MANUFACTURING TRIALS OF INTEGRALLY STIFFENED COMPOSITE PANELS USING AUTOMATED FIBER PLACEMENT

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ABSTRACT

Commercial aircraft structures are frequently manufactured from carbon-epoxy materials because of their weight and stiffness advantages compared to metallic materials. Wing cover panels are regularly manufactured using an automated fiber placement (AFP) process, but current design and manufacturing methodologies do not fully take advantage of the opportunities afforded by AFP. Design and manufacturing studies were undertaken at the NASA Langley Research Center at the Integrated Structural Assembly of Advanced Composites (ISAAC) facility to quantify manufacturing benefits and limitations associated with AFP to create structurally efficient integral stiffeners as an alternative to bonded or mechanically fastened stiffeners. This methodology could save weight and remove failure mechanisms by reducing the need for rivets and bonding materials since the stiffener plies are interleaved within the skin plies. The use of AFP with integral stiffeners can open the design space, but a fundamental, systematic evaluation of manufacturing limitations is necessary. Manufacturing trials are described herein, where considered manufacturing variables included stiffener location, stiffener course staggering, stiffener widths, stiffener intersections, and material thicknesses for both the skin and stiffener plies. The manufacturing process and lessons learned from each trial are described, including the most successful current design which contains staggered stiffeners, non-traditional laminate angles, and a combination of multiple material thicknesses within the same laminate.

Keywords: Carbon-epoxy, Integral stiffening, Structural tailoring
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1. INTRODUCTION

Lighter primary aircraft structures (wings and fuselages) contribute to making aircraft more fuel-efficient, and consequently will lead to aircraft that produce fewer emissions in flight. The usage of composite materials in the manufacturing of commercial aircraft structure has increased because of the weight and stiffness advantages of composite materials compared to metallic materials. Both The Boeing Company[*] and Airbus employ automated fiber placement (AFP) to fabricate large aircraft structures because it is a cost-effective fabrication methodology for building with carbon-epoxy materials. However, the features of carbon-epoxy materials that allow the tailoring of structures to meet loading requirements with the minimum weight are not being fully exploited in large commercial aircraft being built today. In order to more fully take advantage of the

[*] Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the hardware used. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified equipment is the best available.

opportunities afforded by AFP to achieve lightweight designs, some of the traditional design constraints need to be removed. These restrictions include limiting fiber orientations to 0°, ±45°, and 90°, requiring the use of only straight fibers, and keeping each ply thickness to a standard value. Additionally, the skin-stiffener construction typically used today can require additional steps for bonding or adding fasteners to ensure a safe design, while AFP offers opportunities for embedded or integral stiffeners. Integral stiffeners may provide the same benefit as stiffeners that are fastened, but without the additional bonding step, thus reducing part count and removing the crack-initiation potential of added holes.

In the 1980s, designs were investigated where fibers were curved within a ply to maintain a continuous load path around cutouts to increase buckling loads without increasing weight, while additionally, the curved paths also allow for non-uniform stacking sequences in different parts of a panel or cylinder [1, 2]. However, these types of designs could not be fabricated accurately using the typical hand-layup practices available at the time. Subsequently, limited automated capabilities were developed and used to demonstrate the validity of the designs, but the methods were not easily applied to large structures in a cost-effective manner [3, 4, 5]. Tailoring parts with such curved fiber paths has been facilitated by the development of AFP robots, such as the Integrated Structural Assembly of Advanced Composites (ISAAC) system [6] at the NASA Langley Research Center, shown in Figure 1.

Despite the fact that the AFP systems available today allow a larger design space compared to past decades, there are still manufacturing and machine limitations, where violating manufacturing constraints can lead to defects within a part that will reduce its structural integrity. Understanding these limitations and developing guidelines for designers is necessary to achieve minimum-weight designs. In AFP, "tows" of slit tape are placed on a flat or curved placement surface, also shown in Figure 1, in a programmed pattern. Several tows are grouped together to make a course, and multiple courses at the same height make up a ply. Typically, several straight courses are laid next to each other to form a ply that consists of many straight-fiber tows and is similar to a hand-layup construction. Programming the tows to be placed in a curved pattern can introduce defects such as wrinkling, gaps, overlaps, and folding [7], so there are limits to how much those tows can be "steered." Narrow tows (such as 6.35-milimeter wide) allow for tighter curvature than wider tows (such as 12.70-milimeter wide or wider). On the other hand, when those tows partially overlap one another, a nonuniform thickness results that can either be considered a defect or can be incorporated into the design an intentional design feature and treated as an integral stiffener [3].

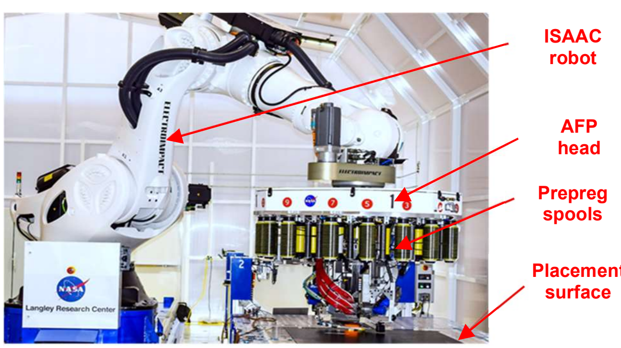


Figure 1. ISAAC AFP robot.

Additionally, patterns can be intentionally placed wherein only a few tows are placed in a ply, so a local area of the panel is built up to create a stiffener. However, areas locally stiffened in this manner can lead to regions that might separate from the skin plies during use, so interleaving full-panel plies with these stiffener plies can be advantageous. Additionally, intersections of these integral stiffeners can create undesirable build-ups or extreme thickness variations, so the benefits as well as any disadvantages of integral stiffeners must be considered in the design, and the manufacturing limitations must be defined. Combining tow-steering with integral-stiffening has the potential to open the design space, but a quantification of manufacturing limitations is necessary.

A series of manufacturing trials are described herein, where successively more complex integral stiffeners are considered for carbon-epoxy panels fabricated using AFP. Manufacturing variables considered include stiffener location, tow staggering, stiffener widths, and stiffener intersections. In addition, material thicknesses were varied for both the skin and stiffener plies. Furthermore, results are included from in situ nondestructive evaluation (NDE) [8] that was conducted on select panels to provide real-time feedback on the quality of the panel.

