ASSESSMENT OF AUTOMATED FIBER PLACEMENT FOR THE FABRICATION OF COMPOSITE WIND TUNNEL BLADES

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ABSTRACT

Composite wind tunnel blades are frequently fabricated by hand layup of prepreg fabrics. Though well proven, this fabrication method is laborious and expensive. The study described in this paper used the Integrated Structural Assembly of Advanced Composites (ISAAC) facility at the NASA Langley Research Center to explore whether automated fiber placement (AFP) could reduce manufacturing time and cost for production of wind tunnel blades. Two blades, taken from two NASA wind tunnels, were investigated as representative geometries. Computer-aided design models of the blade surfaces were created, and AFP process planning and programming were employed to study the manufacturability of the shapes. A placement/cure tool was manufactured for the chosen blade surface from thermoplastic material using an additive manufacturing process. The present study revealed that the AFP head geometry, primarily the heater configuration of the ISAAC system, is the primary constraint that limits the ability to manufacture the selected wind tunnel fan blades using AFP.

1. INTRODUCTION

1.1 Selected Wind Tunnels

The National Transonic Facility (NTF) is a wind tunnel at the NASA Langley Research Center (LaRC) that became operational in 1984 [1]. The NTF was designed for testing of aircraft ranging from subsonic to low supersonic speeds at temperatures from -160 °C to +66 °C. The tunnel operates at cryogenic temperatures using nitrogen gas to achieve Reynolds numbers representative of these flight regimes. The NTF is driven by a set of fan blades that measure 6.0-m diameter at the tips. The wide temperature range, large fan diameter, and the high speed operation inflict large stresses on the blades. Each blade is a hollow structure that is continuous from the airfoil tip to the pin connection at the hub. The root area of the blade is enclosed in a box-like sandwich structure, called the platform, which locates it circumferentially on the hub and forms the interior aerodynamic surface of the fan section. An incomplete NTF blade is shown during fabrication in a test fixture in Figure 1a, and a complete blade is shown in Figure 1b.

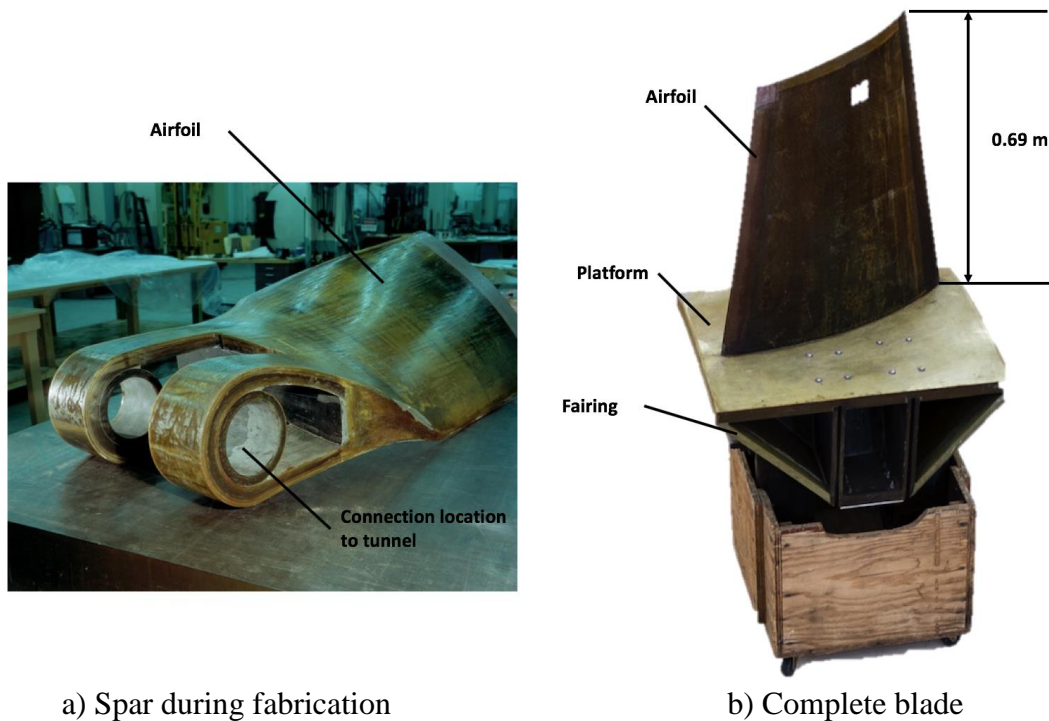a) Spar during fabrication   b) Complete blade

Figure 1. NTF blade.

