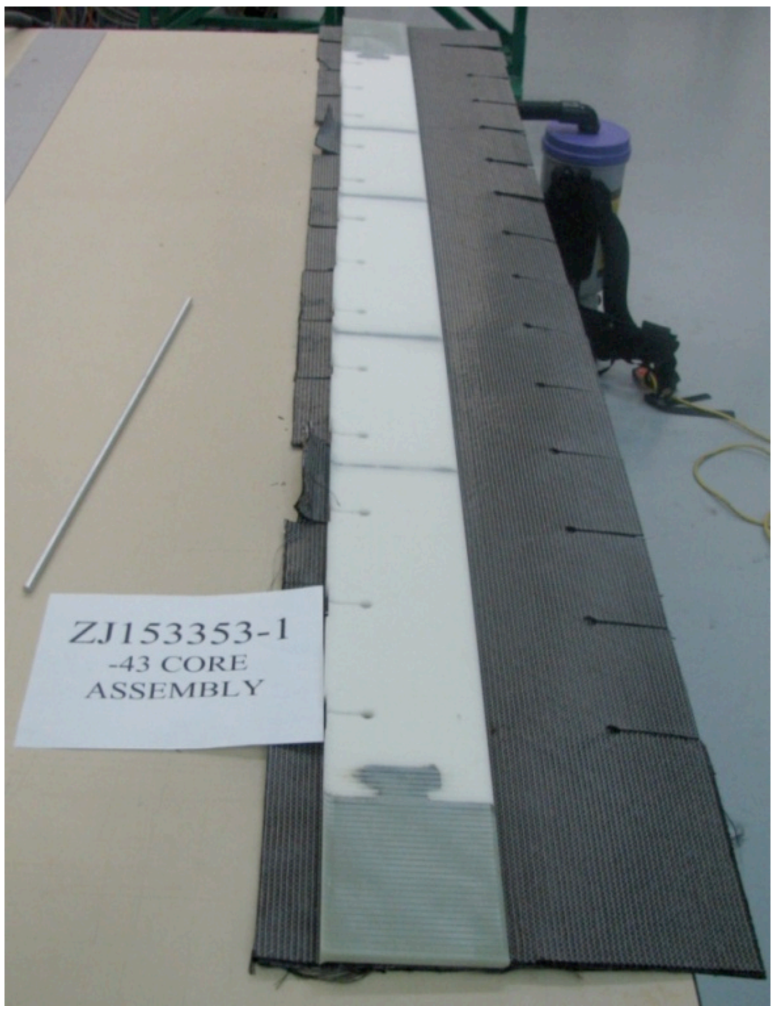

Figure 78. Additional Core Butt Splices Required to Adjust the Stringer Cutout Positions

Due to the shorter length, the frame installation went quickly (Figure 79); as did the installation of the integral cap stacks around the edges (Figure 80).

Figure 79. Frame Installation on First Upper Bulkhead Panel

Figure 80. Integral Cap Stacks at Panel Floor Line Installed

Once all of the integral caps were installed, the flange edges were folded down (Figure 81 and Figure 82). The stringer subassemblies were then loaded into their respective slots. (Figure 83).

Figure 81. Integral Cap Features Installed

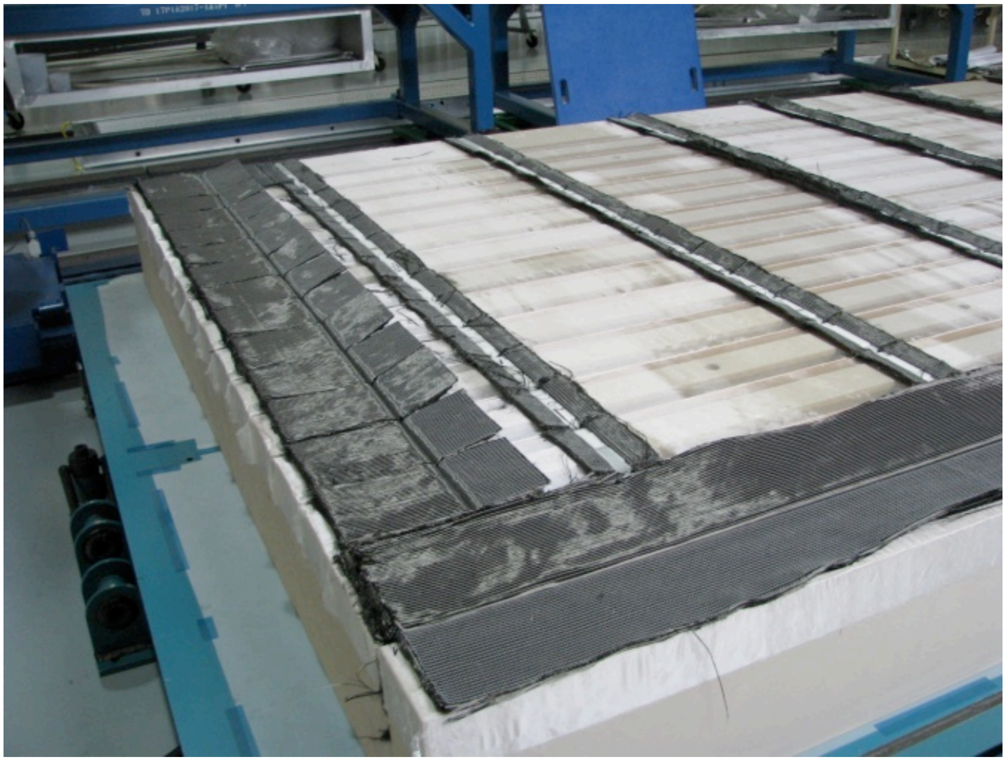

Figure 82. Integral Cap Features Installed and Folded Down

Figure 83. Upper Bulkhead Stringer Stacks Inserted into the Stitching Tool

The next step was to pull the rods through the 30-ft length of the tool. The frictional forces build up as the rod moves through the preform and were primarily driven by the key hole size (diameter) in the frame core and the relative key hole alignment from frame to frame. In this case, the technicians applied hand forces to pull and simultaneously push the rods through the cavities without the use of any specialized tooling (Figure 84 and Figure 85). Once the rods were inserted, the tear straps were added, followed by the skin stacks (Figure 86). The completed stitched preform shown in Figure 87 was ready for infusion.

Figure 84. 30-ft Rods were Inserted into the Preform

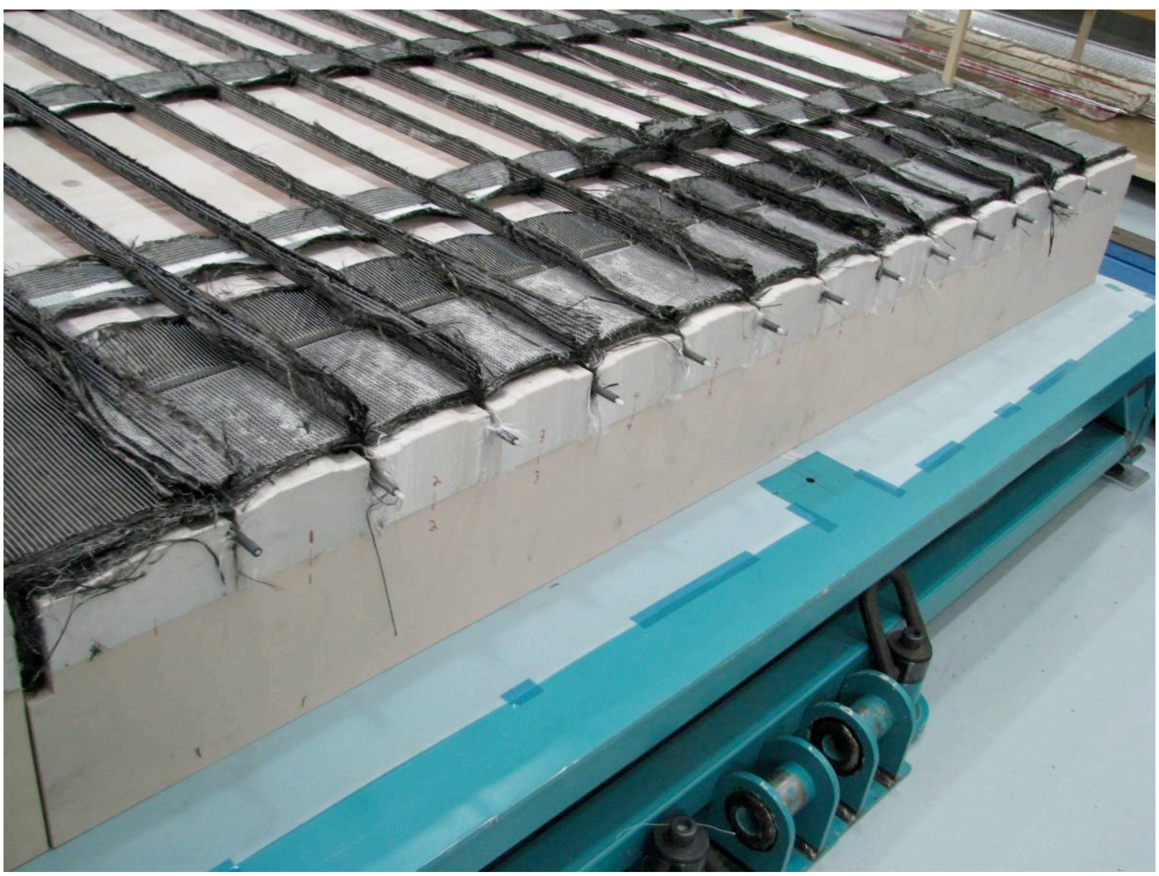

Figure 85. All Stringer Rods Installed in Preform

Figure 86. Tear Straps Placed First, Followed by Skins and Skin Stack Splices

Figure 87. First Upper Bulkhead Panel Stitching Completed

The completed preform was transferred onto the cure tool by rotating the preform assembly tool and releasing the preform from the assembly tool (Figure 88). Hard tooling points were used to precisely index the preform on the cure tool. IML cure details were then pinned into position to accurately locate the key features of the panel (Figure 89). The primary and secondary vacuum bags were installed. The completed preform is then ready to be moved into the oven as shown in Figure 90. The untrimmed cure panel is shown in Figure 91. A special shipping cart (Figure 92) was designed and built to transfer these large panels to and from the vendors for panel trimming. This shipping cart fits into a standard Sea Van container to protect the panel from damage during shipment. The panel was trimmed on a machine that was large enough to trim the entire panel in a single set-up to maintain the tight tolerance of the Determinate Assembly (DA) holes used during assembly of the MBB (Figure 93).