2. MANUFACTURING TRIALS

A fundamental study was conducted to determine manufacturing limitations for straight and curved integral stiffeners employing fiber patterns designed to explore extreme design conditions rather than being defined by panel buckling constraints or resulting from a weight optimization. A series of integral stiffener trials was used to determine programming and manufacturing constraints, which could ultimately be used to guide designers in efforts to obtain minimum weight structures as utilized in References 3 and 4. The integral stiffener manufacturing trials were programmed and built over a series of five different "Activities," in which each successive set of trials employed any lessons that were learned within the previous activity. The topic explored in each Activity is shown in Table 1. Detailed descriptions of the work conducted in each activity listed in Table 1 and the results obtained are provided in each of the following corresponding sections. All panels in Activities 1-4 were made with 6.35-mm (1/4-in.) wide Toray T800S/3900 prepreg unidirectional tape and contained standard thickness (approximately 0.216-mm thick) material. This material and a thinner-ply material were used in Activity 5. In each activity, the manufacturing constraints were assessed by noting ply defects through visual inspection after each ply was placed and using thermography for select plies of select panels.

Table 1. Primary conditions to evaluate in each Activity.

Activity	Condition
1	Tow stagger
2	Interleaving skin and stiffeners
3	Stiffener intersections
4	Ply omissions
5	Curved paths, thin plies, debulks

2.1 Activities 1 and 2

The first set of trials, which consisted of two flat panels and is referred to as Activity 1, was designed to investigate various unidirectional stiffener configurations before studying additional manufacturing variables. Both of the panels in Activity 1 consisted of placing four skin plies (i.e., plies covering the whole panel) on the placement surface, and then placing 28 stiffener plies in three different stiffener locations, as seen in Figure 2, so that each stiffener had a stacking sequence of $[0/45/90/-45/0_{28}]_T$. Note that the subscript 28 has the traditional meaning for one stiffener, but does not equate to 28 plies stacked directly on top each other for the other stiffeners, as described in the following paragraph. The three stiffeners were created to explore various options for building up the stiffener tows on top of one another. In the first stiffener (the leftmost in Figure 2 with yellow arrows), the stiffener tows were placed directly on top of each other, creating a solid stiffener with harsh vertical walls on either side, as shown graphically in Figure 3a. The second stiffener (center in Figure 2 with red arrows) involved staggering consecutive stiffener tows by 1.588 mm (1/16 in.) two times to both the left and right, for a total stagger of 3.175 mm (1/8 in.) on either side. The third stiffener (the rightmost in Figure 2 with purple arrows) was similarly staggered both left and right, but at a distance of 3.175 mm (1/8 in.) twice for a total stagger of 6.350 mm (1/4 in.) on either side. When stagger is employed, the center of the stiffener is full-height (except on the 3.175-mm stiffener within Activity 1a) but the edges are not, as shown in Figure 3b. As shown in Figure 3b, since each tow is 6.35-mm (1/4-in.) wide, the total stagger in the third stiffener is a full tow width. The actual position of the tows shown in Figure 3b is not correct since each tow would bend down toward the placement surface, but the influence of the tow stagger on the stiffener construction is graphically shown this figure. The staggered configurations were designed to reduce the sharp vertical wall in preparation for future trials in which skin plies and/or alternate-orientation stiffener plies would be placed over top of the stiffener plies. The gradual ramps, or tapers, that resulted from the two-stagger configurations can be seen in Figure 2, with the smoothest edge transition resulting from the 3.175-mm stagger.

As mentioned earlier, Activity 1 consisted of two panels, each with three stiffeners. However, these two panels used the same four skin plies since the investigation in this phase was focused solely on the stiffeners. After the completion of each panel, the stiffeners were peeled off the skin plies and new stiffener plies were placed, resulting in Activity 1a on the left of Figure 2, and Activity 1b in the center of the figure. In both images, there are three dots in two locations that represent splices in the material (where the material overlaps due to the termination of one roll on the spool and the beginning of another). These splices would typically be removed on parts that are to be cured and tested, but since the panels were built to explore stiffener manufacturing limitations, the splices were left in the panel skin plies. The stagger configurations were the same for both Activities 1a and 1b, but the number of tows that were placed for each stiffener was different. Activity 1a contained only two tows for each stiffener course, while Activity 1b contained four tows. This design resulted in total stiffener widths of 12.7 mm, 15.875 mm, and 19.05 mm for the two-tow-wide Activity 1a, and stiffener widths of 25.4 mm, 31.75 mm, and 38.1 mm for the four-tow-wide Activity 1b. The smoothest vertical ramps resulted from the stiffener configuration that contained four tows and was staggered 3.175 mm. The sharpest vertical ramp came from stiffeners that contained no stagger containing either two or four tows. These ramps can be seen in the column of cross-section images in Figure 2, where the tow edges are stacked atop one another creating a vertical wall in the top image where there was no stagger, and the smoother ramps are shown in the middle and final image where the ramp can be seen. The subscript notation of 28 representing the plies for each stiffener accurately represents the full height of two- and four-tow stiffeners with no stagger, and the height of the center of the two-tow stiffener with the smaller stagger and all four-tow stiffeners with stagger. In the two-tow stiffener with the maximum stager, the 28 represents the number of plies placed but the stagger causes the stiffener to be shorter by 4 plies.

