# AUTOMATED PLY-BY-PLY LAMINATION AND IN-SITU CONSOLIDATION OF DRY CARBON FIBER NON-CRIMP FABRICS FOR HIGH-RATE AIRCRAFT MANUFACTURING OF STRUCTURAL AIRCRAFT COMPONENTS

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## ABSTRACT

NASA's Hi-Rate Composites Aircraft Manufacturing (HiCAM) program addresses market needs to advance structural aircraft composite manufacturing technologies to significantly increase production rates. Dry, non-crimp fabric (NCF) carbon materials infused with advanced resin systems offer a promising solution to these manufacturing demands. Northrop Grumman's Automated Stiffener Forming (ASF) technology has been adapted for ply-by-ply, in-situ processing of NCF materials. The modular ASF process accommodates flexibility in the laminate stacking, while allowing for ply drops, ply additions, and yaw, pitch, and roll in the laminate geometry. To adapt the ASF process for NCF materials, heating technologies and roller compaction processes were designed and tested on representative structural aircraft part geometries. Key success criteria for the ASF process with NCF materials is forming quality and preform compaction. Trials were performed with multiple NCF materials: unidirectional up to quad-axial formats. The NCF constituents, veils, stitching, and binders, were evaluated with the ASF process. The material performance in the ASF process and the resulting preform quality are presented.

Keywords: dry carbon fiber materials, non-crimp fabrics, resin infused composites, automated stiffener forming
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# 1. INTRODUCTION

Commercial aircraft market growth projections demand that manufacturing rates for Next-Generation aircraft significantly increase to at least 80 aircraft per month. This rate increase forces the industry to improve on and implement new manufacturing methods for aircraft structures. One solution to the manufacturing challenge is to fabricate integrated wing skins, spars, and fuselage frame components via a dry fiber/resin infusion method. This method will require that the dry carbon fiber materials used in these structural components – Omega and T-Stringers, C-Spars, and Z-Frames – are preformed to shape prior to infusion. These structural components vary in length and make up a large number of the structural components in an aircraft. Next-gen factories must rely on automated dry-fiber preforming technologies to meet 80 aircraft/month. Northrop Grumman has adapted their Automated Stiffener Forming technology to process various carbon, dry-fiber, non-crimp fabric (NCF) materials. Each NCF material has its own unique construction and the ASF process must be tailored for each NCF to manufacture dry preforms. The interaction of the NCF construction with the ASF process was evaluated to understand the processing parameters for each material to manufacture well consolidated preforms. The material performance during the ASF process and resulting preform quality are discussed.

## 1.1 Automated Stiffener Forming

Northrop Grumman's Automated Stiffener Forming (ASF) technology is currently being adapted to form and consolidate dry fiber stiffener preforms for resin infused aircrafts structures. ASF technology is used in production today to make composite stiffener components from thermoset materials. [1] For thermoset prepreg materials, ASF is a mature technology proven in a production environment. ASF technology for dry fiber forming is currently being matured with the goal to demonstrate capability for manufacturing aircraft stiffeners at high rates (80 aircraft/month).

The ASF process utilizes material delivery heads and forming/compaction modules to automatically place and consolidate laminates ply-by-ply without the need for intermediate compaction steps, thereby increasing manufacturing rate and decreasing cost. The ply-by-ply nature of the ASF process allows for excellent conformance and compaction of the materials to the mold geometry. ASF machines can form various cross sections, including: Omega, T, C, and Z.

*Figure 1: Automated Stiffener Forming Machine (ASFM) Used for Production Thermoset Stringers*

The ASF process can be described as a ‘progressive roll forming’ approach to laminating and compacting structural aircraft components such as stringers, frames, and spars. The machine dispenses dry NCF materials directly onto the forming mold from the material roll. Multiple different material formats, of varying areal weight and orientation, can be dispensed by the ASF machine. As the material is dispensed, rollers and other compaction features follow behind forming and compacting the material to the part geometry. Figure 2 is a conceptual diagram of the ASF progressive roll forming process. Figure 3 shows one configuration of the progressive forming rollers compacting the NCF laminate.