Figure 88. Transferring the Upper Bulkhead Panel Preform onto the Cure Tool

Figure 89. IML Cure Tooling Located on the Upper Bulkhead Panel

Figure 90. Upper Bulkhead Panel Preform Fully Bagged and Ready for Infusion

Figure 91. Cured Upper Bulkhead Panel Ready for Trim

Figure 92. Upper Bulkhead Loaded on the Shipping Cart

Figure 93. Upper Bulkhead Panel Trimming

1.9 Upper/Lower Center Rib Panel Fabrication

Since the center rib panels are not a critical element in the overall HWB fuselage design, they were designed to minimize the overall cost to the program - which in this case was primarily driven by the tooling costs. Therefore a conventional sandwich panel design was selected with heavy build-up regions around the center cutout and perimeter of the panel. Such an approach, is not necessarily the most weight-efficient design solution but it was an effective way to minimize tooling costs, while also simultaneously moving non-critical structures away from the critical schedule path that converged at the stitching machine. The four panel sections were fabricated by an outside vendor and delivered to Boeing. All of the laminates were fabricated with pre-preg intermediate modulus carbon plan weave cloth fabric per BMS8-276, Class 2A, Style 6K-70-PW, Form 1. The honeycomb was Hexcell's Aramid fiber reinforced 1/8-5 lb hexagonal core per DMS 1974, Type 3, Class 2, Grade A.

The core design is a combination honeycomb core and full-depth solid laminate. The entire perimeter of the center rib panel was solid laminate to support the fasteners clamp-up loads. Straight beams in the panel tied the frames of the crown and floor or floor and side keel panels together. The edge of the large cutout was also reinforced with the solid laminate. The solid laminate details were machined from a large panel. This was the thickest solid laminate that had been fabricated using this material system and a special cure cycle was developed to prevent an exothermal reaction from occurring during the cure cycle. The cure went as planned and a void free laminate was fabricated (Figure 73).

Figure 94. Trimming Solid Laminate Core Details

The face sheets were also pre-cured and trimmed to shape leaving an excess of 0.060-inch to trim after the panel was bonded together (Figure 95). Prior to bonding, all of the details were dry fitted together to check for gaps and any mismatch between the core and laminate heights (Figure 96). Then the parts were prepared for bonding. The secondary bond operation for the solid laminate and core to the face sheet was cured at 250° F using FM73 film adhesive per DMS 2169, Type 2. The honeycomb core was simultaneously bonded to the solid laminate using FM410 foaming adhesive to make the shear tie connection. Tooling pins were used to keep the details in position during the bonding cycle (Figure 97). Separate drill templates were developed for drilling the DA holes in the panel to maintain the positional and perpendicularity tolerance of the holes (Figure 98). Once the holes were checked and bought-off by Boeing personal in the template, the DA holes were drilled in the ribs. The completed sandwich panel assembly is shown in Figure 99.

