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Dry Preform Stitching Using Temporary Vacuum Consolidation

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ABSTRACT

Stitched composites (composite parts stitched in a dry preform state that are infused with resin and cured to a final shape) offer a variety of benefits for modern aircraft structures. In this document one means of stitching dry fabric preforms in a state of temporary vacuum consolidation is discussed. This vacuum consolidation allows for the completion of stitching procedures while the dry preform thickness is temporarily reduced to a thickness reflective of its final cured thickness. Here, a temporary vacuum consolidation process enabling stitching of preforms of unconsolidated nominal thickness greater than the maximum allowable stitching thickness for the Integrated Structural Assembly of Advanced Composite (ISAAC) system is explored as a use case for such processes. Temporary vacuum consolidation processes may lead to simplified manufacturing processes or desirable composite material properties in the future.

LIST OF ABBREVIATIONS AND ACRONYMS

AATT	Advanced Air Transportation Technology
ISAAC	Integrated Structural Assembly of Advanced Composites
LaRC	Langley Research Center
NASA	National Aeronautics and Space Administration
NCF	Non-Crimp Fabric
TTBW	Transonic Truss Braced Wing
VARTM	Vacuum Assisted Resin Transfer Molding

I. INTRODUCTION

As part of the Advanced Air Transportation Technology (AATT) project, the National Aeronautics and Space Administration (NASA) has been tasked with developing technologies that will contribute to the reduction of fuel consumption, noise, and emissions in next generation aircraft. Stitched composite structures are currently being explored for applications on the AATT project. Stitched composite structures are fabricated using dry stitched preforms that are resin infused to form the final composite structure. The resulting composite structures contain thread stitches that serve as through-thickness reinforcement, meaning that stitches serve as an additional load path, complementing resin adhesion between plies. Stitched composites are currently being explored within AATT as a method of reducing the mass of aircraft structures via the elimination of fasteners and new venues of mass optimization, reducing the number of parts in an aircraft assembly via the elimination of fasteners, and increasing damage tolerance [1, 2].

Stitched composite structures are under examination as a possible construction for multiple substructures on a proposed transonic truss braced wing (TTBW) aircraft currently being explored under the AATT project. A rendition of a proposed design is shown in Figure 1. One application of stitched composite structures on this aircraft design is as the primary structure of the jury strut that connects the wing to main strut near the wing/strut attach location, as labeled in Figure 1 [3]. This component was chosen as a candidate component due to its limited size, expected manufacturability, and well-defined end loadings.

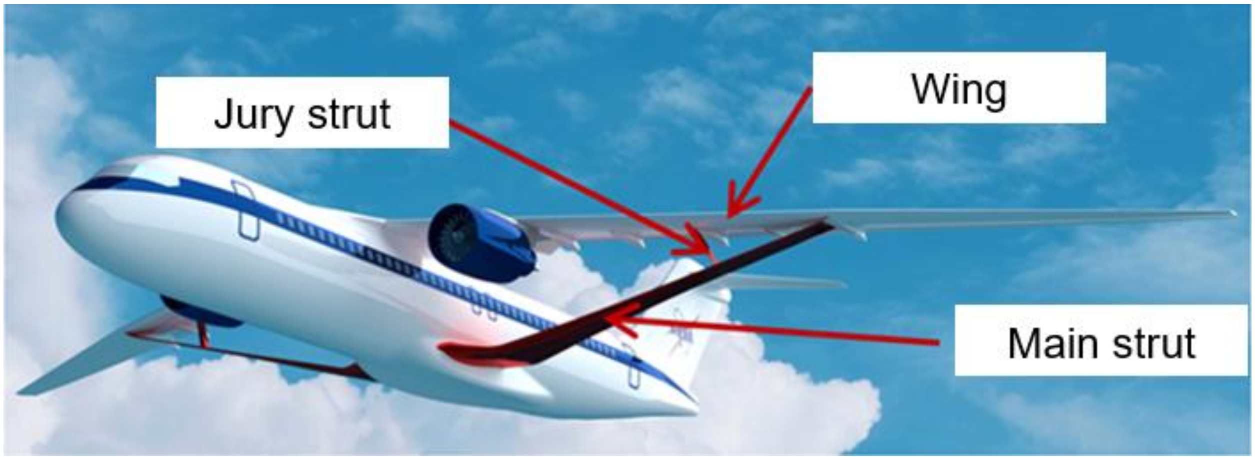

Figure 1. A proposed design for a Transonic Truss Braced Wing (TTBW) aircraft.

The process by which stitched composite structures will be evaluated as a design solution for the TTBW jury strut include coupon level manufacturing development, such as testing of stitched lap shear joints, determination of appropriate design allowables for stitched lap shear joints via experimental means, and design, analysis, and testing of a jury strut test article.

II. METHOD

The suite of stitched coupon tests of interest included single- and double-lap shear specimens tested in static tensile and cyclic fatigue loading. Specimens for lap shear testing were manufactured by cutting and stacking dry carbon fiber fabric into preforms, then stitching each preform using a double-sided, single needle stitching end effector integrated as part of an interchangeable head on the NASA Langley Research Center (LaRC) Integrated Structural Assembly of Advanced Composites (ISAAC) robotic system [4]. The ISAAC system with the double-sided stitching head is shown in Figure 2.

As this stitching method requires access to both sides of a dry preform, the planform size and the thickness of the preform are limited by the geometry of the stitching head. The planform size is limited by the length between the needle assembly and the back plate of the stitching head, referred to as the throat of the stitching end effector. The throat of the single need stitching head is shown by the blue double-arrow line in Figure 3 The preform thickness is primarily limited by the gap between the presser foot and the baseplate, shown by the green double-arrow line in the Figure 3, and to a lesser extent by needle stroke length. An example of a stitching activity for which preform planform size and thickness are acceptable under nominal conditions is shown in Figure 4, where the preform thickness is just less than the 20 mm maximum allowable stitching thickness for this stitching head configuration.