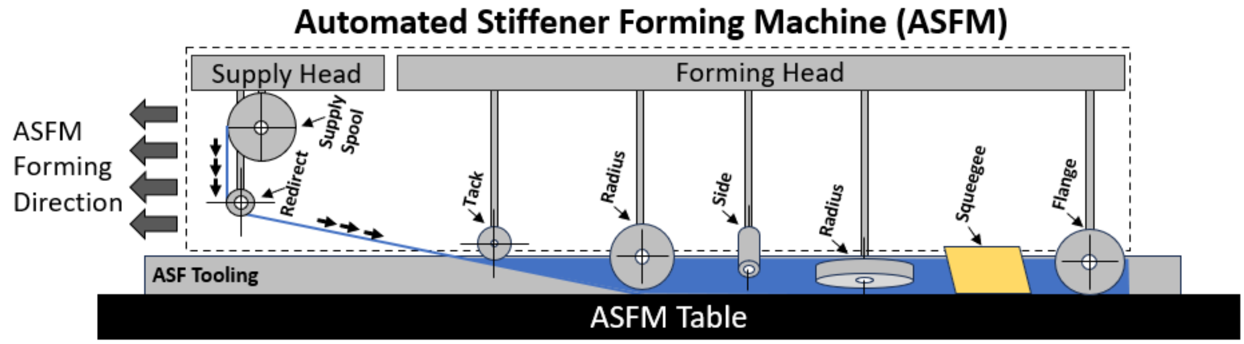

*Figure 2: ASF Progressive Roll Forming Conceptual Diagram*

*Figure 3: ASF Progressive Forming of an NCF Omega Stringer*

## 1.2 NCF Material Considerations for Automated Forming Processes

NCFs can be a single layer or multi layered stacks of carbon fiber oriented at various angles and held together with stitching. The stitching can be a nylon or thermoplastic fine thread capable of holding the ply stack(s) together for ease of cutting and handling. Many NCF constructions include a binder that, when heat activated, further stabilizes the ply stack. Stitch type, density of stitch, and stitch tension play a role in the fabrics ability to conform to complex geometry.

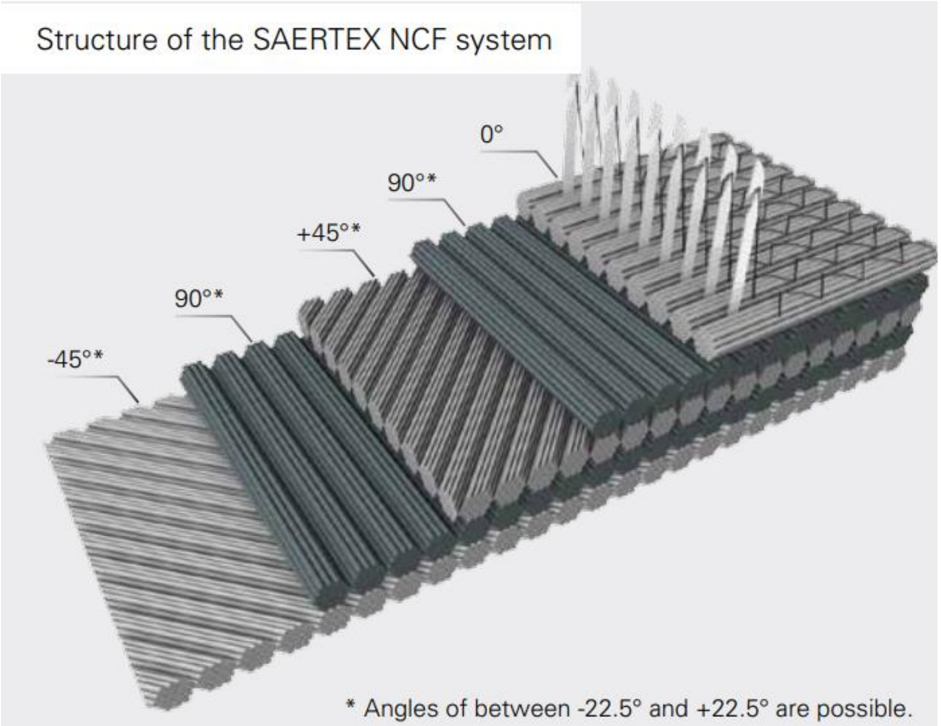

*Figure 4: Saertex Quad-axial NCF Construction Diagram [2]*

Forming and consolidation rates are highly dependent upon the material construction. For instance, to consolidate the materials into a robust preform, the binder and/or veil must be heated to activate and adhere the plies together. The binder and/or veil materials activation temperatures drive the heat requirements for the forming process. Thicker, heavier material formats, like quad axial NCFs (see example in Figure 4), heat more slowly than a one or two ply unidirectional (UD), lightweight material. Similarly, the heavier multi-axial NCFs can require more care during the forming step to avoid wrinkling. The forming rate reductions of multi-axial NCFs are offset by the benefit of multiple orientations combined in a single layer of NCF. This results in fewer machine passes to place and form the full laminate stack, reducing stiffener preform build time.

## 2. EXPERIMENTATION

### 2.1 NCF Materials

NCF materials from Saertex, Hexcel, and Teijin were evaluated. These NCFs had varied constructions, including: single layer UD, biaxial, triaxial, and quad axial formats. Each manufacturer has their own approach to building the NCF materials. The material and weight of the stitching thread and veil vary between products. Some of the NCFs include a light resin binder. The melt temperatures of these constituents drive the processibility of each NCF via ASF. The construction details of many of the NCFs are proprietary and not publicly available at this point. Table 1 shows the NCF materials evaluated and the general construction of each NCF. All the materials included veil and stitching in their construction. The Teijin NCFs and the Saertex triaxial NCF included a light resin binder.