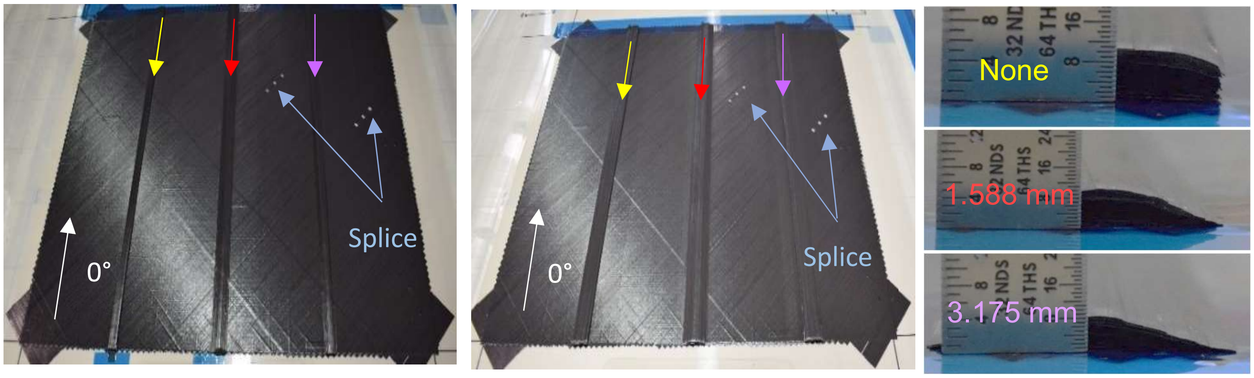
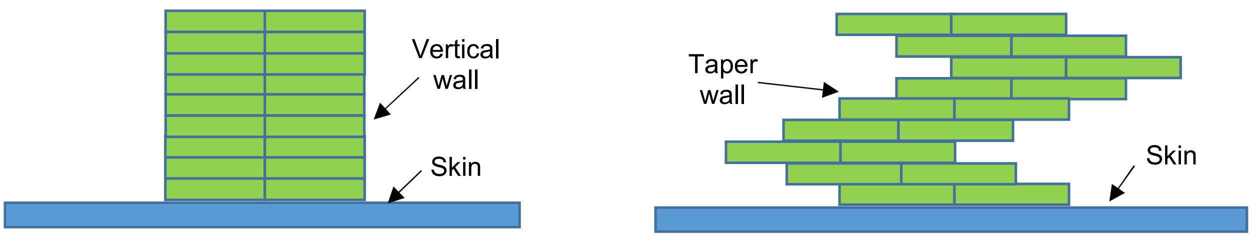


Figure 2. Stiffener locations for Activity 1a (left) and Activity 1b (center) and stagger options within Activity 1b (right).



a) No stagger and 9 plies in height.

b) 6.35-mm stagger and 9 plies in height.

Figure 3. Representative of two-tow stagger in the first and third stiffeners in Activity 1a, not to scale.

Activity 2 was used to determine the best- and worst-case vertical ramp scenarios before adding additional complexity to the designs. In Activity 2, the stiffener width and stagger configurations from Activity 1b were used, but with interleaved skin plies within the stiffener ply build-ups. Alternating between skin and stiffener plies is more representative of what typically occurs with tow steering within laminates [9]. As seen in Figure 4, there was a significant amount of bridging (air-filled gaps in the structure due to one ply not sticking to the ply beneath it) along the sides of each stiffener, as shown in the zoomed in image on the right. As expected, the most severe bridging was along the stiffener with no stagger and the sharp vertical wall as the ply over the top could not stick to the side of the stiffener, only to the skin and the top of the stiffener. The bridging was less pronounced for the 1.588-mm-stagger stiffener than the no-stagger stiffener, and least pronounced for the 3.175-mm-stagger stiffener, both shown in the image on the right within Figure 4. Taking the best and worst results from Activity 2, subsequent Activities were defined to contain stiffeners with no stagger and with 3.175-mm stagger to bound the best and worst possible configuration. It was also concluded that three stiffener plies between each skin ply resulted in too much bridging, even on the best-case stiffener, so the skin plies would be interleaved between two stiffener plies for future trials.

Figure 4. Skin ply interleaved every third stiffener ply showing full panel and close-up.

2.2 Activity 3

The designs in Activity 3 included intersecting stiffeners added to selected configurations from Activities 1 and 2. The Activity 3 series consisted of three panels, each with different investigation considerations and manufacturing layup sequences, as shown in Table 2. (Note that the layup sequences are the plies as laid down for manufacturing and are not necessarily the through-thickness layup at any point within the laminate.) The baseline panel configuration for this activity was four skin plies, two 0° stiffeners, one 90° stiffener and one 45° stiffener. The skin plies were placed, and then all twenty-eight 0° stiffener plies, followed by another twenty-eight 90° and 45° stiffener plies alternating in order. A difference between this configuration and those in the previous trials was the selection of only two stagger values, with one of the 0° stiffeners and the 45° stiffener having no stagger, indicated with yellow arrows in all images in Figure 5, and the 90° stiffener and the other 0° having a 3.175-mm-stagger, indicated with purple arrows in Figure 5. A view of the Activity 3 baseline, panel 3a, is shown in Figure 5 along with the other three panels. The panel shown in Figure 5a demonstrates that placing a large number of stiffener plies, such as 28 plies, and then placing intersecting plies over top of these plies can cause significant bridging, particularly when the 45° and 90° stiffeners approach the 0° stiffener that had no stagger, the stiffener along the top of the image. In contrast, the intersecting plies placed over the staggered 0° stiffener along the bottom of the panel had less significant bridging issues, even near the intersection with the non-staggered 45° stiffener. While this reduced bridging was expected, it was beneficial to demonstrate the behavior since the stiffener shape is similar in appearance to traditional metallic stiffeners that are bolted onto a panel skin, though metallic stiffeners are typically taller.

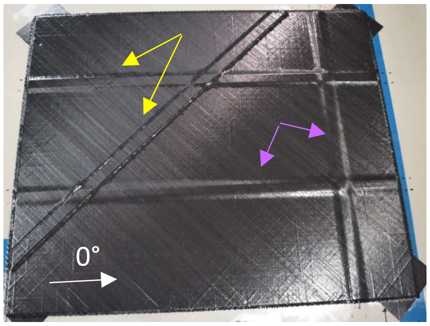
The second panel in Activity 3 contained skin plies interleaved between every two stiffener plies in an attempt to lessen the bridging seen in Activity 2b, where the skin plies were interleaved between every three stiffener plies. Again, as expected, more severe bridging, i.e., a larger region where the subsequent ply does not contact the ply beneath it, was noted along the edges of the stiffeners without any stagger. However, the 3.175-mm stagger was enough to prevent bridging for an additional 12 stiffener plies compared to the stiffener with no stagger. Specifically, a total additional height of 2.591 mm was built before bridging was observed along the staggered stiffener. However, one new defect was seen: the dragging of plies on top of the intersections when 90° and 45° stiffener plies were placed. The dragging problem started occurring during the last 15% of the panel laminate, but the problem was significant enough that a new placement strategy was needed. The final panel of the Activity 3 series contained tow cuts at selected intersections to reduce this material dragging, while still maintaining the full thickness of the stiffeners along the remainder of the stiffener away from the intersections. During the placement of Activity 3c, two pairs of stiffener plies were fully laid up, and then the following two pairs were stopped 6.35 mm (1/4 in.) before each intersection, and restarted again 6.35 mm after the intersections, as indicated in green in Figure 5c. The stiffener cuts (stopping and restarting tows) reduced the height build-up at the stiffener intersections but created a weakness by not having continuous fibers in the stiffener layup.