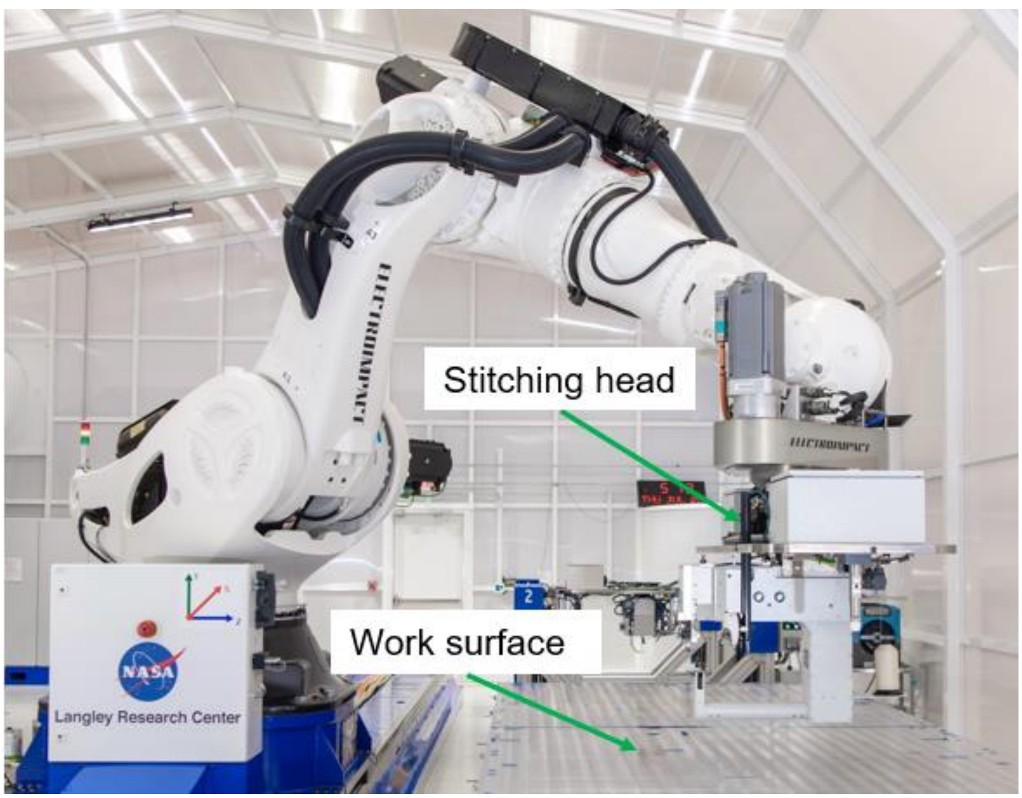

Figure 2. Integrated Structural Assembly of Advanced Composites (ISAAC) robotic system at Langley Research Center with stitching end effector attached.

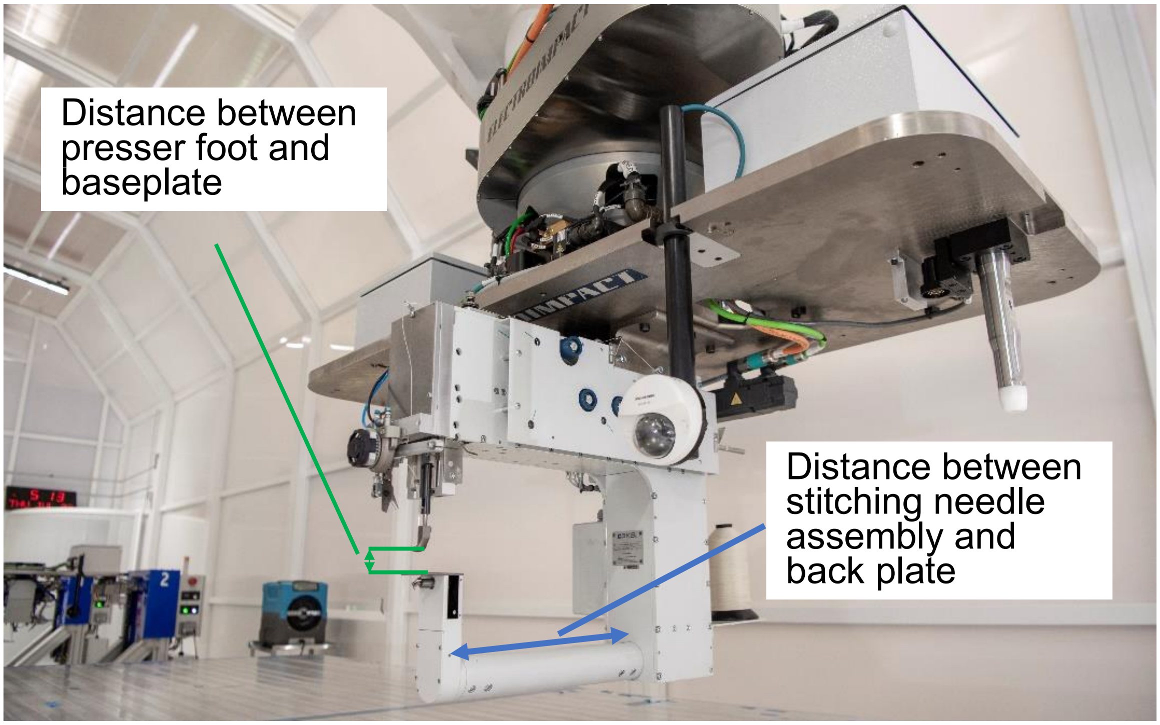

Figure 3. Single needle stitching head detail.

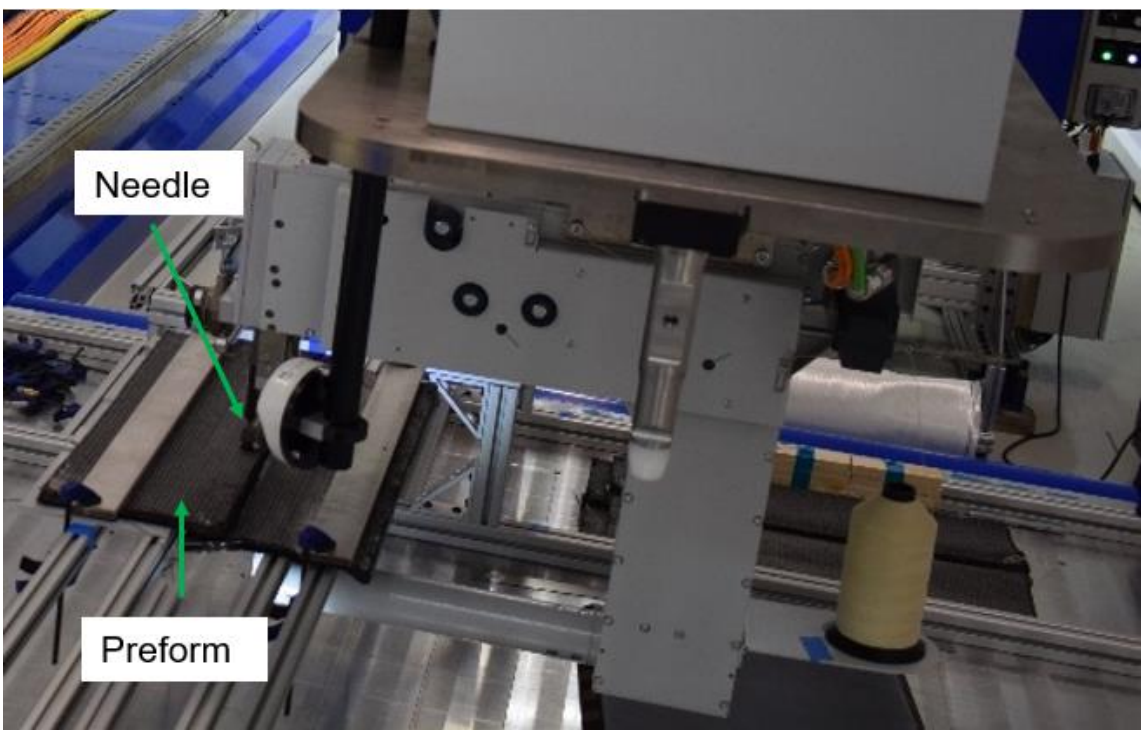

Figure 4. An example of a stitched composite workpiece being stitched by the single needle stitching head under nominal conditions.

