Contract No.: DE-EE0005780

Final Technical Report

ENERGY EFFICIENT THERMOPLASTIC COMPOSITE MANUFACTURING

TECHNICAL CONTACT: MARC MATSEN
THE BOEING COMPANY, ENGINEERING, TEST & TECHNOLOGY
P.O. BOX 3707, M/S 4K-263
SEATTLE, WA 98124-2207
(206) 544-7579; E-MAIL: MARC.R.MATSEN@BOEING.COM

BUSINESS CONTACT: NANCY CWIKLOWSKI
THE BOEING COMPANY, ENGINEERING, TEST & TECHNOLOGY
325 JAMES S MCDONNELL BLVD., M/S S102-2067
HAZELWOOD, MO 63042-2513
(314) 451-6407: E-MAIL: NANCY.J.CWIKLOWSKI@BOEING.COM

DOE PROJECT OFFICER: DEBBIE SCHULTHEIS
(240) 562-1811, E-MAIL: DEBBIE.SCHULTHEIS@EE.DOE.GOV

RECIPIENT ORGANIZATION: THE BOEING COMPANY
PARTNERS: CYTEC ENGINEERED MATERIALS
(COST SHARING PARTNER), AJAXTOCCO (COST SHARING PARTNER),
TEMPER, INC (COST SHARING PARTNER)

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EXECUTIVE SUMMARY

The objective of the project was to establish an effective and affordable method to lay-up and consolidate/join large thermoplastic composite aerospace structure with cycle times measured in minutes rather than hours. Composite airplane designs have proven efficient and effective however future potential product production rates are challenging what the current systems can efficiently produce due to material lay-down constraints and extended thermal cycle times. The ability to lay-up then rapidly heat, consolidate, and cool large complex composite structures plus very accurately tool them (i.e. matching CTE of composite materials) along with very precise thermal control is a difficult challenge. Current systems such as autoclave processing of thermoset materials require long cycle times due to method of heating and the large associated thermal masses. These extended cycle times inhibit the ability to meet higher rate production scenarios due to the need for multiple sets of equipment and tools. Thermoplastic composite materials were used to facilitate more rapid cycle times via the elimination of a need for a cure dwell at temperature. Also, utilized induction heating along with smart susceptors to enable the quick cycle times needed while providing precise intrinsic thermal control. Furthermore, lay-up of thermoset resin based composite requires significant facilities and introduces process flow restrictions at rate.

The intrinsic control of the induction heating process via the smart susceptors along with the use of laser assisted fiber placement were the key innovations areas developed. The ability to rapidly heat and then precisely control the temperature of the consolidation component was paramount to the success of this project. It is this unique processing attribute coupled with the thermoplastic material characteristics along with rapid lay-up methods that are novel and advantageous. While many requirements and influencing factors decide the materials and processes utilized for future airplane construction, the forecast of accelerated production rates and the recent performance successes of composites in airplane construction provide an opportunity for this processing technology to have significant influence.

When successfully developed, this technology would enable affordable and efficient high rate production of large composite aerospace structure. This technology has the potential to assist in de-risking the establishment of high rate composite structures fabrication capability thru rate insensitivity. Lay-up rate and consolidation cycle time along with quality of the components will be key metrics. This technology is projected to provide over 75% energy savings above standard autoclave processing. The economic advantage is lower risk implementation of affordable and efficient high rate production of large composite aerospace structure by providing significantly lower infra-structure and tooling costs.

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Glossary

Prepreg: Ready to process unidirectional fiber, typically impregnated with resin.

Preform: A pre-shaped composite lay-up formed to the desired shape before being cured or consolidated.

Curie point: The temperature at which a magnetic material becomes nonmagnetic.

Smart Susceptor: The surfaces of the induction consolidation tool composed of thin ferromagnetic material which is heated via induction coils with the susceptor controlling the temperature by the intrinsic properties of the alloy. This intrinsic property is the change from the magnetic to non-magnetic state at the Curie point. Once one section of the ferromagnetic material is heated to the Curie point and becomes nonmagnetic it automatically becomes the less preferred path for the magnetic flux to reside. This automatically directs heating to the cooler areas of the material that is still ferromagnetic. The process continues until all of the susceptor is at the Curie point.

1. INTRODUCTION AND BACKGROUND

This project was focused in the area of energy efficient consolidation of large integrated thermoplastic composite structures for aerospace applications. In the next 20 years, more than 38,000 airplanes will need to be delivered to meet the growing population and travel demands [1]. As airplane production rates increase, the production rates for metals and composite structures must similarly increase. The demand for composite materials has continued to grow as many industries are replacing metals with composites. The aerospace industry is a leader in this shift of materials, due to airlines needing to cut the cost curve by reducing airplane weight and drag to increase fuel efficiency. Unfortunately, rates for manufacturing composite structures are not maintaining pace with the increasing production demands. These inefficiencies are becoming more apparent as airplane production rates increase and more floor space and autoclaves are required. Thus, a need to improve these manufacturing methods has emerged as aircraft manufacturers add more composite materials to their airplane structures. There is an opportunity in the aerospace industry to save energy, time, and money by enabling this increased use of composite structures in aircraft design through the utilization of inductively consolidated thermoplastic composite structures.

1.1 Objective

The objective of this project was to demonstrate and document the energy efficiency plus the technical and economic viability of induction consolidation and joining of full-scale integrated thermoplastic composite structures for aerospace application. This was accomplished thru the development of fabrication systems and processes along with the subsequent fabrication of a scale-up component. During the course of this project a scale-up thermoplastic composite component was successfully fabricated and therefore validated the capability to enable high production rates for commercial airplane fabrication when using the subject induction consolidation method.

1.2 Approach

The plan for Budget Period #1 was to first choose and design a full-scale component with which to demonstrate the technology. In parallel with this component selection and design effort risk reduction and process stabilization efforts consisting of analysis, experimentation, and testing was conducted to reduce the project's risk and provide information for the initial program review gates. Once the component selection was completed initial design of the tooling and fabrication equipment for this component was conducted. After sufficient data was available from these risk reduction and process stabilization efforts the fabrication of the scale-up tooling and consolidation equipment commenced. These efforts along with initial energy and economic assessments were the main focus of Budget Period #1.

In Budget Period #2 the effort focused on the design and fabrication of the needed tools and equipment to demonstrate the scale-up of induction consolidation and joining process for large scale aerospace components. Key activities such as fabrication of the consolidation restraint, needed tools, installation of the required power supply, along with the integration of the processing system were conducted during this budget period.

The effort during budget period #3 focused on the fabrication of the scale-up component. The successful fabrication of this component along with the documentation of the energy savings and business advantages demonstrated the value of this technology. These completed activities have significantly reduced the risks and enhanced the capability of this material and processing method combination to reach commercialization. The results of this project are documented here in this final technical report submitted to the Department of Energy.

The project activities fall into 7 main categories as outlined below:

Selection of Scale-Up Part Design:

Task 1 Boeing will select a demonstration scale-up part design that best suit the goals and resources of the project

Concept Feasibility and Validation:

Task 2 (BP#1) This task will provide initial validation of both the induction consolidation and joining methods before scale-up tools and equipment are established.

Task 7 (BP#2 continuation of Task 2): Joining of complex contour stiffeners to skin – Complex contour stiffeners and skins will fabricated and joined skins to form a medium sized (~2 feet by ~4 feet) panel.

Establish Scale-Up Fabrication Capability:

Task 3 This task lays the groundwork for the establishment of the processing equipment capable of laying-up the required pre-forms plus induction consolidating and joining for the scale-up demonstration component

Task 8 This task contain milestones for establishing the restraint system (Task 8.1), the ½" tape laser assisted fiber placement machine (Task 8.2), the induction power supply (Task 8.3) and the integration of the consolidation system (Task 8.4).

Tooling Design and Fabrication:

Task 4 This task contains the design and fabrication effort for the tools required for risk reduction and initial scale-tooling designs.

Task 9 This task completes the final design and fabrication of the tools needed for scale-up component selected

Task 13 This task contains the consolidation system (tool/restraint/power-supply) try-out effort

Demo Component Fabrication and Test

Task 10 This task focuses on preparing for making the needed lay-ups for the large demonstration components.

Task 14.1 This task contains the scale-up skin lay-up effort

Task 14.2 This task focuses on the consolidation of the scale-up component

Task 14.3 This task contains the inspection of the finished components

Energy/Commercial Viability Documentation

Task 5, Task 11, and Task 15 Existing process energy usage and cost information will be compared to the information generated during the demonstration component fabrication effort to determine the energy and money saved

Coordination and Reporting

Task 6, 12, and Task 16 Project management will include monthly virtual team meetings to go thru current status and also discuss the next steps needed as they relate to the project milestones as previously outlined. These meetings will be used to outline risk mitigation actions as technical issues arise.

2. PROGRESS

Progress associated with each of these project categories is outlined in the subsequent portions of this report. Figure 1 below show progress to date in Gantt chart form.

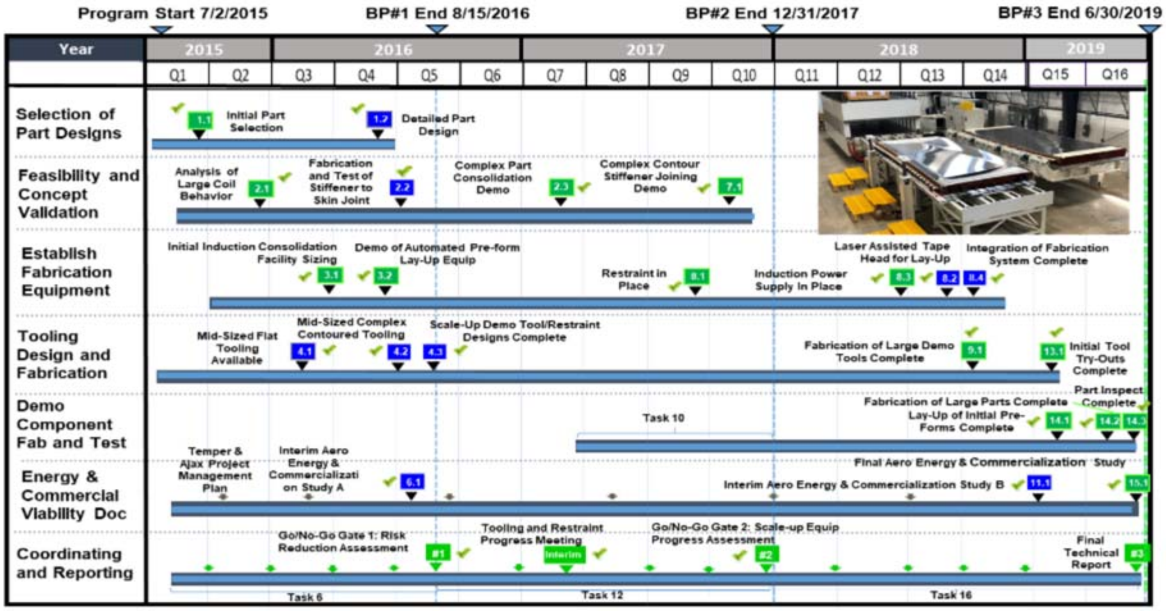


Figure 1. Project Gantt chart showing current status as of June 2019

2.1 Part Selection

The selection of the demonstration component set in motion much of the remaining portions of the project. A section of a lower wing skin was selected as large scale component to be fabricated (see figure 2 below). This is a notional design that covers the standard features in a current composite wing design. The size of the wing would be representative of a potential high rate composite airplane. The wing structure represents the largest portion of the future use of composites and therefore provides the largest potential energy and cost savings. This design has been finalized thereby allowing the tooling and processing system to be sized.

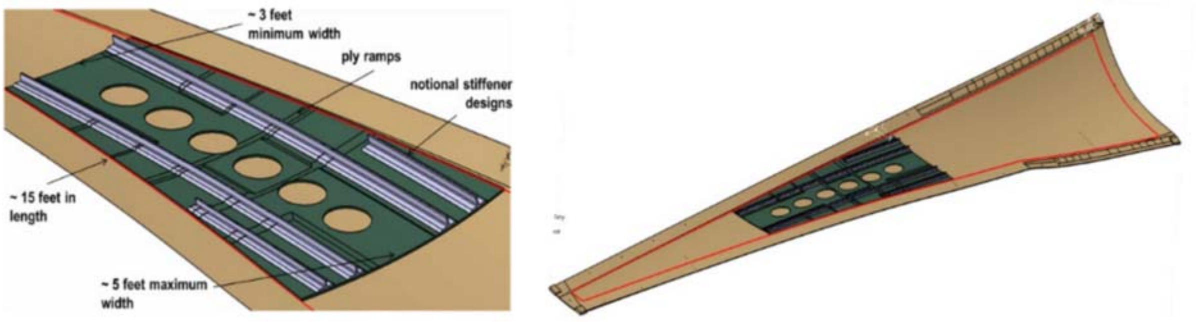


Figure 2. Selected demonstration component consisting of a section of a notional high rate production lower wing skin

2.2 Risk Reduction and Process Stabilization

2.2.1 Risk Reduction

One of the key risk reduction actions was the analysis of the large induction coils and the interaction with the smart susceptors to provide the heat-up rate and control needed to meet the goals of the project. Coupled electromagnetic and thermal models of the large coils and tools needed were conducted by AjaxTOCCO. This model includes the magnetic behavior of the HyMu80 smart susceptor utilized as the smart susceptor. Good thermal uniformity was shown over the 5' by 15' part and with a rapid heat up of 20 minutes for the skin of the large panel as seen in figure 3 below. Also, as can been seen in figure 3 only a small portion of the tooling is heated and furthermore the water flowing through the coils assists in cooling of the tool and also the part during cool down.

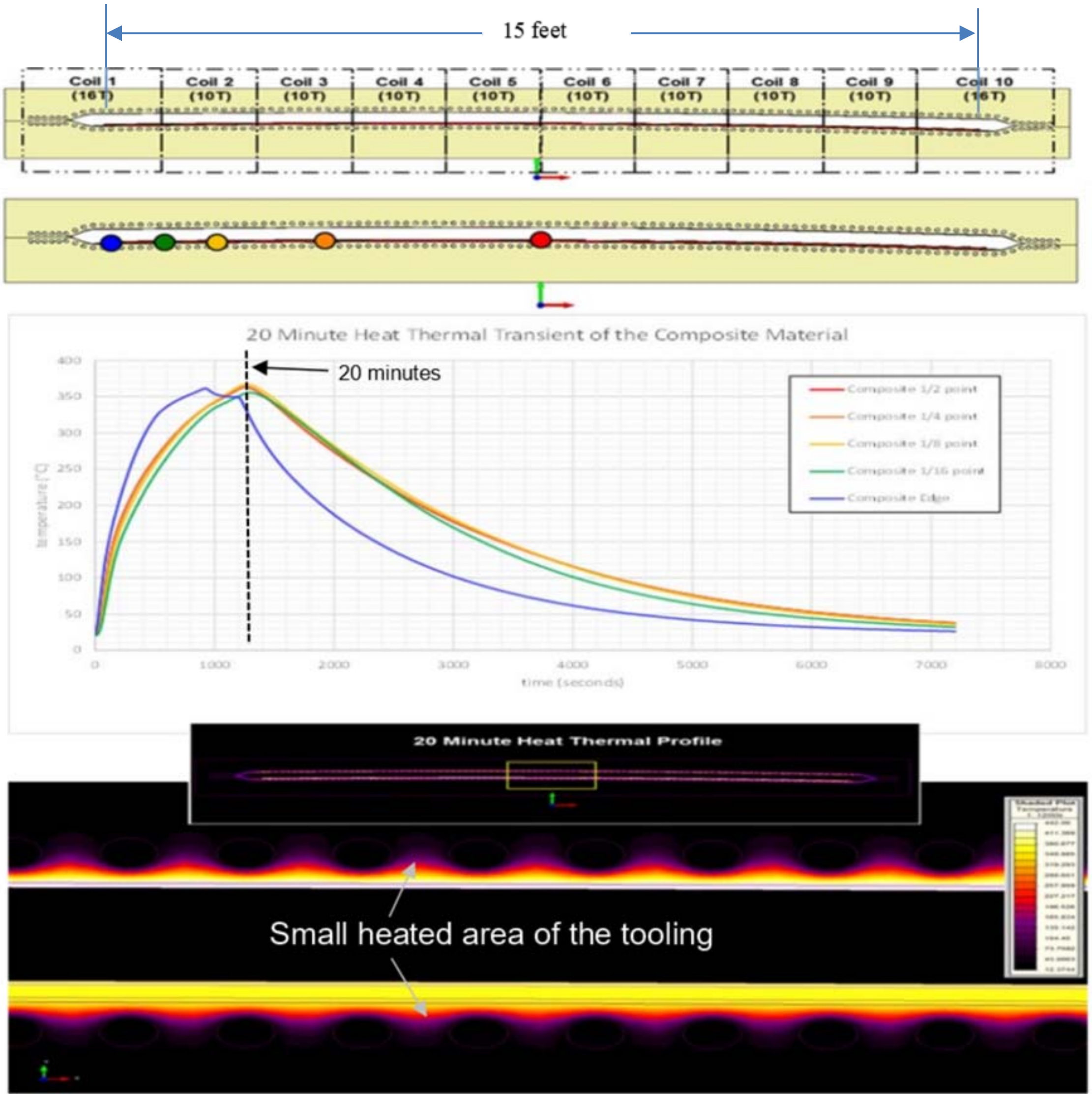


Figure 3. Depiction of coil design and associated thermal response of the part and the tool

2.2.2 Process Stabilization

2.2.2.1 Induction Consolidation and Co-Consolidation

Demonstrating the ability to consolidate/co-consolidate components is an important portion of this project. To provide the proven processing parameters a blade stiffened flat panel is designed (see figure 4). The skin and stiffeners are of similar thickness as those seen in the large demonstration component. To accomplish the desired consolidation the tooling shown in figure 5 was designed. The skin and stiffeners are placed in the tool with the mandrel inserts and a formed aluminum bladder is utilized to provide consolidation pressure (see figure 6).

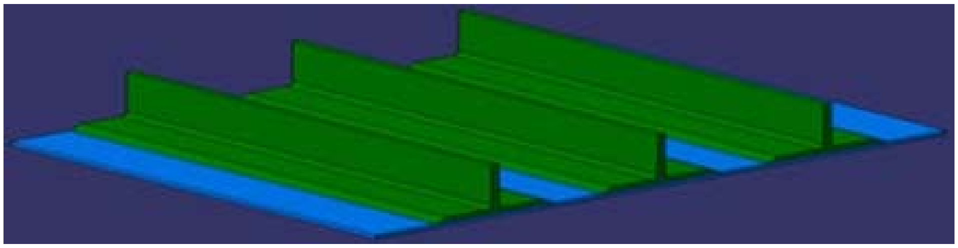


Figure 4. 12” by 24” blade stiffened flat panel typically of wing structure designs

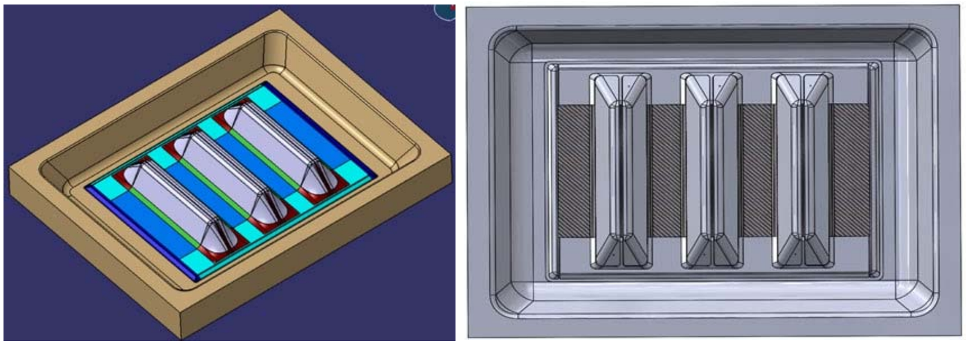


Figure 5. Tooling design for induction co-consolidation of flat blade stiffened panels

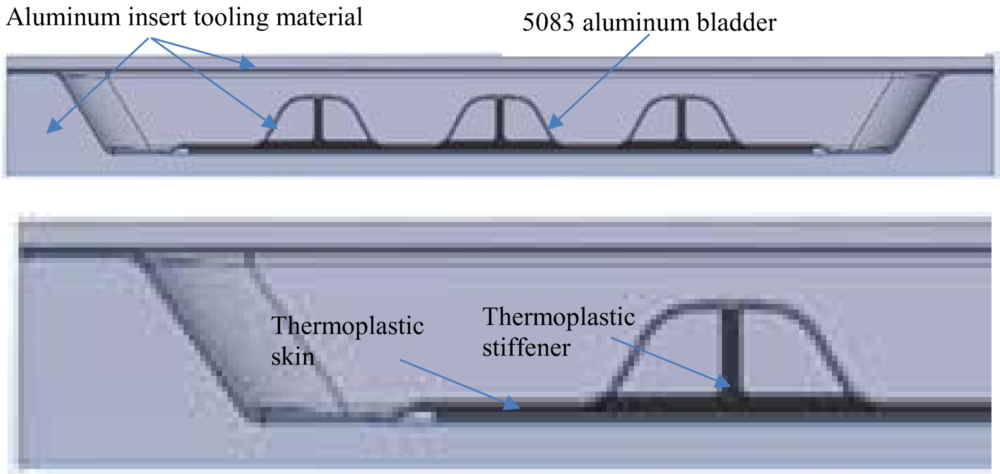


Figure 6. Cross-section of co-consolidation tooling for blade stiffened flat panels

The forming of the aluminum bladder that provides the pneumatic pressure for consolidation is performed via high temperature forming of 5083 aluminum. Two sheet of .080” thick 5083 aluminum were welded around the perimeter with a gas inlet on one side of the bladder. In addition, a mold to form the bladder was machined from 6061 aluminum (see figure 7). An Alloy 49 susceptor was used instead of the HyMu80 alloy used for forming the aluminum bladder. This Alloy 49 smart susceptor levels at approximately 834F. This temperature enhances the forming of the 5083 material and therefore provides the elongation needed to form the bladder (see figure 8).