Table 2. Manufacturing investigations for Activity 3 panels.

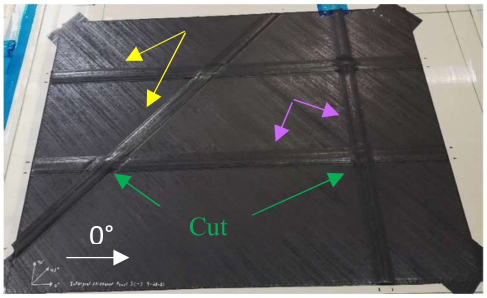
Activity	Name	Layup Sequence†	Brief Description
3a	Stacked-Stiffeners	$[0/45/90/-45/(0)_{28}/(90/45)_{28}]$	Baseline stiffener comparison for Activity 3.
3b	Interleaved-Skin	$[0/45/(0)_2/90/(90/45)_2/-45/(0)_2/90/(90/45)_2/45/(0)_2/90/(90/45)_2/-45/(0)_2/0/(90/45)_2/45]_s$	Skin plies interleaved every two stiffener plies.
3c	Cut-Stiffeners	$[0/45/90/-45/((0)_2/(90/45)_2)_{12}]$	Activity 3a repeat with alternating plies and every other stiffener pair cut at the intersections.

† Black represents skin plies, while red indicates stiffener plies.

a) Baseline stacked stiffeners, 3a.



b) Interleaved skin plies with alternating stiffeners, 3b.



c) Alternating stacked stiffeners with intersection cuts, 3c.

Figure 5. Activity 3 stiffener locations and configuration changes.

Nonlinear finite element analyses were performed to quantify the consequence of cut stiffeners on load-carrying ability. The predicted failure strength of panel 3c with cut stiffeners was compared numerically to the predicted failure strength of panel 3a with continuous stiffeners when subjected to compressive loading. These results indicated that there was loss of strength locally in the intersection regions causing a reduction in failure load of 4% and an increase in maximum strain of 46% when cuts were included. Therefore, while cutting the stiffeners would yield fewer bridging defects, the cut stiffeners resulted in enough strength loss that it was not considered a viable option.

2.3 Activity 4

The two panels created during Activity 4 were designed to address the dragging effects seen within Activity 3b. Only the 3.175-mm stagger configuration was used in Activity 4 since this option was the most successful manufacturing design in the earlier trials. The first panel in the Activity 4 series, panel 4a, contained only 0° and 90° stiffeners. Panel 4a was designed so that test specimens could be extracted that would be used to quantify the strength and failure mechanism differences between intersections that contain all 16 stiffener plies and those in which every third 0° stiffener ply was omitted, reducing those stiffeners by 5 plies compared to the stiffeners without omissions. Note that the 90° stiffeners contained all 16 plies. The stiffener omission provided lower total intersection heights, like the cut stiffeners, but provided continuous fibers through the intersection. In both images shown in Figure 6, the bottom horizontal 0° stiffener contained ply omissions, indicated by the white arrows, while the top horizontal stiffener contained all stiffener plies, indicated with blue arrows. Panel 4b, shown in Figure 6b, was designed to explore angle intersections. Rather than using a 45° stiffener like the previous trials, the off-angle stiffeners were created at 30° angles. It was hypothesized that the narrower triangular sections resulting from the 0°/30° intersections would have more bridging than those at a 0°/45° intersection. However, visually, the 30° intersections did not appear to have more severe bridging than those with 45° intersections.

a) 4a: orthogonal stiffeners only.

b) 4b: 30° stiffeners included.

Figure 6. Panels to quantify manufacturing effects from omitting stiffener plies.

The tow-placement over the tops of the intersecting full stiffeners resulted in similar heights when compared to the previous trials but did not contain the dragging identified previously. Comparing the manufacturing path programs (machine instructions) from the different panels indicated that the earlier panels used a different methodology and were programmed too close to the placement surface, which likely caused the initial dragging. Since there did not seem to be a significant difference in the manufacturing defects from using the full stiffener height, the next round of trials was programmed without any cut or omitted plies because data from mechanical testing of panel 4a is not yet available. In order to quantify the conclusions made from visual inspections, particularly of the bridging in the 30° stiffeners compared to the 45° stiffeners, a method to measure defects was required. This quantification process is discussed in Section 3 after the description of the Activity 5 panel designs in Section 2.4.

2.4 Activity 5

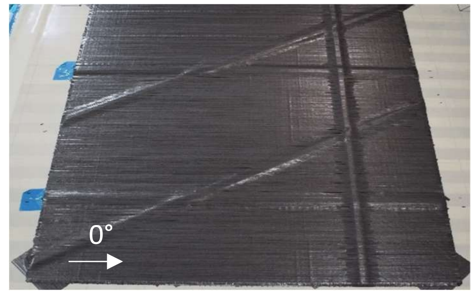
Activity 5 was the most thorough set of manufacturing trials, with continued investigations such as investigations of debulk frequency (discussed in section 3), stiffener angles, curved stiffeners, and material-thickness investigations. The complete set of Activity 5 panels, including panel number, naming convention, layup, and a brief description, is given in Table 3. In the first part of the Activity 5 series, different stiffener angles and curved stiffeners were considered. The stiffener angle investigation was a repeat comparison between the intersecting 45° or 30° stiffeners with 0° stiffeners. The investigation of curved stiffeners was performed as a steppingstone to better understanding tow-steered stiffeners. The first two panels in Activity 5 had 0° and 90° stiffeners along with one 45° stiffener or two 30° stiffeners as shown in Figures 7a and 7b, respectively. The next two panels, panels 5c and 5d, had two curved stiffeners with ±45 starting angles rather than solely straight stiffeners. Activities 5c and 5d contained semi-circular stiffeners with curve radii of 114.3 cm (45 in., indicated in the table with the R45 superscript) or 76.2 cm (30 in., indicated in the table with the R30 superscript), respectively, also shown in Figure 7. The two different radii were chosen to explore manufacturing limitations around curved paths in preparation for additional tow-steered panels in the future.

Table 3. Manufacturing investigation constraints during Activity 5.