The original NTF blades were fabricated from E-glass fabric/epoxy prepreg via a hand lay process. Each ply and the sandwich core were cut by hand, based on a template that defines the ply shape. The total ply count for this design is 149. Though this hand-lay process is robust, and it was state-of-the art in the early 1980s when the first NTF blades were built, it is laborious and costly.

During its operational life to date, NTF has experienced two major incidents that have resulted in damage to the blades, one incident in 1989, and a second subsequent incident. In total, three full sets of blades have been fabricated. At present, one full set is in operation, and a partial spare set exists. If a future incident results in a substantial loss of blades, the tunnel may face a long period of inoperability. A fabrication methodology for the NTF blades that is less expensive and takes fewer labor hours could significantly reduce the costly downtime associated with future blade repairs or replacement.

Ultimately, finding ways to reduce the cost of fabricating wind tunnel blades could benefit other wind tunnels, such as the NASA Ames Research Center 11-by 11-ft Transonic Tunnel (11-Foot TWT)[2]. This tunnel is a closed-return, variable-density tunnel with a fixed-geometry, and ventilated test section with a flexible wall nozzle. It allows testing at continuously variable Mach numbers of 0.2 to 1.4. The 11-Foot TWT blade was selected as a second example blade geometry for consideration in this study.

1.2 Robotic Fiber Placement Facility

The Integrated Structural Assembly of Advanced Composites (ISAAC) facility at LaRC was designed to facilitate automated fiber placement (AFP) for large structures. ISAAC was purchased to support the development of new technologies related to aerospace composites manufacturing [3]. The system is based on a Kuka Titan 1000 six-axis industrial robot, which can wield a variety of end effectors. A 12.6-m-long linear rail and a vertical rotator provide two additional degrees of freedom. AFP is a process by which thin strips of unidirectional prepreg using carbon fiber (towpreg) are placed onto a tool surface. In the case of ISAAC, the strips are 6.35-mm wide. The ISAAC AFP head holds 16 spools of towpreg, and so can place a maximum 102-mm-wide course of material. The workcell is enclosed within a clean room that provides positive control over airborne particulates and ambient temperature and humidity. A photograph of the ISAAC robotic system is shown in Figure 2.
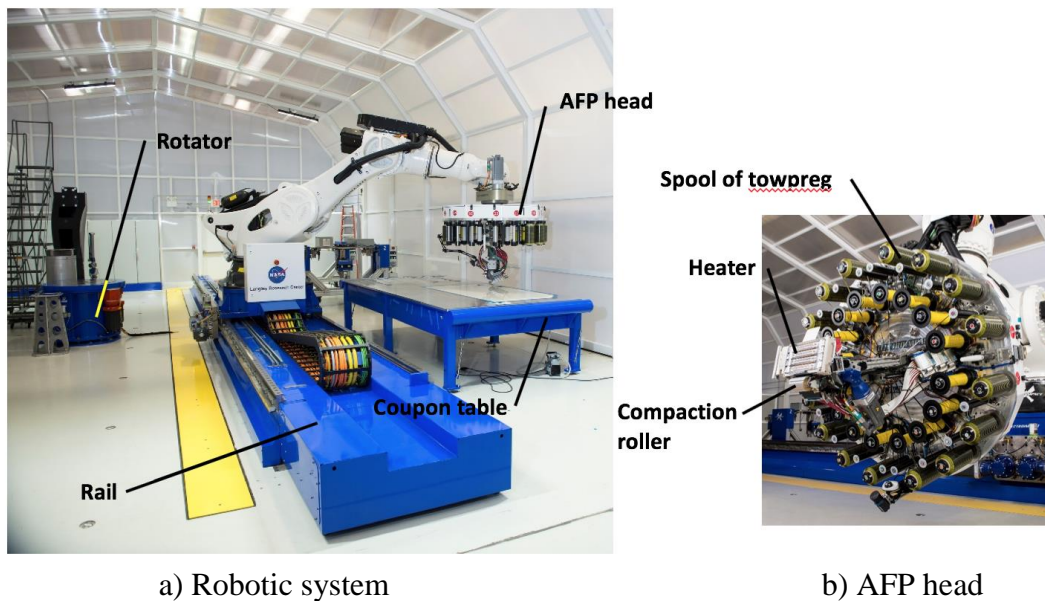