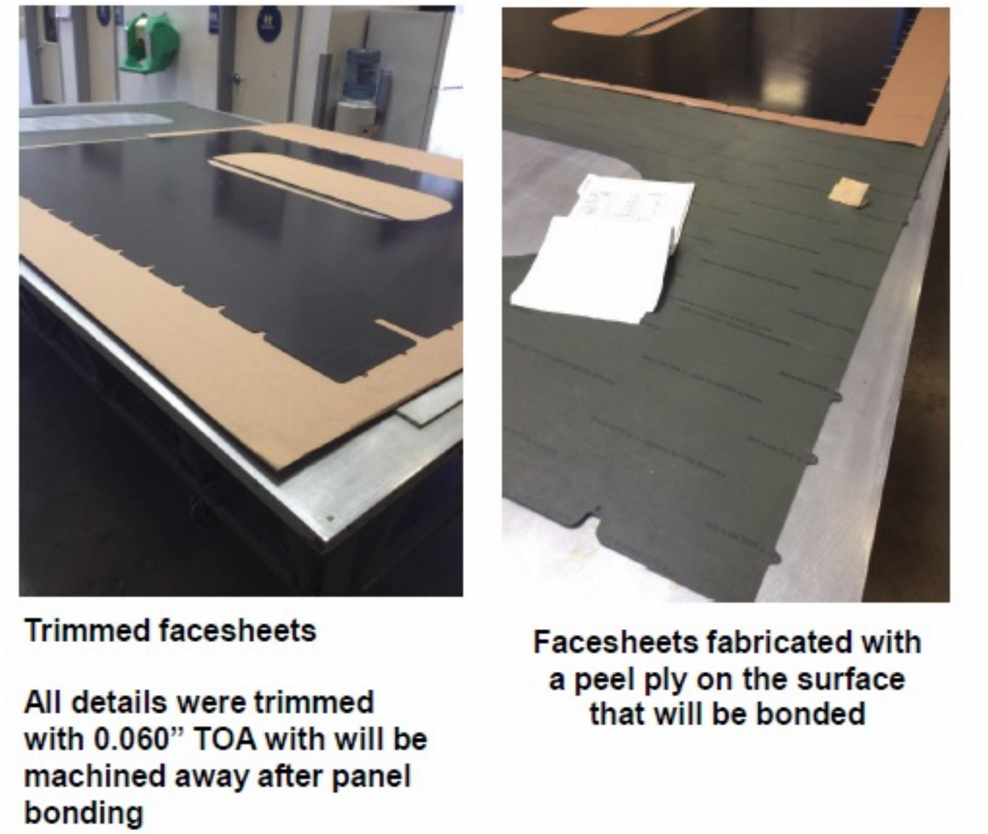

Figure 95. Precured Facesheets Trimmed Net Plus 0.060-inch for Final Trimming

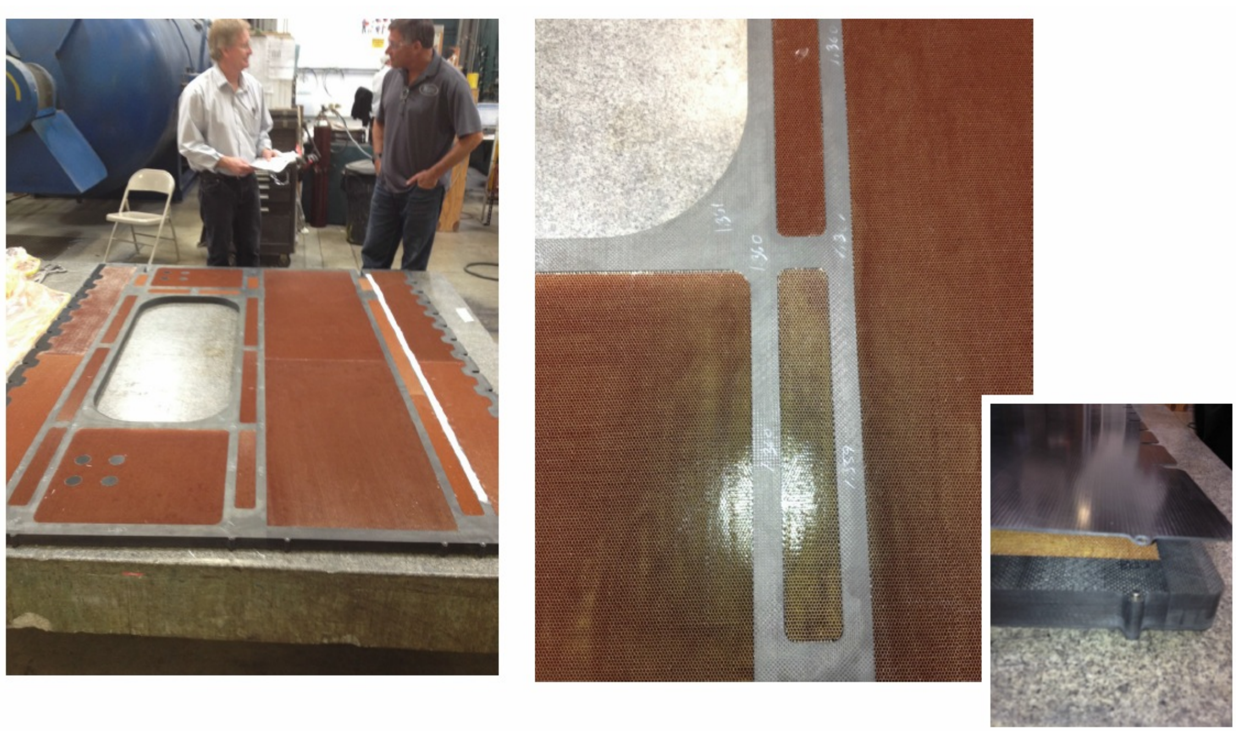

Figure 96. Dry Fit of the Separate Details Prior to Bonding

Figure 97. Tooling Pins Held the Details Together During Bonding

Figure 98. Drill Template was Fabricated to Drill DA Holes on the Panels

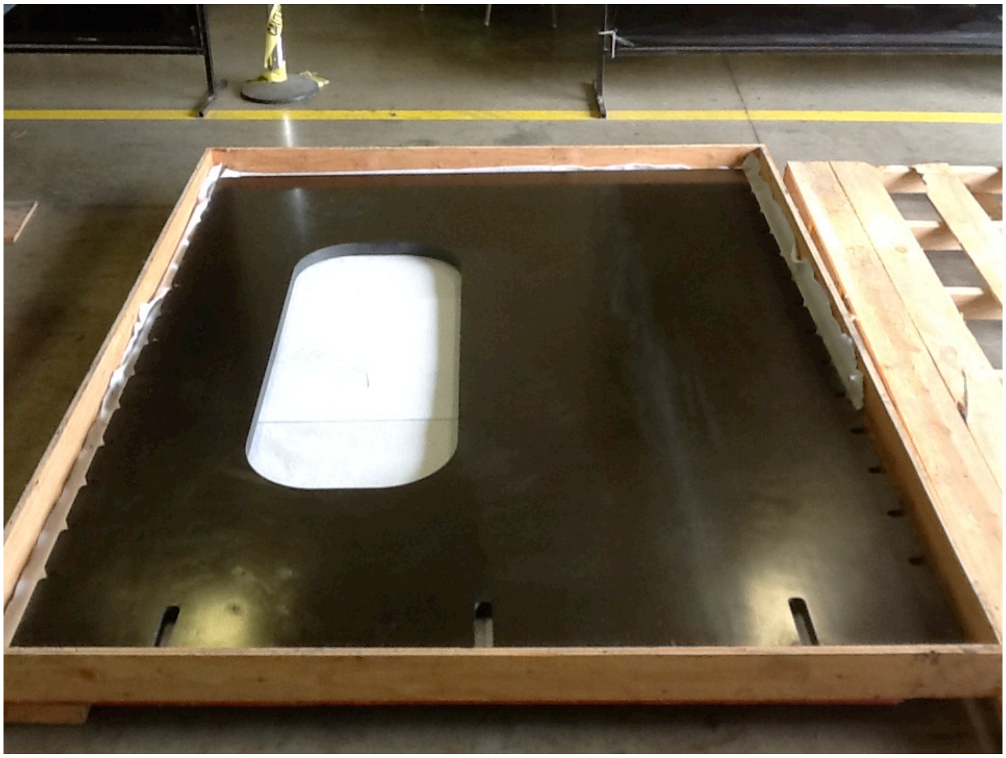

Figure 99. Upper Center Rib Panel Completed by Vendor

1.10 Lower Bulkhead Panel Fabrication

The last two panels that were delivered under this contract were the lower bulkhead panels. All of the frames were spaced at 24-inch on centers like all of the other panels. However the stringer spacing on these panels was not the standard 6-inch spacing and ranged from 4.9-inch to 7.6-inch. The lower edge of the lower bulkhead attaches to the underside (keel) of the fuselage where the sides are at an approximate 30 degree slope. To create better fit between the lower bulkhead and side keel panels, the stringers spacing on the lower bulkhead panel was adjusted. The basic construction and materials for the panels remained the same. All of the frames and shear tees were loaded into the preform assembly tool. Next, all of the stringers were loaded in the tool (Figure 100). Skin doublers were incorporated into the flanges of the stringers to reduce the number of separate stack (ply) details. This can be seen when the flanges of the stringers were folded down. The edges of the flanges flare out creating a butt splice at the center of the bay between the stringers (Figure 101). Additional large doublers were also added to the preform at these high stress areas (Figure 101). A couple of these higher loaded areas were the door cutout located at the center of the panel and the skin splices. The maximum width material purchased for this program was 99-inches wide. This meant that the skin of the 30-ft lower bulkhead (and upper bulkhead) panels required splicing. To achieve this, a double shear joint was used (Figure 102). Layers of DMS2436, Class 75 and 78 were used on the OML and IML surfaces to form the joint. Figure 103 shows the two IML splice strap layers position on the preform assembly. The nine-ply skin stack segments were then positioned. The skin segments were butt spliced together with a maximum gap of 0.060-inch (Figure 104). These simple nine-ply butt splice joints work because only 12% of the fibers in the skin are perpendicular to the joint, and the loads across these joints are low.

Figure 100. Preform Assembly Starts with the Inserting the Frames and then the Stringers

Figure 101. Flanges are Folded Down then Tear Straps and Doublers are Added

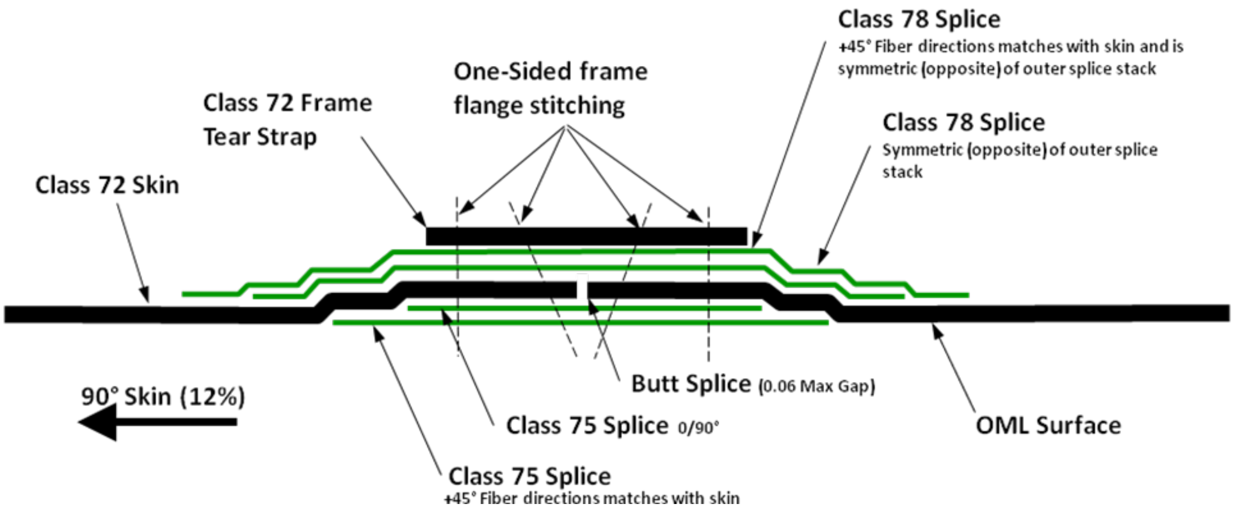

Figure 102. Skin Splice Geometry

Figure 103. IML Skin Splice Straps are Located on the Preform Assembly

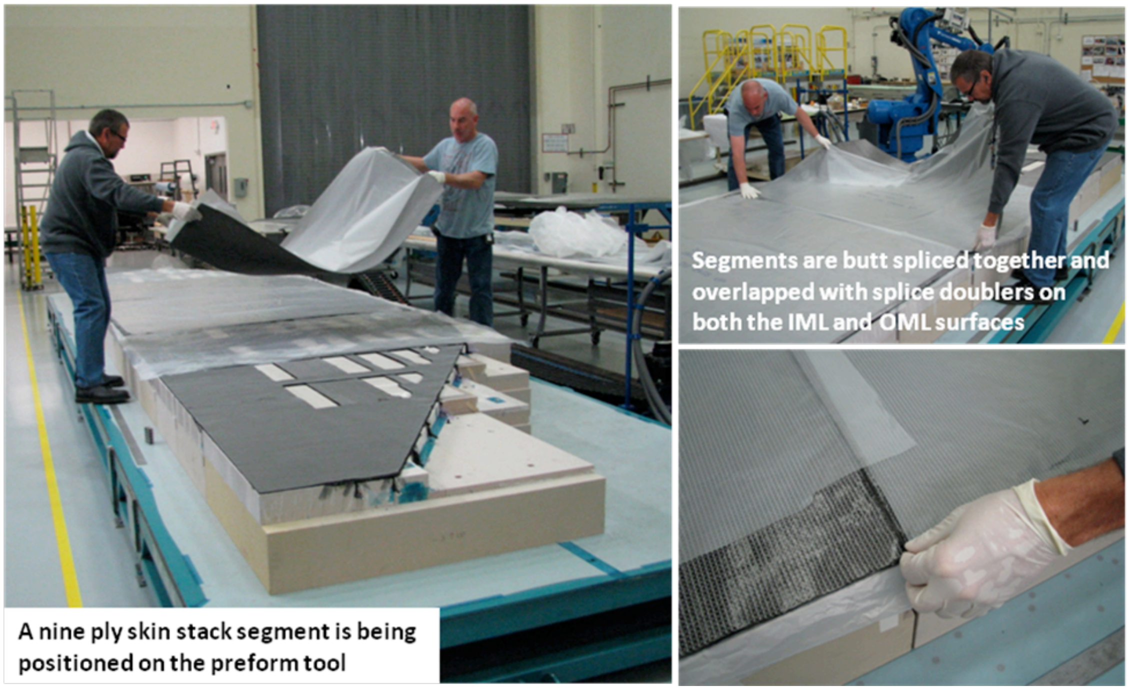

Figure 104. Lower Bulkhead Skin Splice

With the skin in place, the OML skin splice doublers were located. The preform assembly was now ready for stitching. Figure 105 shows the lower bulkhead panel fully stitched. Stitching was inserted in all of the frame and stringer flanges. It is also inserted at the edges of the skin doublers to prevent any ply delaminations when the nine-ply stacks were terminated (Figure 105). Without stitching, dropping nine plies off at a time in the direction perpendicular to the loading would be prohibitive for unreinforced laminates.