Activity	Name	Layup Sequence†	Important Changes
5a	Straight-45	$[45/0/(0/90/45)_2/90/(0/90/45)_2/$ $-45/(0/90/45)_2/90/(0/90/45)_2/0]_s$	Baseline angle comparison for Activity 5.
5b	Straight-30	$[45/0/(0/90/30)_2/90/(0/90/30)_2/$ $-45/(0/90/30)_2/90/(0/90/30)_2/0]_s$	Stiffener with 45° angle is replaced with two 30° stiffeners.
5c	Arc-45	$[45/0/(0/90/\pm45^{R45})_2/90/(0/90/\pm45^{R45})_2/$ $-45/(0/90/\pm45^{R45})_2/90/(0/90/\pm45^{R45})_2/0]_s$	Two arced stiffeners replace two straight stiffeners, radius of curvature is 45 in.
5d	Arc-30	$[45/0/(0/90/\pm45^{R30})_2/90/(0/90/\pm45^{R30})_2/$ $-45/(0/90/\pm45^{R30})_2/90/(0/90/\pm45^{R30})_2/0]_s$	Two arced stiffeners replace two straight stiffeners, radius of curvature is 30 in.
5e	Hybrid-Baseline	$[75/0/(0/90/75)_2/90/(0/90/75)_2/$ $-75/(0/90/75)_2/0/ (0/90/75)_2/75/-75]_s$	Baseline for hybrid series, all 45°-degree plies replaced with 75°.
5f	Hybrid-Skin	$[75_T/0/(0/90/75)_2/90/(0/90/75)_2/-75_T$ $/(0/90/75)_2/0/(0/90/75)_2/75_T/-75_T]_s$	Skin 75° plies are replaced with thin-ply material, stiffeners standard.
5g	Hybrid-Stiff	$[75/0/(0/90/75_T)_2/90/(0/90/75_T)_2/$ $-75/(0/90/75_T)_2/0/(0/90/75_T)_2/75/-75]_s$	Stiffener 75° plies are replaced with thin-ply material, skin plies standard.
5h	Hybrid-All-Stiff	$[75/0/(0_T/90_T/75_T)_2/90/(0_T/90_T/75_T)_2$ $/-75/(0_T/90_T/75_T)_2/0/(0_T/90_T/75_T)_2/75/-75]_s$	All stiffener plies replaced with thin-ply material, all skin plies standard.

† Black represents skin plies, while red indicates stiffener plies.
The subscript "T" (i.e., 75_T) designates thin ply material.
The R30 and R45 designations indicate 76.2-cm (30-in.) and 114.3-cm (45-in.) curve radii, respectively, for the curved paths.

a) 5a: baseline modeling investigation.



b) 5b: baseline angle change.

c) 5c: 114.3-cm-radius arced stiffeners.

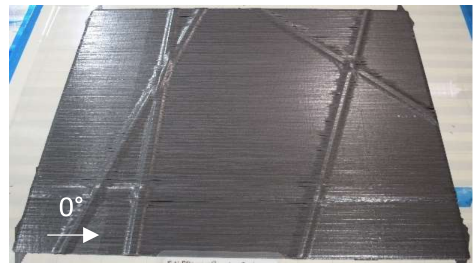
d) 5d: 76.3-cm-radius arced stiffeners.

Figure 7. Activity 5 advanced layup technique panels.

The Activity 5 investigation was concluded with four panels, panels 5e-5h shown in Figure 8, that had different material thicknesses for specific pieces of the laminate. As previously mentioned, all previous panels were made with Toray T800S/3900 prepreg unidirectional tape and contained standard thickness (approximately 0.216-mm thick) material. The material thickness investigation also included thin-ply material, which is classified as half the thickness of a standard-thickness ply or less). In this case, the thin-ply material was 0.102 mm thick. The combination of standard- and thin-ply material is often referred to as a hybrid laminate, and this terminology is used herein. The Activity 5e panel was a standard-ply panel to be used as the baseline comparison for the hybrid laminates of Activities 5f-5h. The primary difference between the Activity 5e laminate and previous panel designs was the substitution of the 45° skin and stiffener plies with 75° plies. This 75° angle was chosen based on prior analysis work also performed at NASA Langley Research Center that showed a strength benefit among hybrid panels that were built with 75° skin plies rather than both an otherwise equivalent hybrid laminate that was built with 45° skin plies and an otherwise equivalent standard-ply laminate that was built with 45° skin plies [10]. This result is not surprising, but since replacing 45° plies with 75° plies can lead to lighter designs, the non-traditional ply orientation was examined.

Activity 5f, named the Hybrid-Skin panel, used the same stacking sequence as Activity 5e except that 75° thin-ply material was used in place of the 75° standard-thickness skin plies in panel 5e. Since the skin plies are interleaved with the stiffener plies, the thickness of the skin plies affects the stiffener height. The thin plies within the laminate are denoted in Table 3 with subscript "T" after the angle values (i.e., 75_T). Alternately, in Activity 5g, only the 75° stiffener plies (of the Activity 5e stacking sequence) were replaced with thin-ply material, while all other plies were standard-ply material. When designers and technicians compared the first three panels within the hybrid-panel investigation, there were clear manufacturing benefits seen in the 5g panel with the thinner stiffeners. Specifically, there was significantly less bridging observed in the Activity 5g panel when compared to the baseline 5e panel. The difference in bridging observed was even more pronounced when panel 5g was compared with panel 5f, which had the thinnest skin and the most bridging observed in panels 5e-5g. It was theorized that this large amount of observable bridging was due to the change in thickness while placing material up and over stiffeners, or the difference between total stiffener and total skin heights. To take full advantage of the smallest difference between the skin and stiffener thickness, all stiffeners were placed with thin-ply material in a final panel, Activity 5h, and as expected panel 5h had the least observable bridging along the edges of the stiffeners and at the stiffener intersections.

a) Activity 5e – baseline with all standard materials.



b) Activity 5f – thin ply off-axis angled skin plies.

c) Activity 5g – thin ply off-axis angled stiffeners.

d) Activity 5h – thin ply for all stiffeners.

Figure 8. Activity 5 material thickness investigation panels.