Figure 7. Forming tool for the flat blade stiffened panel aluminum consolidation bladder

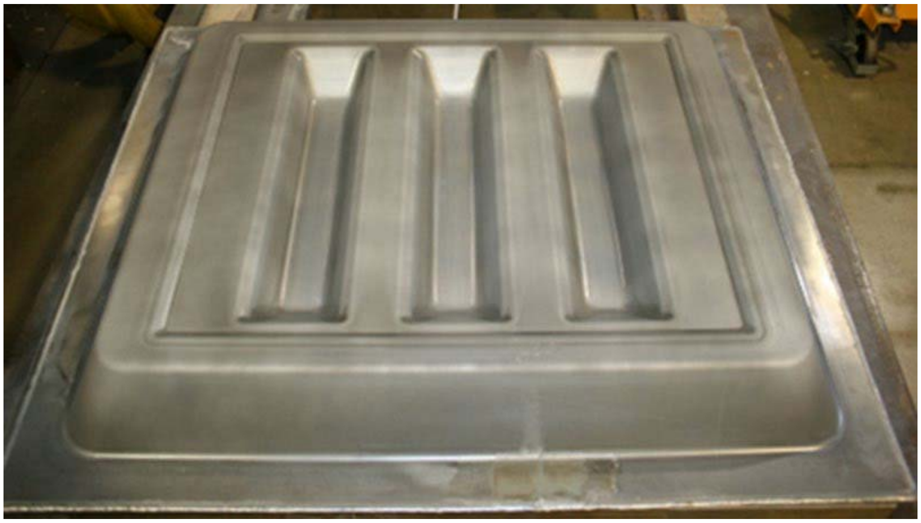


Figure 8. Formed aluminum consolidation bladder for the flat blade stiffened panels

Also, tools were fabricate per the tool designs to perform the co-consolidation of the thermoplastic blade stiffened flat panel (see figure 9). Figures 10, 11, and 12 show the subsequent loading sequence for the thermoplastic elements that make up the panel. These straight constant gauge elements were fabricated using continuous compression molding. This was done to expedite the delivery of these items. The aluminum tooling inserts, aluminum bladder, and thermoplastic elements assembly with smart susceptor surrounding it was loaded into the tool as shown in figure 13. The induction co-consolidation processing cycle was then performed. The result was the component as shown in figure 14. These panels showed acceptable co-consolidation.

Figure 9. Machined aluminum co-consolidation tooling

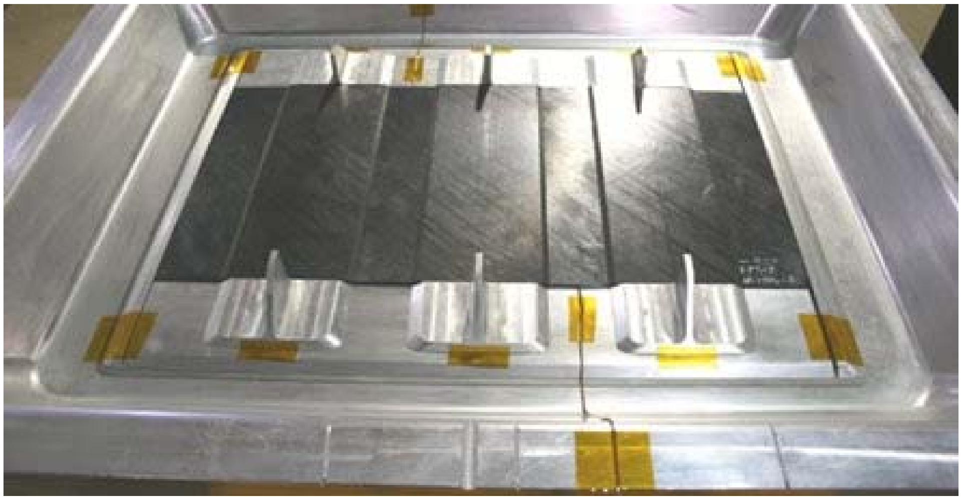


Figure 10. Aluminum insert with thermoplastic skin and blade base charges in place

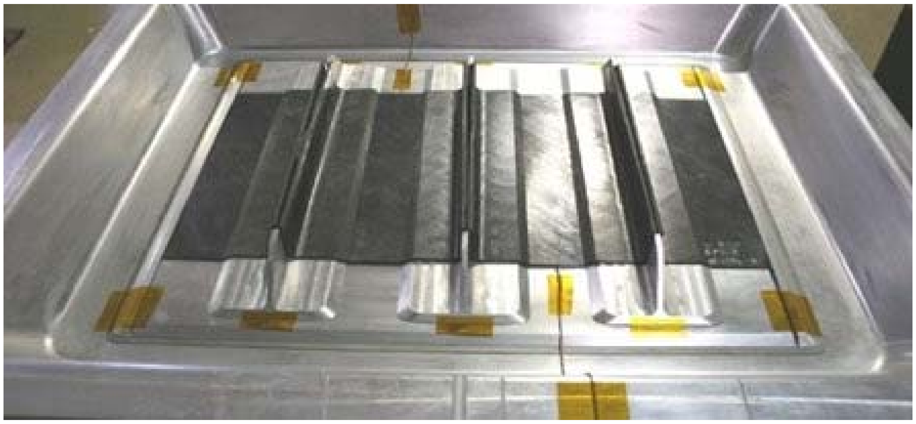


Figure 11. Blade elements are set into position

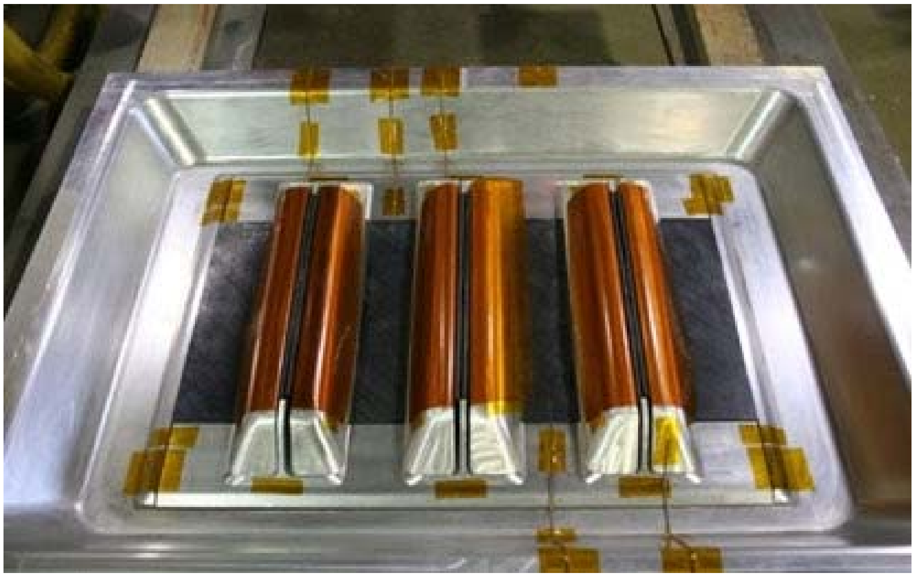


Figure 12. Aluminum stringer mandrels are now set in place

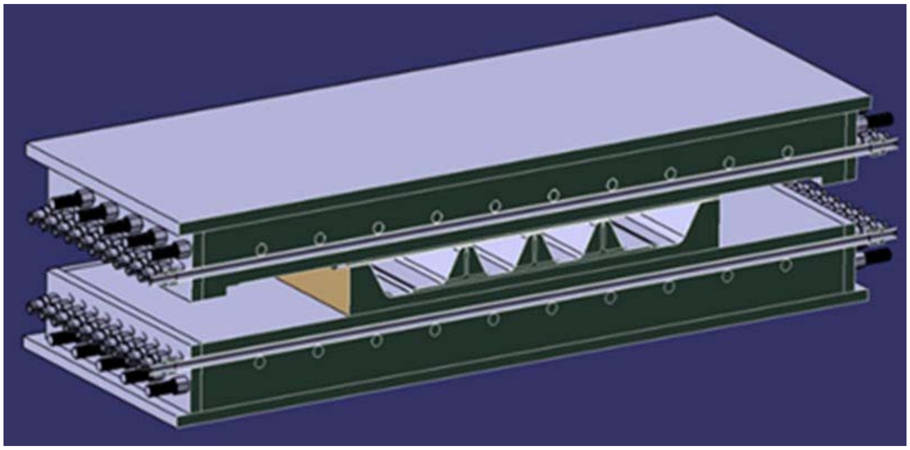


Figure 13. The tool stack-up is loaded into the flat ceramic tooling

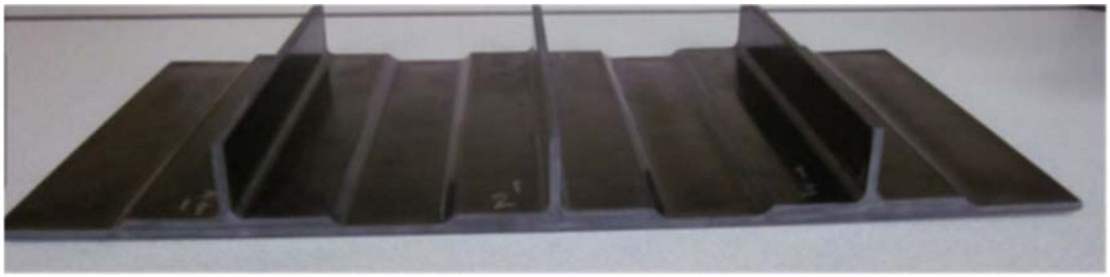


Figure 14. Resulting co-consolidated thermoplastic blade stiffened components

In addition, consolidation of a complex contoured skin panel has been accomplished. The associate tooling and processing system are shown in figures 15 and 16. This panel is 64 plies thick at its thickest and contains numerous ply drops and add areas and a significantly complex contour. The aluminum bladders (see figure 17) has the ability to handle the subtleties of typical composite component design as shown in by the consolidated panel shown in figure 18. The panels showed good quality both from a consolidation and dimensional control perspective (see figure 19). This same complex contoured panel design is also being co-consolidated with blade stiffeners. The part design and associated tooling are shown in figure 20. The formed aluminum bladder used for this co-consolidation effort is shown in figure 21. The processing set-up for the co-consolidated blade stiffened panel is shown in figure 22. Figure 23 shows the finished co-consolidated component.

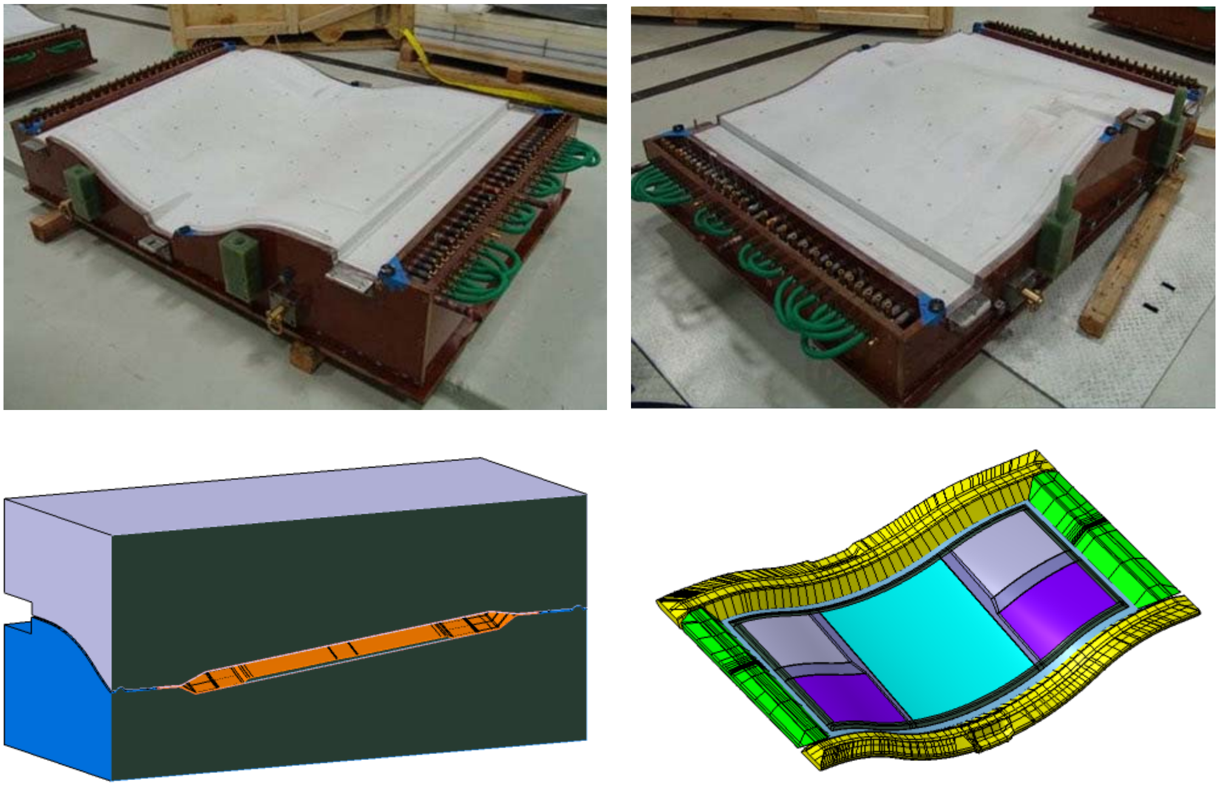


Figure 15. Tooling is being prepared for induction consolidation of complex contoured thermoplastic skin

Figure 16. Induction consolidation processing system set-up for part fabrication cycle

Figure 17. Formed aluminum bladder for induction consolidation of complex contoured thermoplastic skin

Figure 18. Formed aluminum bladder for induction consolidation of complex contoured thermoplastic skin

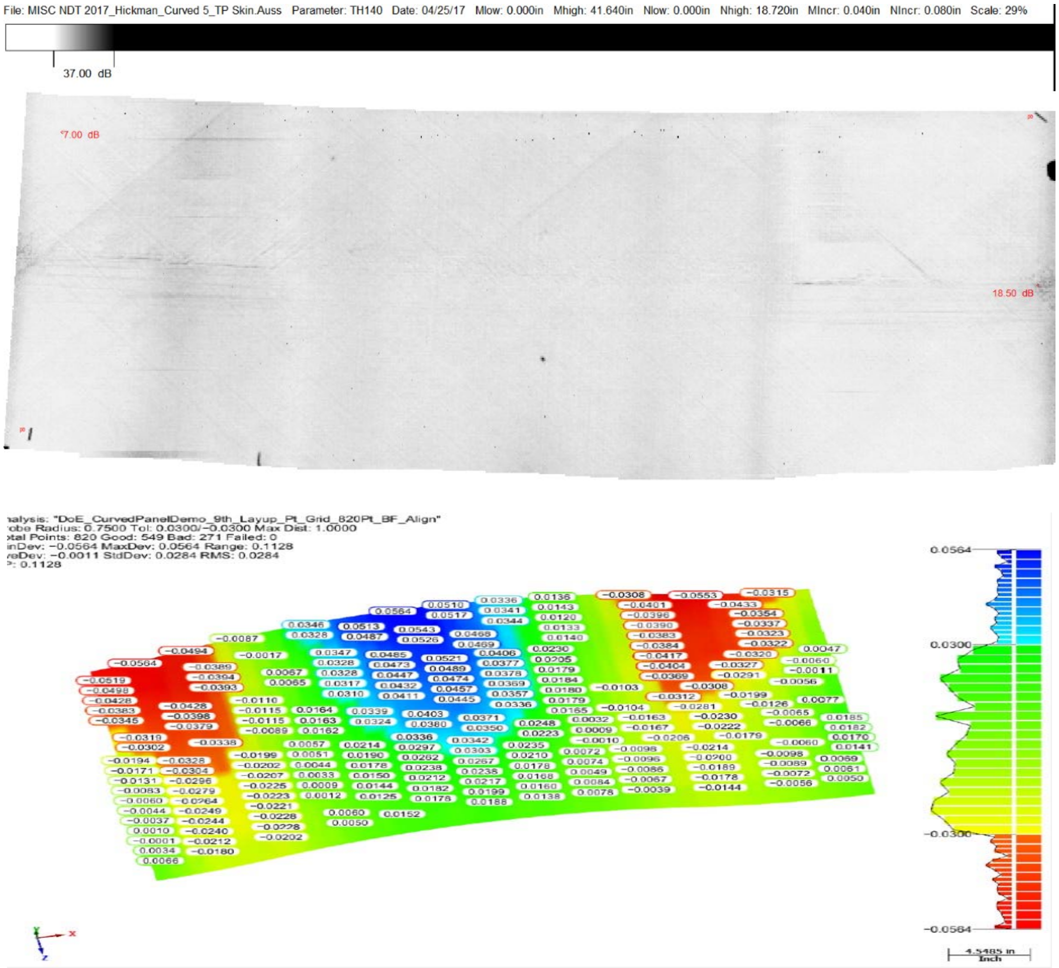
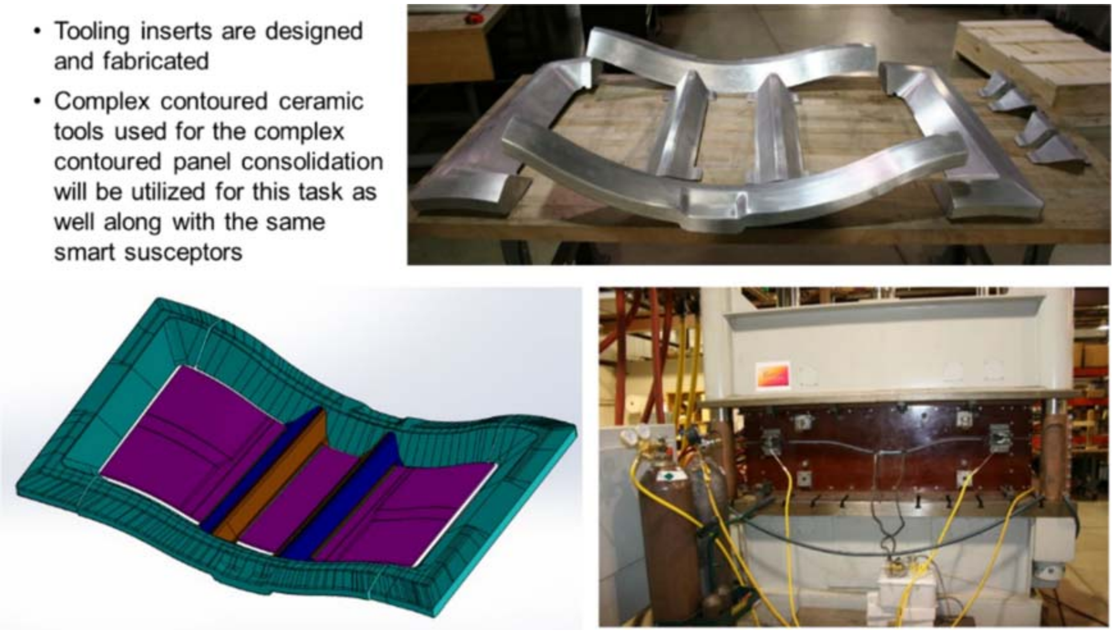