Given that dry fabric preforms are in a pre-consolidated and pre-infused state while being stitched, it is possible to reduce the nominal thickness of the preform to near the thickness of its consolidated state. This thickness reduction may aid in fitting the preform into the gap between the presser foot and the baseplate, thus allowing stitching of additional layers of preforms. Further, this consolidation may reduce the preform thickness sufficiently to allow the needle to fully penetrate the preform to complete a stitch. Likewise, as the completed composite piece will undergo consolidation as part of the infusion process, minimization of the pre-infused preform thicknesses may be desirable to minimize length of stitching thread serving as through-thickness reinforcement in a completed composite part. This consolidation process reduces slack in the stitches and, hence, reduces waviness of the through-thickness stitch thread in the post-cured composite piece. During this process, stitching is completed without increasing tension in the thread, unlike other processes currently in use.

Presented herein is a novel method of temporarily reducing the thickness of a dry fiber fabric preform by the application of a vacuum consolidation process. This process enables stitching of thicker laminates or minimization of the through-thickness length of stitched threads in a pre-infused state. Reasons for using vacuum bagging for stitching and an explanation of the vacuum bagging process for stitching are presented in the following sections.

III. INSTIGATING PROBLEM

As part of the stitched jury strut investigation, stitched lap joint composite coupons were manufactured and tested under static tensile and cyclic fatigue loads to determine manufacturing capabilities and to determine an initial set of design allowables for stitched lap joints. Lap shear tensile testing was selected as a test modality as it reflected the anticipated design of the TTBW jury strut. Two lap shear joint types were explored: single and double. Specimen lap joint geometry was designed to align with ASTM D5868-01 to the greatest extent possible, with a stitched joint replacing the adhesive joint described in the standard [5]. The geometry of these test specimens, including expected stitch penetration locations and spacing and the intended tabbing for installation into a test frame, are shown in Figure 5.

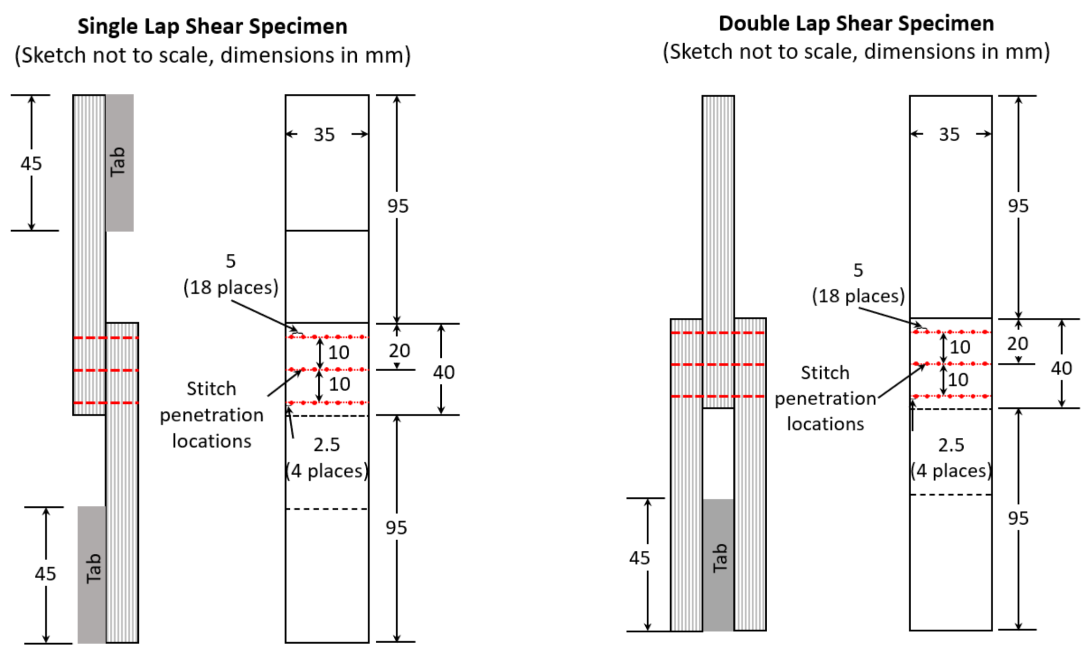

Figure 5. Side and face view depictions of the geometry of a stitched composite single-lap shear tensile test specimen (left) and a stitched composite double-lap shear tensile test specimen (right). Expected stitch penetration locations and lengths shown in red.

Both types of lap shear specimen were constructed out of Saertex Q-C-586 gsm A/B non-crimp fabric (NCF), where A and B constitute 4-ply NCF with mirror image construction that, when combined, produces an 8-ply quasi-isotropic stack of 1172 gsm. Each adherend consisted of four of the quasi-isotropic NCF stacks, for which the anticipated cured thickness of the lap-joint region was 5.7 mm. The specimens were stitched and infused as panels, which were then trimmed before individual specimens were cut for testing. The width and length of the panels were 342 mm by 560 mm, respectively, with stitched portions comprising 350 mm of the panel length. The anticipated locations of test specimens on the stitched and infused panels are shown as dashed green lines in Figure 6. The dotted red lines in this figure represent the locations of three rows of continuous stitches.