*Table 1: NCF Materials Evaluated with ASF Process*

| **Manufacturer** | **Format** | **Carbon Fiber Areal Weight (gsm)** | **Binder and/or Veil in Construction** |
|---|---|---|---|
| Hexcel | UD | 240 | No binder or veil |
| Saertex | UD | 240 | Binder |
| Teijin | Biax | 480 | Binder and veil |
| Hexcel | Biax | 300 | Veil |
| Saertex | Triax | 817 | Veil |
| Hexcel | Quad | 760 | Veil |
| Saertex | Quad | 760 | Veil |

### 2.2 NCF Compaction Trials on Flat Panels

Tests were conducted on 254 mm x 254 mm (10 in x 10 in) NCF laminates of varying thickness ranging from 2.54 mm (0.1 in) to 15.3 mm (0.604 in) to determine the processing parameters required to consolidate the laminates to net thickness. The dry, NCF laminates were heated and compacted at a range of temperatures and pressures then measured to determine the bulk factor of the compacted laminate. Laminate bulk factor was used as the indicator of panel consolidation quality. This value is calculated as a percentage by taking the difference between the measured thickness and the theoretical thickness and dividing the result by the theoretical thickness. The theoretical thickness is calculated using the ply count and the manufacturer provided consolidated ply thickness (CPT).

Each flat panel was compacted while heated then cooled to room temperature to set the panel thickness. Temperatures ranged from 23 °C (70 °F) to 180 °C (356 °F) in the trials. Panels were compacted under a vacuum bag only and in a press with varied clamping pressures. Each panel was held at temperature for a timed duration before it was cooled to room temperature. The preformed panel thicknesses were measured at room temperature immediately after the compaction trial and periodically afterward to determine if and how much a preform would deconsolidate over time.

### 2.3 NCF Stringer Preforming Via ASF

Using lab ASF equipment, dry fiber preforms of various stiffener geometries, representative of production aircraft structural components, were laminated with various NCF material formats. The processing parameters determined from the flat panel compaction trials were used in the automated lamination process. Omega, T, C, and Z cross-section geometries for aircraft structures were trialed. These structures ranged in length from 1 meter up to 17 meters. Preforms of long stringers that would stiffen a wing or fuselage skin were formed with the lab Automated Stiffener Forming Machine (ASFM). Curved sections, representative of a fuselage frame, were also formed with the lab ASFM.

The lab ASFM is used for process development activities. It can be configured for different stringer geometries. The forming rollers and heating systems can be modified for each stringer geometry and NCF material. To ensure good forming quality, the forming roller configurations for each stringer geometry were validated on prepreg materials. Since prepreg adheres to itself at room temperature, the forming roller design could be validated separate from the heating systems needed to consolidate NCF materials. Once the forming roller design had been shown to successfully form wrinkle-free laminates, the heating systems for NCF materials were implemented, tested, and refined.

# 3. RESULTS

## 3.1 NCF Compaction Results

For each NCF tested, processing parameters: heat and pressure were determined specific to each material system. Both temperature and pressure drove the final part thickness. A panel could be compacted to the net thickness with pressure alone but, without heat, when the pressure was removed the panel deconsolidated. When the panel was heated to the appropriate process temperature, but inadequate pressure was applied, the panel did not achieve the desired bulk factor. Table 2 displays the results from the flat panel consolidation trials showing the relationship between processing pressure and resulting bulk factor. Figure 5 illustrates the relationship between temperature and the final preform thickness when processed at a specific pressure.

*Table 2: Consolidation Trials on NCF Laminates: Constant Temperature, Varying Pressure*

| NCF Material | Consolidation Temperature (°C / °F) | Consolidation Pressure | Resulting Bulk Factor (%) |
|---|---|---|---|
| Teijin Biaxial 0/90 | 129 / 265 | Low | 16.0 |
| Teijin Biaxial 0/90 | 129 / 265 | High | 14.5 |

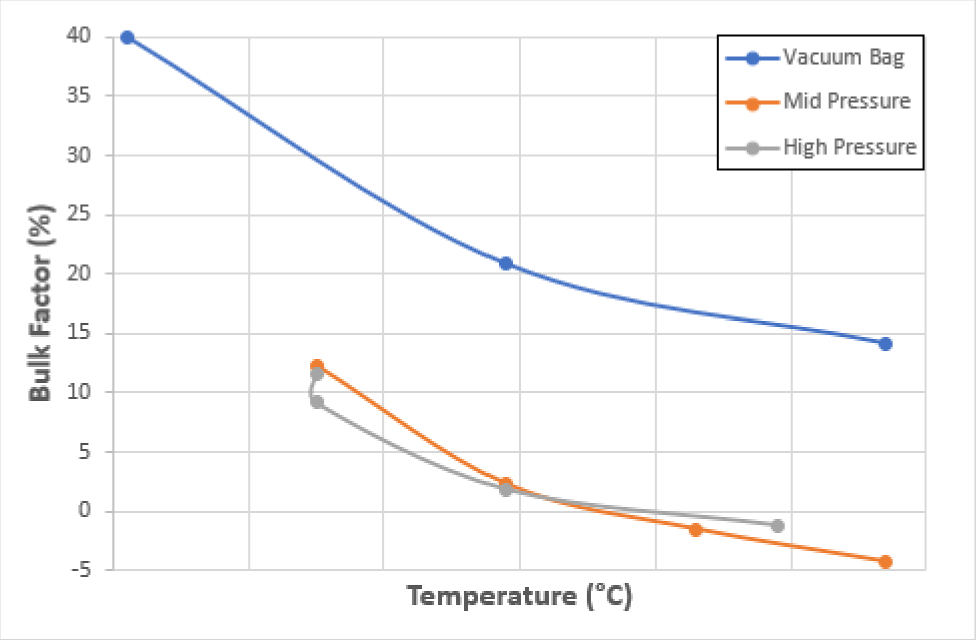

*Figure 5: Consolidation Trials on Quad NCF Preforms: Constant Pressures, Varying Temperatures*

It was found necessary to cool the consolidated panels before removing the panel from the test setup. If the pressure on the panel was released while it was hot, it immediately deconsolidated. The hold duration at temperature was found to have little effect on the panel bulk factor. Once the panel had reached the processing temperature, holding at this temperature for longer than a minute did not show any improvement to the panel's consolidation level. The orientations in the NCF construction were found to have no effect on the consolidation results.

