Fabrication of a Composite Tow-Steered Structure for Air-Launch Vehicle Applications

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Abstract

Generation Orbit (GO) is developing the GO Launcher-1 (GO-1), a single stage liquid rocket that is launched from a Gulfstream III carrier aircraft platform. The vehicle is designed as the next generation platform for hypersonic flight testing and suborbital microgravity research. To reduce mass and increase payload, GO partnered with NASA Langley Research Center to design, analyze, optimize, and fabricate a tow-steered manufacturing development unit of a cylindrical section of a liquid oxygen tank. The fabrication process of using the ISAAC (Integrated Structural Assembly of Advanced Composites) system is described. The structural design challenges and the concept design solutions are also presented to provide the context for the fabrication process. The in-situ nondestructive evaluation supporting the effort is also described.

Nomenclature

AFP	=	automated fiber placement
FAW	=	fiber areal weight
GO	=	Generation Orbit Launch Services, Inc.
GO-1	=	GO Launcher-1
IR	=	infrared
ISAAC	=	Integrated Structural Assembly of Advanced Composites
ISO	=	International Organization for Standardization
LaRC	=	NASA Langley Research Center
LO_x	=	Liquid Oxygen
MDU	=	manufacturing development unit
NDE	=	nondestructive evaluation

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I. Introduction

Additive manufacturing is a term that encompasses many fabrication technologies that typically build structural components in a layer-wise fashion. Automated fiber placement (AFP) systems such as the Integrated Structural Assembly for Advanced Composites (ISAAC) system are used to place resin impregnated tows (towpreg) onto tool surfaces for the manufacture of complex structures. The AFP material and placement process both form the constituent towpreg material into shapes, and influence local material properties. Present state-of-the-art composite structures and manufacturing methods do not fully exploit the potential of composite materials to leverage local control of material properties. Significant improvements in structural efficiency may be obtained by taking advantage of the inherent tailorability of composite materials. In a cooperative design and manufacturing effort, NASA Langley Research Center (LaRC) and Generation Orbit Launch Services, Inc. (GO) are developing methodologies to design and build lighter launch vehicle structures than those that are in service today.

GO is developing the GO Launcher-1 (GO-1), as described at http://generationorbit.com/golauncher1/, which is a single stage liquid rocket launched from a Gulfstream III carrier aircraft platform. The vehicle is designed as the next generation platform for hypersonic flight testing and suborbital microgravity research. The current baseline design utilizes aluminum primary structural components. GO seeks to reduce weight and cost of the baseline design by replacing the aluminum primary structure of the liquid oxygen (LO_x) tank with advanced composite materials. The project described in this paper exercised LaRC composite design, analysis, and manufacturing expertise on the GO-1 technical requirements. As part of this research activity with GO, LaRC fabricated two cylindrical manufacturing development units (MDUs) with a highly tailored laminate design. The cylinder design utilizes tow steering to align fiber direction with the local load paths associated with the captive carry flight conditions. The tow-steering design, fabrication process using ISAAC, and an in-situ nondestructive evaluation (NDE) method are described in this paper.

The benefits and challenges of using AFP tow-steering for fabrication is discussed first. Then the structural design challenges and the concept design solutions are presented second to provide the context for the subsequent fabrication discussion. The manufacturing activity is described next and includes a discussion of the main fabrication process, and prior risk mitigation trials conducted on a flat panel representing the tow-steered paths of the cylinder. The described in-situ NDE method and step by step fabrication process are documented.

II. Benefits of Tow-Steered Structures

Analytical studies demonstrated the benefits of tow-steered, or curvilinear, fibers well before automated systems were developed to manufacture such parts or make their use cost-effective [1-7]. These studies showed that flat tow-steered panels, or panels with variable stiffness, can improve structural efficiency to obtain a lighter structure for a specified load. In addition, varying the fiber angle within a layer offers the opportunity to optimize local laminate architecture to local loads. Tow-steering could also be used to alter load paths within a structure and obtain higher factors of safety than would otherwise be achievable with constant fiber orientation.