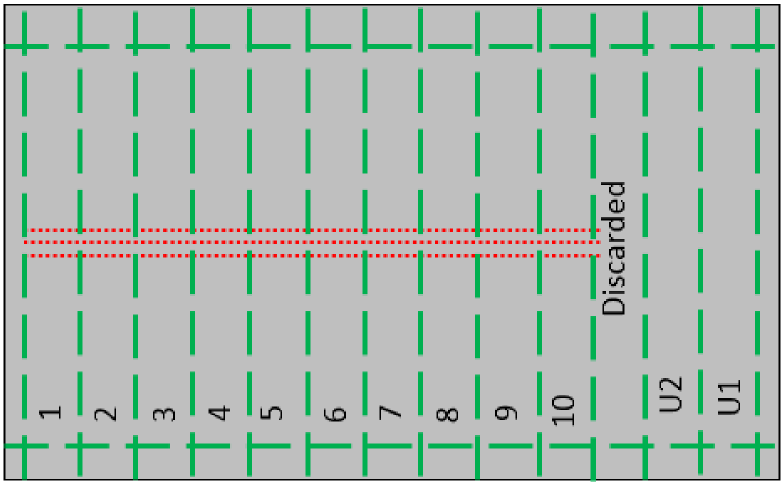

Figure 6. Approximate locations of stitched and unstitched lap shear specimens as cut from the manufactured panels (dashed green) and the locations of three rows of continuous stitches (dotted red).

Single- and double-lap shear specimens were assembled and stitched using the double-sided stitching head on the ISAAC robotic system. The single-lap shear specimens were stitched first, using a stitching jig constructed out of off-the-shelf T-slot aluminum extrusions. This stitching jig allowed the double-sided stitching head access to the seam location. A completed single-lap shear specimen as installed in the stitching jig is shown in Figure 7. As the maximum gap between the presser foot and the base plate of the double-sided stitching head is approximately 20 mm, and the maximum thickness of the unconsolidated single-lap shear preforms was less than 20 mm, the single-lap shear specimens were stitched without issue.

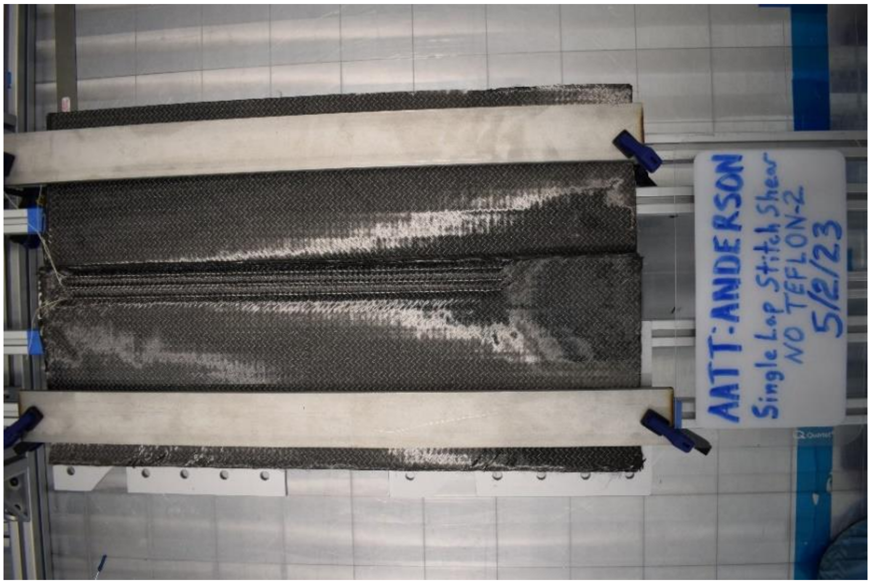

Figure 7. A stitched single-lap shear specimen installed in the stitching frame.

The double-lap shear specimens, consisting of three composite adherends, had an unconsolidated nominal preform thickness of slightly less than 30 mm in the joint region. This total preform thickness was greater than the maximum gap between the presser foot and the base plate (maximum 20 mm). Initial attempts to mitigate this issue included compressing the lap joint portion of the preform by hand to enable insertion of the preform into the stitching head. While this manual compression allowed the preform to be placed, the lap joint region of the preform returned to its initial thickness as stitching began, and the needle stroke was not long enough to penetrate the entire preform thickness to complete a stitch. Alternate methods were considered, including reconfiguring the stitching fixture to clamp the preform closer to the stitched region and implementing temporary, hand placed tack stitches at the edges of the preform lap joint area. None of these simplified approached were successful in obtaining a properly stitched preform, so a new approach was developed to pre-consolidate the preform for stitching.

IV. TEMPORARY VACUUM CONSOLIDATION FOR STITCHING THICK PREFORMS

Given that the preforms were to be infused using a vacuum assisted resin transfer molding (VARTM) technique, the final approximate thicknesses of both the single- and double- lap shear specimens were expected to reduce to approximately 60% of the unconsolidated thicknesses. The double-lap shear specimen joint region was well defined by prior experience and was expected to be between 17 mm and 18 mm at final consolidated thickness. As this thickness was less than the 20 mm maximum thickness for stitching, it was postulated that temporarily consolidating the preforms to this thickness via a vacuum process was a feasible solution. Trials were conducted to investigate temporary preform consolidation during stitching.

An initial proof of concept process was developed and implemented. A preform comprising 12 NCF stacks representing the maximum thickness of the double-lap shear specimen preforms was placed into an envelope-style vacuum bag using various materials. After trials using the various materials, a vacuum bag cut from resin infusion release film material was found to be the most suitable. Release film was selected as it resisted tearing after puncture but was thin enough to remove from between stitches after stitching was completed.

This vacuum bag was sealed with sealant tape, colloquially referred to as “tacky tape.” A vacuum pump connected to a surface valve inserted through the vacuum bag was used to evacuate the air from the vacuum bag to 15 in. Hg or 50.8 kPa. Under vacuum, the total thickness of the preform and vacuum bag was measured to be slightly more than 18 mm. An example of this bagging technique is shown in Figure 8.