## 3.2 Stiffener Preforming Results

Stringer preforms were manufactured with NCF materials using the ASF process. While the specific processing parameters for each material varied, the resulting preforms all were successfully formed and compacted to within 10 % of the final cured part thickness with no wrinkles.

### *3.2.1 T-Stringer Preforms*

Constant cross-section, 0.6 meter (2 ft) long T-stringers were formed with quad axial NCF (See Figure 6). To make the T-Stingers, two L preforms were formed then brought together to create a T. After the T-Stringer had been formed to the appropriate compaction level it was moved to an ultrasonic trimming station where the perimeter was trimmed to the final part dimensions. Numerous T-Stringer preforms were fabricated and demonstrated the feasibility of compacting a complex NCF laminate to near net thickness. The thicknesses of these T-Stringers were just below the designed net thickness averaging a -2 % bulk factor. These preforms were stable over time, showing no measurable deconsolidation over multiple weeks.

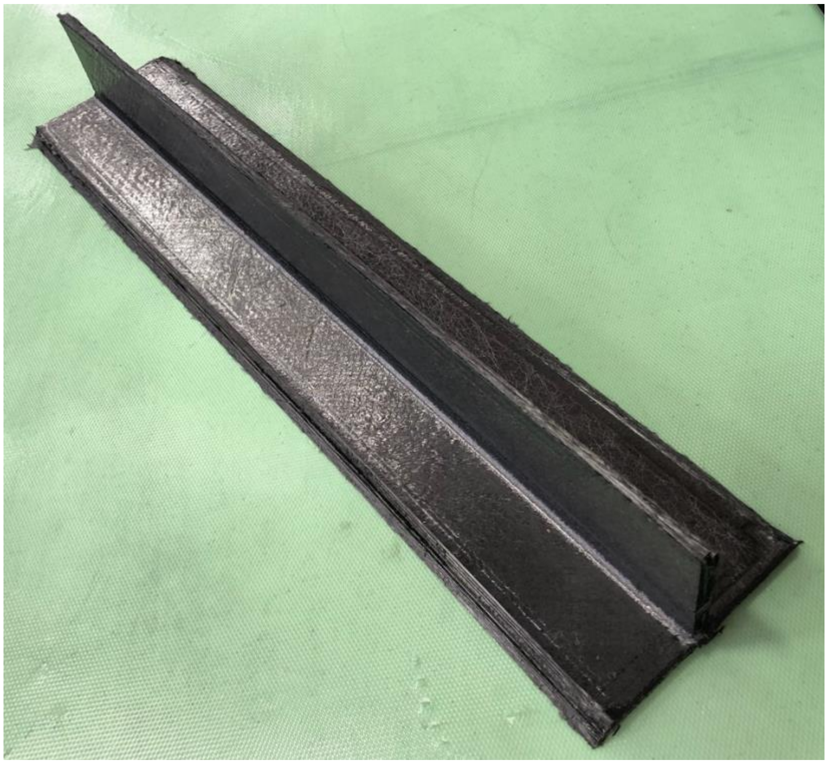

*Figure 6: T-Stringer Preform Made from Quad NCF*

### *3.2.2 C-Spar Preforms and RTM*

C-Spar preforms, 1.5 meters (5 ft) long and just over 0.3 meters (12 in) wide were formed via the ASF process from Saertex, Hexcel, and Teijin NCFs. The laminate tapers from nearly 18 mm (0.7

in) at the thick end, down to nearly 8 mm (0.3 in) at the thin end. Quad axial and biaxial NCFs were successfully formed and consolidated to near net thickness with the final C-Spar preform demonstrator having a global consolidation level of 0.25 % bulk factor.