However, the analytical and manufacturing complexity brought by tow steering is far beyond that of typical straight-fiber composite structures. Typical contemporary composite design holds fiber angles nominally constant within each ply. The material properties of a given point on a structure depend on the laminate schedule at that point. Broad areas of a structure share a common laminate, and those areas require a single material property set to define their properties wherever they are located. By allowing fiber angles to vary within a ply, the number of unique laminates in a structure increases exponentially. In addition, local fiber angles within a lamina are dependent on all of the rest of the fiber orientations with that particular lamina. Extended to every lamina within a laminate, the degree of complexity in a design and analysis process become very large.

Some design options presented by tow steering include moving the load path away from cutouts [8], locally increasing stiffness to increase buckling loads and/or improve post-buckling performance [4, 8-10], and delaying first-ply failure [10]. Tow steering greatly enlarges the design space, offering the potential to pursue design optimization to a significantly greater extent than possible with traditional methods. One example of taking advantage of the unique manufacturing opportunities offered by AFP is the incorporation of integral stiffeners into a panel. By overlapping tows rather than dropping tows during placement of tow-steered layers, additional stiffness benefits are gained from the presence of the extra material. These overlaps create sinuous integral stiffeners that self-assemble during the layup process. Tow steering where tows are dropped were found to increase the buckling load by approximately 10% compared to similar straight-fiber laminates, while the additional material thickness in laminates with overlaps buckled at nearly twice the load of their straight-fiber counterparts [8]. This result showed that the deviation from the typically desired uniform layup was actually an advantageous feature if treated properly in the design, analysis, and manufacturing process.

As a practical matter, manufacturing constraints pose limits on which fiber angles can be achieved in a tow-steered structural design. These constraints must be incorporated into the structural design process to ensure that the structure will have the material properties and the structural response that is required. Some of the benefits of tow-steering, manufacturing difficulties posed by tow steering, and possible means of overcoming those challenges are discussed in Ref. [11]. A particular challenge encountered in tow steering is keeping the tows of the new ply in complete contact with the surface of the substrate. In particular, the stresses created by in-plane bending of the tows act to either buckle the inner edge of the tow away from the substrate surface (compressive stresses) or, pull the outer edge away from the surface such that the edge attempts to take a path approximating secant to path of the centerline of the tow. Evaluating and addressing the tow deformation away from its nominal position is a key characteristic of tow-steered cylinder fabrication described in this paper. The application of tow steering to wingbox structures is described in Ref. [12-14], but the interplay of design and manufacture in the MDU cylinder described herein is significantly more extensive.

III. Design – Challenge and Solution Concept

For air-launch systems, a significant structural challenge stems from the presence of concentrated forces and moments from the attachment to the carrier aircraft, which distinguishes these structural requirements from those of vertical launch vehicles. These loads can include severe conditions associated with, e.g., the pitch up maneuver just prior to the separation of the air-launch system, or the hard landing condition when the launch is aborted while already airborne when the launch vehicle is returned to the ground, still attached to the carrier aircraft. These conditions require redistribution of concentrated out-of-plane loads from the proximity of the attachment points to the acreage of a thin-walled structure. Tow steering can be used to address this requirement by providing additional options for laminate design when compared to the tradition straight-fiber design.

While the design of the LO_x tank for GO-1 is not in scope of this paper, a few features of the design are discussed to facilitate the subsequent discussion pertaining to the manufacturing effort. A photograph of the first MDU during fabrication is shown in Figure 1. The manufactured MDUs were 73-in.-long and had a 25-in. inner diameter. In the design described herein, all plies in the LO_x tank design were classified in one of the three categories. The acreage plies cover the entire surface of the cylinder. These plies would be responsible for cryogen containment and would also play an important role in carrying pressure loads. The patch plies, covering only selected parts of the structure, provided an enhanced stiffness to suppress buckling in the localized areas of the acreage not covered by hanger plies. The most pronounced application of the patch plies was in the crown section of the cylinder to increase the axial bending stiffness of the structure. The two ply categories described in this section comprised straight fibers only and, therefore, are not discussed further in this paper as their layup was a routine AFP operation.