Figure 19. Consolidated complex panel void content and dimensional inspection results



- Tooling inserts are designed and fabricated
- Complex contoured ceramic tools used for the complex contoured panel consolidation will be utilized for this task as well along with the same smart susceptors

Figure 20. Tooling and resistance welded aluminum bladders are ready to begin the forming of the bladder and subsequent stiffener to panel co-consolidation

Figure 21. Formed aluminum bladder is now ready for co-consolidation of the stringers to the complex contour panel

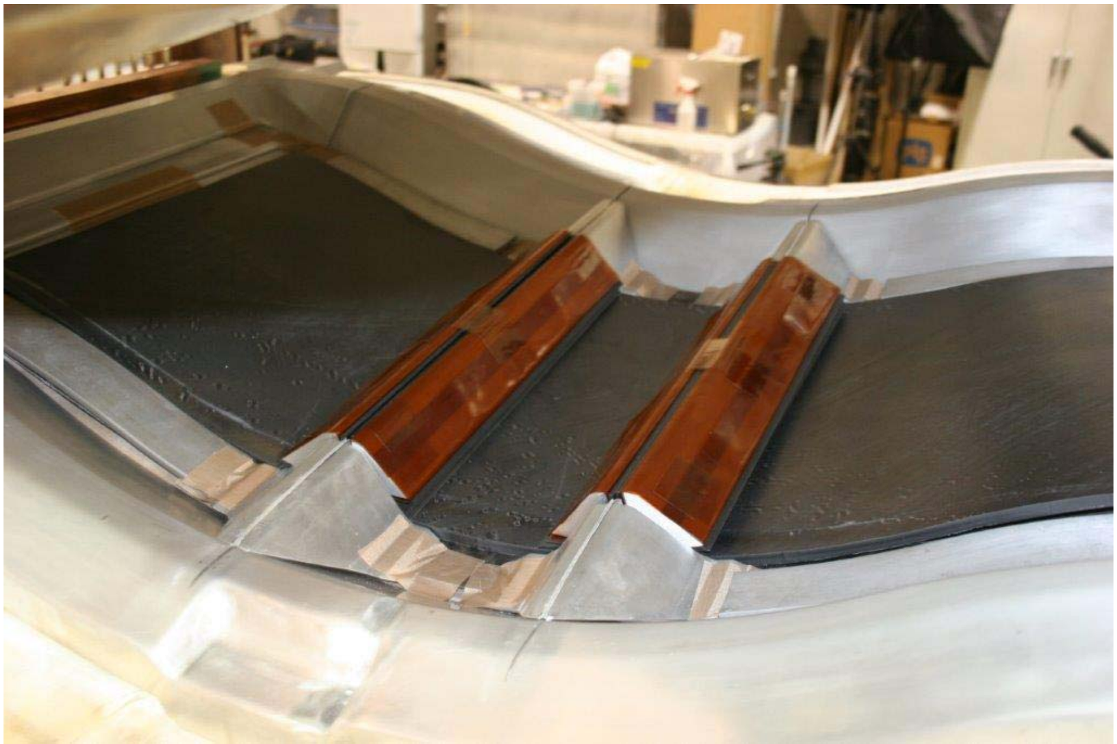


Figure 22. Set-up for the co-consolidation of the stiffened panels

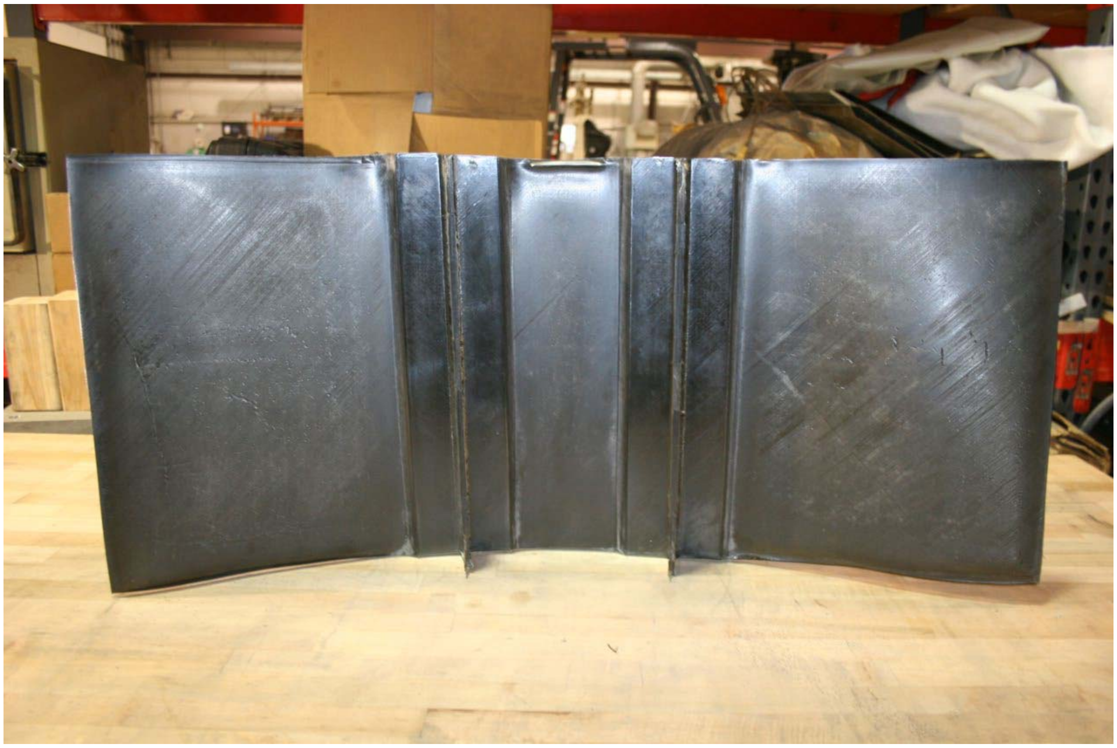


Figure 23. Finished co-consolidated blade stiffened complex curvature component

2.2.2.2 Laser Assisted Fiber Placement

Laser assisted fiber placement is a key capability for the success of the project. Standard thermosetting resin systems have inherent tack to the slit pre-preg tape. This tack is used when using automated lay-up techniques to hold the material in place. Thermoplastic resins are inherently dry and boardy and do not exhibit tack. This project is using the combination of the melt characteristics of the thermoplastic resin activated by precisely controlled heat from a laser to provide the needed tack for lay-up. Figure 24 shows the laser installed on a standard fiber placement robot head used for automated fiber placement. The laser is aimed at the point where the nip roller impinges on the ply and lay-up thus melting the tape material and the lay-up surface simultaneously. It is the precise control and compact forms now available for these lasers that now enable them to be used for this purpose. As the fiber placement head traverses a weld that holds the material in place is created. Another modification made was the improvement of the tape dispenser to accommodate the springier thermoplastic tape. These modifications are shown in figure 25. Also, improvements to the nip roller were accomplished to remove damage by impingement of the roller this enables the precise cuts and adds shown in figure 26. The laser assisted fiber placement system was used to lay-up skins for the flat panel. The 48 ply lay-up sequencing for the skins of the flat panel is depicted in figure 27. An example of the subsequent robot courses for the flat panel is shown in figure 28 and a 45 degree ply being applied on the flat skin lay-up is shown in figure 29. In addition, this system is being used to lay-up the complex contoured skin panel shown in figure 30. This panel has adds and cuts in the middle of the panel in addition to the complex curvature of the panel. Figures 31, 32, and 33 show the progress made on this complex contour lay-up task.

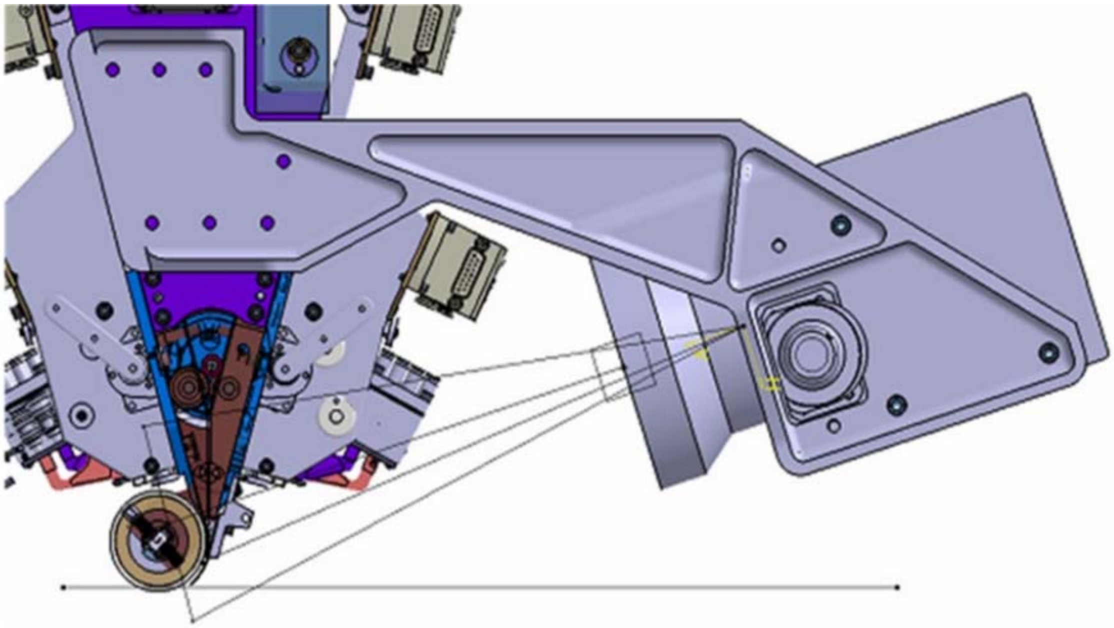


Figure 24. Depiction of the laser mounted to the standard fiber placement head

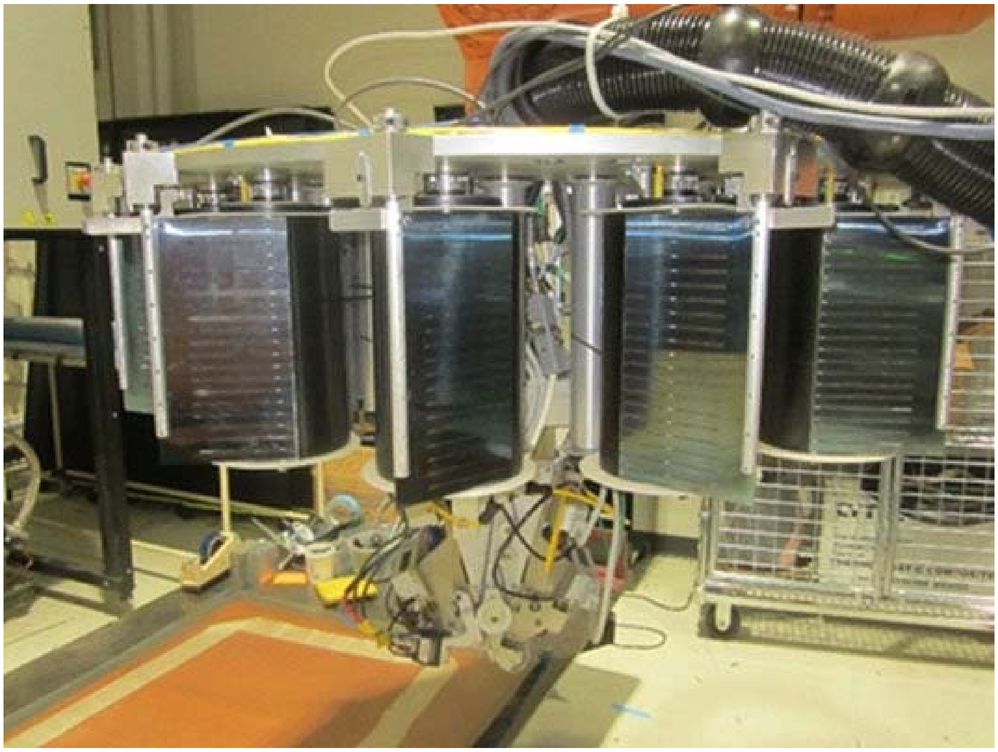


Figure 25. Picture of improved slit tape dispensers

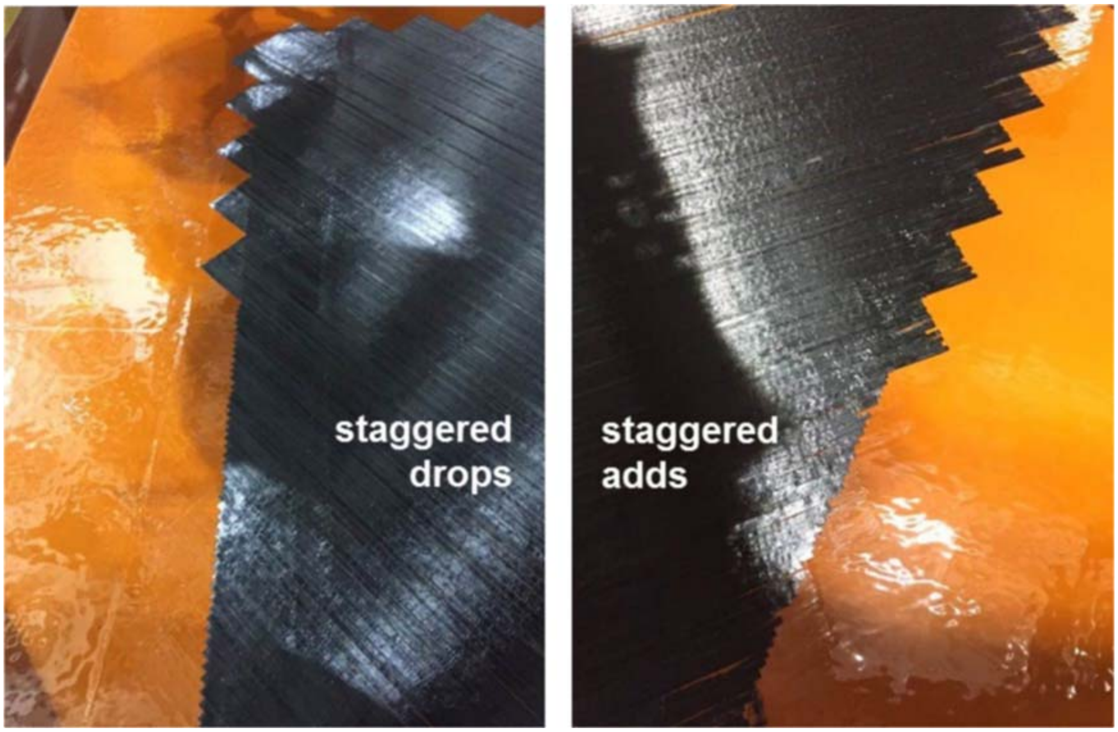
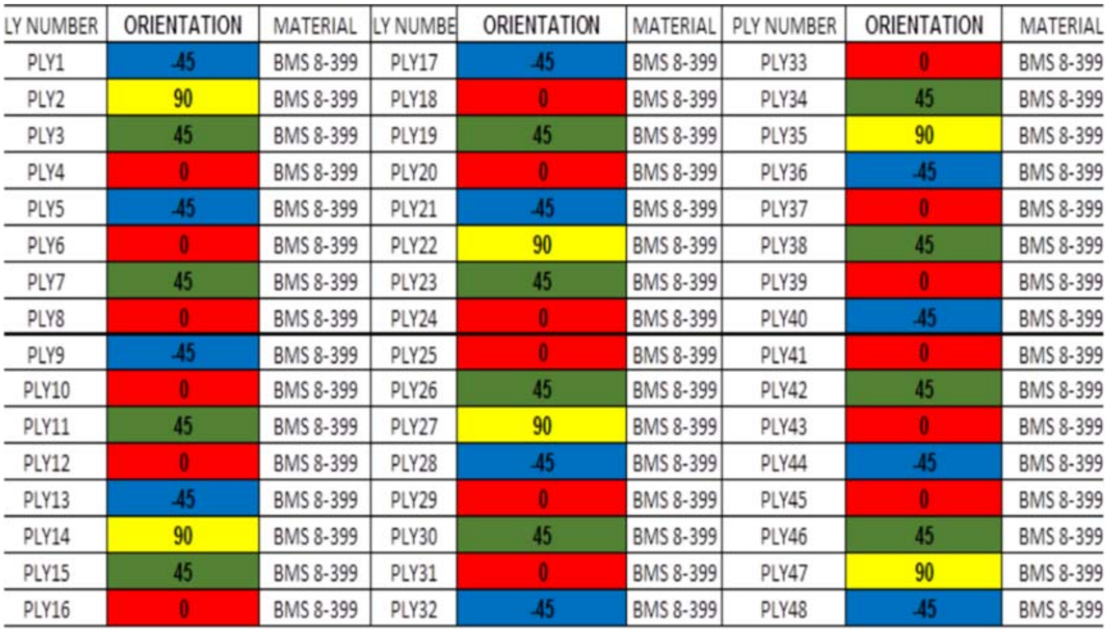


Figure 26. Examples of staggered adds and drops need for tailored lay-ups



LY NUMBER	ORIENTATION	MATERIAL	LY NUMBE	ORIENTATION	MATERIAL	PLY NUMBER	ORIENTATION	MATERIAL
PLY1	-45	BMS 8-399	PLY17	-45	BMS 8-399	PLY33	0	BMS 8-399
PLY2	90	BMS 8-399	PLY18	0	BMS 8-399	PLY34	45	BMS 8-399
PLY3	45	BMS 8-399	PLY19	45	BMS 8-399	PLY35	90	BMS 8-399
PLY4	0	BMS 8-399	PLY20	0	BMS 8-399	PLY36	-45	BMS 8-399
PLY5	-45	BMS 8-399	PLY21	-45	BMS 8-399	PLY37	0	BMS 8-399
PLY6	0	BMS 8-399	PLY22	90	BMS 8-399	PLY38	45	BMS 8-399
PLY7	45	BMS 8-399	PLY23	45	BMS 8-399	PLY39	0	BMS 8-399
PLY8	0	BMS 8-399	PLY24	0	BMS 8-399	PLY40	-45	BMS 8-399
PLY9	-45	BMS 8-399	PLY25	0	BMS 8-399	PLY41	0	BMS 8-399
PLY10	0	BMS 8-399	PLY26	45	BMS 8-399	PLY42	45	BMS 8-399
PLY11	45	BMS 8-399	PLY27	90	BMS 8-399	PLY43	0	BMS 8-399
PLY12	0	BMS 8-399	PLY28	-45	BMS 8-399	PLY44	-45	BMS 8-399
PLY13	-45	BMS 8-399	PLY29	0	BMS 8-399	PLY45	0	BMS 8-399
PLY14	90	BMS 8-399	PLY30	45	BMS 8-399	PLY46	45	BMS 8-399
PLY15	45	BMS 8-399	PLY31	0	BMS 8-399	PLY47	90	BMS 8-399
PLY16	0	BMS 8-399	PLY32	-45	BMS 8-399	PLY48	-45	BMS 8-399

Figure 27. 24” by 12” quasi isotropic skin panel design (48 plies thick)