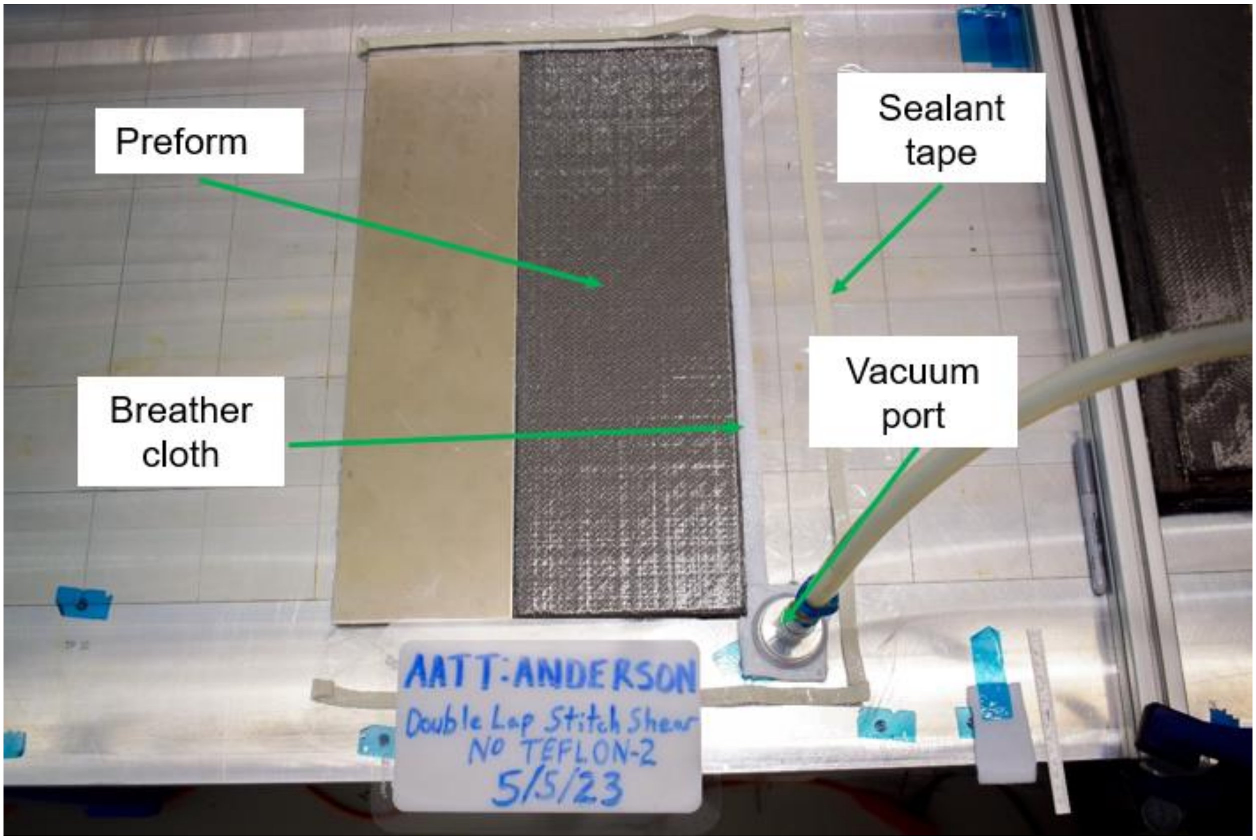

Figure 8. A double-lap shear preform under temporary vacuum consolidation in an envelope-style vacuum bag.

The preform and bag assembly were moved into the stitching fixture while under vacuum. With the vacuum pump running, the preform was stitched through the bag, completing one row of stitches equivalent to those shown in Figure 6. At this point, the bag was compromised, but the continuous flow from the vacuum pump maintained a reduced preform thickness that allowed for the completion of two more rows of stitches. Given the high rate of fluctuation of the vacuum pump gauge during continuous stitching, an accurate recording of the gauge reading could not be made. However, increasing the vacuum pump flow after completion of a continuous row of stitches resulted in a stable gage reading of 15 in. Hg or 50.8 kPa between continuous stitching operations. An image of the stitching procedure is shown in Figure 9.

Figure 9. A temporarily vacuum consolidated preform being stitched.

After stitching was completed, the preform and vacuum bag were removed from the stitching fixture and the vacuum pump was removed from the vacuum bag assembly. Significant portions of the vacuum bag were removed using scissors. Small pieces of the vacuum bag remained on the preform, trapped by the lateral portion of the stitches. These pieces were removed with tweezers, and the preform was carefully inspected on both sides for remaining vacuum bag pieces. When it was determined that all vacuum bag pieces had been removed, the specimen was inspected for stitch quality. Stitch quality using this method was determined to be acceptable. A completed stitched specimen is shown in Figure 10. A complete example process for temporarily vacuum bagging a preform for stitching is provided in Appendix A.

Figure 10. A completed dry specimen stitched under temporary vacuum consolidation after removal from vacuum bag.

V. RESULTS AND DISCUSSION

The temporary vacuum process described herein allowed for a reduction in preform thickness from a nominal stack thickness of 30 mm to a temporarily consolidated thickness of 18 mm, representing a 40% reduction in thickness. This reduction is comparable to the expected thickness associated with the completion of consolidation during the VARTM infusion process. Four double-lap shear specimen preforms were stitched using this method, resulting in stitched preforms suitable for tensile testing. It should be noted that once the vacuum was removed from the vacuum bag, the preform returned to its nominal thickness where it was not held in place by stitches. The expansion of the preform associated with removal of the vacuum resulted in high tensile stress in the thread but did not result in any observable damage to the thread or the preform.

VI. CONCLUSION

The described process is a promising method of manufacturing stitched composite preforms for which a high nominal thickness is desired. Preforms with an unconsolidated nominal thickness greater than the gap between the presser foot and the base plate or greater than the needle stroke length may be stitched using this process. This method may also be used to minimize through-thickness stitch length or increase stitch tension without requiring increased tension in the stitching thread. Further developments may include identifying an improved bag material, other modes of stitching such as single-sided stitching, or an exploration of the maximum number of stitches that can be completed using this process before the vacuum is insufficient to maintain the consolidated thickness.

VII. REFERENCES

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APPENDIX A. TEMPORARY VACUUM CONSOLIDATION OF DRY PREFORMS FOR STITCHING

A temporary vacuum consolidation of dry preforms for stitching process will be described in stepwise fashion in this Appendix. The materials that are required and notes are listed in Table A1.

Table A1. Required Materials and Notes.

Item	Quantity or Notes
Dry Fiber Preform	
Preform Tooling as Necessary	
Vacuum Bag Material	Infusion Release Film Suggested
Sealant Tape	Low Temperature ¼ in. Sealant Tape Suggested
Breather Cloth	
Vacuum Pump	
Vacuum Pump Attachments as Necessary	
Stitching Fixture	
Stitching Head	Single Needle Head

Step 1 Prepare Dry Fiber Preform, Tooling, and Bagging Material
Materials in this step: Preform, Tooling, Bagging Material.

A. Cut vacuum bag material such that dry fiber preform and all necessary tooling can be enveloped. Ensure sufficient material for placement of breather cloth, sealant tape, and any through-bag vacuum attachment equipment.
B. Place preform and tooling layup on vacuum bag material offset from center such that the bag material can be folded to completely cover the preform and tooling. See Figure A.1 for example tooling and preform layup.