The third group of plies, designated as the hanger plies, are illustrated in Figure 2 with red, orange, green, and blue bands. These plies converge to nearly circumferential paths (±85° with respect to the cylinder longitudinal axis) in five locations on the crown region of the cylinder, and then are steered onto spiral paths into the acreage of the cylinder as the tows move further away from the crown. At the keel section of the cylinder the fiber paths are at ±30° angles, covering nearly the entire surface of the cylinder, as shown in the bottom view of Figure 2. The five locations in the crown section of the cylinder are the carrier aircraft attachment points, although the specific attachment brackets are not shown. To provide continuity of fiber in the hanger plies, they were designed in a periodic fashion, such that the same band of tows would cover an attachment point in the crown section every fourth or fifth attachment location. At the same time, most of the hanger ply curvatures were designed as constant radius curves with the curvatures alternating their direction at the keel location. This design feature, combined with the MDU cylinder diameter, resulted in tow paths with radii of curvature ranging from 42.5 in. on the inner hanger ply edge of the tows passing through every fourth attachment point to 66.35 in. on the outer hanger ply edge of the tows passing through every fifth attachment point. The two radii are presented in the unfold hanger ply map in Figure 3 on the red and purple hanger ply courses. The placement and evaluation of the quality of the hanger ply tows are the subject of further discussion, especially since the lower range of the tow-steering radius applied in the present effort was below the lower limits recommended in the literature for 0.25-inch-wide tows, such as the 70 inches recommended as a lower limit in Ref. [12]. and radius of 48 in. exercised on the tow-steered cylinders described in Ref. [15].

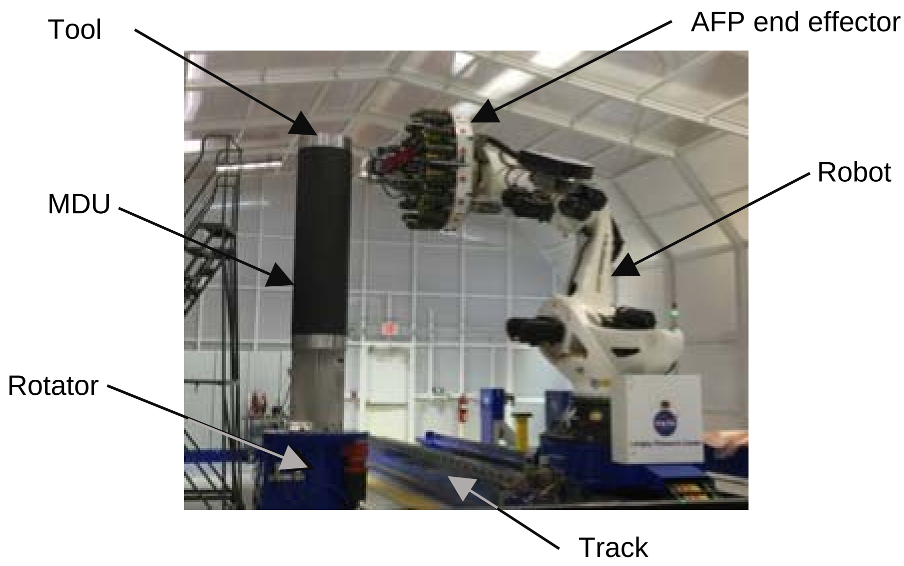


Figure 1. The cylindrical MDU being fabricated with the ISAAC system.