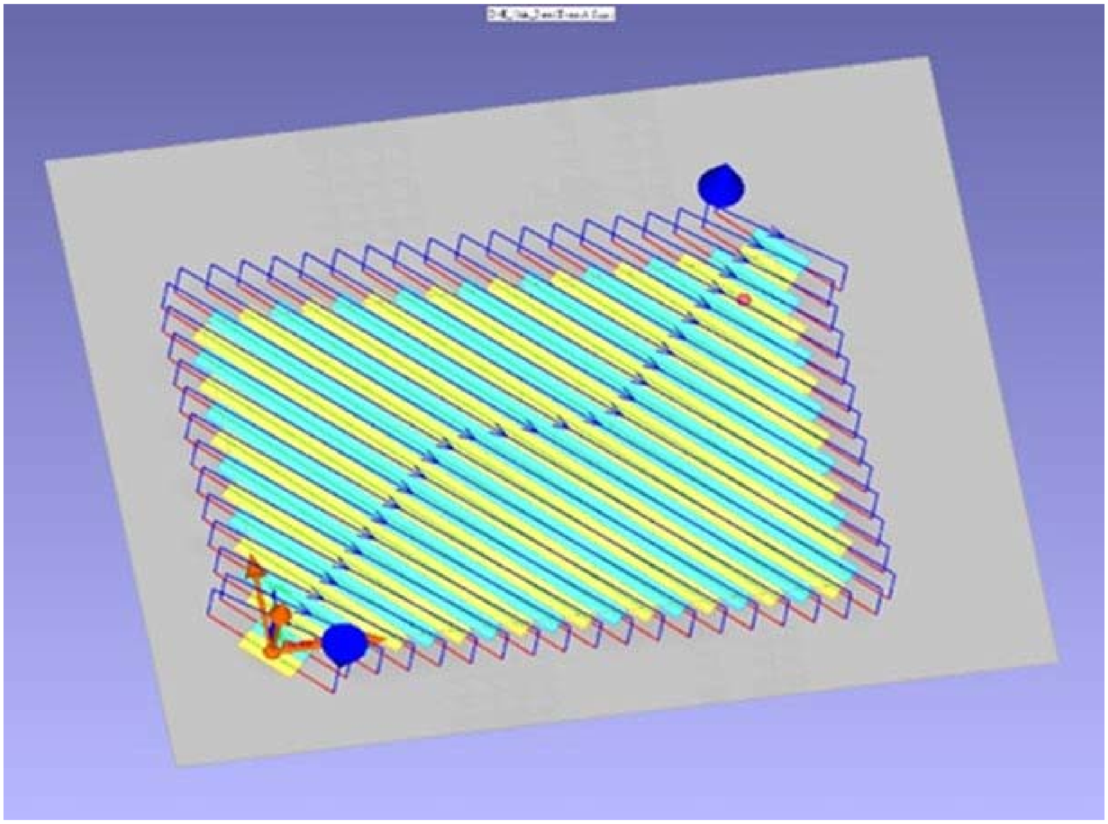


Figure 28. Depiction of a robot coarse for a 45 degree coarse on the flat skin panel

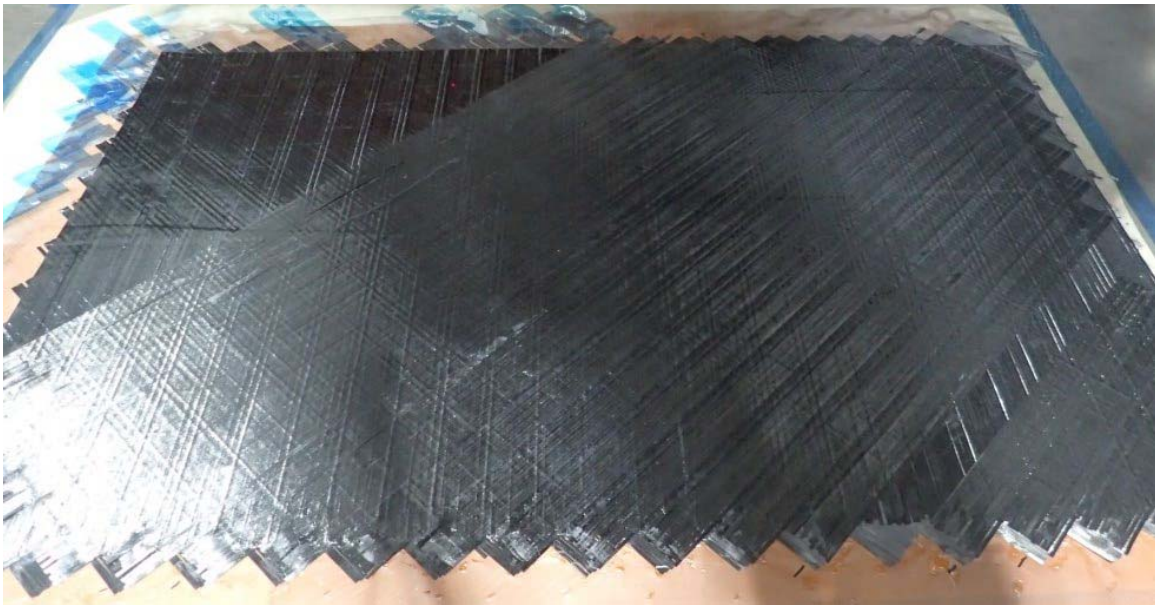


Figure 29. Picture of the flat panel skin lay-up depicting a 45 degree ply

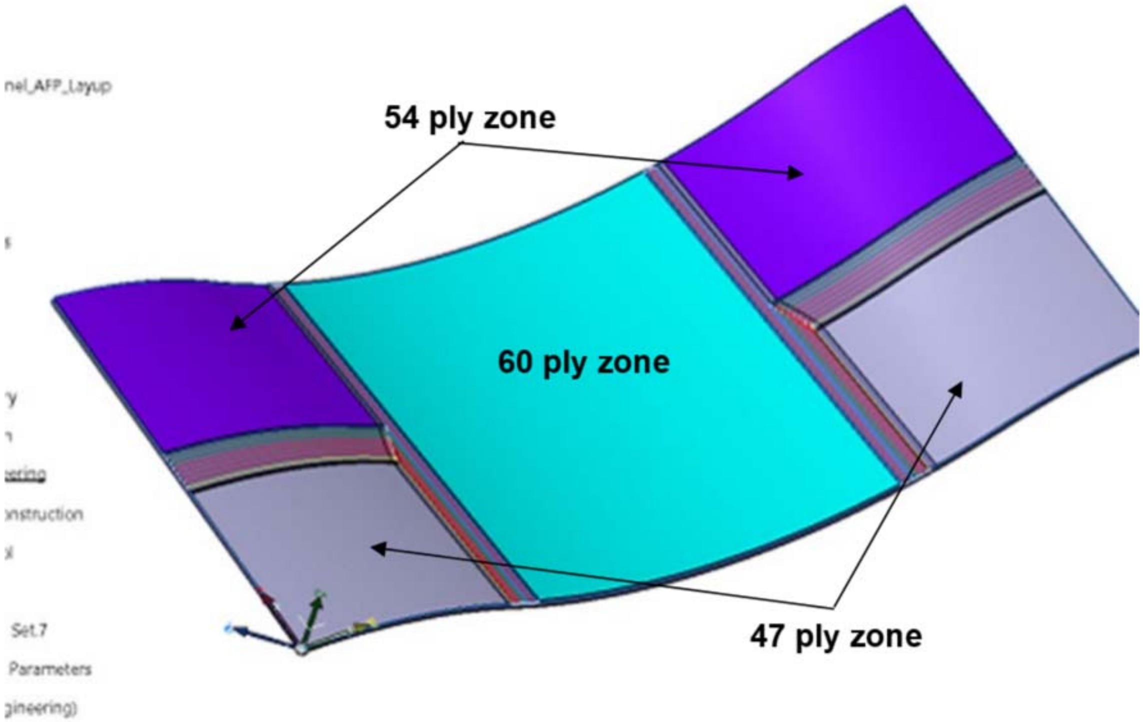


Figure 30. Complex contour lay-up with pad-ups (60 plys)

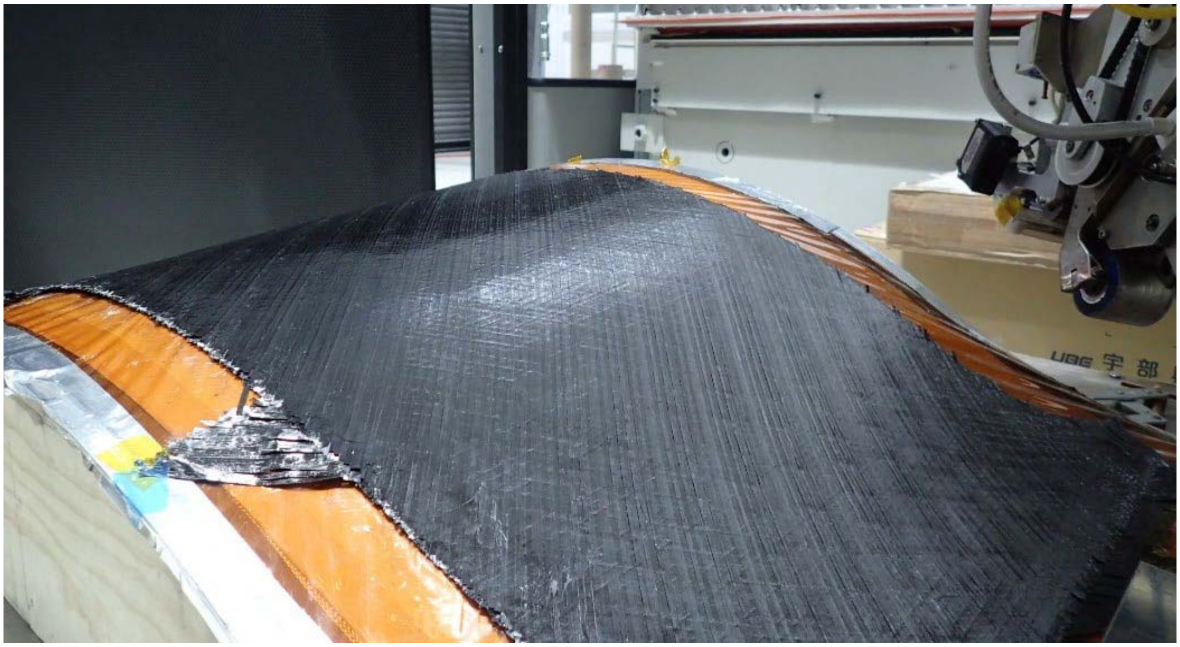


Figure 31. Ply 4 of the complex contour panel lay-up

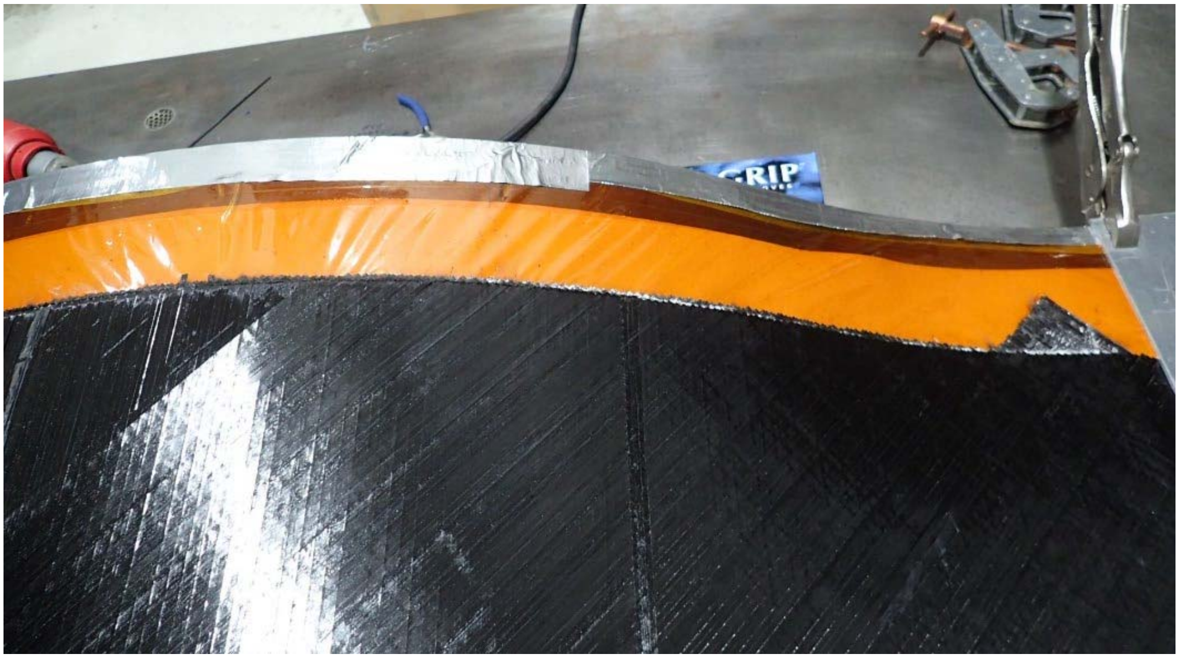


Figure 32. Ply 12 of the complex contour panel lay-up

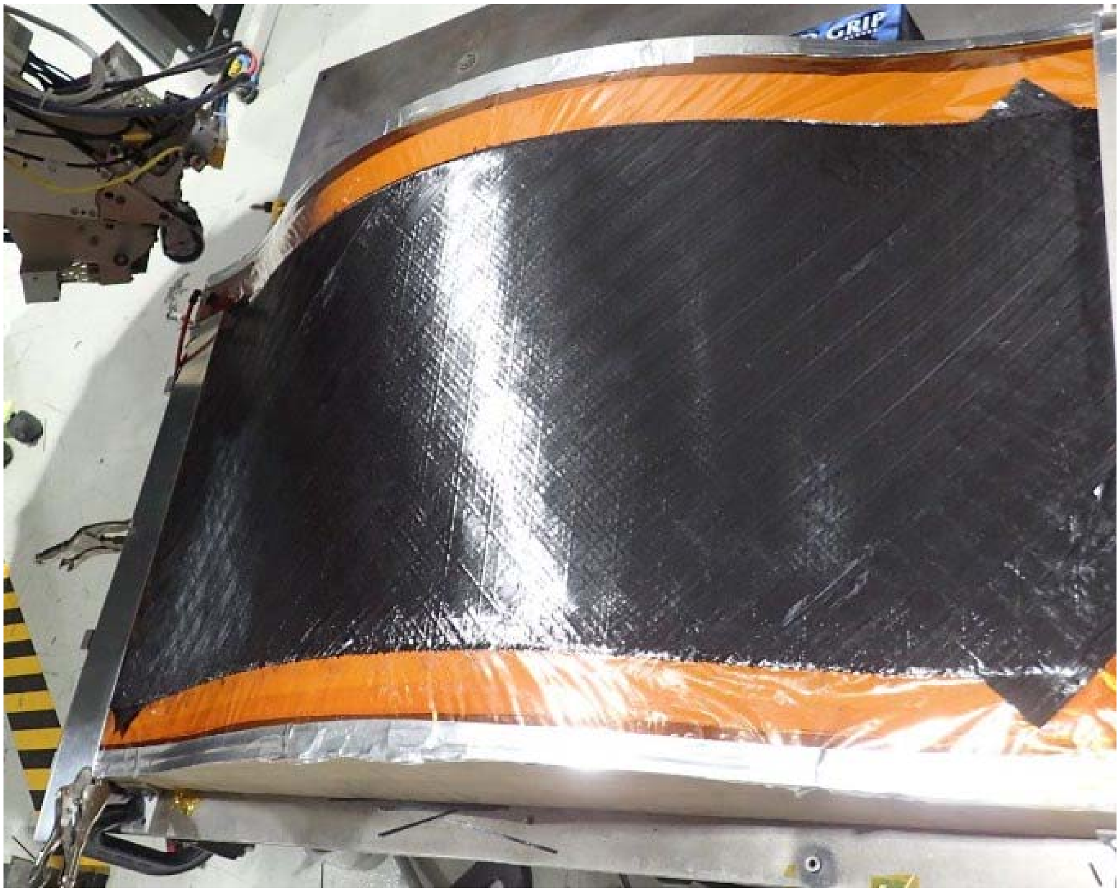


Figure 33. Ply 24 of the complex contour panel lay-up

2.3 Induction Consolidation and Lay-up Systems Scale-Up

2.3.1 Induction Consolidation Restraint and Tooling Handling Fixture

The following figures (figures 34, 35, 36, and 37) depict the processing system and tooling designs that have been developed to fabricate this component. This system has been sized to accommodate the 5’ by 15’ part and also handle up to 300 psi of consolidation force in the aluminum consolidation bladder. With this system the tool slides in between the top and bottom platens. When the process is complete the tool is slid out of the “restraint” and can be unloaded. The aluminum consolidation bladder is located in the tool cavity between the tool halves and applies the consolidation force as shown previously in the development efforts. A significant amount of analysis was conducted to ensure that the cast ceramic tooling and the restraint system was adequately sized to meet the processing needs. Figures 38, 39, and 40 show the results of the analysis. These figure show that the ceramic tool with compressive load applied by the fiberglass rods is capable of resisting the internal pressure and maintain a compressive load state during processing. Also, the restraint design is well under any critical stress states for the materials used in its construction. Figures 41 through 45 show various stages of fabrication and assembly of the restraint system. Figures 46 and 47 show the completed restraint and tool handling fixture.

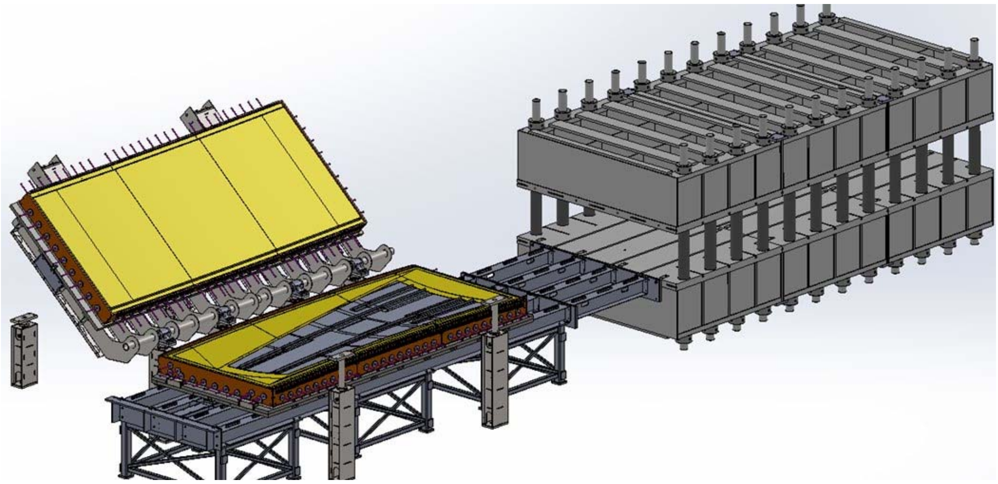


Figure 34. Depiction of the consolidation system including the restraint and the tool flipping and loading mechanism.

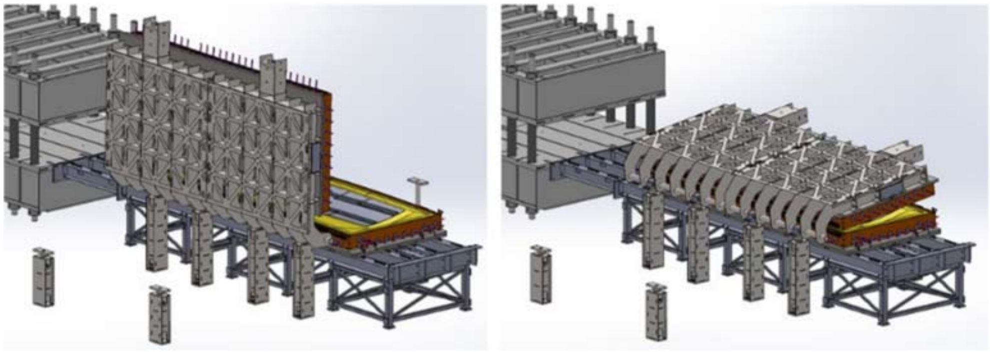


Figure 35. Depiction of the tool flipping system for part load and unload. Crane (not shown) is used to activate the flipping system.

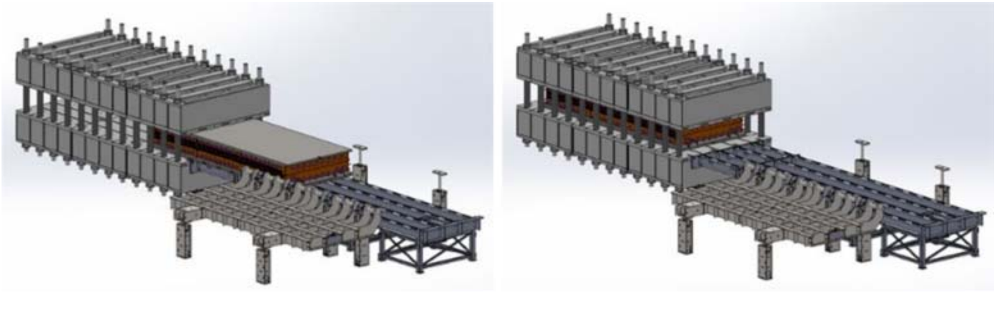


Figure 36. Depiction of tool load system. The required wench system for pulling the tool in and out to the restraint is not shown.