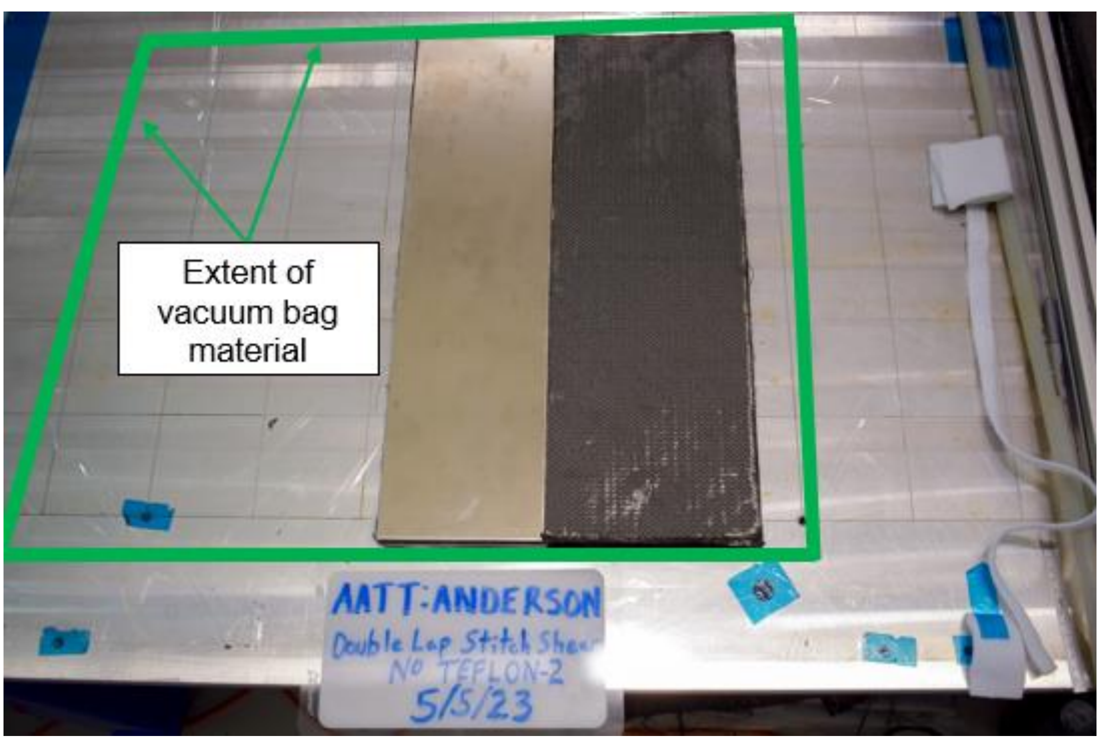

Figure A.1. Representative preform and tooling layup on vacuum bag material. Edges of vacuum bag material indicated by light green lines for clarity.

Step 2 Seal Vacuum Bag
Materials in this step: Results of Step 1, Sealant Tape, Breather Cloth, Any Vacuum Attachments to Remain in Bag.

A. Apply sealant tape to one half of the vacuum bag.
B. Place breather cloth along outer edge of preform and tooling stack and beneath vacuum attachment. See Figure A.2 for detail.

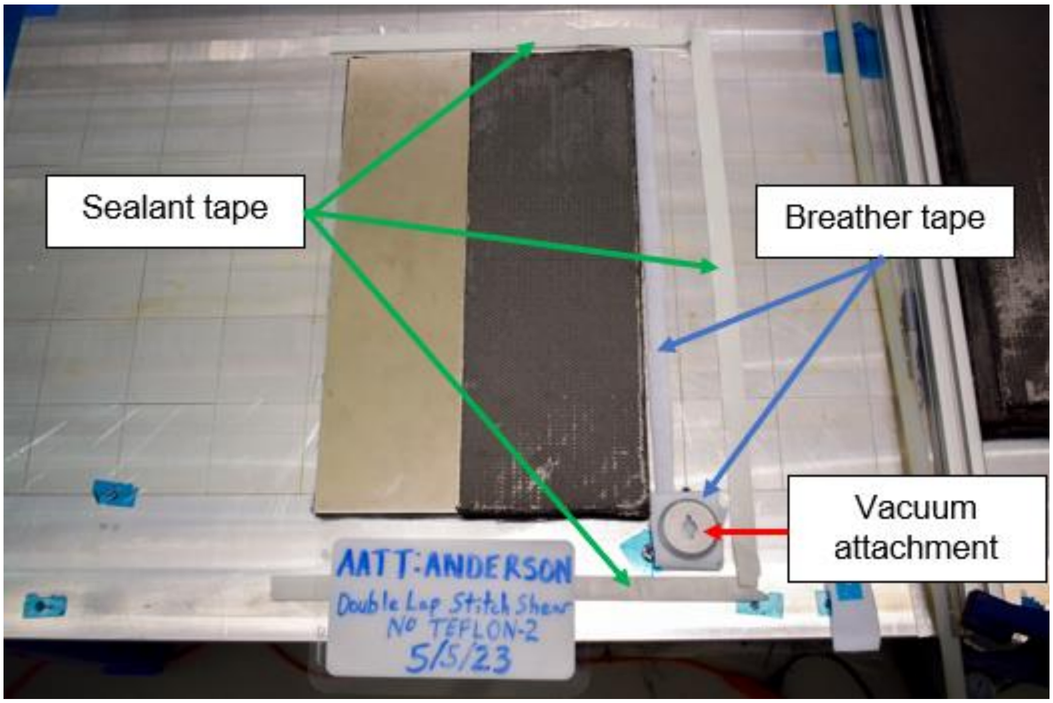

Figure A.2. Placement of sealant tape, breather cloth, and vacuum attachment.

C. Remove paper backing from sealant tape and carefully fold remaining vacuum bag material over preform stack, breather cloth, and vacuum attachment. Press bag against sealant tape to create an air-tight seal. Cut a small slit to allow for vacuum attachment to pass through bag and interface with in-bag attachments. See Figure A.3 for detail.

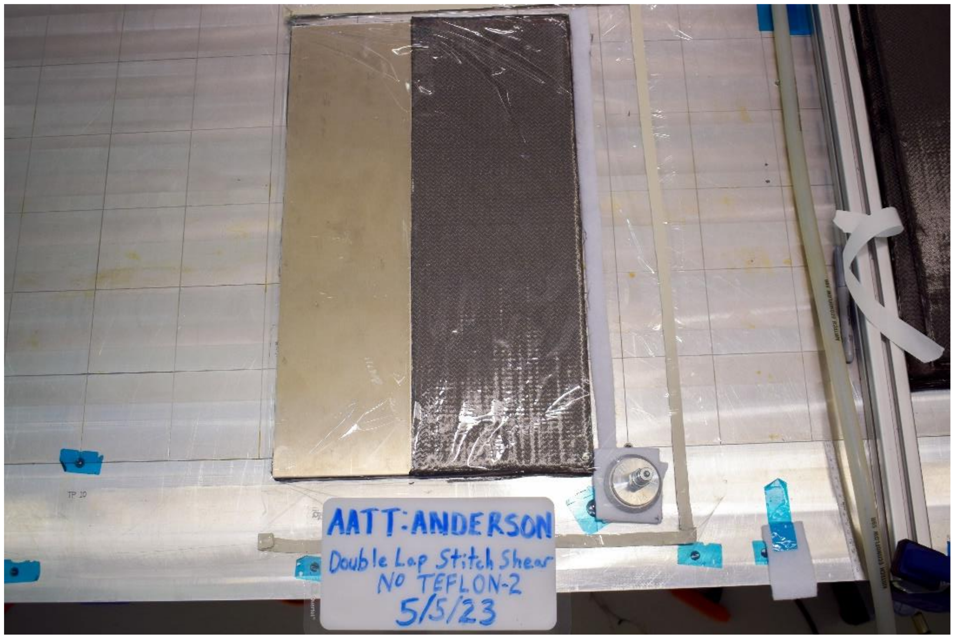

Figure A.3. Sealed vacuum bag with vacuum attachment installed.