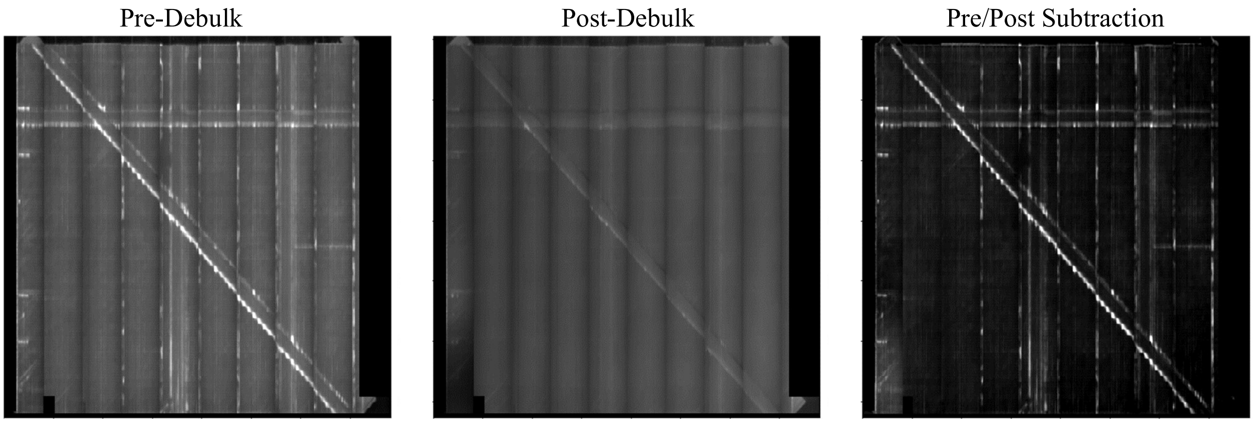
As previously mentioned, though visual inspections provided some information about manufacturing limitations, the need for quantifiable data to make more informed design decisions was obvious. The use of NDE helped provide this necessary data and was employed during the manufacture of all panels within Activity 5.

3. DEFECT QUANTIFICATION

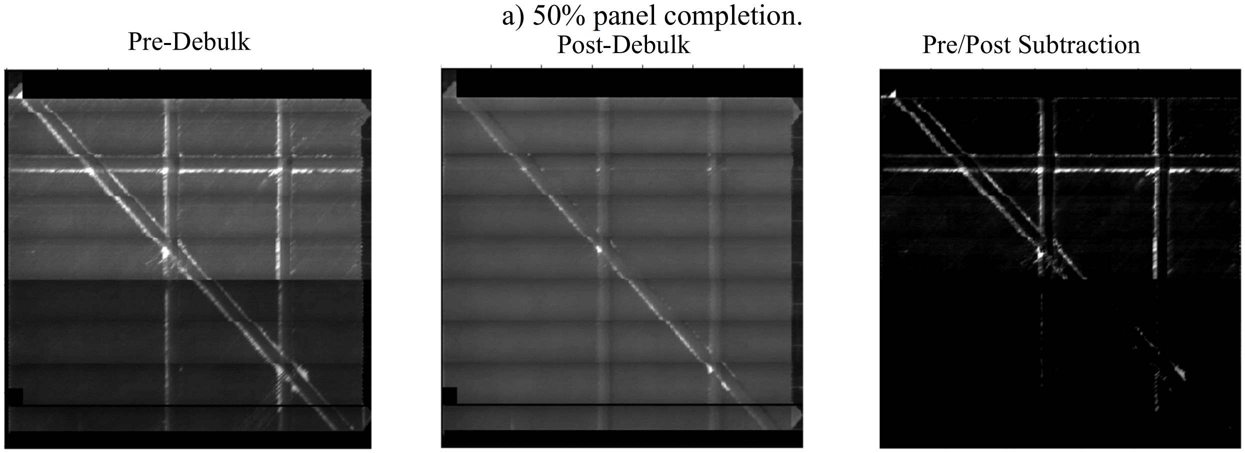
Thermography was the NDE process selected for evaluation of the integral stiffened panels during fabrication. During the AFP process, heat is applied to the placement surface, or previously placed plies, as new tows are placed so that resin from the layer being placed will stick to the layer underneath. Thermography takes advantage of this application of heat to track the heat flow within the structure as it cools. A heat-sensing camera is attached to the AFP head and temperature data is recorded as the head passes over the structure during material placement [8]. The differences in the heat flow within composite layers is represented graphically as temperature-field variations, which can then be used to locate bridging, gaps (instances in the laminate with unplanned space between two tows within the same ply), or overlaps (tows at least partially placed over top of each other within the same ply). The temperature-field-variation images from each pass over the laminate are compiled together, creating a scan of the entire panel, known as a line scan. Heat passes more quickly through regions where one ply is in direct contact with the one above it, so the temperature variation is represented by lighter and darker regions is the line-scan image. Since air is trapped in the laminate where gaps and bridging are present, these areas are lighter in the image while regions where there is good contact appear as darker regions.

Line scans can be performed while each ply is placed, after a full ply is placed, or after important manufacturing processes such as debulking. A panel debulk is the process of sealing the full panel underneath a mylar material, and then using vacuum pressure to compact all plies in the thickness direction. These debulks are done at various intervals to reduce bridging defects, but they can be a time-consuming process and are not a practical option for complex-shaped parts. One goal of this activity was to determine the minimum number of debulks necessary to obtain a final specimen with little-to-no bridging, so Activity 5a was subjected to debulks at 50%, 75%, and 100% of the panel build. In the thermal images taken 50%, 75%, and 100%, shown in Figures 9a, 9b, and 9c, respectively, the images on the left are before debulking the panel, the images in the middle are immediately after debulking, and the images on the right are the difference between the two. The methodology by which this subtraction is done is described in Reference 8. For all debulks, the majority of the measured defects were either removed completely or significantly reduced by the vacuum process. It is assumed that the negligible difference in defects between the 50% post-debulk thermography results and the 100% post-debulk thermography results indicates that the 75% debulk process was likely unnecessary. Considerable time can be saved by only conducting debulks at 50% and 100% of the panel build so all of the subsequent Activity 5 panels, panels 5b-5h, were completed with only two debulks, rather than the three debulks for Activity 5a.