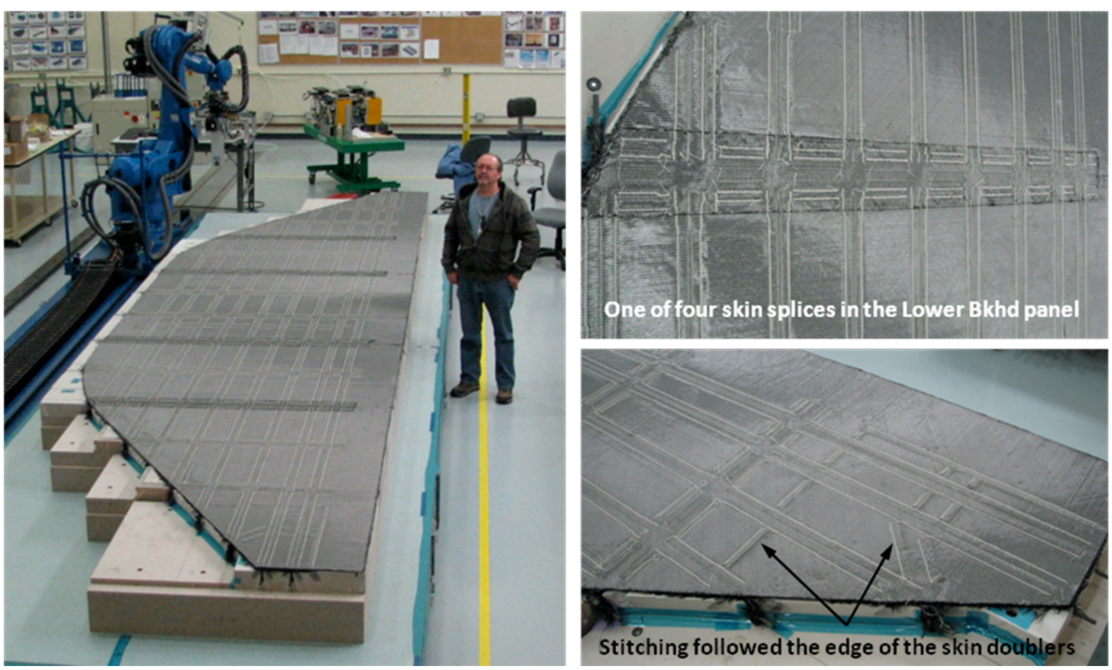

Figure 105. Lower Bulkhead Preform Stitching Complete

With the preform on the cure tool, the IML cure tool details were added around the perimeter of the preform assembly (Figure 106). The primary and secondary vacuum bags were then installed. All of the inlet and outlet plumbing lines for resin infusion were attached. The part was now ready to be transferred to the oven for infusion (Figure 107). The infusion process for both lower bulkhead panels was successful without issues. The OML surfaces were flat and smooth and the IML stringers, shear tees and frames were straight and completely filled with resin (Figure 108).

Figure 106. IML Cure Tool Positioned on the Preform

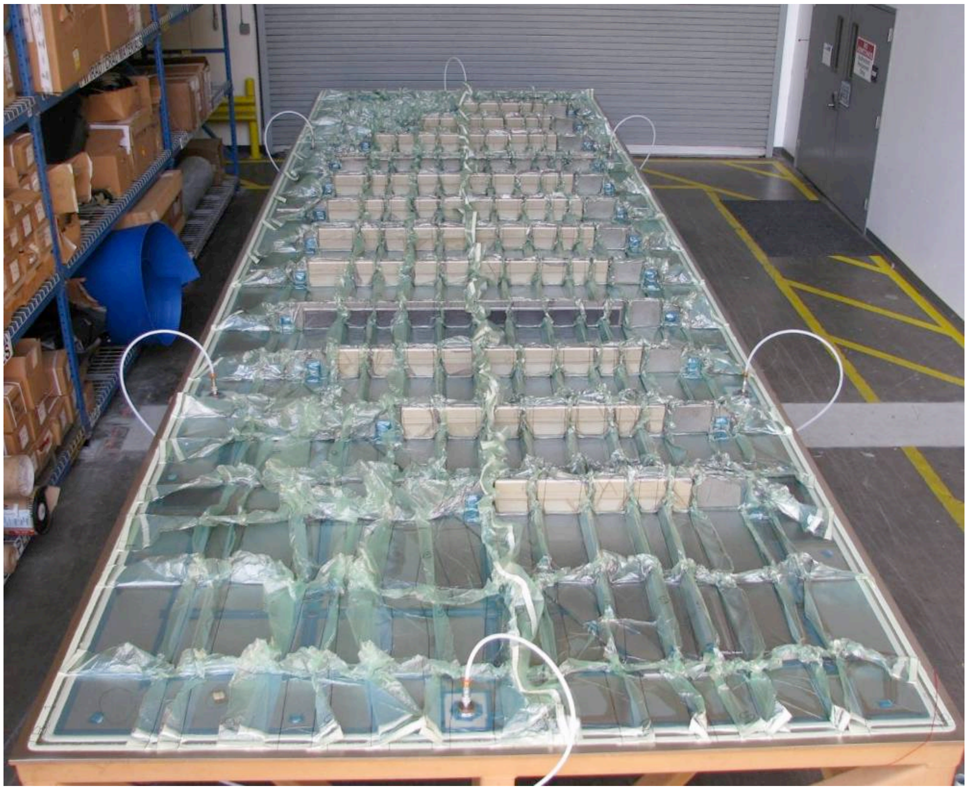

Figure 107. Vacuum Bagging Complete Ready for Transporting the Assembly to the Oven

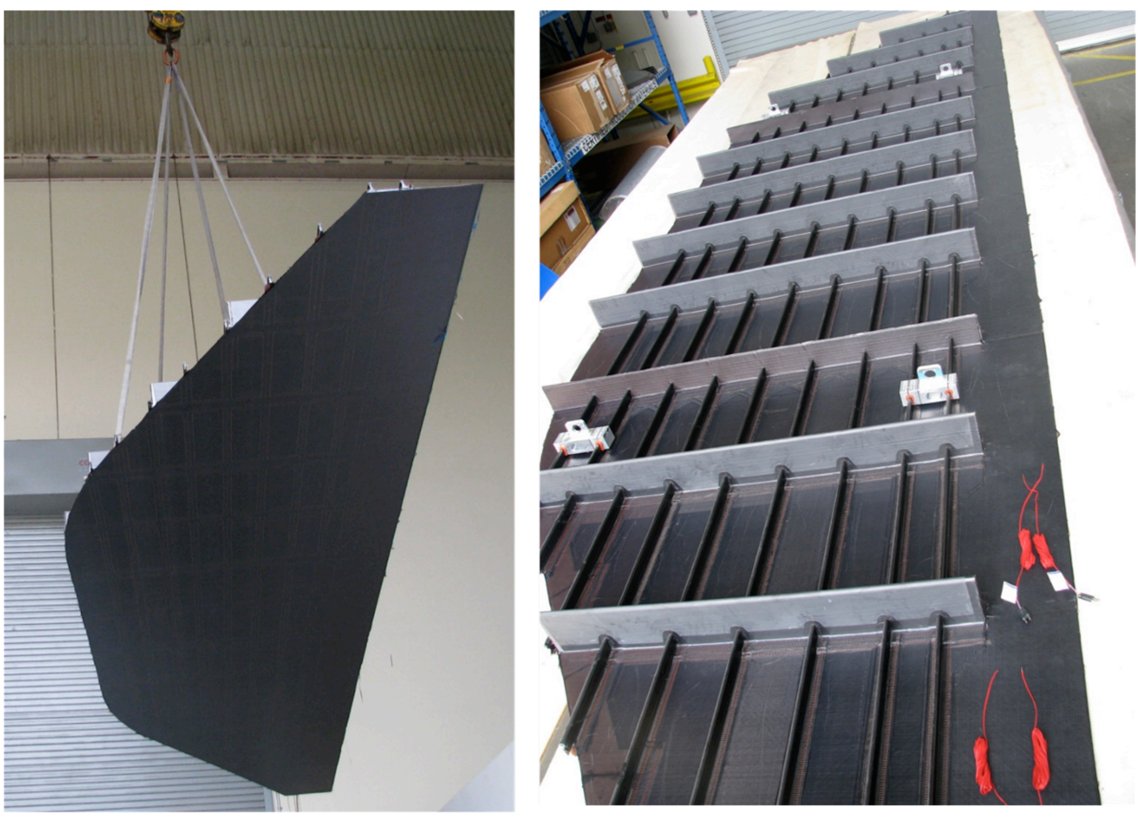

Figure 108. OML and IML Surfaces of the Cured Lower Bulkhead Panel Prior to Trimming

2.0 Metallic Fittings

There are 723 fittings required to build the MBB assembly. Figure 2 shows the fitting rigged in space. This quantity of fittings was the collection of 249 different configurations (includes left and right hand (mirrored) parts). The load introduction areas on each end of the MBB required a total of 108 fittings. For fully integrated panels this may seem like a lot of fittings, but the MBB test specimen is a very short fuselage section. The forward and aft pressure bulkheads are only 7-ft apart. For an actual aircraft, were the forward and aft pressure bulkheads could be 100-ft apart, full 100-ft length integrated panels would be fabricated. Now the pressure bulkhead fittings would be averaged out over 100-ft instead of 7-ft. Increasing the fuselage section from 7-ft to 100-ft increases the fuselage length 14 times. Calculating the total number of fitting for the 100- ft fuselage section would only increase the total number of fitting by 3 times. Or another way to look at it would be to just look at the number of fitting that would be required for the fuselage not considering the pressure bulkheads or the load introduction fittings. Using this scenario, there would only be 152 fittings in the entire 30-ft x 7-ft double-deck fuselage section.