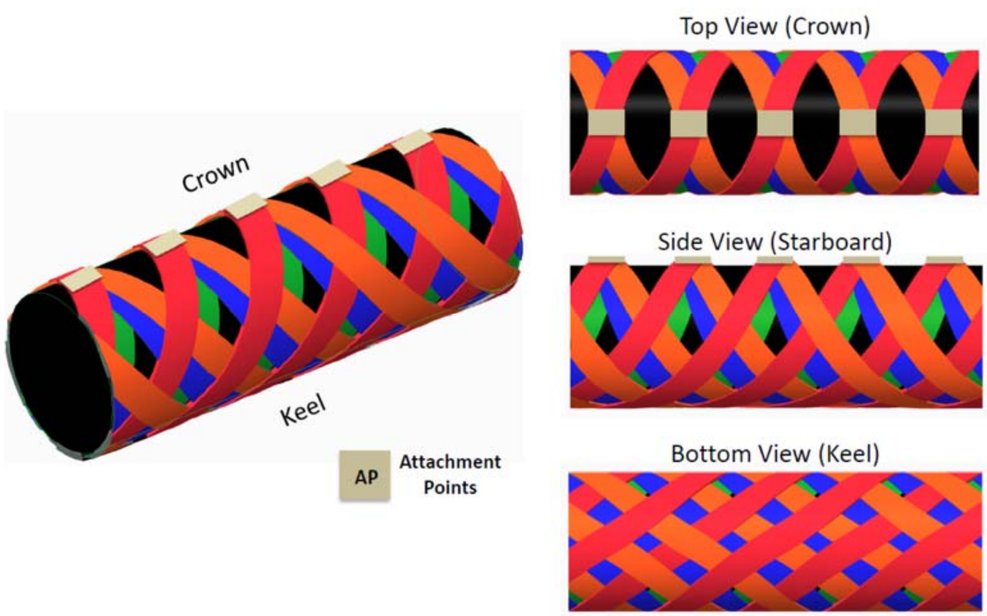


Figure 2. The tow-steered MDU cylinder design with the tow-steered hanger plies.

IV. Fabrication

Toray T800S-3900-2C* with the fiber areal weigh (FAW) of 190 g/m^2 was used in the fabrication effort. While the material properties in the cryogenic environment were not available at the time of the material system selection, this material system was affordable and readily available, leading to its selection for this work in exploring the envelope of a cryotank design with aggressive tow-steered features.