a) Robotic system   b) AFP head

Figure 2. ISAAC

1.3 Wind Tunnel Blade Manufacturing Development Project

The Preparing Researchers to Evaluate and Develop Impact–Driven Collaborative Technologies (PREDICT) project was initiated to develop an improved understanding of the NTF fan blades and to begin assessing whether advanced manufacturing methods and tools can reduce the cost and time required to fabricate blades for NTF and other agency wind tunnels. The project was carried out over the summer of 2018 by a small team working at the ISAAC facility. The end goal of the project was to use the ISAAC facility to fabricate a manufacturing demonstration unit (MDU) that incorporated geometric features that are representative of those in a wind tunnel fan blade. The NTF blade, shown in Figure 1a, was the primary focus of the project. It is a highly contoured structure that poses potential fabrication problems on ISAAC. A second blade, a prototype for the 11-Foot TWT composite blade, shown in Figure 3, was chosen as a backup in the event that the NTF blades were found to be too highly contoured to build using the current ISAAC AFP head.
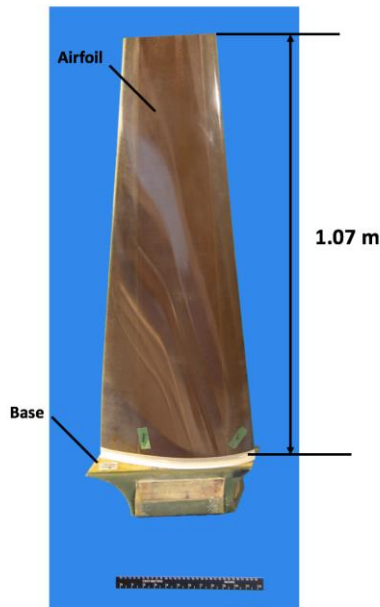
Figure 3. Ames blade.

2. BLADE MANUFACTURING STUDIES

The manufacturing development methodology consisted of several phases. First, material that was available from a previous project was selected for fabrication of the MDU. Next, part surface geometry was selected from two available fan blade concepts, and a fiber placement tool was fabricated using the selected geometry. Finally, ISAAC was programmed to place material on the surface geometry and the part was fabricated.

2.1 Materials

The PREDICT project culminated in the fabrication of a MDU. This MDU was fabricated from Toray T800H/3900-2, slit into 6.35-mm-wide towpreg and wound onto 76.2-mm diameter spools for use on the ISAAC AFP head.

2.2 Tool Geometry and Programming Trials

The ISAAC system is programmed primarily using the composite manufacturing planning software Vericut Composite Programming (VCP) [4]. The general process can be described in several steps. First, computer-aided design (CAD) geometry is created to represent the AFP tool surface and any nearby fixturing in the workcell that could restrict the robot motion. Curves are then created on the surfaces to delineate ply boundaries, and both the CAD surfaces and curves are imported into VCP. The program is then properly configured for the tool and material to be used. Courses are then programmed on the tool surface using the appropriate curves. Off-part motion, which links the end of each course with the start of the next one, is then planned. The laminate thickness is incremented, and a tool path file is then generated.

Two levels of simulation are available. VCP provides the capability to check for interference between the AFP head and the tool surface. In most programming situations, this capability is disabled because it is computationally intensive and unnecessary due to the proximity of the part with its surroundings. In the present project, the highly contoured nature of the tool surface necessitated use of collision checking. After generating the tool path file, Vericut Composite Simulation (VCS) software can be used to simulate the full kinematics of the robot and AFP head. In this case, the use of VCS was required to avoid violating the limits on the robot joint rotation, and to avoid collisions between the robot and other hardware in the robot workcell. For this part, VCS was especially useful due to the highly contoured tool surface. VCS was used to determine a location and orientation of the tool within the workcell that was reachable by the compaction roller over the full tool surface. The roller arrangement is shown in Figure 2b.

Process planning trials were performed on two tool geometries. Under the PREDICT project, resources and time were insufficient to design and manufacture a tool for use with the rotator. Therefore, the fabrication tool had to be mounted to the flat table in the ISAAC workcell. This constraint proved to be problematic because of the range of joint motion required by the robot with placement on the coupon table. The additional degree of freedom provided by the rotator would have reduced the required range of joint motion. Also, the additional space available around a tool on the rotator would have greatly reduced the risk of collision between the AFP head and the placement surface.