	7 ft Fuselage	100 ft Fuselage	Increase
Fuselage Length Increase	----	93	14 times
Composite Panels	15	15	0
Metallic Fittings	615	1,985	3 times

Figure 109. Increasing the Fuselage Length by 14 Times would only Increase the Number of Fittings by 3 Times

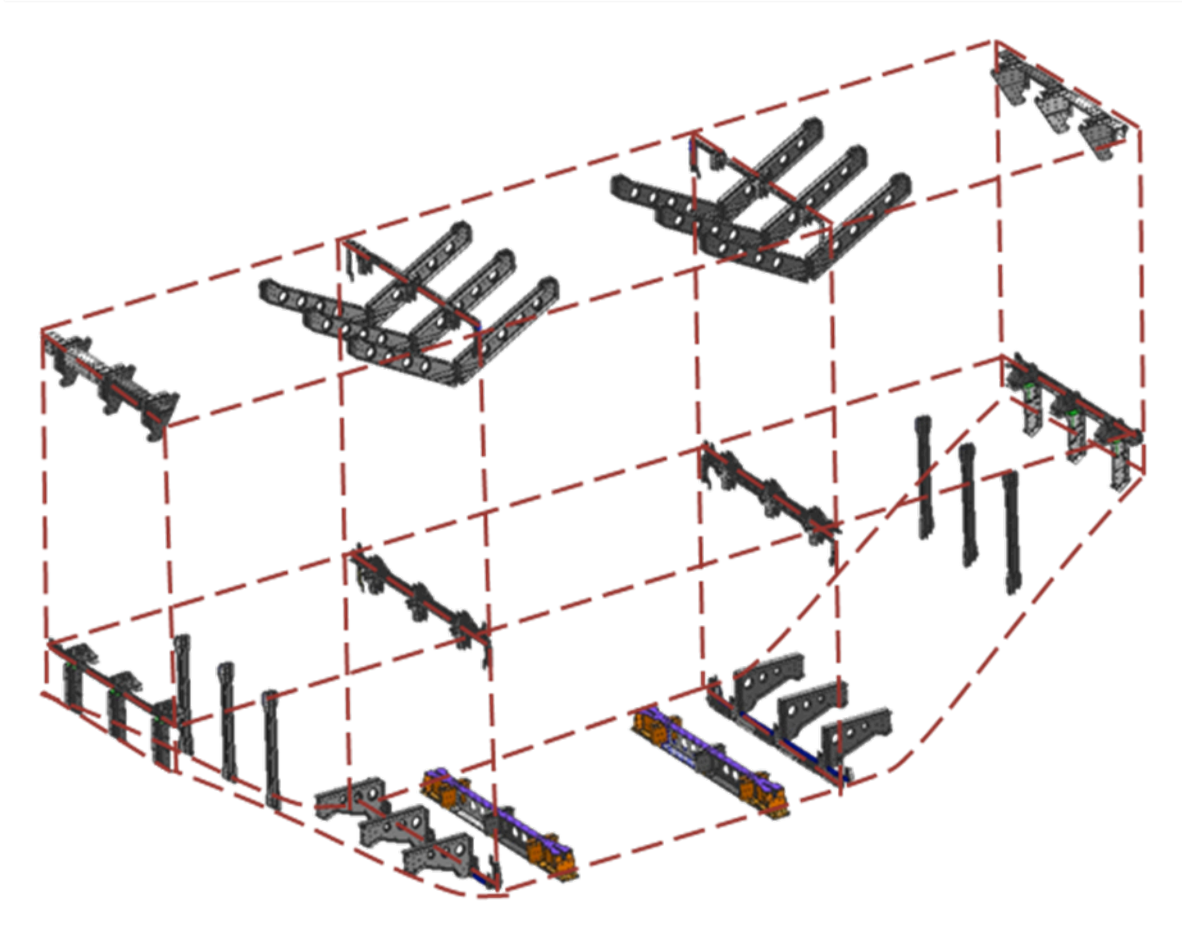

Figure 110. Typical Mid Fuselage Fitting Arrangement without the Pressure Bulkheads and Load Introduction Fittings

A complete list of fittings with qualities that were procured is provided in Table 1. All of the fittings have been transferred to the Multi-Bay Box assembly site for assembly (Figure 111).

Table 1. List of Machined Fittings Ordered for the MBB Assembly

<table>
<tr><th>Item No.</th><th>Part No.</th><th>Qty.</th><th>Description</th></tr>
<tr><td>1</td><td>ZJ153343-1</td><td>2</td><td>Upper Test Adapter Box</td></tr>
<tr><td>2</td><td>ZJ153344-1</td><td>2</td><td>Lower Test Adaptor Box</td></tr>
<tr><td>3</td><td>ZJ153345-1</td><td>2</td><td>Upper OML Load Introduction Fitting</td></tr>
<tr><td>4</td><td>ZJ153346-1</td><td>2</td><td rowspan="6">Upper IML Load Introduction Fitting</td></tr>
<tr><td>5</td><td>ZJ153346-2</td><td>2</td></tr>
<tr><td>6</td><td>ZJ153346-501</td><td>2</td></tr>
<tr><td>7</td><td>ZJ153346-502</td><td>2</td></tr>
<tr><td>8</td><td>ZJ153346-503</td><td>2</td></tr>
<tr><td>9</td><td>ZJ153346-504</td><td>2</td></tr>
</table>

Item No.	Part No.	Qty.	Description
10	ZJ153346-505	2	
11	ZJ153346-506	2	
12	ZJ153347-1	6	Upper IML External Frame Load Intro Fitting
13	ZJ153348-1	4	Upper IML Internal Frame Load Intro Fitting (outside frames)
14	ZJ153348-2	4	
15	ZJ153348-501	2	Upper IML Internal Frame Load Intro Fitting (Center frame)
16	ZJ153348-502	2	
17	ZJ153349-1	2	Auxiliary Outer Rib Plate
18	ZJ153650-1	2	Lower OML Load Introduction Fitting
19	ZJ153651-1	4	Lower IML Load Introduction Fitting
20	ZJ153651-501	4	
21	ZJ153652-1	2	Lower IML External Frame Load Intro Fitting
22	ZJ153652-2	2	
23	ZJ153652-501	6	
24	ZJ153652-502	6	
25	ZJ153653-1	6	Lower IML Internal Frame Load Introduction Fitting (Keel & Floor)
26	ZJ153653-2	6	
27	ZJ153654-1	2	Lower External Side Load Introduction Fitting
28	ZJ153654-2	2	
29	ZJ153655-1	2	Mid Continuous Load Introduction Fitting
30	ZJ153656-1	2	Mid Discontinuous Load Introduction Fitting
31	ZJ153656-2	2	
32	ZJ153656-501	2	
33	ZJ153656-502	2	
34	ZJ153657-1	2	OML Skin Splice Plate
35	ZJ153658-1	4	Keel Splice/ Bulkhead Intercostal Fitting (frame to cap)
36	ZJ153658-501	4	Keel Splice/ Bulkhead Intercostal Fitting (frame to frame)
37	ZJ153658-503	4	Keel Cap Flange Splice Plate
38	ZJ153658-505	4	Keel Cap Splice Fitting
39	ZJ153659-1	2	Keel Splice Intercostal Fitting
40	ZJ153659-2	2	
41	ZJ153659-501	4	
42	ZJ153659-503	2	Keel Splice Strap
43	ZJ153660-1	20	Bulkhead Frame to Panel Stringer Fitting
44	ZJ153660-2	20	
45	ZJ153660-501	2	
46	ZJ153660-502	2	
47	ZJ153662-1	8	Bkhd Frame Splice Fitting
48	ZJ153662-2	8	
49	ZJ153662-501	4	
50	ZJ153662-502	4	

Item No.	Part No.	Qty.	Description
51	ZJ153662-503	4	
52	ZJ153662-504	4	
53	ZJ153662-505	4	
54	ZJ153662-506	4	
55	ZJ153663-1	1	Access Door, Lower Bulkhead
56	ZJ153663-501	1	Access Door, Upper Bulkhead
57	ZJ153663-503	1	Access Door, Lower Bulkhead w/ Instrumentation Holes
58	ZJ153663-505	1	Access Door, Upper Bulkhead w/ Instrumentation Holes
59	ZJ153664-1	2	Bkhd Frame to Canted Stringer #14 Fitting
60	ZJ153664-2	2	
61	ZJ153664-501	2	
62	ZJ153664-502	2	
63	ZJ153664-503	2	Bkhd Frame to Canted Stringer #18 Fitting
64	ZJ153664-504	2	
65	ZJ153664-505	2	
66	ZJ153664-506	2	
67	ZJ153664-507	2	Bkhd Frame to Canted Stringer #22 Fitting
68	ZJ153664-508	2	
69	ZJ153664-509	2	
70	ZJ153664-510	2	
71	ZJ153664-511	4	Bkhd Frame to Stringer #2 Fitting
72	ZJ153664-512	4	
73	ZJ153664-515	2	
74	ZJ153664-516	2	
75	ZJ153666-1	4	External Center Keel Stringer Support
76	ZJ153666-501	20	External Crown Stringer Support
77	ZJ153667-1	6	Keel Gusset
78	ZJ153667-2	6	
79	ZJ153668-1	3	Wire Clamp Fitting
80	ZJ153669-1	6	Crown Gusset
81	ZJ153669-2	6	
82	ZJ153669-501	6	
83	ZJ153669-502	6	
84	ZJ153900-1	2	Gang Channel for Access Door
85	ZJ153900-501	1	
86	ZJ153900-503	1	
87	ZJ153900-505	2	
88	ZJ153900-506	2	
89	ZJ153900-507	2	
90	ZJ153900-509	2	
91	ZJ153900-511	2	
92	ZJ153901-1	2	External Bulkhead Cap Load Introduction Fitting
93	ZJ153901-2	2	