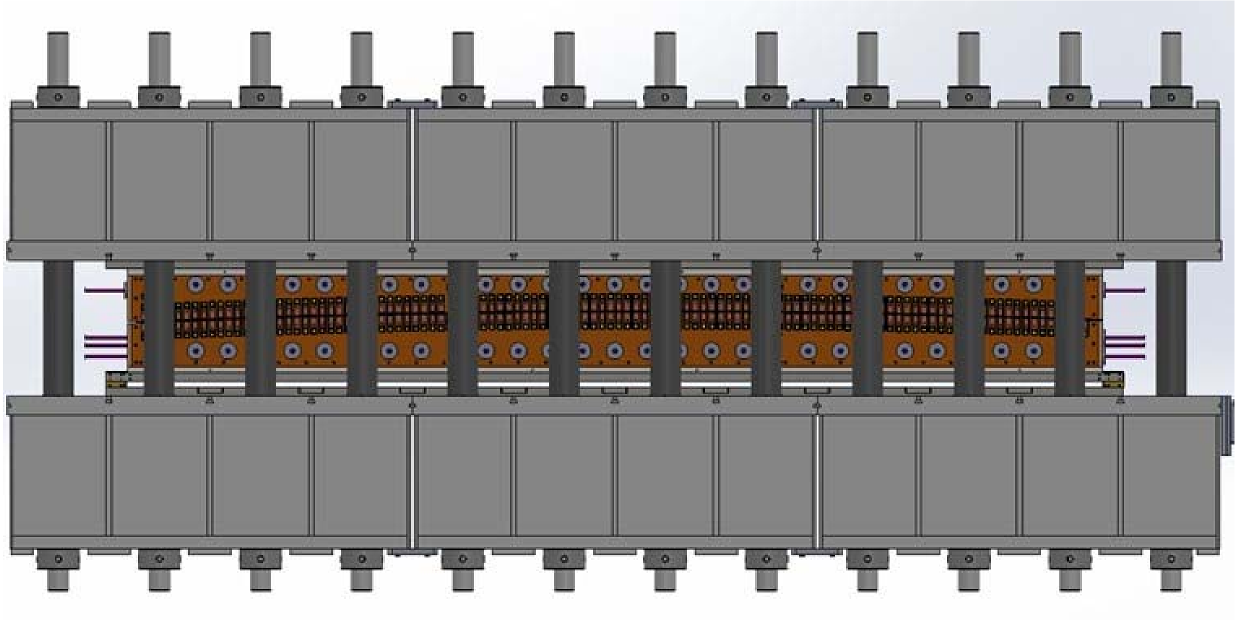


Figure 37. Side view of the finalized induction consolidation restraint device design.

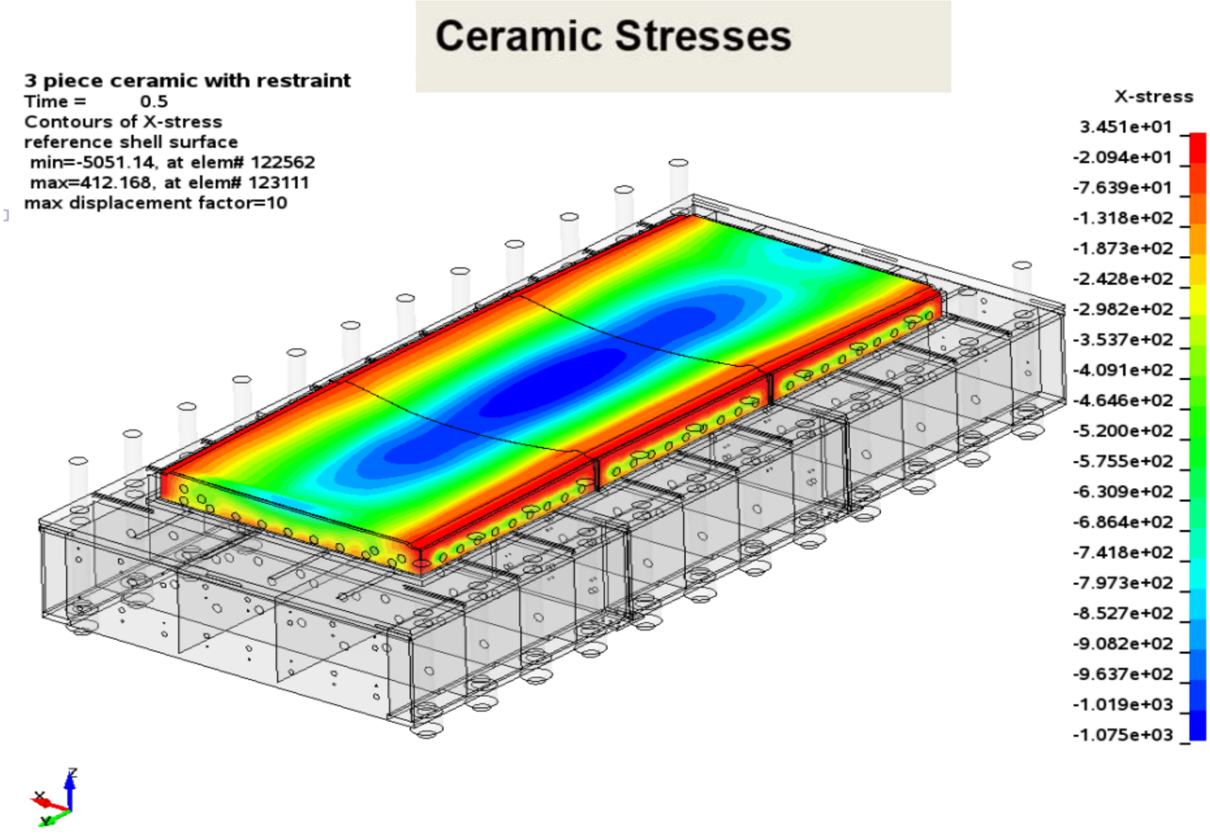


Figure 38. This image shows the stresses developed in the ceramic tooling at 300psi in the aluminum consolidation bladder

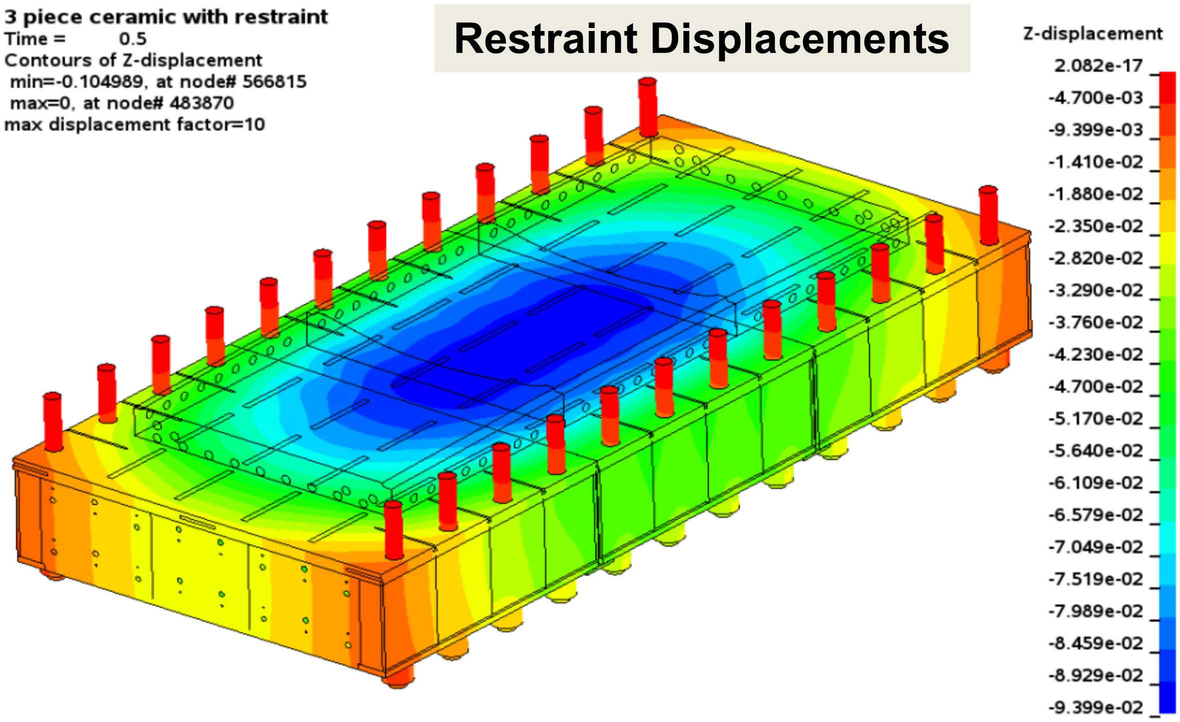


Figure 39. Depiction of overall tool displacement at 300 spi consolidation pressure

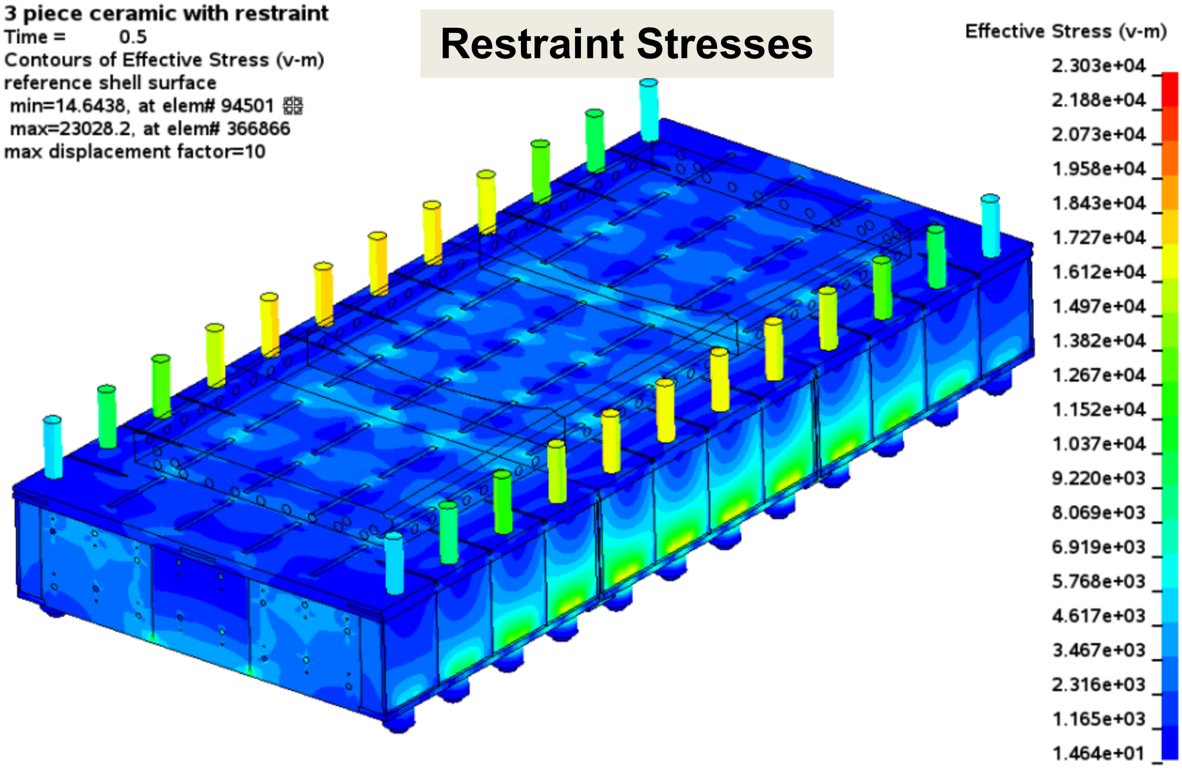


Figure 40. Depiction of stresses in the restraint at 300 psi consolidation pressure

Figure 41. Pictures of the detail parts for the restraint during fabrication steps

Figure 42. Initial placement of the first restraint element

Figure 43. Placement of the first upper restraint element

Figure 44. Lower and upper restraint elements in place and columns installed

Figure 45. Picture of completed restraint with a portion of the die handling tooling installed

Figure 46. Picture of completed restraint with a portion of the die handling tooling installed

Figure 47. Picture of completed restraint with the die handling tooling in the open position

2.3.2 Induction Consolidation System Integration

A large scale power supply was needed to provide the required power to heat the susceptor and component in a timely manner to meet the goal of a 1 hour cycle time. An analysis of the tool/coil along with the work load was run and it was determined that a minimum of a 1MW power supply was needed to meet the required cycle time when optimally tuned. Figure 48 shows the power supply during installation.

Figure 48. Picture of the 1MW 1 to 3 KHz induction power supply during installation adjacent to the large scale restraint.

2.3.3 Induction Consolidation System Integration

The integration of the consolidation system consists of installing of the water cooling and induction power to the system. Figures 49 and 50 show schematics depicting the arrangement of the system and figure 51 shows the installation completed.

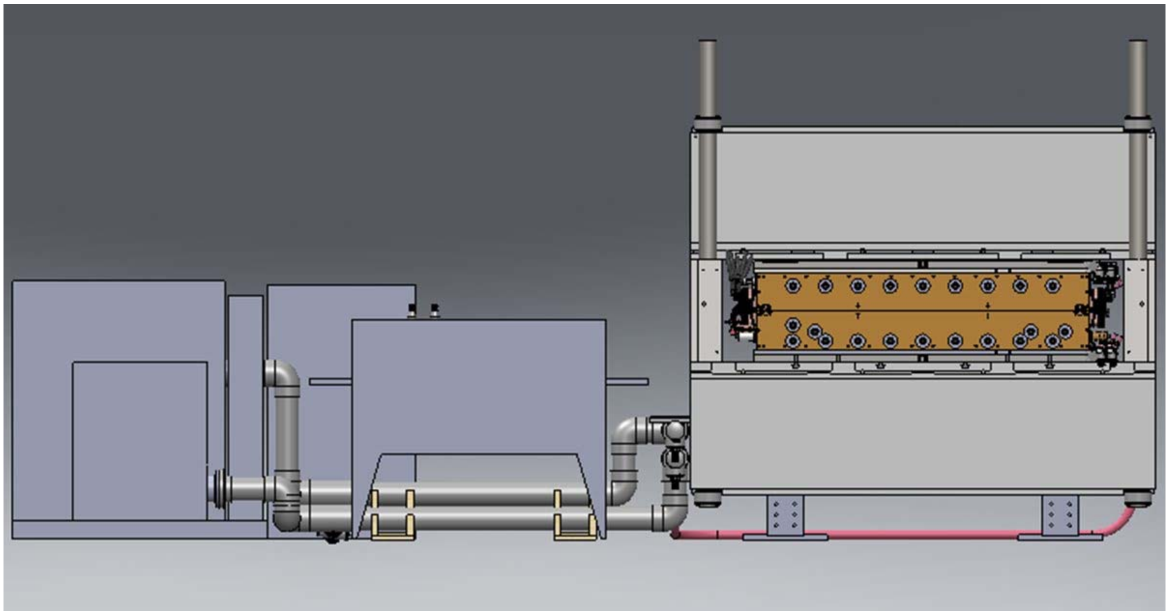


Figure 49. Depiction of the elements and integrated design of the induction consolidation system

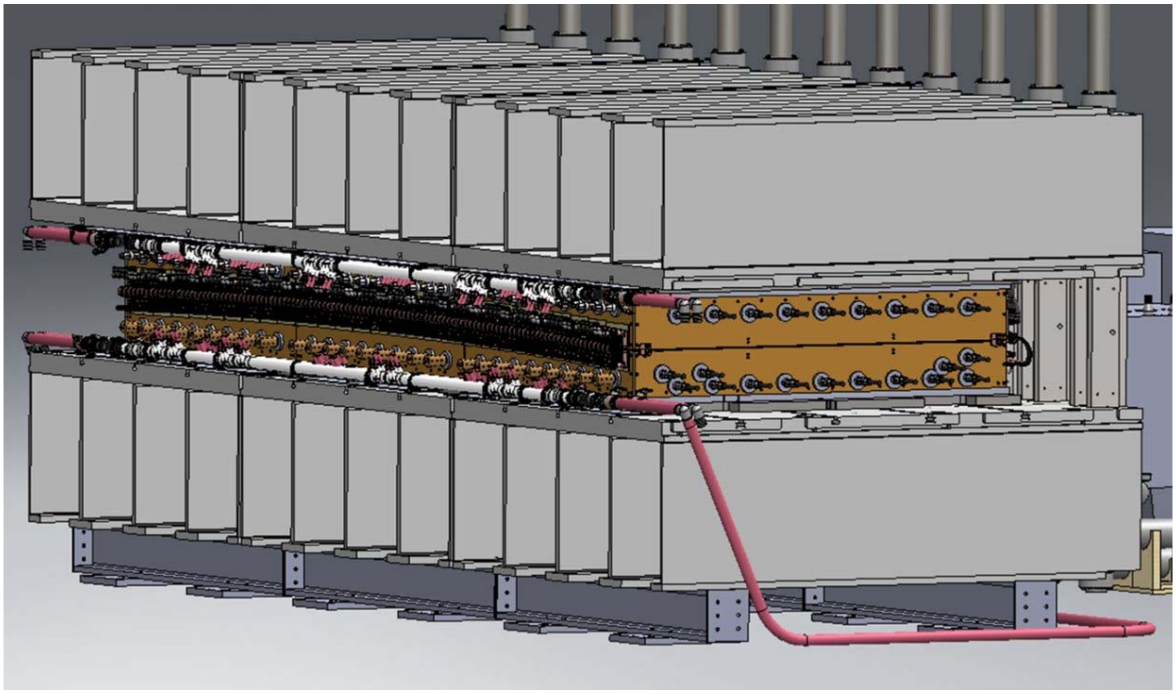


Figure 50. Depiction showing the water supply to the coil/tool of the upper and lower tool halves when placed together and inserted into the restraint

Figure 51. Picture of 1MW power supply connected to the tool along with the water supply with pump connected to the power supply and tool

2.3.4 Laser Assisted Fiber Placement System

Scale-up the laser assisted fiber placement processing capability is progressing. Establishment of the need course paths for the skin lay-up have been readied (see figure 52). In addition, the large robotic capability is in place and the ½" wide tape head has been installed and the tape dispensing capability is nearly operational (see figure 53).