Step 3 Apply Vacuum

Materials in this step: Result of Step 2, Vacuum Pump, External Vacuum Attachments

A. Attach vacuum pump to vacuum attachment.
B. Turn on pump to maximum pressure differential. Allow 2-5 minutes for complete air evacuation from bag. See Figure A.4 and A.5 for detail.
C. Check for leaks in vacuum bag and repair if necessary.

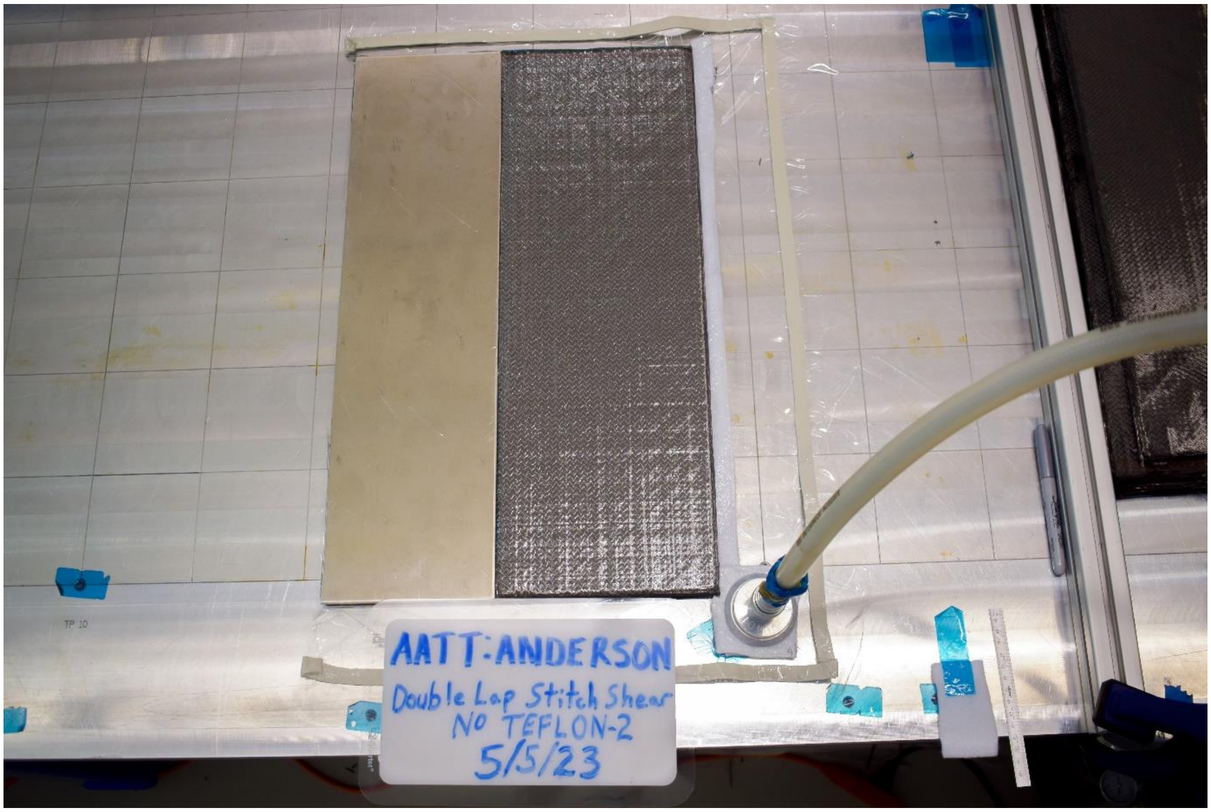

Figure A.4. Vacuum bag assembly with vacuum applied.

Figure A.5. Example vacuum pump gauge reading.

<u>Step 4 Assemble Vacuum Bag Assembly into Stitching Head</u>
Materials in this step: Results of Step 3, Stitching Fixture, Stitching Head.

A. Move vacuum bag assembly, including vacuum pump, to stitching fixture and align preform as necessary. See Figure 6.

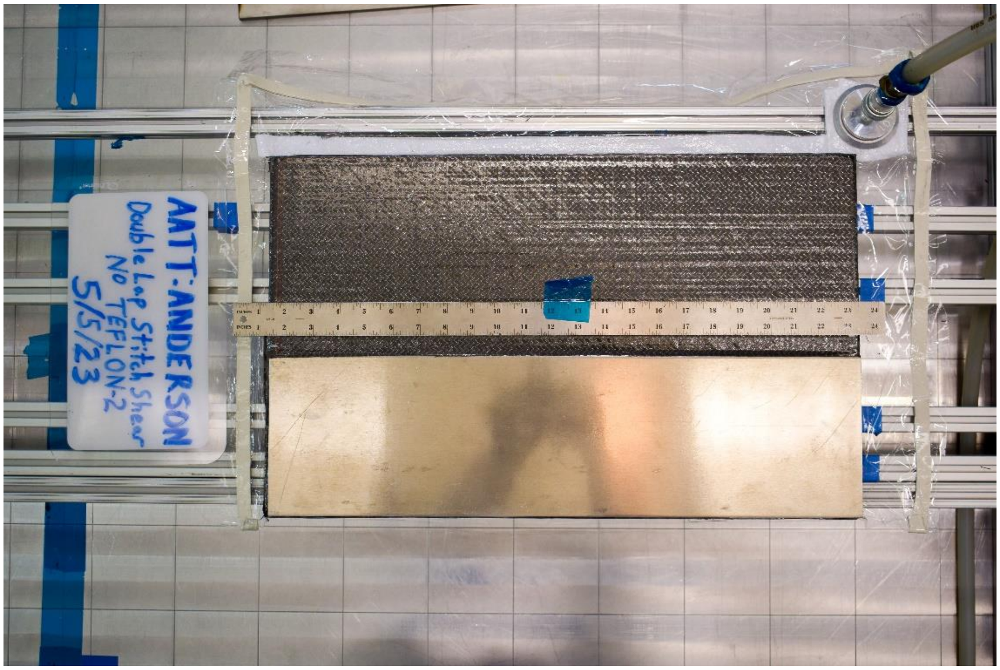

Figure A.6. Vacuum bag assembly on stitching fixture.