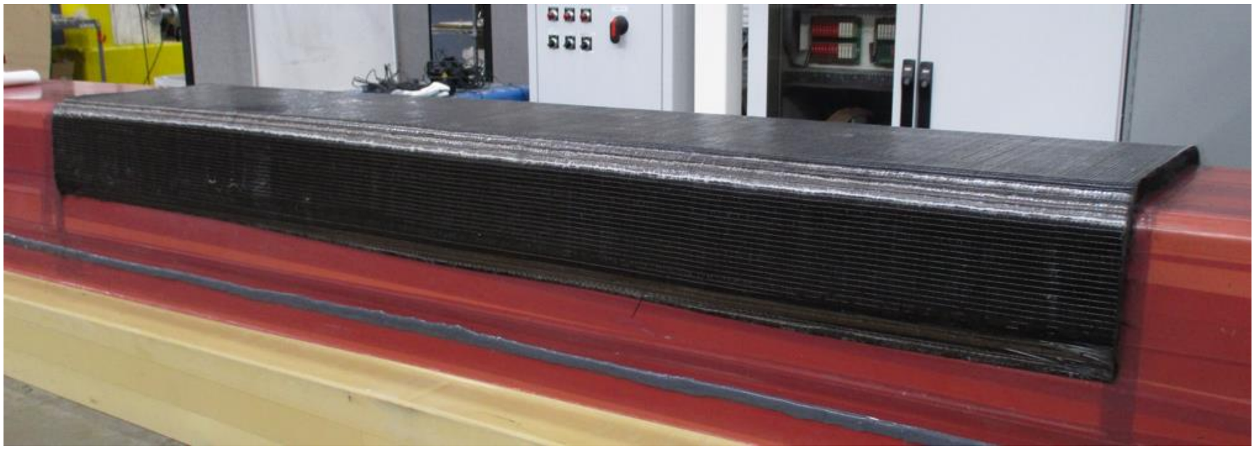

*Figure 7: Teijin Biax NCF – Impressive Part Finish and Forming Quality on a Thick Spar Laminate*

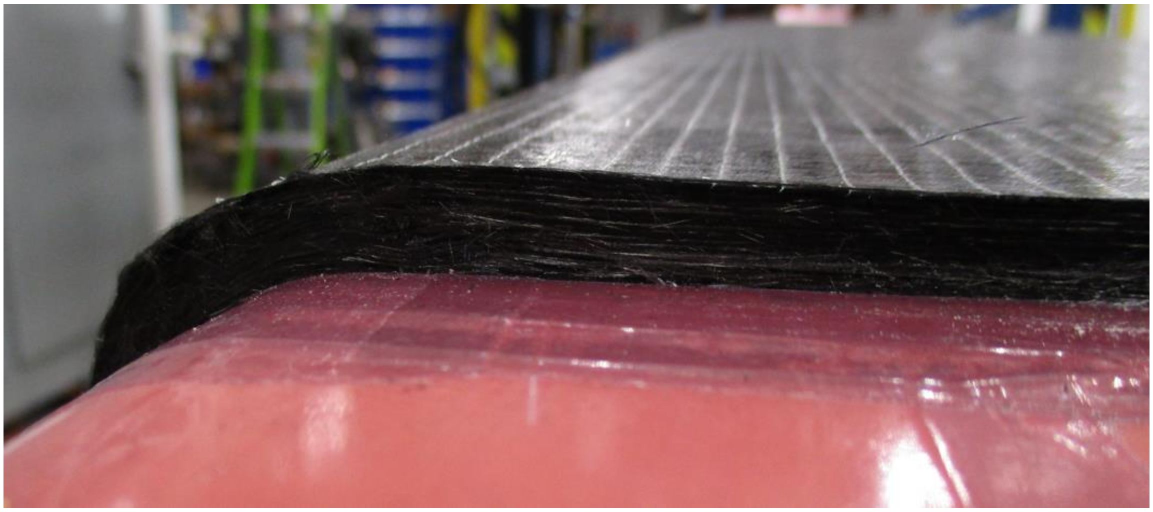

*Figure 8: C-Spar Laminate Compacted to Net Thickness of 8 mm*

The ability to consolidate the thick laminate of the C-Spar is a key enabling technology for net-shape structures infused via RTM processes. To load the preform into the closed mold used in the RTM process, the bulk factor of the preform must be tightly controlled. If the preform is too thick the mold will be difficult to close. During the mold closing process, a thick preform could be wrinkled or the mold could be damaged. A preform that is too thin may not deconsolidate during the RTM process and the finished part could have regions of resin richness. The preform quality and consolidation level directly impact the final part quality. To validate the compaction level and therefore the processing parameters of the ASF process, three C-Spar preforms were infused in a closed mold with an RTM process. The results of the RTM trials showed the ideal bulk factor for the thick C-Spar laminate to be between 0 % and 5 % - a consolidation level that can easily be achieved via ASF.

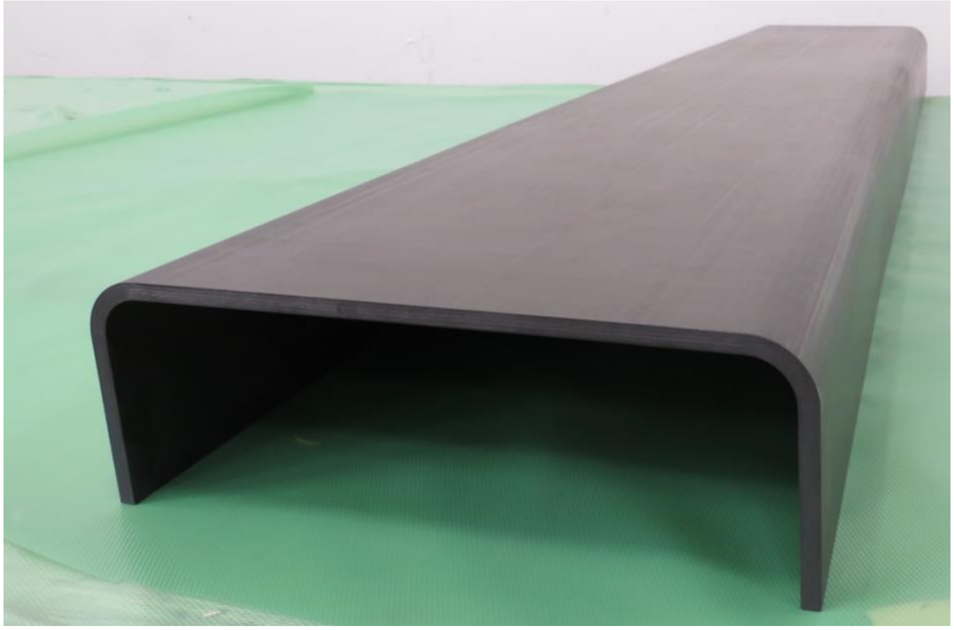

*Figure 9: C-Spar Demonstrator Part:  The Preform was Manufactured with the ASF then RTM Infused in a Closed Mold*