2.2.1 NTF Blade Geometry

Investigation of the fabrication of the original NTF fan blades determined that they were built on an internal mandrel in a complex process that involved several series of prepreg layups, cure cycles, the manufacture and assembly of numerous subcomponents, and many inspection and machining operations. The drawings for the blades were reviewed, and a decision was made to investigate the viability of AFP for fabrication of the blade's internal spar.

The spar was built on a removable mandrel early in the blade manufacturing process. It had a maximum ply count of 100 plies of E-glass fabric/epoxy prepreg. With this very thick laminate, the layup required a great deal of labor and time. Because the spar includes most of the geometric attributes of the finished blade, it was selected for the evaluation of the value of automated manufacturing processes for these blades. The general contour of the spar was derived from drawings of the NTF fan blade component as shown in Figures 4a, 4b, and 4c. Note that portions of the spar are ultimately buried inside the platform portion of the blade shown in Figure 1 and hidden by fairings which join to the adjacent blades in the assembled system. One priority of the MDU design was to include this hidden region because this complex shape was expected to lead to placement difficulties for the AFP head compaction roller. In Figure 4a, the yellow section includes the clevis where the blade is bolted to the wind tunnel hub. The section of the blade colored blue extends above a platform (not shown) into the airflow. The spar coordinate system is shown in Figure 4. The root-to-tip, or axial, direction is the Z direction and the chord, or pin, direction is the X direction.
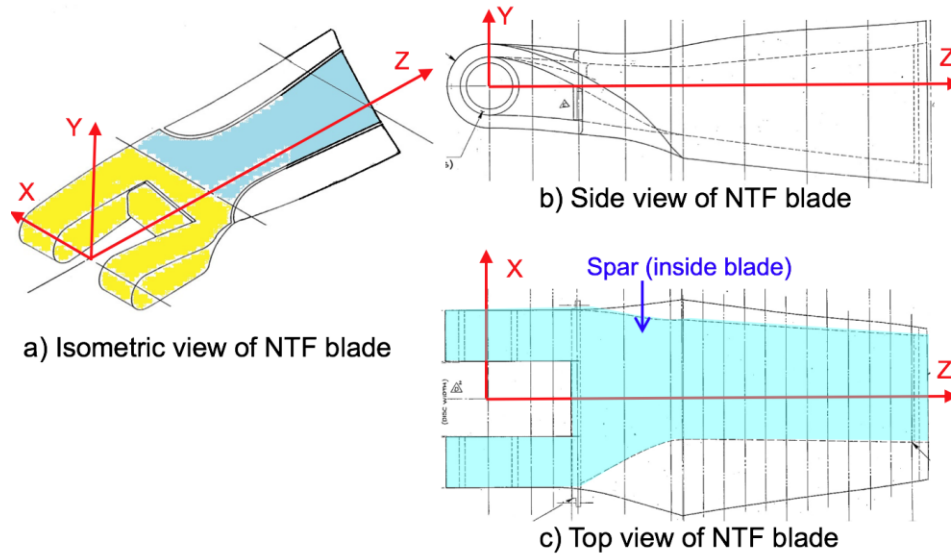
Figure 4. NTF blade spar.

Dimensions of the blade spar are presented in Table 1. Because portions of the spar are buried inside the platform portion of the blade shown in Figure 1, a direct measurement of this surface was not possible so drawings were used. In Table 1, the axial station (Z) and bolt-axis positions (X) for the leading edge and the twist angle were obtained from engineering drawings. The depth (Y) coordinate values were computed from a digital image of the blade by calculating the distance between pixels. No information about the airfoil was available, so a flat helical surface was assumed in its place.

Table 1. NTF wind tunnel blade spar dimensions.

Axial Station, Z (m)	Position of Leading Edge of Blade		Twist Angle (deg)
	Pin Direction, X (mm)	Depth Direction, Y (mm)	
1.791	-243.8	104.7	0.0
2.316	-233.0	-134.6	26.9
3.002	-175.0	-224.6	47.4

A feature worth noting is that the NTF spar undergoes a 26.9° twist from the bolt (station 1.791 m) to the platform of the blade (station 2.316 m). The rate of twist along the blade aerodynamic surface (above station 2.316 m) is only 20.5°. The result of the change in twist is a notable hollow in the spar top surface near the top of the platform. It should be noted that additional joint motion of the robot would be required to maintain roller contact on the actual, complexly curved spar surface, so this helical surface approximation is not conservative. In spite of this limitation, time constraints drove a decision to proceed with process planning studies on this geometry.