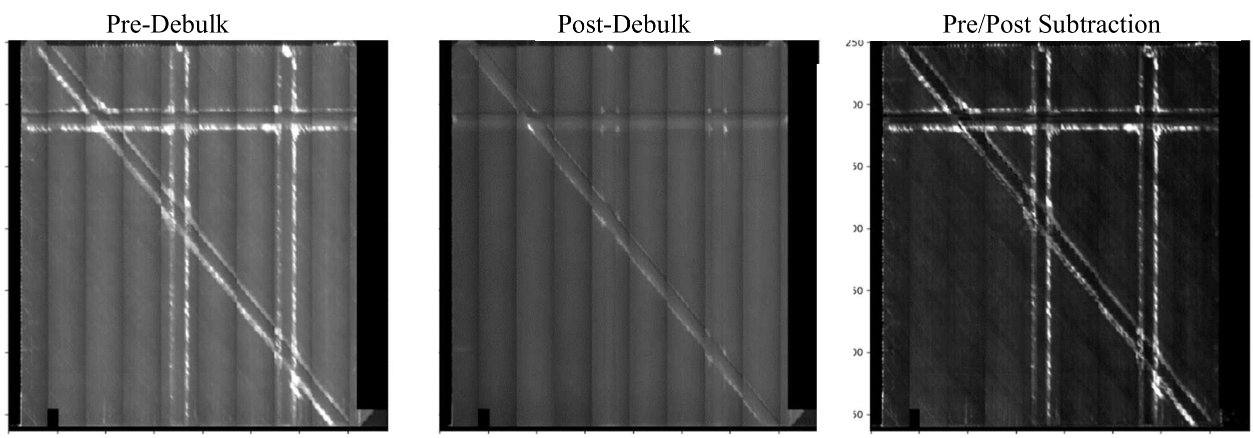
Once the number of debulks was reduced to only at the midway point and at completion, the question of how much the defects were being reduced by the debulk process was examined. By looking at the subtraction images, particularly at 100% completion in Figure 9c, significant defect reduction from the debulk process was evident. Additionally, at full panel completion, minimal bridging remained, as indicated by the lighter regions being mostly concentrated at the stiffener intersections and along the off-axis angled stiffener. Though still qualitative, these post-debulk 100%-panel-completion line scans would be the best information to use to make design decisions for future panels.



a) 50% panel completion.



b) 75% panel completion.



c) 100% panel completion.

Figure 9. Activity 5a line scans before and after panel debulks.

The first design comparison in Activity 5 was the angle change comparison between a 45° stiffener (panel 5a) and 30° stiffeners (panel 5b). The panels contained the same 0° and 90° stiffeners. In Figure 10, the thermography scan after the 100%-panel-completion debulk of panel 5a, with the 45° stiffener, is shown on the left, and the thermography scan of panel 5b, with the 30° stiffener, is shown on the right. In both of these scans, concentrations of bridging at all intersections can be seen. However, it was apparent that the panel with 30° stiffeners had significantly less bridging than the panel with the 45° stiffener. In fact, there is no discernable bridging in the 30°/90° intersections on panel 5b (right image), while all intersections in Activity 5a had noticeable bridging and more severe amounts of bridging in the 45° intersections than the 90° intersections. This comparison between the panels with 45° and 30° stiffeners led to a conclusion that 30° stiffener intersection regions had fewer defects, particularly when they intersected 90° stiffeners, and may be good candidates for future designs.

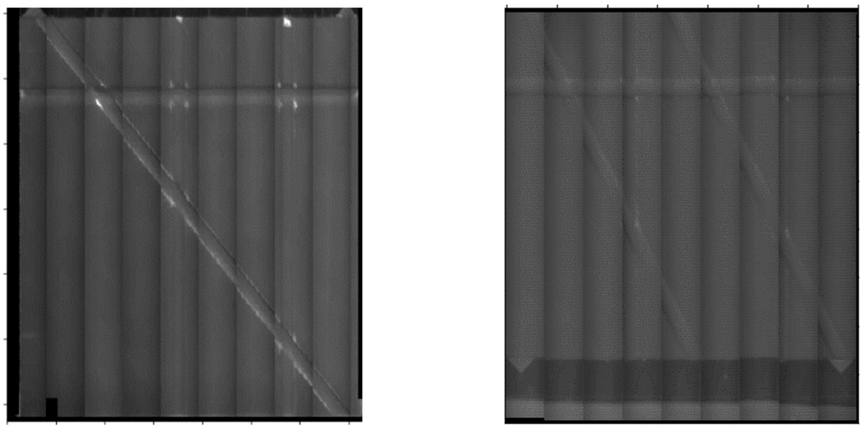


Figure 10. Post-debulk scans at 100% panel completion for Activity 5a (left) and Activity 5b (right).

The next design comparison in Activity 5 was the inclusion of curved stiffeners (panels 5c and 5d), rather than solely straight-fiber stiffeners in the panels. As previously mentioned, the two radii of curvature that were used were 114.3 cm (panel 5c) and 76.2 cm (panel 5d); the thermography scans for these two panels are shown in Figure 11 on the left and right, respectively. Unexpectedly, the panel 5d stiffener with the smaller turn radius showed fewer signs of bridging at the intersections than the panel 5c stiffener with the larger turning radius. However, there were more instances of light areas around the curved paths themselves, indicating the presence of a fold or wrinkle. Two views of the folding and wrinkling on the panel can be seen in Figure 12. In cases where the material was fully folded over, the thermography line scan shows a dark spot. However, since the majority of the folding seems to leave the material sticking up from the surface, it presents itself as a light line, as shown in the zoomed-in view in Figure 12b. The wrinkling is also shown as light spots since wrinkling leads to the same kind of air-filled gap that occurs with bridging. Although the tighter turn radius, 76.2 cm, has less severe stiffener intersection defects, the significant folding makes the design less desirable. The use of a 114.3-cm radius should produce working designs, but there may also be opportunities for radius-of-curvature values between 76.2 cm and 114.3 cm to be explored in future manufacturing trials.