## 3.3  Interactions Between the NCF Material Construction and the ASF Process

The following sub-sections describe the observations of how the materials performed with the ASF process.

### *3.3.1  Format: UD, Biax, Triax, Quad*

The greatest difference observed between the different NCF formats was the amount of care required to form and consolidate each layer without creating wrinkles in the material.  The lighter areal weight NCFs conformed easily to the stringer contours.  The biaxial NCFs exhibited excellent formability with the ASF process.  Figure 10 shows a biaxial NCF ply being formed and compacted with the ASF machine.  The material draped well to the stiffener contour and conformed well to part features such as, radii and joggles, without wrinkling (see Figure 11).  Because each ply was pristine after deposition and forming, each subsequent ply in the laminate was also pristine.  This resulted in thick laminated preforms with superb quality.  Figure 11 is an example of a biaxial NCF preform made via the ASF process that is greater than 17 mm thick.

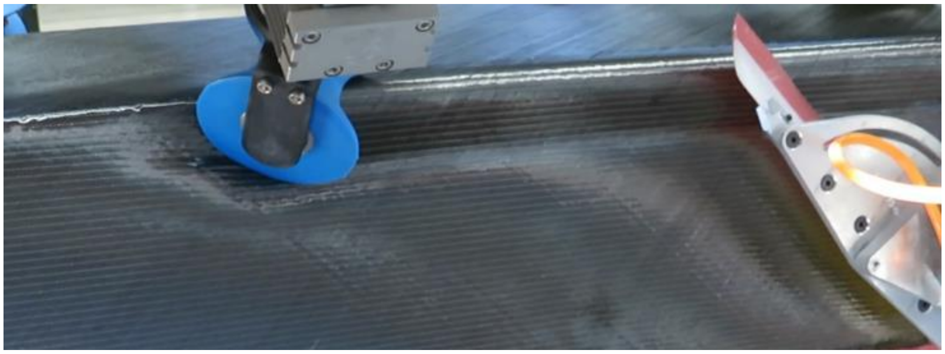

*Figure 10: ASFM Forming a Biaxial NCF on a C-Channel*

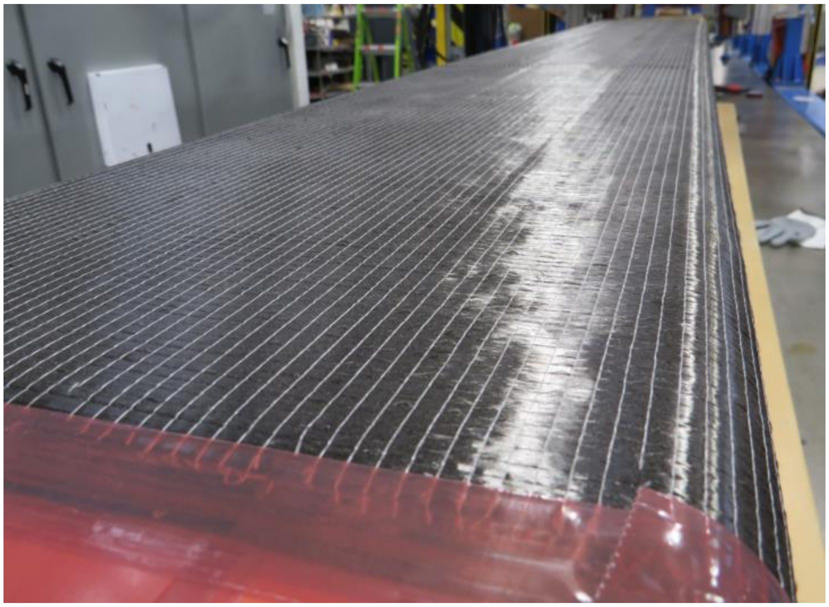

*Figure 11: Teijin Biax NCF Showing Excellent Conformance to the Radius*

The triaxial NCF tested also exhibited excellent formability to high contour geometries. The Saertex triaxial NCF with a +45/90/-45 construction proved to conform very well to the curved geometry of a representative fuselage frame structure. This NCF construction enabled the fibers to follow the curved shape without wrinkling. Figure 12 illustrates the forming quality of the triaxial NCF on a frame geometry.