CREO 3.0 [5] CAD software was used to fit spline curves to the two sets of points defining the leading and trailing edges. A blended surface was created from the two splines, which yielded a simply curved surface. A 10.4-cm radius was added to the pin end of the tool to capture the

curvature of the spar around the pin sleeve. The entire tool surface was rotated 45 degrees around its span axis and tool sides were added. A 5-cm radius was added to the leading edge to permit programming of courses around that edge. Finally, curves were added to the surfaces previously created to represent ply boundaries. Due to the time required for collision checking, the program was confined to the bottom half of the spar, where the greatest concavity existed. The model of the blade and a representation of the placement surface of this half tool is shown in Figure 5.
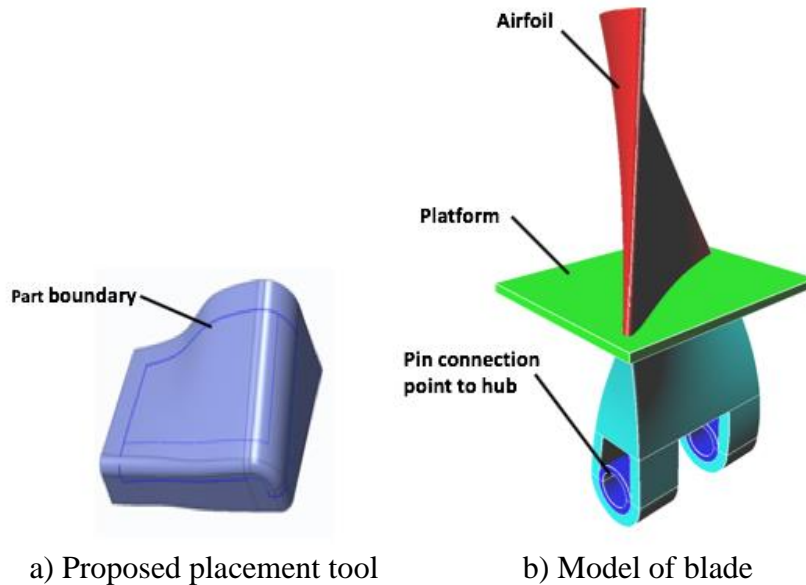

a) Proposed placement tool   b) Model of blade

Figure 5. NTF blade simulation.

2.2.2 Ames Blade Geometry

The Ames blade, shown in Figure 3, is a simpler design than the NTF blade. Because the Ames blade was available, its external surface shape could be easily measured. To measure the shape, adhesive tape was used to divide the blade into five approximately equal length sections in the spanwise direction. A Faro Arm [6] with a touch probe was used to extract lines of points along the top and bottom surfaces of the blade to obtain the shape of the Ames blade. Points were captured on five stations along the length of the blade; one set at the root end, one set at the tip of the blade, and three sets equally spaced between the root and tip. CREO was used to fit spline curves to the two sets of points at each station. A blended surface was created from the five splines that defined the upper and lower contours. This approach captured the full contour of the blade and the geometry appeared to be manufacturable in the time frame allotted to the project.

The Ames blade is sufficiently thin to be of solid laminate construction. Its sharp leading and trailing edges eliminated the need to consider programming over those edges. CAD surfaces were created in the same manner as those for the NTF tool. The CAD geometry of the blade itself provided the basis for the placement tool surface. This surface was expanded to include border regions that were necessary for fabrication. The spline curves of the Ames blade and the model of the placement surface tool are shown in Figure 6. Through iteration between VCP and VCS, a

position on the coupon table was identified where plies could be placed on the tool surface that would satisfy all of the kinematic limitations on robot motion.
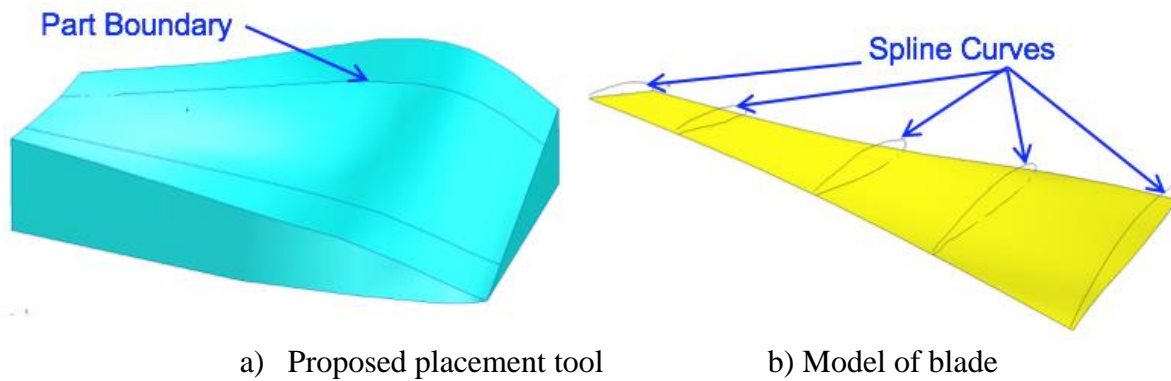

| a) Proposed placement tool | b) Model of blade |

Figure 6. Ames blade simulation.