Item No.	Part No.	Qty.	Description
94	ZJ153902-1	2	Internal Bulkhead Cap Crown Load Intro Fitting
95	ZJ153902-2	2	
96	ZJ153903-1	20	Bkhd Frame to Floor Cap Clip
97	ZJ153903-2	20	
98	ZJ153903-501	4	
99	ZJ153903-502	4	
100	ZJ153904-1	8	Lower Bkhd Skin Splice Strap
101	ZJ153904-501	4	Floor Skin Back-Up Plate
102	ZJ153905-1	6	Lower Center Rib Clip
103	ZJ153905-2	6	
104	ZJ153905-501	2	Upper Center Rib Clip
105	ZJ153905-502	2	
106	ZJ153905-503	2	
107	ZJ153905-504	2	
108	ZJ153905-505	2	
109	ZJ153905-506	2	
110	ZJ153906-1	2	Outer Rib Frame to Floor Fitting
111	ZJ153906-2	2	
112	ZJ153906-501	4	
113	ZJ153906-502	4	
114	ZJ153906-503	6	Radius Block
115	ZJ153906-504	6	
116	ZJ153907-1	4	Auxiliary Outer Rib Access Cover
117	ZJ153907-501	4	
118	ZJ153908-1	6	Floor Strut
119	ZJ153908-2	6	
120	ZJ153909-1	2	Floor Corner Fitting – Lower Center Rib
121	ZJ153909-2	2	
122	ZJ153910-1	2	Keel Corner Fitting – Lower Center Rib
123	ZJ153910-2	2	
124	ZJ153911-1	2	Mid Internal Side Load Introduction Fitting
125	ZJ153911-2	2	
126	ZJ153912-1	2	Lower Internal Side Load Introduction Fitting
127	ZJ153912-2	2	
128	ZJ153912-501	2	Stringer Shear Fitting (Lower Bkhd Panel)
129	ZJ153912-502	2	
130	ZJ153913-1	2	Corner Fitting – Upper Center Rib
131	ZJ153913-2	2	
132	ZJ153915-1	4	Lower Center Rib to Keel Center Fitting
133	ZJ153915-2	4	
134	ZJ153915-501	2	
135	ZJ153915-502	2	
136	ZJ153916-1	2	Center Rib to Bulkhead Fitting

Item No.	Part No.	Qty.	Description
137	ZJ153916-2	2	
138	ZJ153916-501	2	
139	ZJ153916-502	2	
140	ZJ153917-1	2	Center Rib to Crown/Floor Corner Fitting
141	ZJ153917-2	2	
142	ZJ153917-501	2	
143	ZJ153917-502	2	
144	ZJ153918-1	4	Center Rib to Floor Center Fitting
145	ZJ153918-2	4	
146	ZJ153918-501	2	Center Rib to Crown Center Fitting
147	ZJ153918-502	2	
148	ZJ153918-503	2	Center Rib to Crown Center Fitting
149	ZJ153918-504	2	
150	ZJ153918-505	2	Center Rib to Floor Center Fitting
151	ZJ153918-506	2	
152	ZJ153918-507	2	Center Rib to Floor Center Fitting
153	ZJ153918-508	2	
154	ZJ153919-1	2	Upper Center Rib to Floor Fitting (flat side)
155	ZJ153919-501	2	
156	ZJ153945-1	44	Corner Strut Fitting
157	ZJ153945-2	44	
158	ZJ153945-501	44	Corner Strut Fitting
159	ZJ153945-502	44	
160	ZJ153956-1	44	Strut, Corner Brace
161	ZJ153957-1	4	Shim, Side Keel Tee to Center Rib
162	ZJ153957-501	4	
163	ZJ153957-503	4	Shim, used with 3910-1
164	ZJ153957-505	12	Shim, used with 3908-1 at Floor Struts
165	ZJ153957-507	8	Shim, used with 3658-1 Keel Splice
166	ZJ153957-509	8	Shim, used with 3653-1 at Outer Frame
167	ZJ153957-511	4	Shim, used with 3652-1 at outer Frame
168	ZJ153957-513	4	Shim, used with 3652-1 at Cap
169	ZJ153957-515	4	Shim, used with 3653-1 at Center Frame
170	ZJ153957-517	2	Shim, used with 3652-501 at Center Frame

Figure 111. Fittings were Stored on Shelves in the MBB Assembly Area

3.0 Panel Hardware

A quick study was conducted comparing the number of fasteners that would be required to assemble a Multi-Bay Box specimen using different technologies. The first comparison was made to a typical aluminum fuselage construction with separate skin, stringers, frames and frame shear tees. The second was a typical state-of-the-art (SoA) composite fuselage with co-cured skin with stringers, separate frames and frame shear tees (Figure 112). The integrated concept using stitching to support the out-of-plane loads and damage containment would only require 35% of the fasteners required to assemble a comparable state of the art composite fuselage or 20% of an aluminum fuselage.

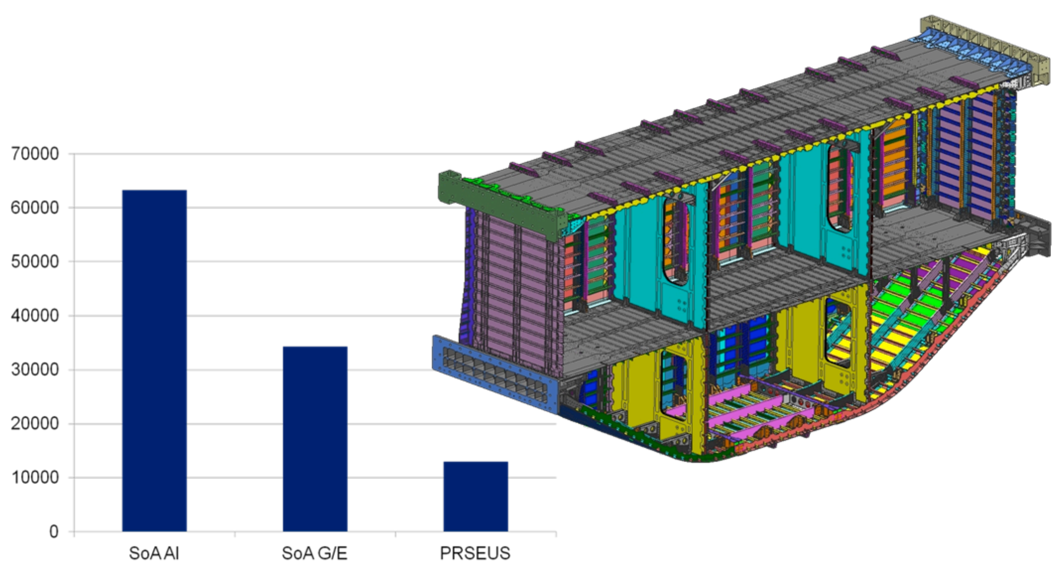

Figure 112. Fasteners Required to Assemble the Multi-Bay Box for Different Technologies (State-of-the-Art Aluminum, State-of-the-Art Graphite Epoxy, and PRSEUS)

All of the expected hardware to assemble the MBB was ordered under this contract and are listed in Table 2. Additional fasteners that attach the panel-to-panel joints were ordered one grip length (0.062-inch) less as a risk mitigation step. The first step in the assembly of the Multi-Bay Box was to assemble the panels together then install all of the fittings. Waiting for shorter grip length fasteners to assemble the panels together would have delayed the entire assemble task with no work around plan. All of the fasteners were transferred to the assembly site and are stored inside a locked cage (Figure 113).