*Figure 12: Saertex Triaxial NCF Formed on a Curved Z Geometry*

Fuselage frames with the 0° fibers following the curvature of the part can be challenging to form without fiber buckling. Because the inside flange radius is tighter than the outer flange radius, the 0° fibers must shear past each other to conform to the frame curvature. For wide, UD prepreg tapes, the resin in the prepreg prevents the fibers from shearing and the ply will not follow the curvature of the frame without significant deformation. The nature of the UD NCFs allows for individual tows to slide past each other to follow the radius of the frame. The amount the 0° tows can shear past each other is dependent upon how tightly the NCF is stitched. A loose stitching will allow for greater tow shearing. See Figure 13 for an illustration of the tow shearing effect.

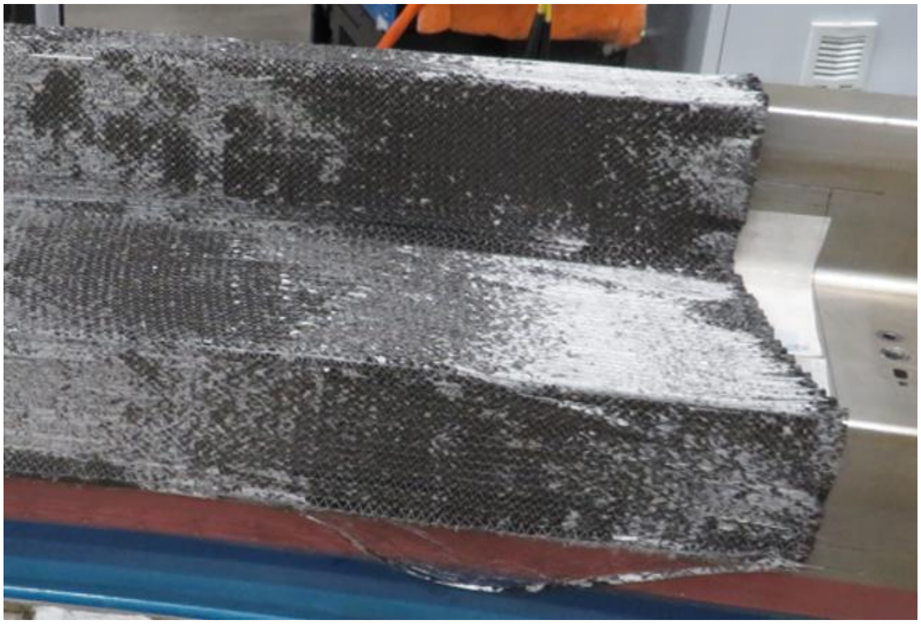

*Figure 13: Saertex UD - 240gsm, Tow Shearing and Compliance to a Curved Frame Geometry*

Extra care was required with the quad axial NCFs to avoid buckling of the fibers within the NCF stack. The heavier materials also required careful heat application to penetrate through the thickness of the NCF and adequately soften the veil to adhere the NCF layers together in the laminate, yet not damage the stitching required for effective material handling/placement.

### *3.3.2 Stitching and Veil*

The melt temperatures of the stitching and veil impact the forming process. It was found that the stitching would stabilize the NCF material during material dispensing and the initial forming steps. Once heat was applied and the veil softened, the veil adhered the NCF layers together and stabilized the compacted laminate. During the forming process, if the stitching material melted at a lower temperature than the veil material, the stitching could be damaged before the veil softened and stabilized the fibers (see Figure 14 & Figure 15). This effect also occurred with the NCF materials with a fine stitching thread. It was found that the stitching needs to stay intact to stabilize the NCF until the veil can soften and stabilize the laminate. When the stitching was damaged before the veil softened, the fibers in the NCF would distort. The stitching could be damaged either from too much heat or from the pressure and friction of the forming rollers.

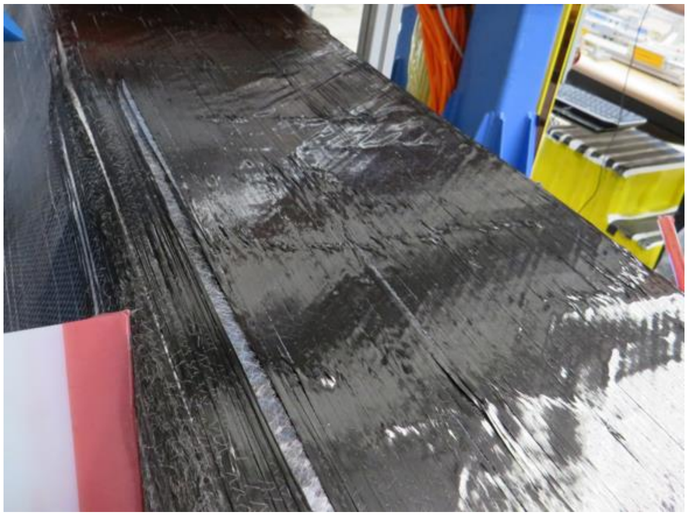

*Figure 14: NCF Stitching Melted before Veil softened resulting in Fiber Distortion*