2.3 Tool Fabrication

The same tool used for placing the carbon fiber towpreg was also used for curing the MDU in the autoclave. To reduce the cost to create the fabrication tool, a three-dimensional (3D) printing process was used. As a proof of the 3D printing concept, a prototype tool was printed on a Stratasys 900 machine using Ultem 1010 polyetherimide filament. The heat deflection temperature of this material is rated by the supplier as 213 °C, which was adequate for curing the MDU in the autoclave at 177 °C. The complete tool size exceeded the 3D printer capacity, so the tool was fabricated in two pieces and combined with a key that interlocked with the support structure of the two halves, as shown in Figure 7. The tool was first prototyped as a 230-mm by 230-mm unit cell to validate the design details, the assembly method, and the finishing process.
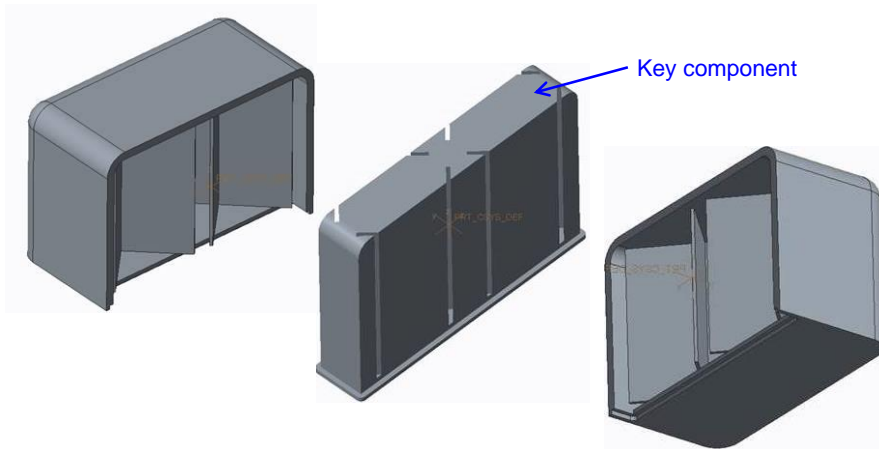

Figure 7. Prototype tool.

The prototype tool was designed with a 6.35-mm-thick skin, which was backed up by an internal square grid support structure of 76.2-mm spacing and 1.8-mm wall thickness. A finite element (FE) analysis was conducted to check that the tool thicknesses and spacing were sufficient to withstand the ISAAC roller pressure. The 344 kPa roller pressure produced a stress of 10.3 Pa on the FE model, which was 25% of the yield stress of 41.3 MPa for the Ultem material. Small holes

were included through the bottom of the internal cells to vent the tool internal structure while it was under a vacuum bag. The prototype was assembled and tested under a vacuum bag as a check on its ability to sustain pressure. The tool was finished by sanding with sandpaper. The smooth surface was then sealed and a release coat was subsequently applied over the sealer to prevent adhesion between part and tool.

3. AFP PLANNING STUDIES

The NTF and Ames blade geometries were evaluated in computer simulations using VCP/VCS where restrictions to the robot motion were considered. The large AFP head, the heater geometry, and the limitations of the robot motion were considered in the simulations. Note that on any complex tool shape, the use of the rotator can be advantageous since it minimizes the required robot joint motion and maximizes the amount of clearance around the tool. In the present study, time and resources were insufficient to support the design and manufacture of fixturing to attach the tool to the ISAAC system rotator, so the tools were assumed to be attached to the coupon table. An appropriate location of the placement surface relative to the coupon table had to be determined based on all fiber orientations to be placed. This location could be significantly above the coupon table surface if the extra height would allow more clearance for the AFP head to avoid collisions between ISAAC and the tool or table.