Table 2. Fastener Ordered for the MBB Assembly

Item No.	Part No. *	Qty.	Description	Substitute Part No.
1	3D0006-4	400	1/4" Self-Aligning Nut	
2	3D0006-5	200	5/16" Self-Aligning Nut	
3	3D0006-6	50	3/8" Self-Aligning Nut	
4	3D0031-4-17	18	Bolt-Tension, Double Hexagon Flanged, 220 KSI, 1/4" diam., 1-1/16" grip	
5	3D0031-4-18	18	Bolt-Tension, Double Hexagon Flanged, 220 KSI, 1/4" diam., 1-1/8" grip	
6	3D0031-4-20	9	Bolt-Tension, Double Hexagon Flanged, 220 KSI, 1/4" diam., 1-1/4" grip	
7	3D0031-8-38	13	Bolt-Tension, Double Hexagon Flanged, 220 KSI, 1/4" diam., 2-3/8" grip	
8	3D0096-8	500	Collar, Pin Rivet, Threaded, Torque Controlled, Alum, 1/4"	
9	3D0097-12-13	5	Pin - Rivet, Threaded, 3/8" dia., 100° Flush Crown Hd	
10	3D0097-12-16	18	Pin - Rivet, Threaded, 3/8" dia., 100° Flush Crown Hd	
11	3D0097-8-10	48	Pin - Rivet, Threaded, 1/4 dia., 100° Flush Crown Hd	
12	3D0097-8-11	88	Pin - Rivet, Threaded, 1/4 dia., 100° Flush Crown Hd	
13	3D0097-8-12	26	Pin - Rivet, Threaded, 1/4 dia., 100° Flush Crown Hd	
14	3D0097-8-14	5	Pin - Rivet, Threaded, 1/4 dia., 100° Flush Crown Hd	NAS7604U14
15	3D0097-8-16	31	Pin - Rivet, Threaded, 1/4 dia., 100° Flush Crown Hd	
16	3D0097-8-7	141	Pin - Rivet, Threaded, 1/4 dia., 100° Flush Crown Hd	
17	3D0097-8-8	92	Pin - Rivet, Threaded, 1/4 dia., 100° Flush Crown Hd	

Item No.	Part No. *	Qty.	Description	Substitute Part No.
18	3D0097-8-9	57	Pin - Rivet, Threaded, 1/4 dia., 100° Flush Crown Hd	
19	3D0098-8-10	158	Pin - Rivet, Threaded, Ti, 1/4" dia., 100° Fl Crown Shear Hd	WC198-8-10
20	3D0098-8-13	106	Pin - Rivet, Threaded, Ti, 1/4" dia., 100° Fl Crown Shear Hd	WC198-8-13
21	3D0098-8-7	211	Pin - Rivet, Threaded, Ti, 1/4" dia., 100° Fl Crown Shear Hd	
22	3D0099-10-15	9	Pin - Rivet, Threaded, Ti, 10/32" dia., Protruding Head	
23	3D0099-10-18	101	Pin - Rivet, Threaded, Ti, 10/32" dia., Protruding Head	
24	3D0099-10-19	9	Pin - Rivet, Threaded, Ti, 10/32" dia., Protruding Head	
25	3D0099-10-21	9	Pin - Rivet, Threaded, Ti, 10/32" dia., Protruding Head	
26	3D0099-10-22	70	Pin - Rivet, Threaded, Ti, 10/32" dia., Protruding Head	
27	3D0099-10-32	40	Pin - Rivet, Threaded, Ti, 10/32" dia., Protruding Head	NAS6705U32
28	3D0099-10-7	18	Pin - Rivet, Threaded, Ti, 10/32" dia., Protruding Head	
29	3D0099-10-8	18	Pin - Rivet, Threaded, Ti, 10/32" dia., Protruding Head	
30	3D0099-12-11	18	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	
31	3D0099-12-16	106	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	NAS6706U16
32	3D0099-12-17	158	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	
33	3D0099-12-18	59	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	
34	3D0099-12-19	304	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	
35	3D0099-12-20	9	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	
36	3D0099-12-21	176	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	NAS6306U21
37	3D0099-12-22	9	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	
38	3D0099-12-23	26	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	
39	3D0099-12-26	13	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	NAS6706U26

Item No.	Part No. *	Qty.	Description	Substitute Part No.
40	3D0099-12-27	15	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	NAS6306U27
41	3D0099-12-29	9	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	NAS6706HU29
42	3D0099-12-8	18	Pin - Rivet, Threaded, Ti, 3/8" dia., Protruding Head	NAS6706HU8
43	3D0099-14-22	9	Pin - Rivet, Threaded, Ti, 7/16" dia., Protruding Head	
44	3D0099-14-23	5	Pin - Rivet, Threaded, Ti, 7/16" dia., Protruding Head	
45	3D0099-14-25	26	Pin - Rivet, Threaded, Ti, 7/16" dia., Protruding Head	NAS6307U25D
46	3D0099-6-6	53	Pin - Rivet, Threaded, Ti, 3/16" dia., Protruding Head	
47	3D0099-6-7	53	Pin - Rivet, Threaded, Ti, 3/16" dia., Protruding Head	
48	3D0099-6-8	26	Pin - Rivet, Threaded, Ti, 3/16" dia., Protruding Head	
49	3D0099-6-9	18	Pin - Rivet, Threaded, Ti, 3/16" dia., Protruding Head	WC199-6-9
50	3D0099-8-10	26	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	WC199-8-10
51	3D0099-8-11	211	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	WC199-8-11
52	3D0099-8-12	244	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	WC199-8-12
53	3D0099-8-13	44	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	
54	3D0099-8-14	40	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	
55	3D0099-8-15	141	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	
56	3D0099-8-16	48	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	
57	3D0099-8-17	150	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	HST528DL8-17
58	3D0099-8-18	22	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	WC199-8-18
59	3D0099-8-19	35	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	
60	3D0099-8-28	53	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	NAS6404U28
61	3D0099-8-31	5	Pin - Rivet, Threaded, 1/4" dia., Protruding Head	NAS6404U31

Item No.	Part No. *	Qty.	Description	Substitute Part No.
62	3D0099-8-32	5	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	NAS6404U32
63	3D0099-8-33	5	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	NAS6404U33
64	3D0099-8-6	35	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	WC199-8-6
65	3D0099-8-8	26	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	
66	3D0099-8-9	88	Pin - Rivet, Threaded, Ti, 1/4" dia., Protruding Head	WC199-8-9
67	44615K434	4	1/2" Nipple	
68	4513K293	1	3" Union	
69	4513K93	4	1/2" Union	
70	4D0012-4C	66	Washer	
71	4D0012-4P	66	Washer	
72	4D0012-8C	15	Washer	
73	4D0012-8P	15	Washer	
74	7733K319	1	3" Nipple	
75	92511A053	310	Spacer, 0.252" id x 0.9375" Long	
76	92620A703	12	3/8" Bolt 1.38 Long, Wire Feed Thru on Door	
77	98017A200	12	3/8" Washer - NAS1149C0663R	
78	BACN10JZ3B2CM	105	3/16" Nut Plate, Self Sealing	
79	BACN10JZ5B2CM	5	5/16" Nut Plate, Self Sealing	
80	MS21042L3	525	Nut, Self-locking, dry film lubricant, 3/16"	
81	MS21042L4	990	Nut, Self-locking, dry film lubricant, 1/4"	
82	MS21042L6	248	Nut, Self-locking, dry film lubricant, 3/8"	
83	NAS1080-08	313	Collar, Swage Locking, 1/4"	
84	NAS1080-10	365	Collar, Swage Locking, 5/16"	
85	NAS1149C0332R	590	3/16" ID x .032" thick washer	
86	NAS1149C0432R	1353	1/4" ID x .032" thick washer	
87	NAS1149C0532R	390	5/16" ID x .032" thick washer	
88	NAS1149C0632R	398	3/8" ID x .032" thick washer	
89	NAS1401-3C3	100	3/16" Fillet Washer	
90	NAS1401-4C3	300	1/4" Fillet Washer	
91	NAS1401-5C3	100	5/16" Fillet Washer	
92	NAS1401-6C3	100	3/8" Fillet Washer	
93	NAS1401-7C3	100	7/16" Fillet Washer	
94	NAS1401-8C3	100	1/2" Fillet Washer	
95	NAS1805-7L	11	Nut, Self-locking, CRES steel, Dry film lube, 7/16" diam.	
96	NAS1805-8L	115	Nut, Self-locking, CRES steel, Dry film lube, 1/2" diam.	

Item No.	Part No. *	Qty.	Description	Substitute Part No.
97	NAS6803U10	202	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/16" diam.,	
98	NAS6803U11	114	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/16" diam.,	
99	NAS6803U5	114	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/16" diam.	
100	NAS6803U6	106	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/16" diam.,	
101	NAS6803U7	141	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/16" diam.,	
102	NAS6803U8	26	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/16" diam.,	
103	NAS6803U9	35	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/16" diam.,	
104	NAS6804U10	9	Bolt, Hex Head, Close Tolerance, Unplated Ti, 1/4" diam.	
105	NAS6804U11	9	Bolt, Hex Head, Close Tolerance, Unplated Ti, 1/4" diam.,	
106	NAS6804U12	70	Bolt, Hex Head, Close Tolerance, Unplated Ti, 1/4" diam.,	
107	NAS6804U13	141	Bolt, Hex Head, Close Tolerance, Unplated Ti, 1/4" diam.,	
108	NAS6804U14	44	Bolt, Hex Head, Close Tolerance, Unplated Ti, 1/4" diam.,	
109	NAS6804U15	9	Bolt, Hex Head, Close Tolerance, Unplated Ti, 1/4" diam.,	
110	NAS6804U16	246	Bolt, Hex Head, Close Tolerance, Unplated Ti, 1/4" diam.,	
111	NAS6804U17	48	Bolt, Hex Head, Close Tolerance, Unplated Ti, 1/4" diam.,	
112	NAS6804U18	92	Bolt, Hex Head, Close Tolerance, Unplated Ti, 1/4" diam.,	
113	NAS6805U10	31	Bolt, Hex Head, Close Tolerance, Unplated Ti, 5/16" diam.,	
114	NAS6805U6	24	Bolt, Hex Head, Close Tolerance, Unplated Ti, 5/16" diam.	
115	NAS6805U8	79	Bolt, Hex Head, Close Tolerance, Unplated Ti, 5/16" diam.,	
116	NAS6805U9	90	Bolt, Hex Head, Close Tolerance, Unplated Ti, 5/16" diam.,	
117	NAS6806U13	97	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.	
118	NAS6806U20	79	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	