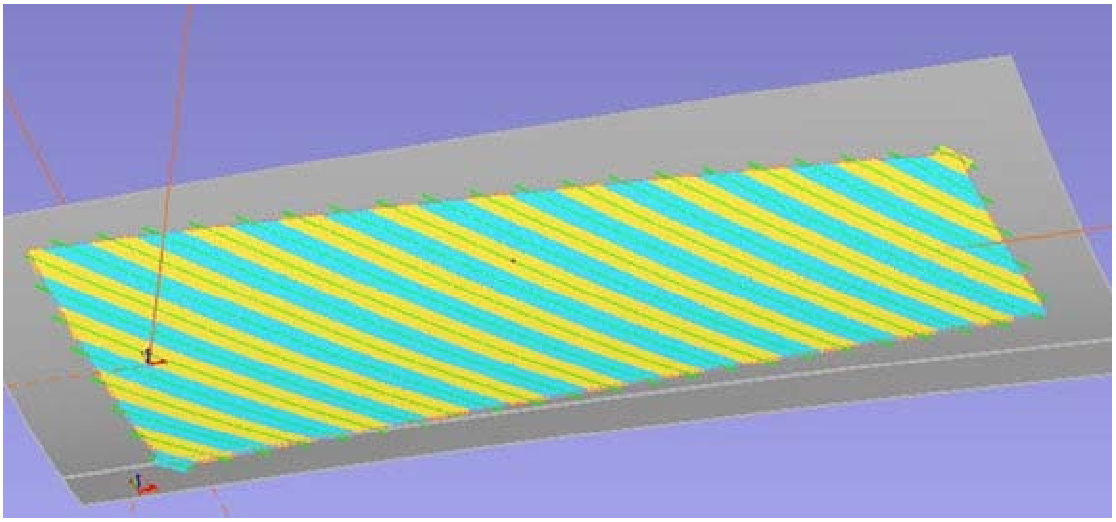


Figure 52. Depiction of a set of robot courses that make up one ply of the skin lay-up sequence

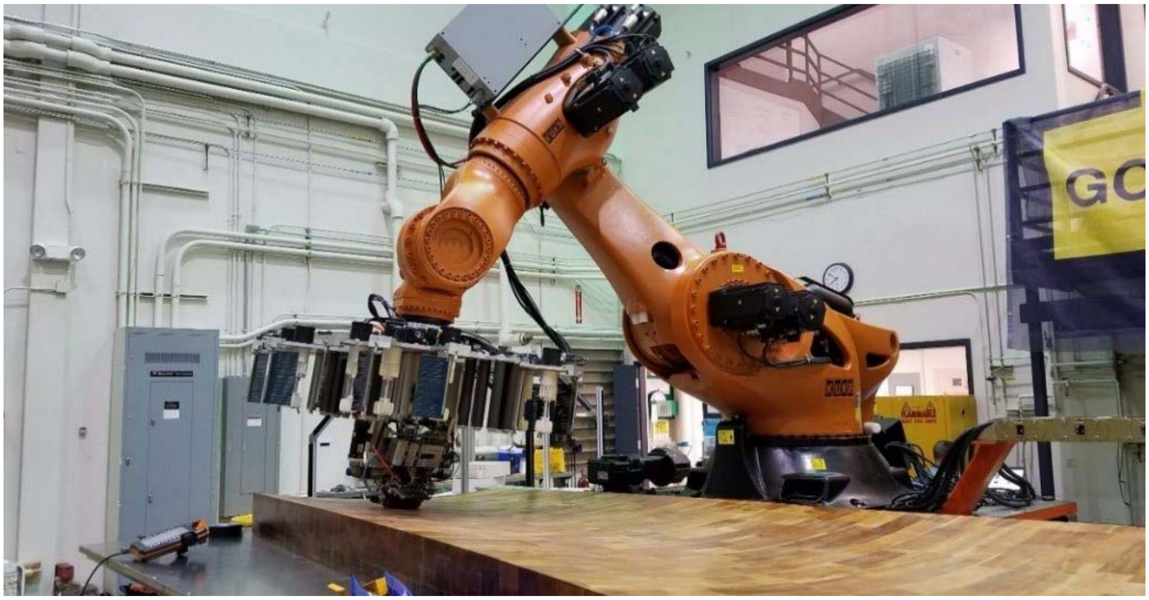


Figure 53. Picture of ½" wide tape head installed onto the robot performing a mechanical test showing tape laying course travel over the demo skin lay-up tool

2.4 Large Scale Tooling for Demonstration Component

2.4.1 Large Scale Tool Design

The reinforced cast ceramic tools that make up the induction consolidation tools for the large scale skin panel demonstration article will be fabricated in segments. These segments will utilized a construction sequence shown in figure 54. Once cast these segments will be aligned and long fiberglass bolts will be inserted along passages cast into in each tool. These long fiber glass bolts will be tightened to apply compressive force that holds the tools together and puts the entire tool in compression (see figure 55). Figures 56 and 57 show the upper tool and lower tool respectively in the assembled state. Figure 58 shows the upper and lower tools placed in position ready to slide into the restraint assembly.

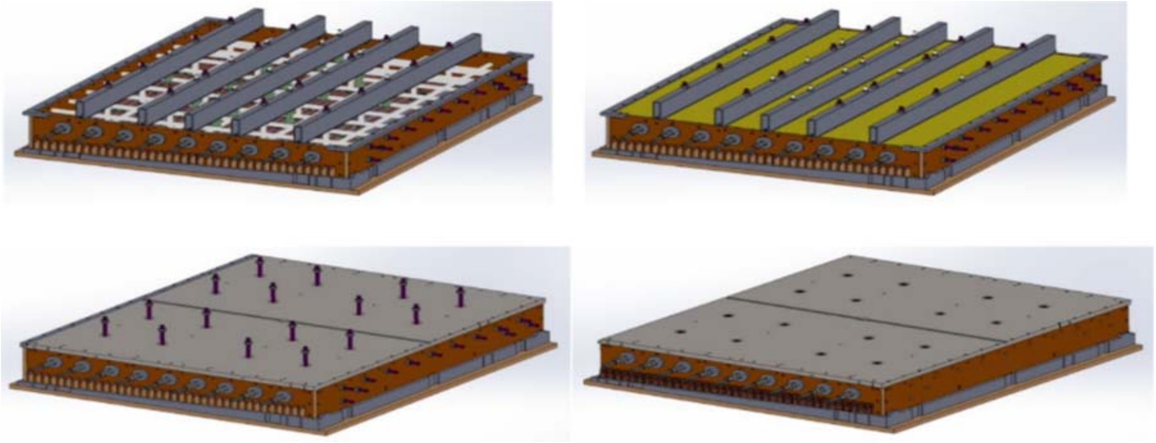


Figure 54. Depiction of the build-up to enable casting of the tool segments

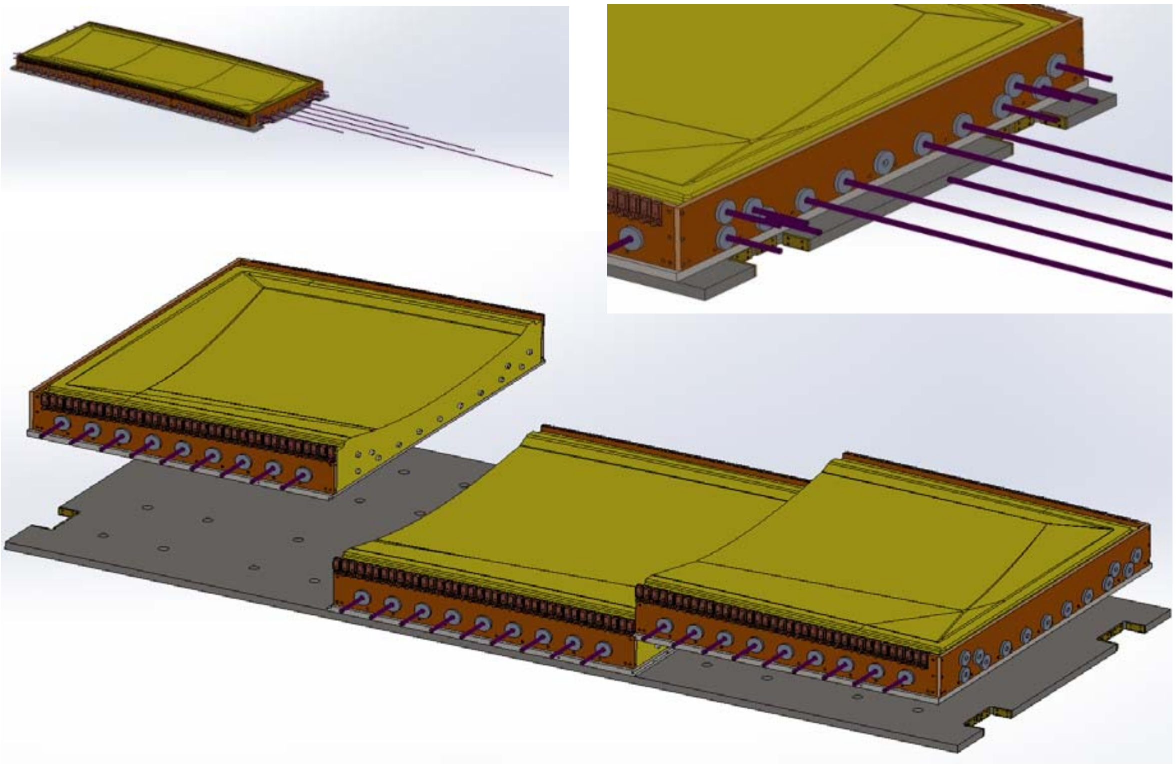


Figure 55. Depiction of the section by section build of the lower cast ceramic tool. Each of the individual tooling sections are place together and reinforcing fiber glass rods are used to hold the tools together under compression.

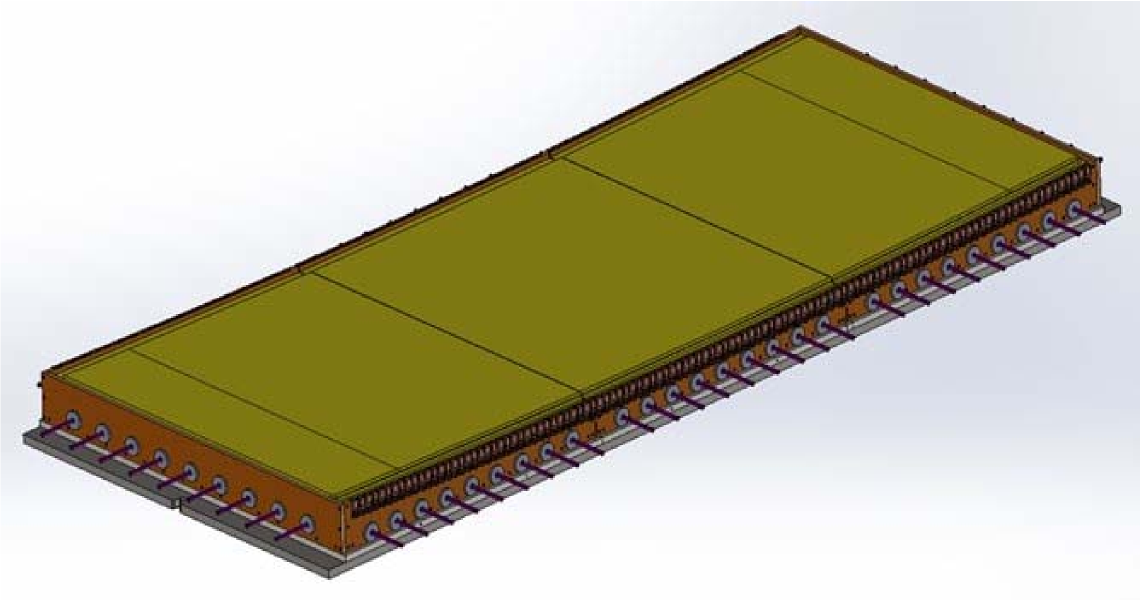


Figure 56. Depiction of the assembled upper tool made from 3 separately cast sections held together under compressive loads with fiberglass rods.

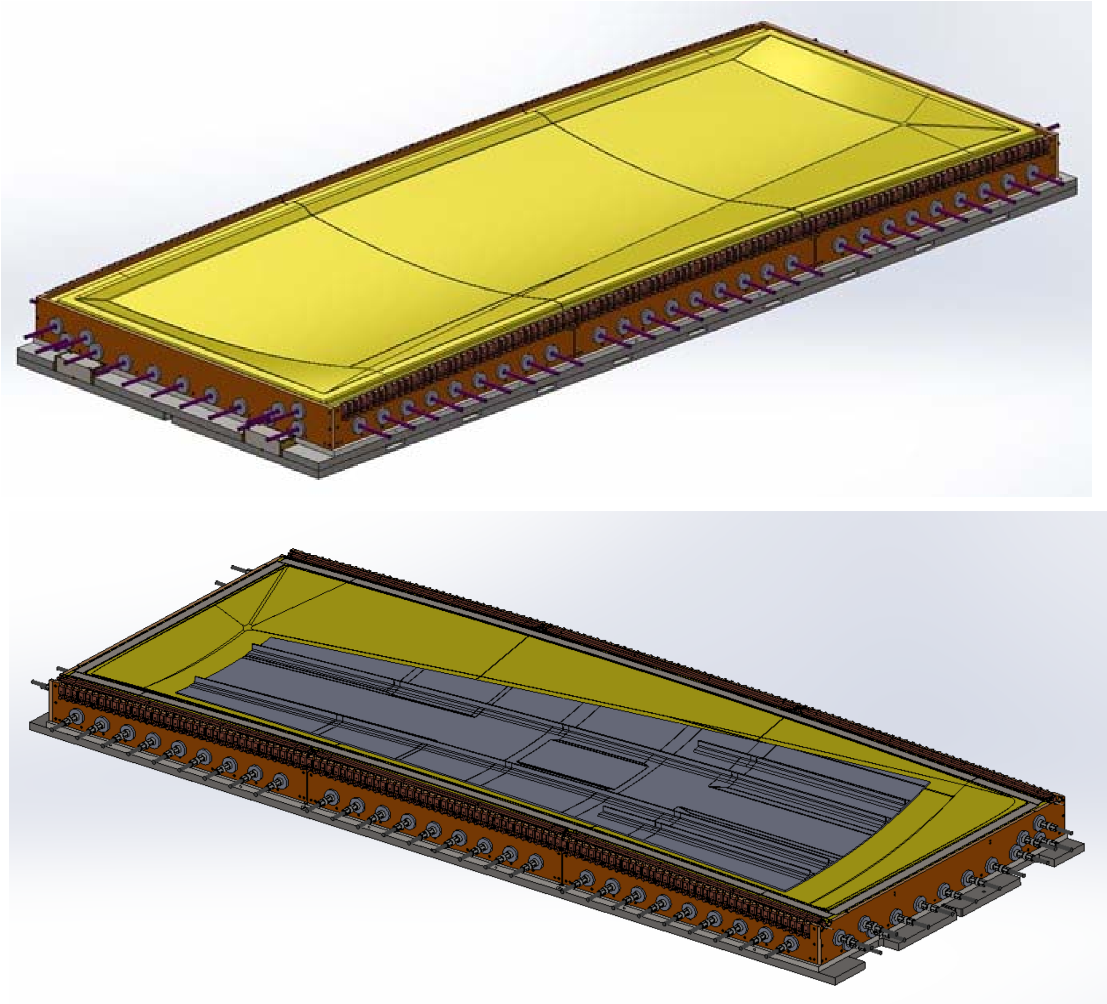


Figure 57. Depiction of the assembled lower tool made from 3 separately cast sections held together under compressive loads with fiberglass rods with the top sketch showing the tool without the part and the lower sketch showing the tool with the part

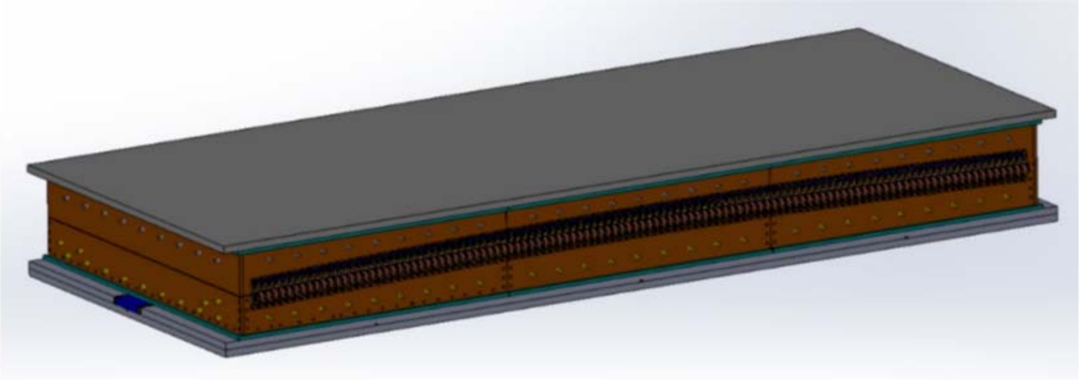


Figure 58. Depiction of the upper and lower tool halves placed together and ready to be loaded into the restraint

2.4.2 Large Scale Tool Fabrication

The first step for fabrication of the large scale-up tooling was to machine the ren-board to create the casting surface. The machined base was used to assemble the casting form box (see figures 59 and 60). For the most part this form box stays with the tool and creates the sides of the tool and hold the fiberglass reinforcement rods and the induction coils. Figure 61 shows the secured coil segments located in the tool assembly build-up prior to casting of the Ceradyne 120 material. Figures 62 and 63 shows one of the assembled tooling segments ready for casting. Figure 64 shows the mixer needed to mix the Ceradyne 120 for casting. Figure 65 shows the tool segment assembly directly after casting has been completed. Figure 66, 67, and 68 show the finished tooling segments being loaded onto the tool handling mechanism and being assembled. Figure 69 shows the copper coil connectors after joining to the tool coil segments. Finally, figure 70 shows the completed tool halves placed together in reparation for part processing.

Figure 59. Picture of a machined casting mandrel for one of the tool modules

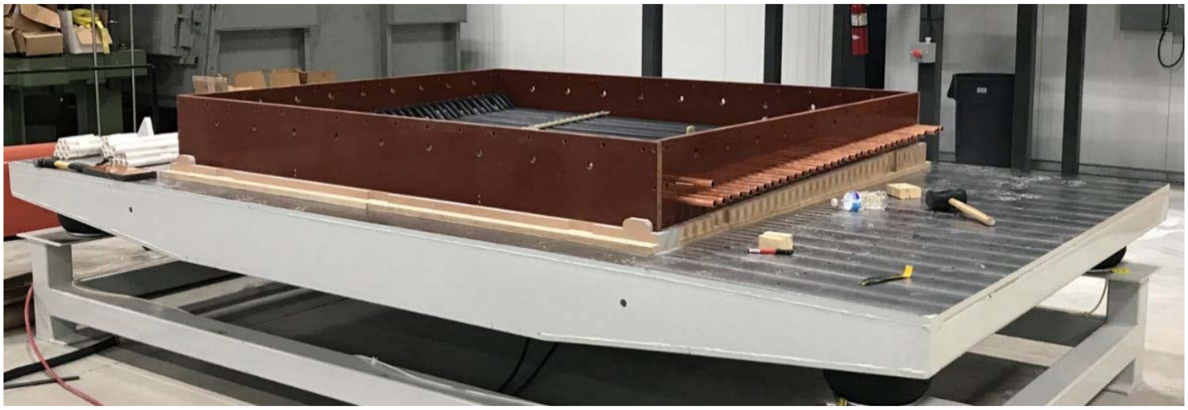


Figure 60. Picture of a machined casting mandrel with phenolic side board and coil segments in place all located on the vibration table used to aid in the casting process

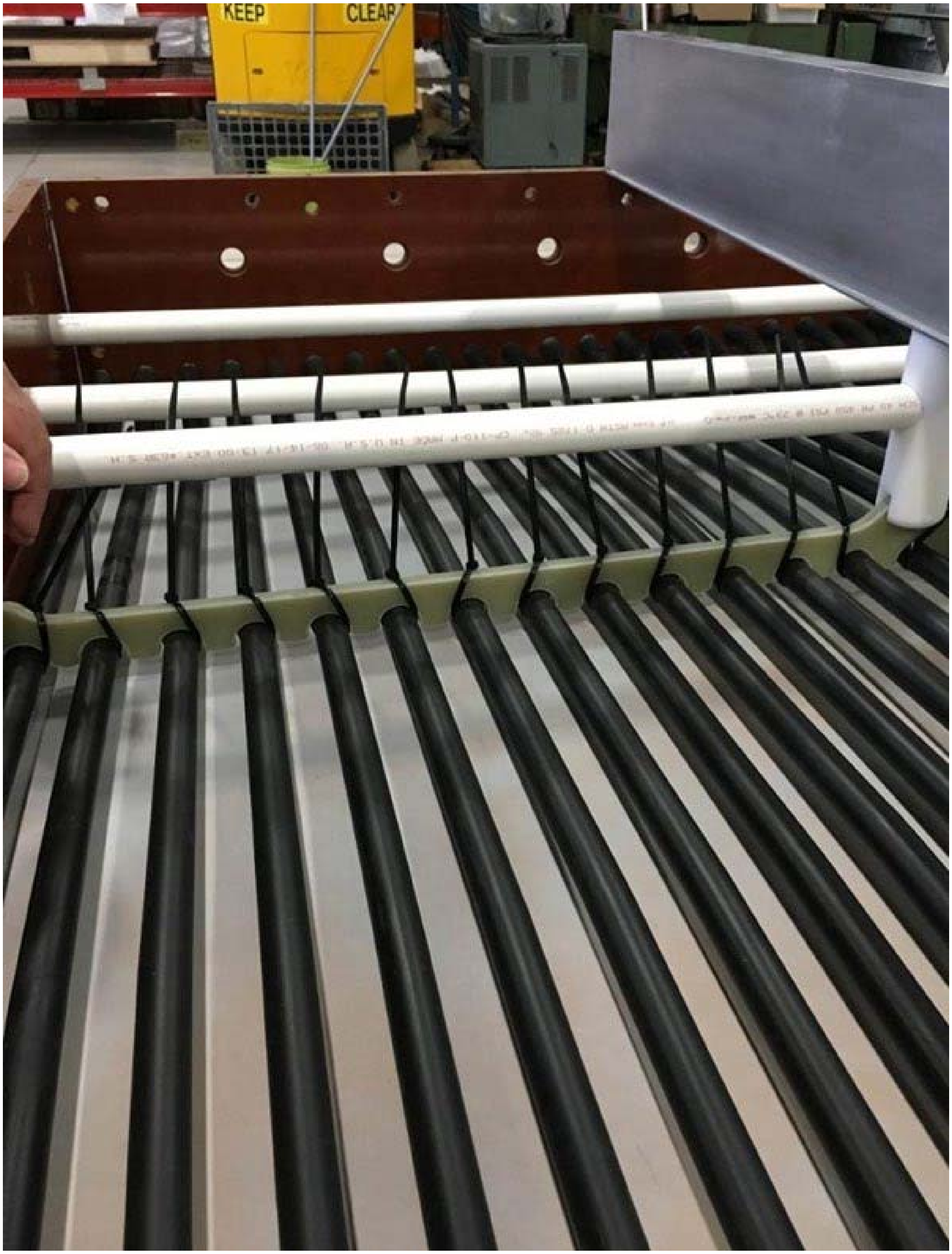


Figure 61. A picture of the secured coil segments located in the tool assembly build-up prior to casting of the Ceradyne 120 material