3.1 NTF Blade

Courses were programmed on the NTF tool in 0°, 90°, and ±45° orientations to explore the use of the ISAAC robot for fiber placement of these blades. This shape was found to be extremely challenging because the placement surface covers the top and two orthogonal side surfaces of the tool.

Several locations for the tool were considered. With the tool positioned parallel to the table surface, placement on all three surfaces forced the AFP head to turn to a horizontal orientation along the 0° and 90° directions. The ISAAC AFP head is approximately 1.8 m in diameter, which necessitated that the tool be elevated as much as a meter above the table surface to assure that the spools on the head cleared the table with the head in this orientation. The tool was also rotated about two axes to improve accessibility of its surface to the robot, and the tool was oriented in the 0°, 90°, and ±45° orientations relative to the table axes. After numerous trials, a position was found for the tool above the table surface where the robot could touch the entire placement surface without exceeding any kinematic limits of the robot. The final position was approximately 305 mm from the edge of the table which was closest to the rail, with the tool 0° direction pointed 45° away from the robot linear rail. A vertical position of approximately 0.7 m above the table with the tool canted downward at a 45° in two directions was required to keep the AFP head away from the table surface. This position required construction of a box pedestal that was larger than the size of the proposed tool.

With a location found for the tool above the flat table, the collision detection feature was activated in VCP to identify locations where the AFP head would impact the tool. The concavity of the NTF blade near the top of the platform caused collisions between the tool and the heater on the AFP head. The AFP heater was designed for use on tools with large radii of curvature, and it is suitable for most projects that have used the ISAAC facility. For the present application, though, the size, location, and proximity of the heater to the placement surface caused collisions between

the heater and the surface of the NTF blade tool for 0°, 90°, ±45°, and other fiber orientations. Eventually, the problems posed by the concavity were deemed insurmountable, given the limited resources available for this project. Attention was subsequently turned to the Ames blade.

3.2 Ames Blade

Programming trials were initially conducted using the CAD surface that was representative of the top surface of the Ames blade. However, the curvature of the top surface was too deep to permit the compaction roller to contact its entire area without collisions. Therefore, programming trials were then conducted on bottom surface of the blade. These trials indicated that 0°, 90°, ±60°, and ±30° orientations could be successfully programmed without collisions between any portion of the AFP head and the tool surface. Through several trials, a viable position was found for the tool on the coupon table surface that permitted full robot motion without violation of kinematic limits, and showed no collisions with the tool or coupon table. A 12-ply laminate with stacking sequence [+30/0/-30/90/+60/-60]$_S$ was programmed based on this tool and was successfully simulated with VCS. A more detailed description of the process planning activity is presented in reference 7. An image of the placement simulation in progress is shown in Figure 8.
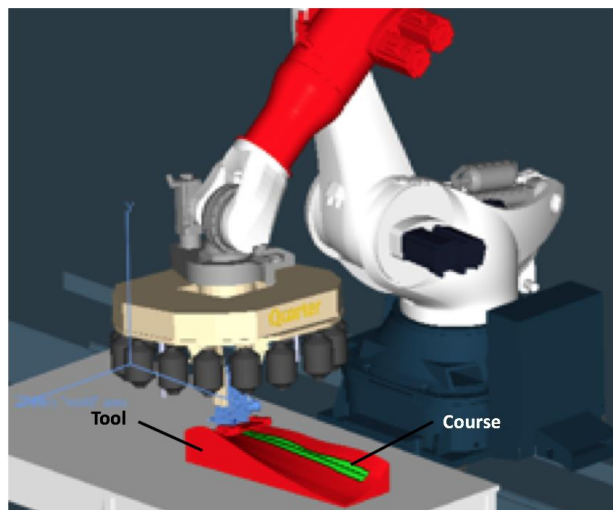

Figure 8. Ames blade placement simulation.

The AFP cure tool appropriate for the Ames blade surface was manufactured from Ultem thermoplastic over a three-week period in the month following the programming trials that verified its design. Dry runs were performed on a proxy tool made on a Gigabot 3 printer, using PLA filament. The two-week print time for an adequately accurate, minimum gage replica of the AFP tool allowed the performance of dry runs while the Ultem tool was being built. The use of this proxy tool for initial checks allowed more time for planning and preparation for manufacturing. It is worth noting that the AFP tool and its 230-mm by 230-mm prototype required approximately $18,000 worth of Ultem filament, whereas the proxy tool was fabricated with only $300 worth of PLA filament. This use of high-end and low-end 3D printers in parallel was highly useful, and it will be considered as an option for future projects in which early prototyping of tooling is found

to be advantageous. The tool with a shape representative of the blade bottom surface is shown in Figure 9.