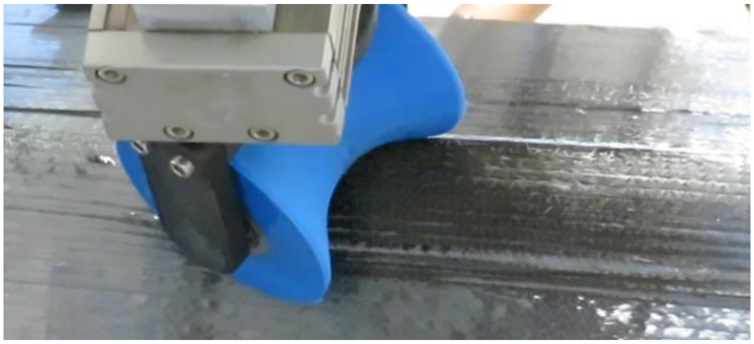

*Figure 15: Stitching Breaking/Melting Before Activation of Veil Causing Disturbance in Fiber Alignment*

A robust stitching material was found to be optimal for the ASF process. The robust stitching held up to the heat needed to soften the veil and the pressure from the forming rollers. While the ASF process can accommodate NCF with fine stitching, extra care is needed to prevent damaging the stitching. The following figures illustrate the different results of the same process parameters on NCFs with robust and fine stitching. Figure 16 shows a preform made with an NCF constructed with a robust stitching while Figure 17 shows a preform made with fine stitching. Both preforms were manufactured with the same ASF forming parameters. While these two images compare the impacts different stitching can have on the preform quality, when processed with the same forming parameters, it is not meant to indicate that the NCF preform made with fine stitching is a lower quality product. Again, the ASF process can be tailored for a specific material construction.

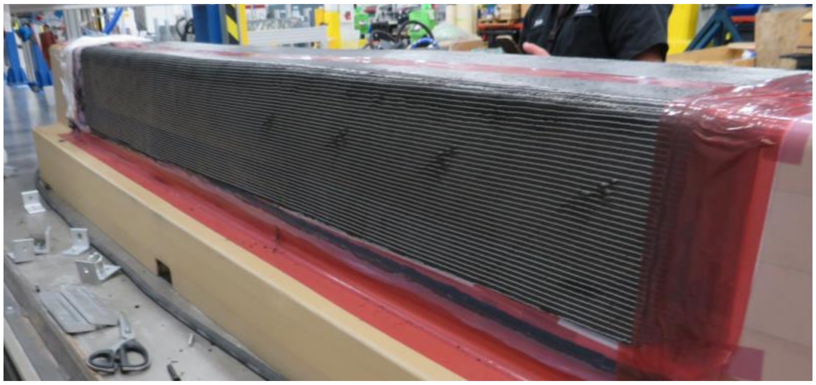

*Figure 16: Triax NCF with Robust NCF Stitching and Excellent Preform Quality*

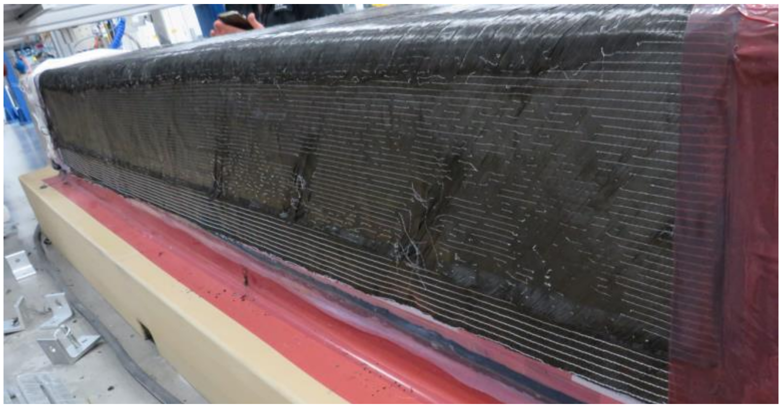

*Figure 17: Quad NCF - 760 gsm with Fine Stitching Formed with the Same Process Parameters as the Above Picture*

In order to create a stable preform, compacted to near net thickness, the veil must be activated to hold the NCF layers tightly together. As discussed above, the stitching is needed to stabilize the tows in the NCF blanket during the forming process until the veil has reached its processing temperature to adhere the blankets together. That adherence at each ply interface in the NCF stack and between NCF stacks is critical to achieving near net thickness preforms.

### *3.3.3 Binder*

The NCF materials that included powder binder (light resin powder sintered onto the interface surfaces during NCF fabrication) in their construction were shown to be compatible with the ASF process. These NCFs required lower processing temperatures than the NCFs without binder material. The activated binder adhered the NCF layers together well and kept the compacted preforms stable, enhancing forming rates.

Another benefit is that the NCF materials with binder were able to be re-worked much easier. An NCF blanket with binder could be pulled from the laminate without disrupting the preform. Conversely, the veil in an NCF, once activated, does not allow the laminate to be easily separated layer by layer. Preforms showed significant damage when an NCF adhered with veil was removed from the laminate.

# 4. CONCLUSIONS

The ASF process has been successfully modified to process dry carbon fiber NCF materials. NCF formats varying from single ply unidirectional to quad axial have been used to build stringer preforms compacted to near net thickness. T-Stringer and C-Spar preforms were manufactured via the ASF process to demonstrate the automation capability to form and consolidate NCF materials. Successful closed-mold infusions of the C-Spar preforms validated the ASF forming process parameters. Additional work forming NCF materials on a highly curved Z-Frame geometry indicate the ASF process is viable for a large family of aircraft stiffeners. Further development of the ASF process is underway to improve the manufacturing rates of dry fiber preforms, in support of high-rate composite manufacturing for future aircraft.

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