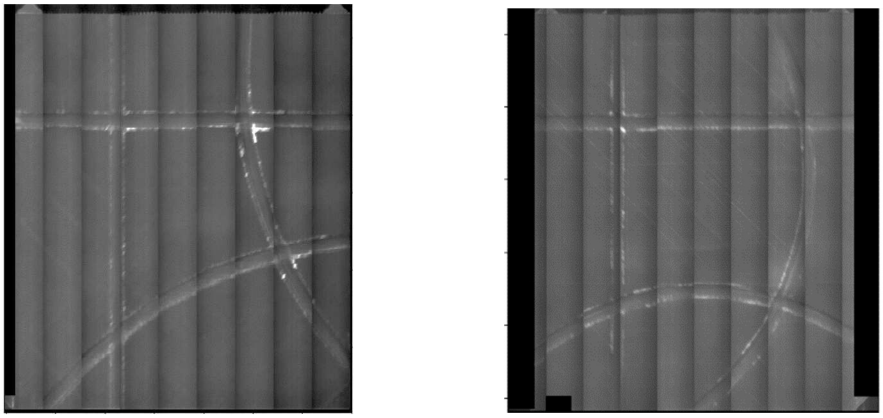
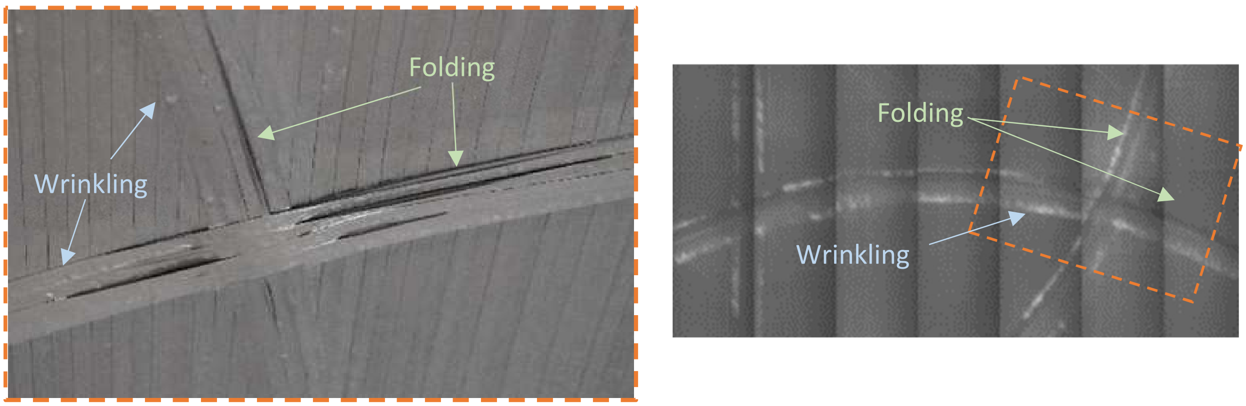


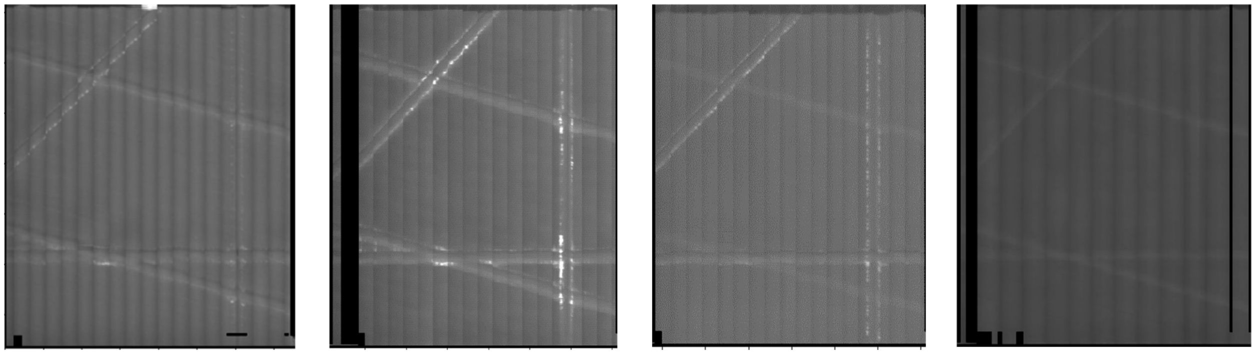
Figure 11. Post-debulk scans at 100% panel completion for Activity 5c (left) and Activity 5d (right).



a) Traditional camera image. b) Zoomed in thermography line scan image.

Figure 12. Closeup images of wrinkling and folding in Activity 5d.

The final comparison investigated in Activity 5 was the varying usage of thin-ply materials as a replacement to certain standard plies (panels 5e-5h). As a reminder, the baseline panel with all standard-ply material was created in Activity 5e. From there, the 75° skin plies were replaced with thin plies in Activity 5f, the 75° stiffener plies were replaced with thin plies in Activity 5g, and all stiffener plies were created with thin plies in Activity 5h. As seen in the thermography images in Figure 13, the baseline panel, Figure 13a, had the most pronounced bridging along the sides of the 45° stiffener, and at the 75°/90° intersection at the bottom. Activity 5f, shown in Figure 13b, had the thickest stiffeners, those with solely standard ply material just as in the Activity 5e baseline, resulting in significant bridging at all intersections and along most of the 90° and 45° stiffeners. Activity 5g had thin-ply 75° stiffeners, so there was almost no bridging indicated along the 75° stiffeners and their intersections. However, bridging was still observed along the 45° and 90° stiffeners, which were standard-ply thickness. After manufacturing the 5e-5g panels and receiving the NDE feedback about the most significant and least significant defects, Activity 5h was conducted to demonstrate that using solely thin-ply stiffeners would almost completely eliminate any bridging, as is shown in Figure 13d. This bridging-reduction information is critical for future designs as well because standard-ply skin and thin-ply stiffeners can be manufactured with minimal defects, and the previous analytical study showed increased strength with thin-ply usage as well [10].



a) Activity 5e. b) Activity 5f. c) Activity 5g. d) Activity 5h.

Figure 13. Post-debulk thermography scans at 100% panel completion for the material thickness investigations.

The use of NDE during the most recent manufacturing trial provided vital information that visual inspection alone could not provide. Any additional design comparisons should continue to employ NDE practices to have the beneficial quantification that can be provided back to designers in the beginning phases of panel design and provide live feedback to technicians during AFP to assist in defect location for repair.

4. CONCLUDING REMARKS

Five sets of manufacturing trials were completed at NASA Langley Research Center using the Integrated Structural Assembly of Advanced Composites (ISAAC) robotic automated fiber placement (AFP) system. Each set of trials provided valuable feedback to technicians and designers about manufacturing variables and the associated manufacturing defects, and this feedback was then used to improve each successive trial. The lessons learned through visual inspection and nondestructive evaluation (NDE) during these five sets of trials were that, within the set of manufacturing variables considered, the laminate that can be created with the fewest and least severe manufacturing defects includes nontraditional off-axis stiffener angles (i.e., 75° in these trials), curved stiffeners with a curve radius of at least 114.3 cm, and stiffeners that are placed with thin-ply material while the skin plies are comprised of a standard-thickness material.

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