B. With vacuum pump running, stitch first row of stitches through both sides of vacuum bag and preform. Inspect bag and preform for stitch placement and quality. Inspect vacuum bag for damage. See Figure A.7 and Figure A.8.

Figure A.7. Stitching of Vacuum Bag Assembly.

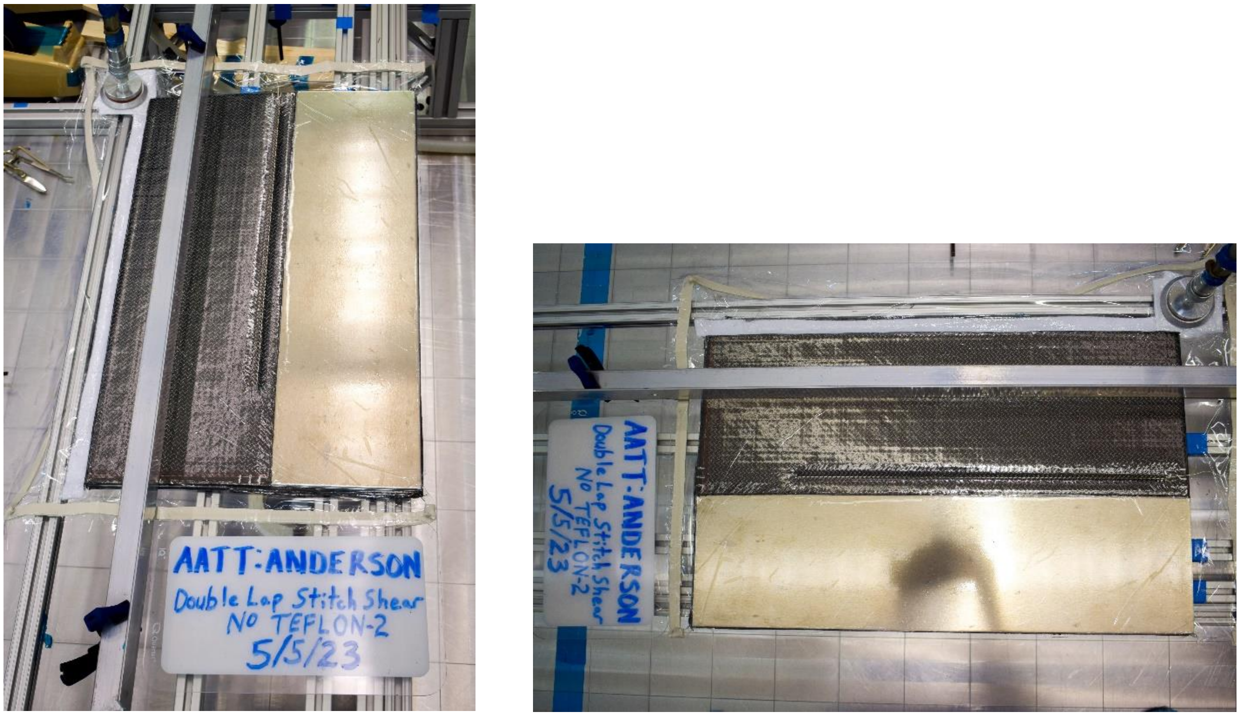

Figure A.8. First completed row of stitches.

C. With vacuum running, complete remaining stitches. Vacuum bag will be compromised, but vacuum should continue running while stitching is occurring. See Figure A.9 for example.

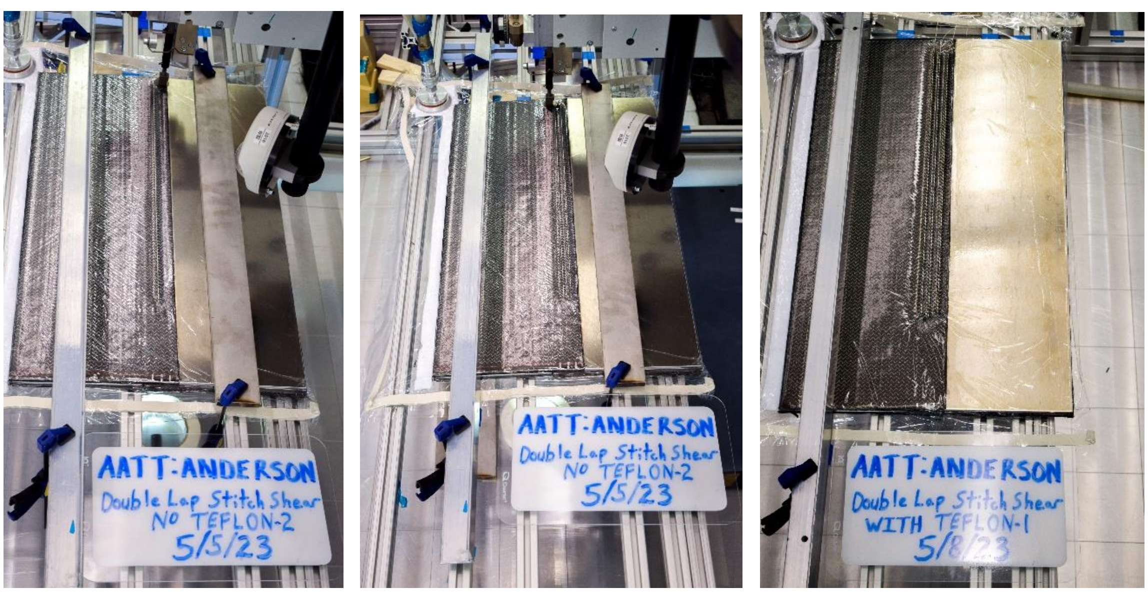

Figure A.9. From left to right: 2nd stitch, 3rd stitch, and completed stitching in fixture under vacuum.

Step 5 Removal of Preform and Completion

Materials in this step: Vacuum Bag Assembly, Tweezers (optional).

A. Turn off Vacuum pump and disengage external vacuum attachments.
B. Remove vacuum bag assembly from fixture.
C. Tear or cut vacuum bag material to remove preform and tooling.
D. Inspect both sides of preform for remaining bag material. Bag material is often trapped beneath the lateral portions of stitches and may be tucked into stitches. This material may be removed with tweezers. A completed stitched preform is shown in Figure A.10.

Figure A.10. Completed stitched preform.

The process temporary vacuum consolidation of dry preforms for stitching is now complete.