Figure 62. Picture of a section of the tool ready for casting (side view)

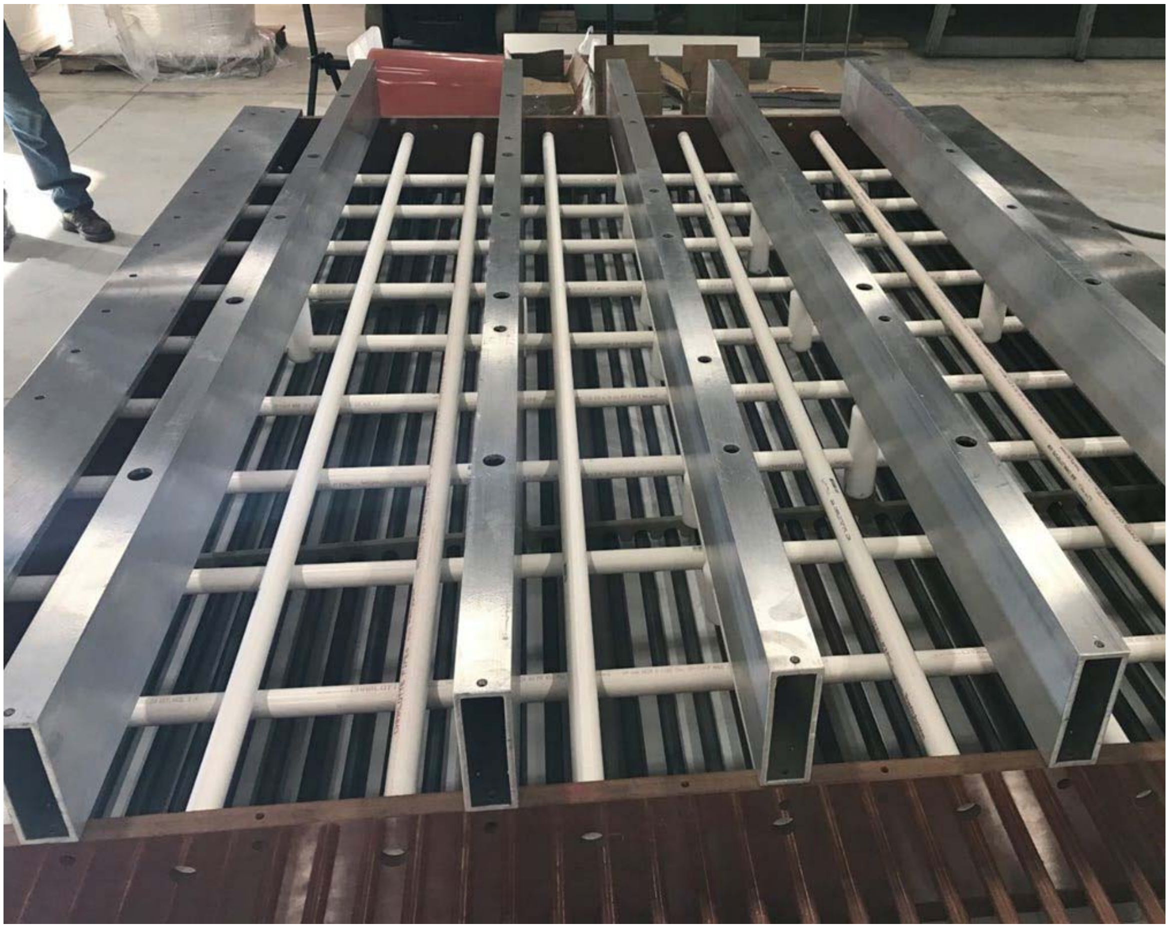


Figure 63. Picture of a section of the tool being prepared for casting (front view)

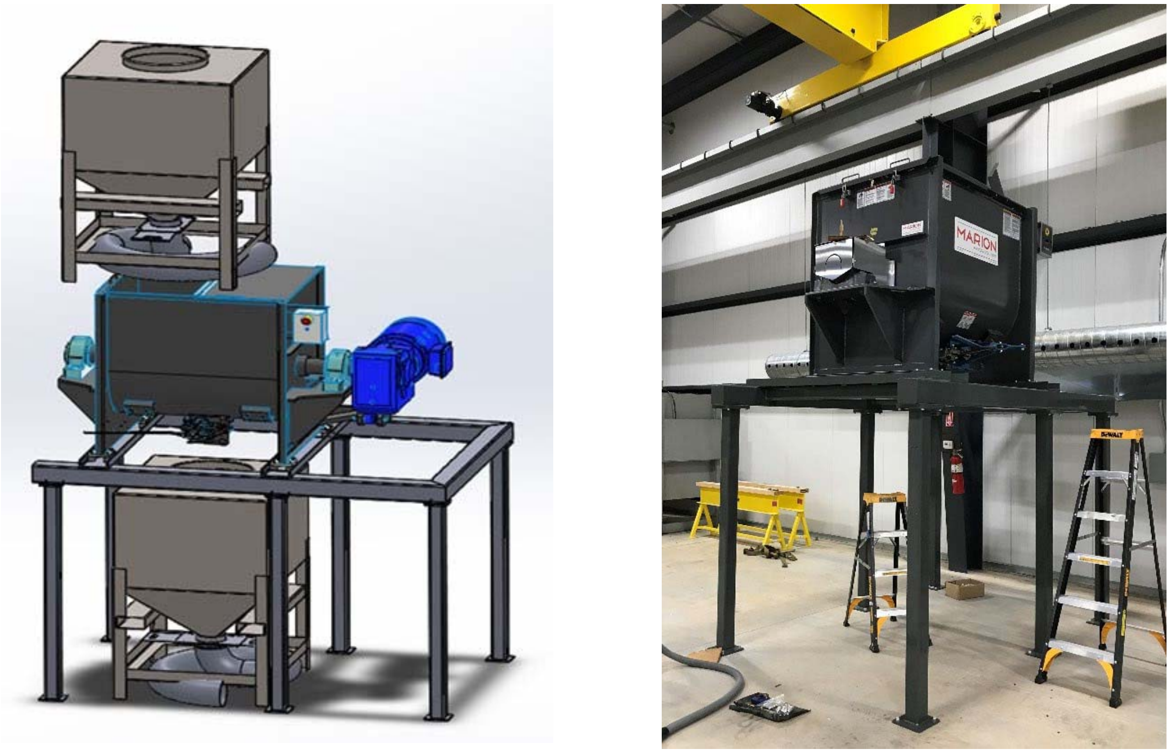


Figure 64. Depiction and picture of the ceramic mixer and tool casting system

Figure 65. Picture of tooling section after casting of the Ceradyne 120 material

Figure 66. Picture of cast tool section being transported to the tool handling fixture to be installed and readied for processing trials

Figure 67. Picture of tool handling fixture with the first cast tool section loaded

Figure 68. Picture of tool handling fixture with all six tooling sections loaded and assembled

Figure 69. Picture of copper coil connectors after brazing

Figure 70. Depiction of the upper and lower tool halves placed together and ready to be loaded into the restraint

2.4.3 Large Scale Tool Try-Out

The initial heat trial of the tooling was used to form the aluminum bladder and process the tool for the first time. The stack-up of the susceptors etcetera in the tool are shown in figures 71, 72, 73, 74, and 75. Figures 76 shows the upper tool being rolled over on top of the lower tool and stack-up. Figure 77 shows the stack-up and tooling assembled and ready to be placed into the restraint. Figure 78 shows the bladder after the forming run has been completed. The forming of the bladder was completed using the same smart susceptor set that is to be used to consolidate the thermoplastic composite preforms as well.

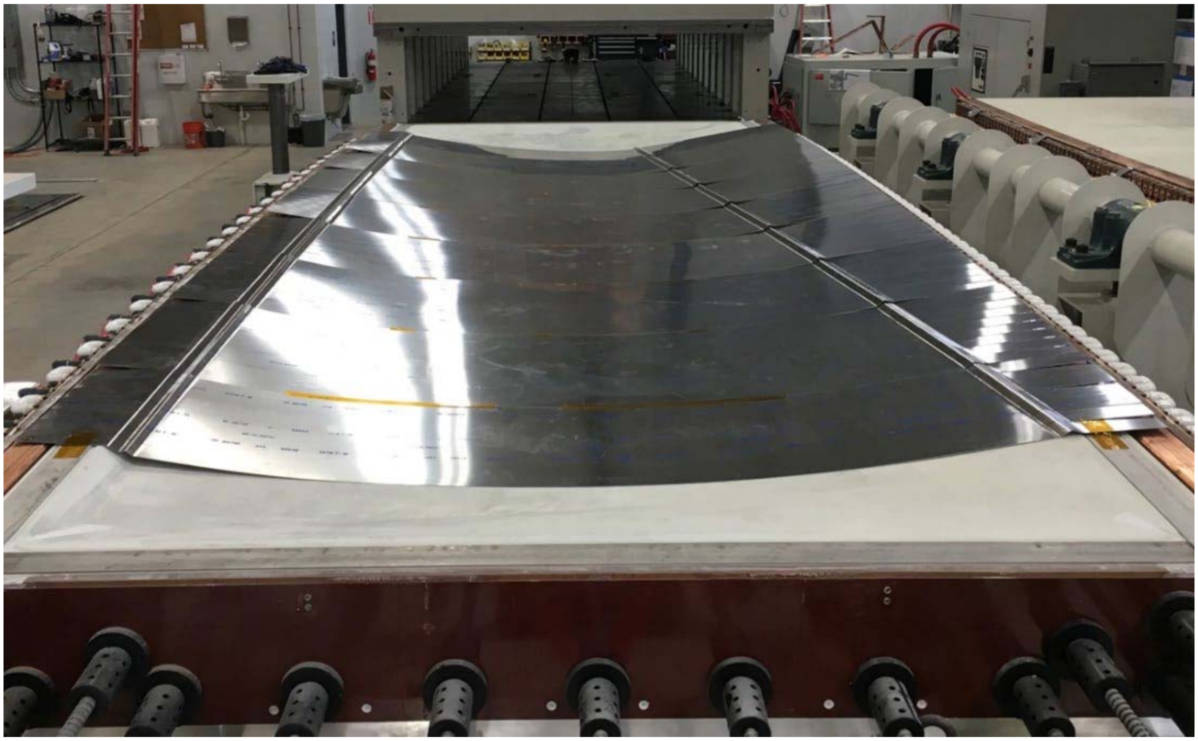


Figure 71. Picture of lower smart susceptor placed on the cast ceramic tool

Figure 72. Picture of titanium caul sheet placed on the surface lower tool

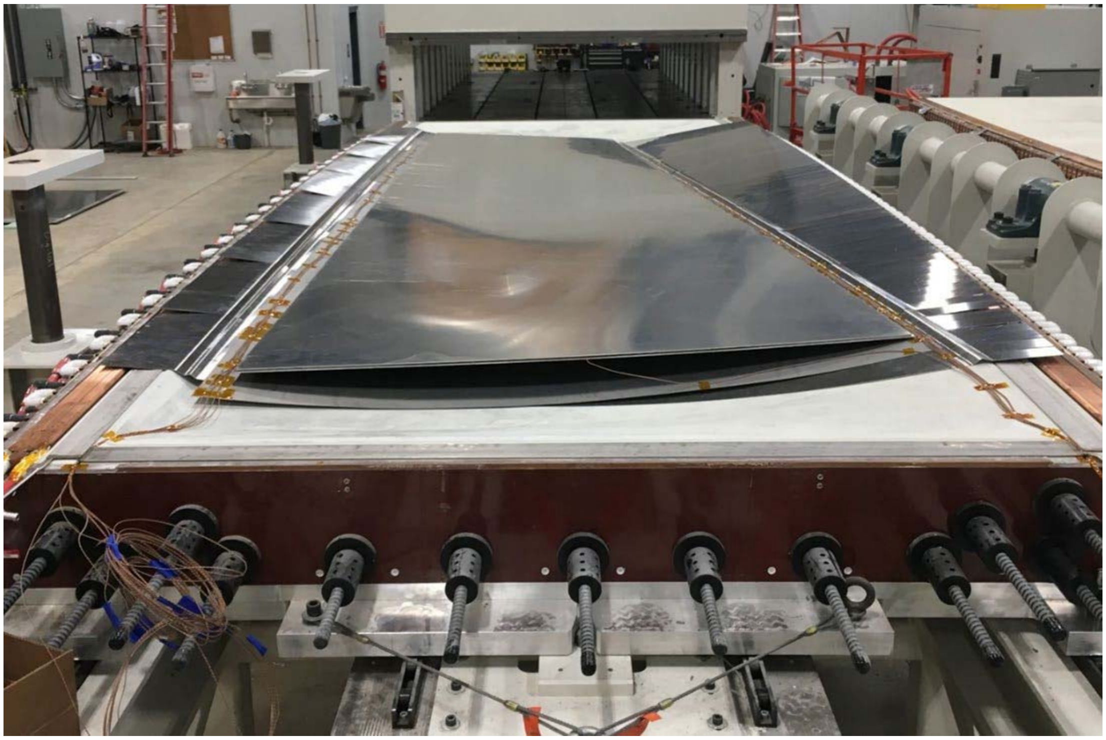


Figure 73. Pictures showing the aluminum sheets being used to simulate the part during the initial bladder forming cycle

Figure 74. Picture of the unformed aluminum bladder placed on the lower tool with the lower smart susceptor, titanium caul, and simulated part (aluminum sheets)

Figure 75. Picture of the upper smart susceptor placed on the tool which completed the stack-up of the internal components needed to form the bladder

Figure 76. Picture of the upper tooling rolled over in preparation for forming of the bladder

Figure 77. Picture of tooling stack-up and simulated part ready for loading into the restraint for processing

Figure 78. Forming of the bladder was completed plus this processing run validated the capability of the system to heat and apply pressure

2.5 Large Scale Component Fabrication

2.5.1 Lay-up of Large Preforms to Support Scale-Up

A preform based on the component design (see figure 79) was constructed using laser assisted fiber placement. Figure 80 shows this completed lay-up in the shipping crate being prepared for shipment to the induction processing system for consolidation. This lay-up represented the complexity of a typical aircraft wing skin.

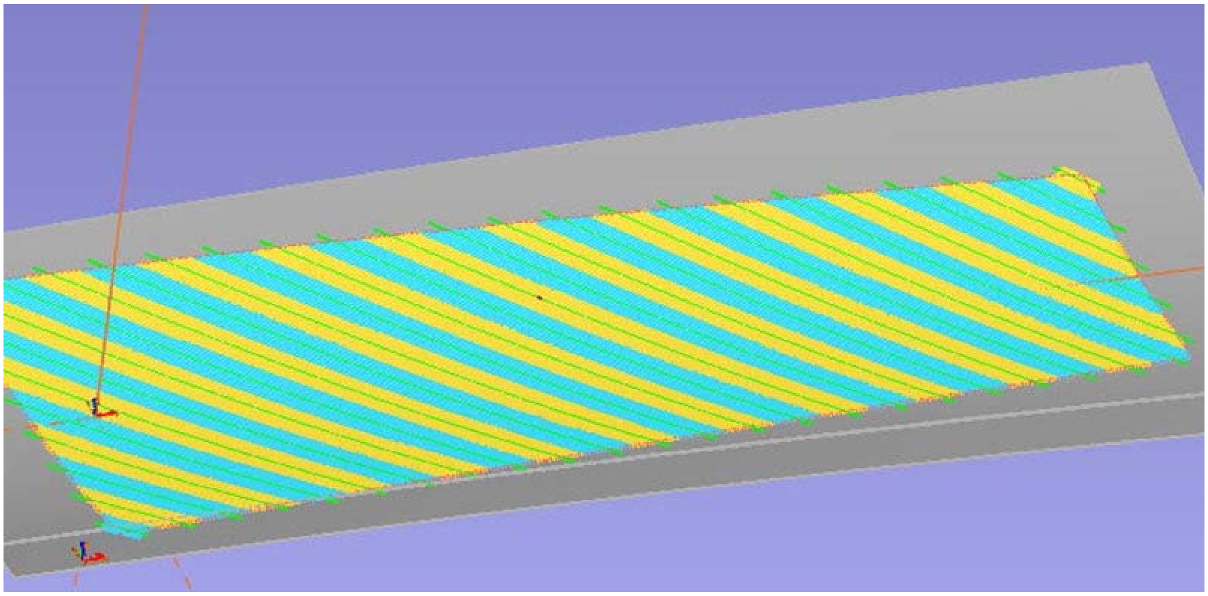


Figure 79. Depiction of the ply lay-up of the large scale component

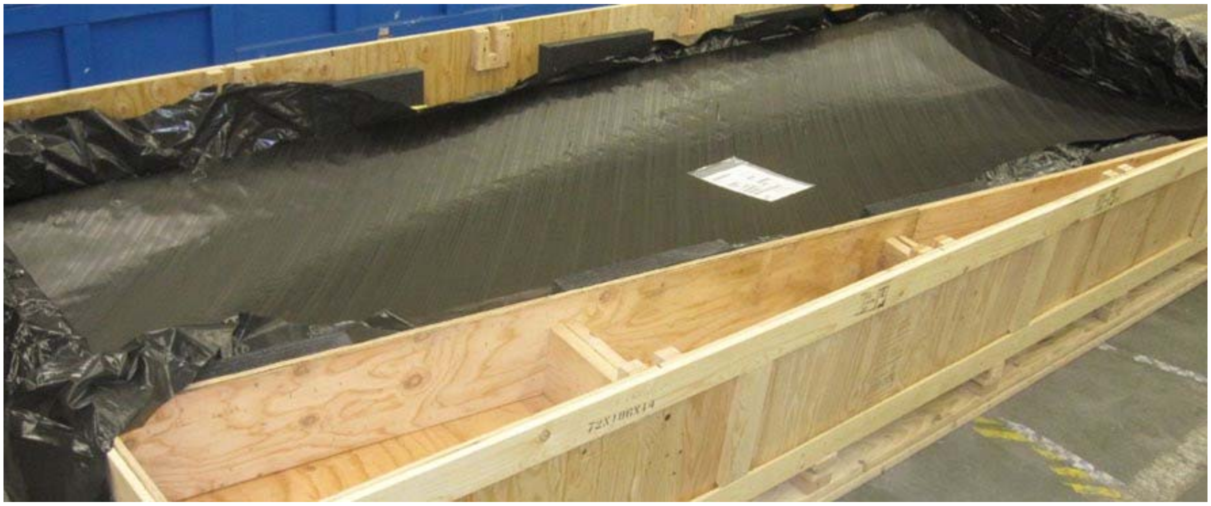


Figure 80. Picture of completed laser assisted fiber placement lay-up of the large scale component preform

2.5.2 Induction Consolidation of Scale-Up Component

Figure 81 shows a depiction of the thermal profile performed during the consolidation of the thermoplastic preform shown in preform in figure 80. Particular features of note are the rapid heat-up rate, the precise leveling of the temperature at the consolidation temperature, and the rapid cool down rate. It is felt that the elongated hold before the final ramp to temperature would not be necessary for a successful consolidation cycle. Even with this unnecessary hold the cycle time was only approximately 2 hours. Figure 82 shows the finished thermoplastic skin post consolidation.