Figure 9. Placement/cure tool.

4. MDU FABRICATION

The AFP placement/cure tool was positioned at the end of the coupon table, parallel with the rail of the robot and 305 mm from the nearest edge of the coupon table, as shown in Figure 10. This position placed the lowest corner of the tool at the table edge, a position which provided sufficient clearance to prevent collision between the towpreg spools and the table surface. Dry runs of the part (without material feed activated) further verified the validity and safety of the ply programs. However, the dry runs showed that one corner of the AFP heater came within 2.5 mm of the tool surface during the placement of one ply. With its present heater configuration, the concavity of this particular tool is nearly a limiting case for the ISAAC AFP head. The 12 plies of material were placed on the tool surface, as shown in Figures 10 and 11.
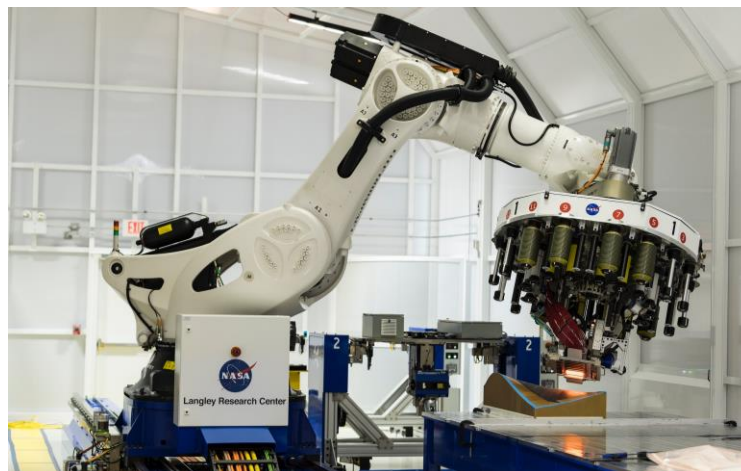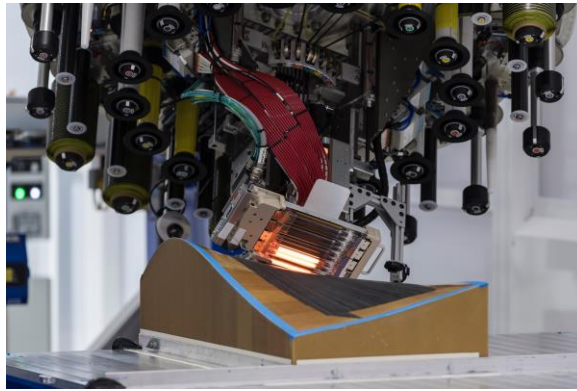

Figure 10. Fabrication of MDU.

Figure 11. Placement of 0° layer.

After the fiber placement, the laminate was held under a vacuum bag overnight and then cured the following day at 177 °C for 2 hours under 207 kPa of autoclave pressure. The vacuum bag was vented to the atmosphere when the autoclave pressure reached 138 kPa. The resulting part released easily from the 3D-printed tool. However, the sealant appeared to come off the tool and adhere to the part surface. Some local roughening of the tool surface was noted after removing the part, and small cracks (approximately 50 mm long) were found in two areas under the part.

The MDU was trimmed to remove scrap and the edges were sanded to complete the MDU. The part appeared well consolidated, but the aggressive schedule did not permit non-destructive evaluation of the part. The final part is shown in Figure 12.

Figure 12. Cured and trimmed MDU.

5. CONCLUDING REMARKS

Composite wind tunnel blades are frequently fabricated by hand layup of prepreg fabrics. Though well proven, this fabrication method is laborious and expensive. An AFP robotic system was used to explore whether manufacturing time and cost for production of wind tunnel blades could be reduced compared to hand layup. Two blades, taken from two NASA wind tunnels, were investigated as representative geometries. CAD models of the blade surfaces were created, and AFP process planning and programming was employed to study the manufacturability of the shapes. A placement/cure tool was manufactured for the chosen blade surface from thermoplastic material using an additive manufacturing process. A MDU was fabricated to demonstrate a methodology to fabricate a complex shape representative of a wind tunnel blade. The present study revealed that the heater configuration on the ISAAC AFP robotic system is the primary constraint that limits its ability to use AFP for wind tunnel blade manufacturing.

6. REFERENCES

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