Item No.	Part No. *	Qty.	Description	Substitute Part No.
119	NAS6806U21	9	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
120	NAS6806U22	26	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
121	NAS6807U14	26	Bolt, Hex Head, Close Tolerance, Unplated Ti, 7/16" diam.	
122	NAS6808U11	5	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.	
123	NAS6808U12	70	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
124	NAS6808U13	31	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
125	NAS6808U14	26	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
126	NAS6808U15	48	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
127	NAS6808U16	31	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
128	NAS6808U17	31	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
129	NAS6808U18	9	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
130	NAS6808U19	31	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
131	NAS6808U20	26	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	NAS6308U20
132	NAS6808U21	123	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	NAS6708U21
133	NAS6808U22	75	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	NAS6408U22
134	NAS6808U23	114	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
135	NAS6808U24	157	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
136	NAS6808U25	123	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	NAS6808U25 NAS6308U25
137	NAS6808U26	108	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	NAS6308U26D
138	NAS6808U27	100	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
139	NAS6808U30	5	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
140	NAS6808U31	62	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	

Item No.	Part No. *	Qty.	Description	Substitute Part No.
141	NAS6808U32	5	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
142	NAS6808U33	136	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	NAS6408U33
143	NAS6808U37	173	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/8" diam.,	
144	NAS9308M-4-05	40	Rivet-Blind, 100° Flush Head, Monel-Cres, 1/4" dia., .251-.312" grip	
145	NAS9308M-4-06	40	Rivet-Blind, 100° Flush Head, Monel-Cres, 1/4" dia., .313-.375" grip	
146	NAS9308M-4-07	125	Rivet-Blind, 100° Flush Head, Monel-Cres, 1/4" dia., .376-.437" grip	
147	NAS9308M-4-08	70	Rivet-Blind, 100° Flush Head, Monel-Cres, 1/4" dia., .438-.500" grip	
148	NAS9308M-4-09	90	Rivet-Blind, 100° Flush Head, Monel-Cres, 1/4" dia., .501-.562" grip	
149	S124682-3E12-6	50	Fender Washer, CRES steel, .203" inner dia., .750" outer dia., .064" Th	
150	S124682-3E8-5	40	Fender Washer, CRES steel, .203" inner dia., .500" outer dia., .051" Th	
151	S124682-4E14-9	20	Fender Washer, CRES steel, .265" inner dia., .875" outer dia., .091" Th	
152	S124682-4E16-9	10	Fender Washer, CRES steel, .265" inner dia., 1.0" outer dia., .091" Th	
153	S124682-5E14-9	20	Fender Washer, CRES steel, .328" inner dia., .875" outer dia., .091" Th	
154	S4932869-08-04	112	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
155	S4932869-08-05	123	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
156	S4932869-08-06	212	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
157	S4932869-08-07	348	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
158	S4932869-08-08	937	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
159	S4932869-08-09	588	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
160	S4932869-08-10	889	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
161	S4932869-08-11	1138	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
162	S4932869-08-12	826	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	

Item No.	Part No. *	Qty.	Description	Substitute Part No.
163	S4932869-08-13	554	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
164	S4932869-08-14	332	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
165	S4932869-08-15	722	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
166	S4932869-08-16	526	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
167	S4932869-08-17	53	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
168	S4932869-08-18	24	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
169	S4932869-08-19	114	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
170	S4932869-08-21	22	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
171	S4932869-08-28	53	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
172	S4932869-08-29	313	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
173	S4932869-08-30	713	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	NAS6804U30
174	S4932869-08-31	216	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
175	S4932869-08-32	44	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	
176	S4932869-08-33	31	Pin-Rivet, Grooved-P-Type, Ti, 1/4" dia., Crown Protruding Hd	3D0010-8-33
177	S4932869-10-09	235	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
178	S4932869-10-10	235	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
179	S4932869-10-11	418	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
180	S4932869-10-12	353	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
181	S4932869-10-13	216	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
182	S4932869-10-14	251	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
183	S4932869-10-15	106	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	NAS6705U15
184	S4932869-10-16	132	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	

Item No.	Part No. *	Qty.	Description	Substitute Part No.
185	S4932869-10-17	136	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
186	S4932869-10-18	35	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
187	S4932869-10-19	40	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
188	S4932869-10-20	31	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
189	S4932869-10-23	5	Pin-Rivet, Grooved-P-Type, Ti, 5/16" dia., Crown Protruding Hd	
190	S4932869-12-10	9	Pin-Rivet, Grooved-P-Type, Ti, 3/8" dia., Crown Protruding Hd	
191	S4932869-12-11	5	Pin-Rivet, Grooved-P-Type, Ti, 3/8" dia., Crown Protruding Hd	
192	S4932869-12-13	18	Pin-Rivet, Grooved-P-Type, Ti, 3/8" dia., Crown Protruding Hd	
193	S4932869-12-14	22	Pin-Rivet, Grooved-P-Type, Ti, 3/8" dia., Crown Protruding Hd	
194	S4932869-12-16	48	Pin-Rivet, Grooved-P-Type, Ti, 3/8" dia., Crown Protruding Hd	NAS6706U16
195	S4932869-12-18	57	Pin-Rivet, Grooved-P-Type, Ti, 3/8" dia., Crown Protruding Hd	NAS6306U18
196	S4932869-12-19	57	Pin-Rivet, Grooved-P-Type, Ti, 3/8" dia., Crown Protruding Hd	NAS6406U19
197	S4932869-12-20	145	Pin-Rivet, Grooved-P-Type, Ti, 3/8" dia., Crown Protruding Hd	
198	S4932869-12-22	51	Pin-Rivet, Grooved-P-Type, Ti, 3/8" dia., Crown Protruding Hd	
199	S4932869-12-23	51	Pin-Rivet, Grooved-P-Type, Ti, 3/8" dia., Crown Protruding Hd	NAS6406U23D
200	3D0099-6-5	9	Pin - Rivet, Threaded, Ti, 3/16" dia., Protruding Head	
201	3D0099-12-14	5	Pin - Rivet, Threaded, Ti, 3/8" dia.,	
202	NAS6807U15	26	Bolt, Hex Head, Close Tolerance, Unplated Ti, 7/16" diam.	
203	NAS1474R3	160	Sealing Nutplate	
204	MS20426M3-4	310	Monel Rivet	
205	92620A703	20	3/8" Bolt 1.38 Long, Wire Feed Thru on Door	
206	91030A430	20	3/8" Nut	
207	11255A13	16	Handle	
208	91771A196	100	8-32 CSK Screw	
209	4513K425	4	1/2" Pipe Plug - Used for testing only	

Item No.	Part No. *	Qty.	Description	Substitute Part No.
210	3D0099-6-10	9	Pin - Rivet, Threaded, Ti, 3/16" dia., Protruding Head	
211	3D0099-6-12	9	Pin - Rivet, Threaded, Ti, 3/16" dia., Protruding Head	
212	3D0099-6-14	5	Pin - Rivet, Threaded, Ti, 3/16" dia., Protruding Head	
213	3D0099-10-23	14	Pin - Rivet, Threaded, Ti, 10/32" dia., Protruding Head	
214	3D0099-10-24	14	Pin - Rivet, Threaded, Ti, 10/32" dia., Protruding Head	
215	3D0031-4-15	9	Bolt	
216	3D0031-4-16	9	Bolt	3D0108H4-16
217	3D0031-4-21	5	Bolt	
218	3D0031-5-15	10	Bolt	
219	3D0031-5-17	5	Bolt	3D0073-5-17
220	3D0031-5-18	5	Bolt	
221	3D0031-5-19	9	Bolt	
222	3D0031-6-25	22	Bolt	
223	NAS6804U19	31	Bolt, Hex Head, Close Tolerance, Unplated Ti, 1/4" diam.,	
224	4D0012-5P	30	Washer	
225	4D0012-5C	30	Washer	
226	4D0012-6P	22	Washer	
227	4D0012-6C	22	Washer	
228	3D0042-4	16	Nut	
229	3D0042-5	30	Nut	
230	3D0042-6	24	Nut	
231	NAS6403U6	135	Bolt, Hex Head, Close Tolerance, Unplated Ti, 3/16" diam.,	

* Fastener part numbers may be substituted with an equivalent part number based on fastener availability

Figure 113. Fastener Cage at the Multi-Bay Box Assembly Site

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01- 01 - 2014

2. REPORT TYPE
Contractor Report

3. DATES COVERED *(From - To)*
July 2013 - December 2013

4. TITLE AND SUBTITLE
PRSEUS Panel Fabrication Final Report

5a. CONTRACT NUMBER
NNL13AA11C

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Linton, Kim A.; Velicki, Alexander; Hoffman, Krishna; Thrash, Patrick; Pickell, Robert; Turley, Robert

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
699959.02.22.07.01.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, Virginia 23681

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/CR-2014-218149

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 39
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES
Langley Technical Monitor: Dawn C. Jegley

14. ABSTRACT
NASA and the Boeing Company have been working together under the Environmentally Responsible Aviation Project to develop stitched unitized structure for reduced weight, reduced fuel burn and reduced pollutants in the next generation of commercial aircraft. The structural concept being evaluated is PRSEUS (Pultruded Rod Stitched Efficient Unitized Structure). In the PRSEUS concept, dry carbon fabric, pultruded carbon rods, and foam are stitched together into large preforms. Then these preforms are infused wiht an epoxy resin into large panels in an out-of-autoclave process. These panels have stiffeners in the length-wise and width-wise directions but contain no fasteners because all stiffeners are stitched to the panel skin. This document contains a description of the fabrication of panels for use in the 30-foot-long Multi-Bay Box test article to be evaluated at NASA LaRC.

15. SUBJECT TERMS
CAPRI; Composites; Graphite-Epoxy; Out-of-Autoclave Processing; PRSEUS; Pultruded Rod; Stitching

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	99	(443) 757-5802