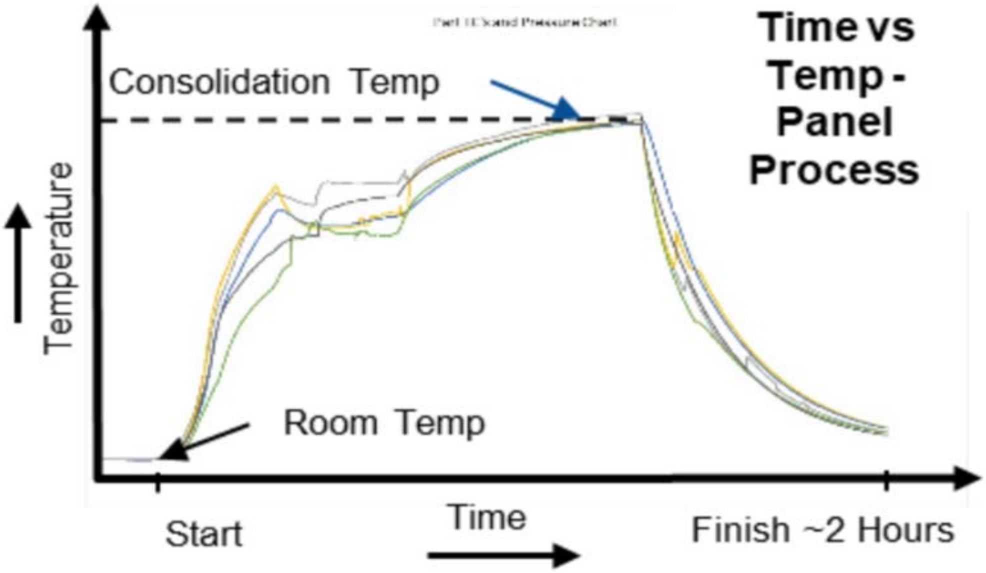


Figure 81. Thermal cycle for scale-up part consolidation

Figure 82. Photo of scale-up skin panel after consolidation

2.6 Initial Energy and Economic Assessments

2.6.1 Energy Savings Assessment

The current baseline method for curing composite materials for aerospace structures is via autoclave processing. The main equipment for operating an autoclave, all of which contribute to the overall energy consumption, includes electrical heaters, fans, pumps, and an inert gas system. Besides energy consumption from autoclave-specific equipment, significant energy is required to fabricate tooling and transport gases needed during autoclave operation. Upon review of the heating methods it is apparent that the autoclave must heat not only the part but also large massive tools and the inside structure to the autoclave. This leads to the large energy consumption numbers in the table below in table 1. The values for the autoclave was data from an autoclave of comparable size that processes similar components to the one being developed on this project. Furthermore, when analyzing the induction consolidation system only the part and a small mass of tooling is heated during processing. The value for the induction process in the table was generated from the energy required for the analysis shown in figure 3 and corroborated by the energy usage values (~85% to 90% savings) measured during the consolidation run shown in figure 81.

Table 1. Energy comparison between autoclave and induction processes

Process	Btu/lb.
Gas Autoclave (Boeing)	83,161
Induction Consolidation with Smart Susceptors*	8,092

*** Energy Savings (83,161 – 8,092)/83,161*100 = 90.2% energy savings**

To estimate the energy saved one must consider robust growth in airplane manufacturing rates (figure 83) coupled with continued increased use of composites in aerospace structures (figure 84). These trends signal and opportunity for significant energy savings given widespread adoption of this processing method. Assume and average of at least 200,000 tons of composites used each year for the next 20 years (figure 85). That results in 400M lbs of composite used each year. Over 20 years that would amount to 8B lbs total. Next, assume all of this structure was converted to induction consolidation tomorrow. The savings would be 75,000 BTU multiplied by 8B. The result is 600T Btu's saved. Now considering that it will take 10 years to implement, the process will predominantly be used for high rate production airplanes, and Boeing will produce 50% of the airplane demand. The result would be approximately 75T Btu's saved.

Additional benefits when using thermoplastics is that the material is fully recyclable. Since the resin can be re-melted the opportunity exists to grind or shred the thermoplastic composite structure at the end of life and remold the material for other applications. Also, the thermoset material requires constant refrigeration before use to ensure that the cure is not advanced beyond a certain point before autoclave processing. The thermoplastic material is already fully reacted and needs no refrigeration. The elimination of the need to refrigerate large volumes of material will further enhance the energy savings.

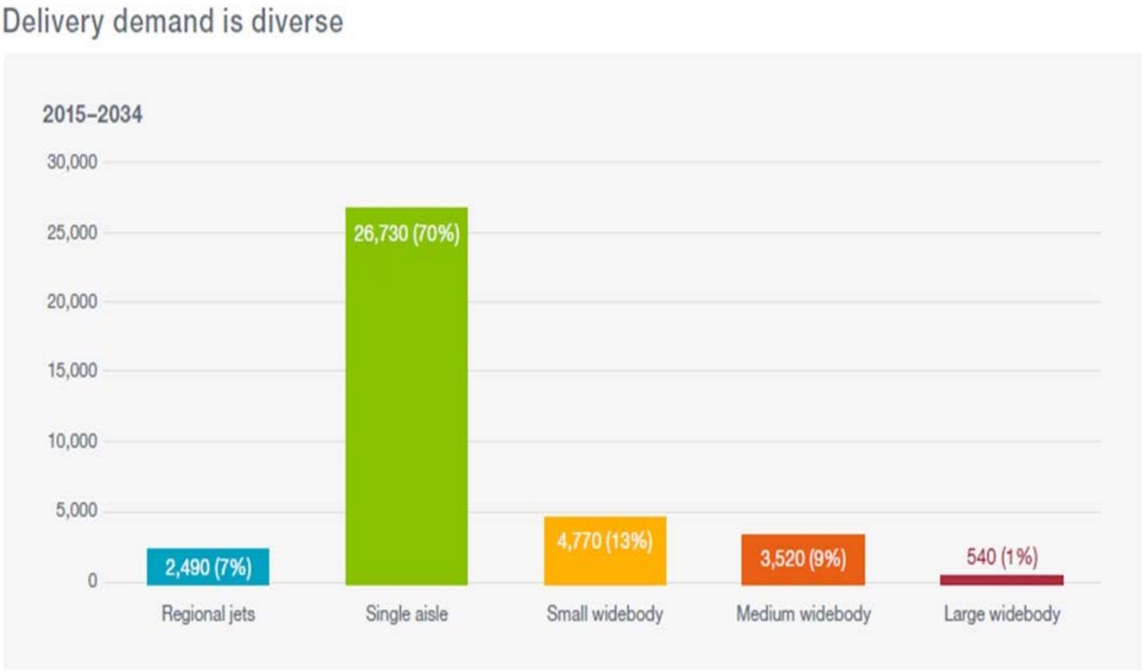


Figure 83. Prediction of airplane market in the next 20 years

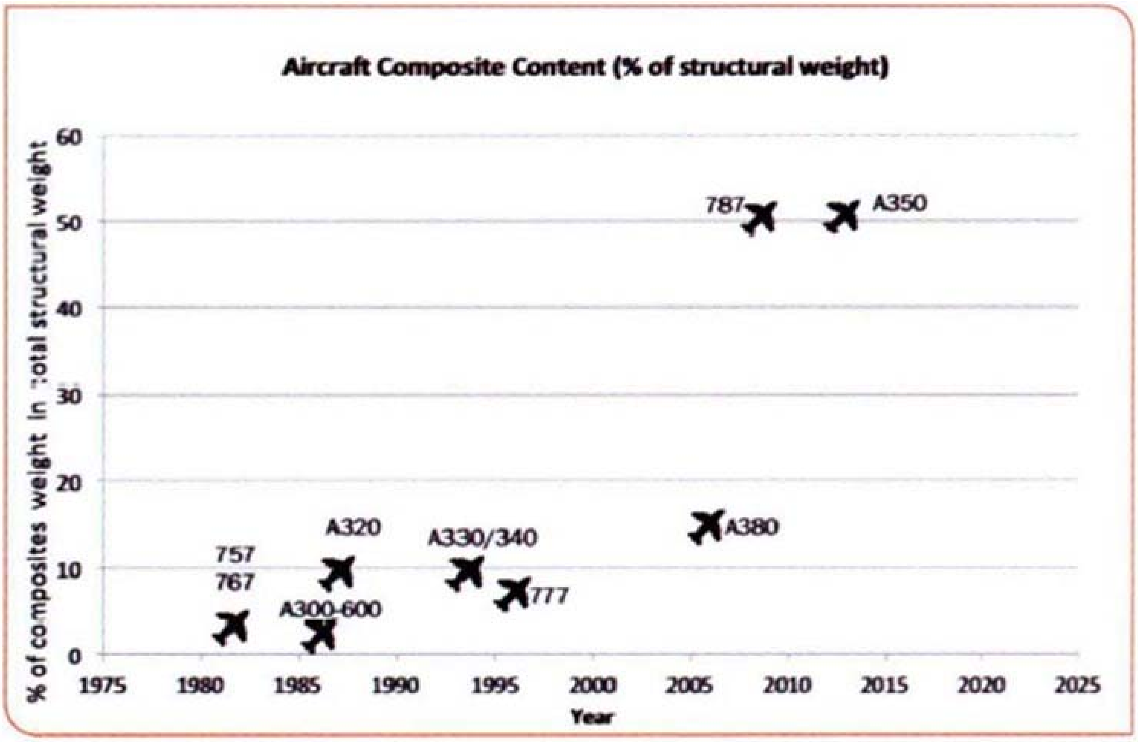


Figure 84. Depiction of the increasing percentage that is making up the content of new airplane models being introduced

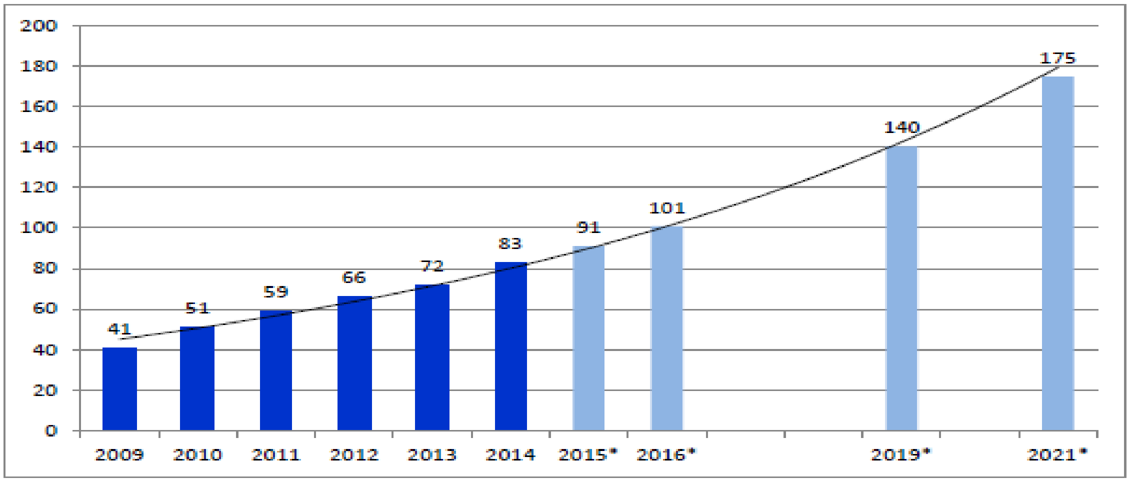


Figure 85. Global CRP demand in 1,000 tons 2009 – 2021 (* estimate)

2.6.2 Economic Assessment

The largest economic advantage when considering the induction consolidation of thermoplastic composites for aerospace is generated by the rapid thermal cycle for large component fabrication. The graphs below were calculated using a 1 hour cycle for the induction consolidation process. The cost advantage is realized when estimating the needed equipment and tools plus the floor space occupied (see figures 86 and 87).

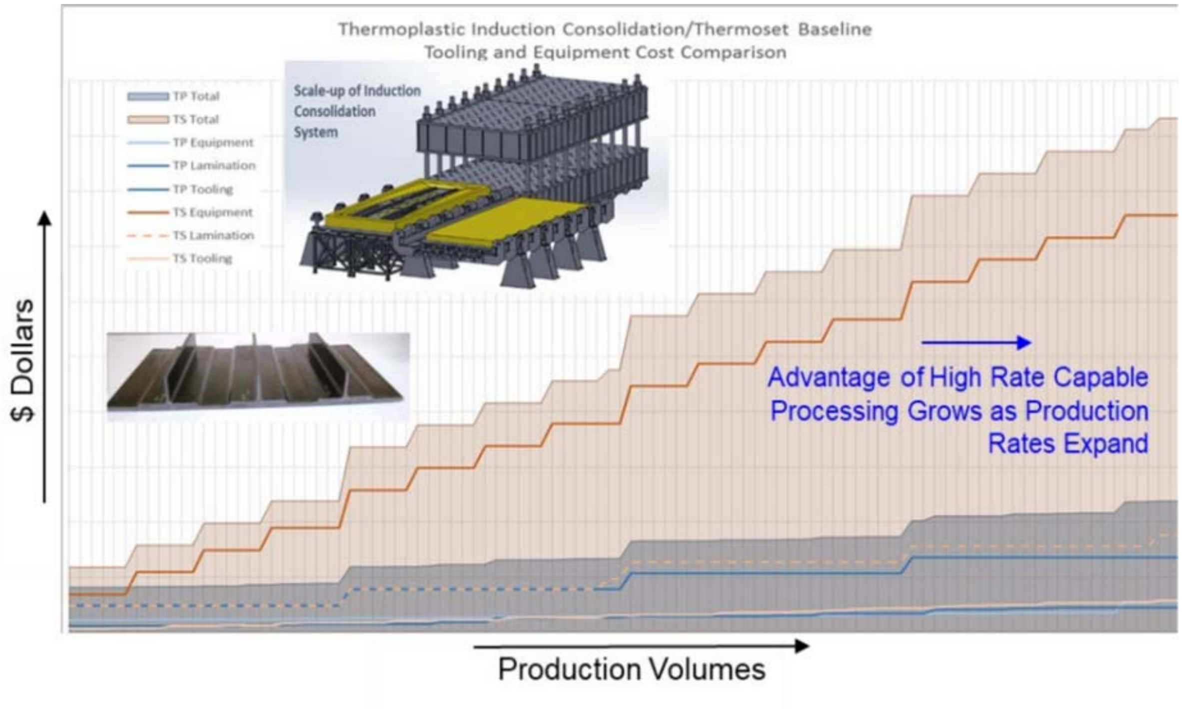


Figure 86. Graph showing the cost savings in equipment and tools for the induction consolidation process using thermoplastic composites at high rates of production

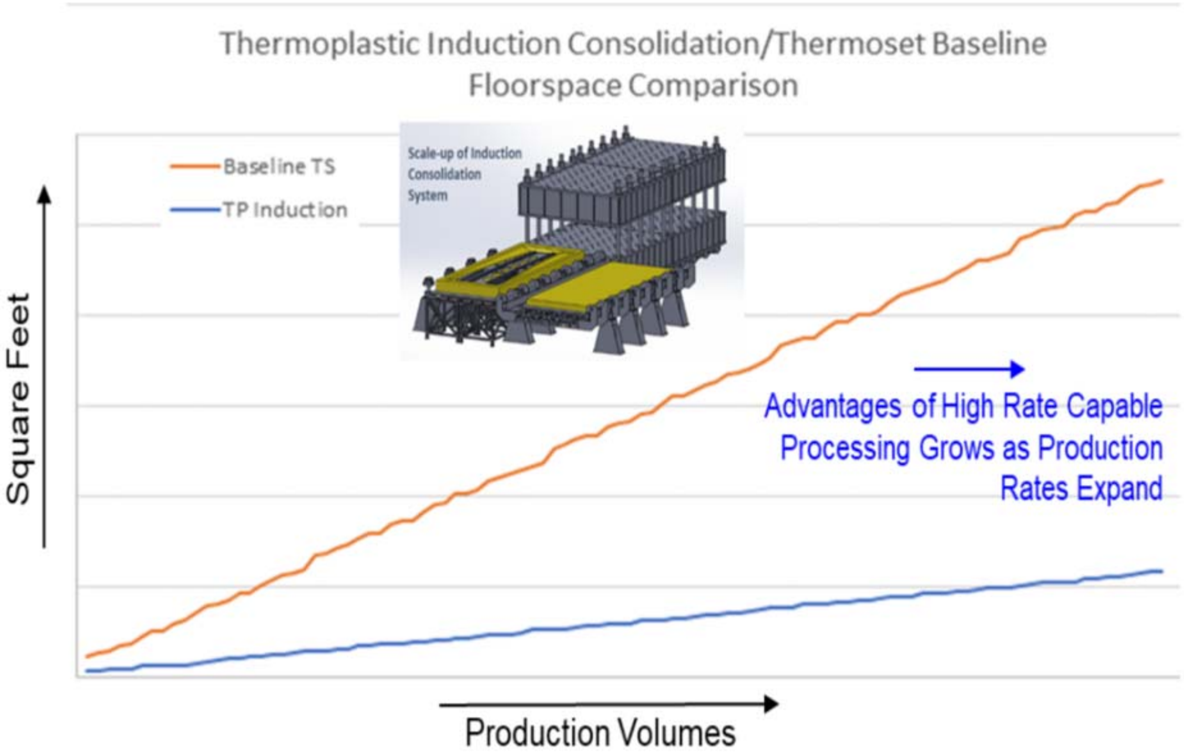


Figure 87. Graph showing the floor space savings for the induction consolidation process using thermoplastic composites at high rates of production

3. NEAR TERM CHALLENGES

As with all development projects technical challenges emerge as the projects progress. Below are the significant challenges we are facing as we progress into the next year of the project. The tools we are using to address these issues are three fold. The first is computer simulation and modeling of these issues. This gives us a method to address these issues by simulation before significant effort and cost is incurred. Also, many solutions can be investigated in a short amount of time. Secondly, small element tests were performed to ensure the models are providing data that matches the real world results. Thirdly, the team consists of several skills and industrial perspectives. The diverse team provides a broad view thereby resulting in a significant number of ideas and different potential solutions.

3.1 Mitigation of Thermal Expansion Mismatch between the Aluminum Tools and Composite Components

The use of aluminum stringer mandrels are planned to provide the needed mechanical and thermal tooling behavior. However, the coefficient of thermal expansion does not match. A novel solution is being developed and an invention disclosure has been submitted.

3.2 Improving the Thermal Response of Panel with Integral Stiffeners

Furthermore, the addition of the stringers and the stringer tools into the consolidation cycle to form the blade stiffened skins adds additional time. Several concepts to boost both the heat-up and also boost cool down. Forced gas cooling of the interior of the consolidation bladder is an example to boost cool down speeds. The use of Ceradyne 220 instead of Ceradyne 120 castable ceramic to fabricate the tools is another example. The Ceradyne 220 is about twice as thermally conductive as the castable 120. This will allow the water cooled induction coil to generate a significantly improve the cooling effect.

4. ACCOMPLISHMENTS AND CONCLUSIONS

4.1 High Level Accomplishments

- A representative scaled-up demonstration component was selected and designed
- The needed laser assisted fiber placement capabilities have been developed and validated on a component of meaningful scale and complexity.
- Subsequently, a thermoplastic preform of the part scale-up part design was laser assisted fiber placed and made availalbe for consolidation.
- An induction consolidation system was sized, designed, and fabricated resulting in the full capability to consolidate the scale-up component.
- The tool for induction consolidating of the scale-up component was designed and fabricated.
- An aluminum pressure bladder was welded and formed for use as the pressurization membrane to perform the needed application of pressure on the part at temperature to achieve consolidation.
- The induction consolidation system consisting of the restraint, induction power supply, induction tool with integrated induction coils and smart susceptor liners, along with the aluminum bladder were successfully used to consolidate a thermoplastic skin.
- The capability of accomplishing rapid heat-up rates and cool down rates for consolidation of large thermoplastic skins with precise thermal control and even pressure application at the consolidation temperature was validated.

4.2 General Conclusions

- The use of induction consolidation with smart susceptors is an effective method to rapidly and efficiently consolidate large thermoplastic composite components and enable affordable high rate manufacturing of composites.
- A restraint type induction consolidation system provides an affordable option over the standard press when using the induction consolidation processing method.
- Aluminum bladders can be formed to the complex shapes needed and supply uniform pressure for consolidation and co-consolidation of thermoplastic composite materials.
- Straightforward modifications can be made to existing fiber placement robotic systems to enable their use for thermoplastic lay-up applications.

References

[1] [1] The Boeing Company Market Research. Current Market Outlook 2015 – 2034. Boeing, 2015. Web.