A. AFP System

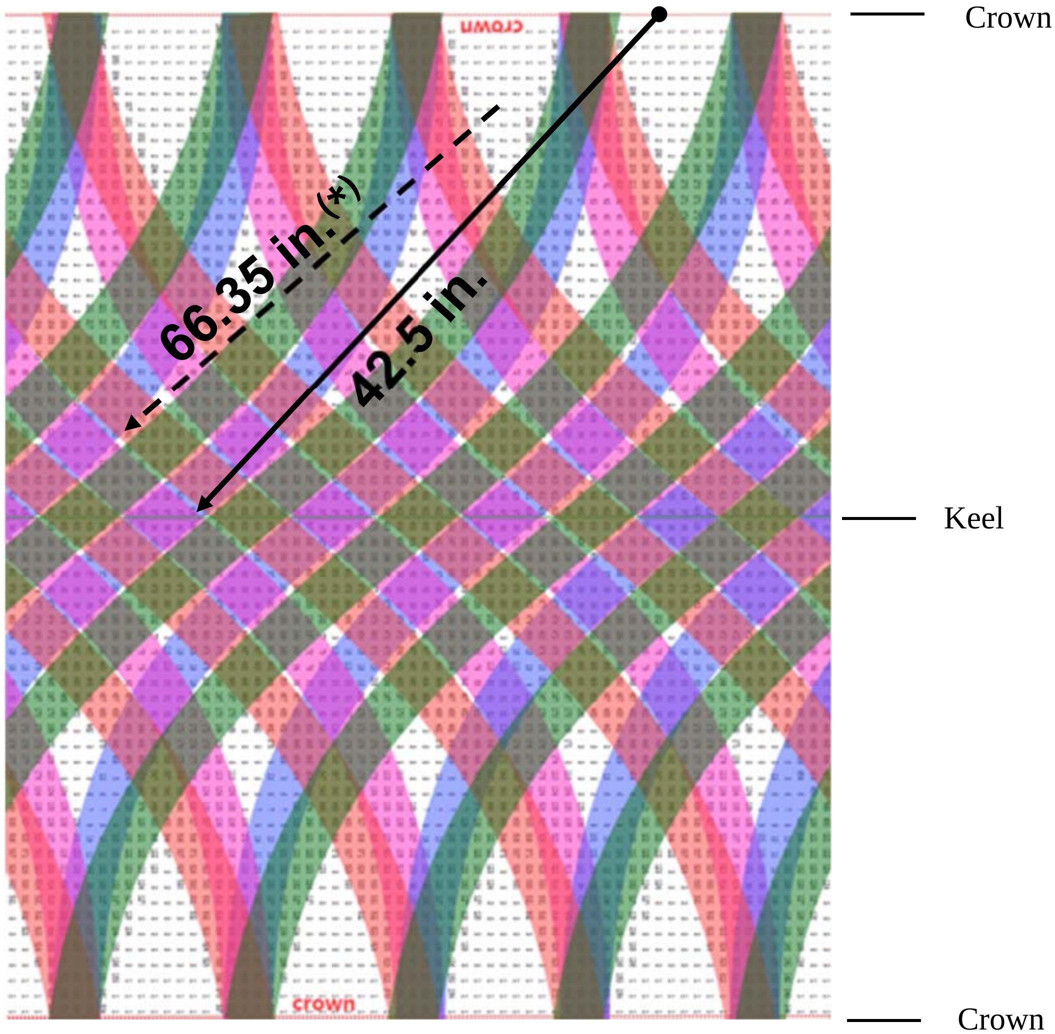
The structures described were fabricated on the ISAAC robotic system. The ISAAC system, inside of an ISO-7 (International Organization for Standardization Class 7) clean room enclosure, is shown in Figure 4. The system was designed and built by Electroimpact, Inc*. The system comprises a commercially robot with six degrees of freedom, a 40-foot long linear track system with integrated carriage allowing 30 feet of travel, and a vertical rotational axis. A more detailed description of the AFP process is presented in Ref. [16] and more details about ISAAC are presented in Ref. [17].

ISAAC is a highly accurate, robotic platform for AFP that is used to support research on the design, analysis, manufacturing, and evaluation of advanced composite materials and structures. The AFP end effector, shown in Figure 5, is a self-contained unit with all of the components necessary to simultaneously place up to sixteen 0.25-in.-wide tows. The system has independent feed and cut control on each individual tow. In the AFP process, the resin-impregnated tows are separated from the backing films and collimated into a continuous course of material through a set of rollers and guides. The course of material is robotically placed onto a tool surface with high accuracy at a spatial location and fiber direction. During fiber placement, the infrared (IR) heater preheats the surface of the laminate ahead of the compaction roller to permit the tows to be fully consolidated upon the substrate. Compaction force is controlled via an air pressure regulator. A default placement speed is defined in the tool path programming, but the machine operator uses an override control to manually regulate the machine speed as required during portions of the program, such as approach to the tool surface and initial feeding of the material at the beginning of each course. The heater output power and the machine speed are linked such that the substrate surface temperature is held relatively constant regardless of machine speed on the part.

B. Risk Mitigation Panel

The tight tow-steering radii required by the cylinder design posed a risk of manufacturing imperfections, so a risk mitigation effort was undertaken. Prior to fabricating the cylindrical MDUs, a flat panel representative of a section of the cylinder was laid up (but not cured) to better understand the challenges that could be encountered during construction of the tow-steered layers of the cylinder. This flat panel contained tow-steered fiber paths representative of the paths in the cylindrical MDU design, including the afore-mentioned paths with a relatively small radius of curvature ranging from 42.50 in. to 66.35 in. The section of the cylinder used to define the “unfold” panel, and the features of the “unfold” panel itself are presented in Figure 6. The tow-steered hanger plies, the underlying acreage plies, and patch plies were included in the unfold risk mitigation panel to render it more representative of the cylindrical MDU design.

* This is not an endorsement by the National Aeronautics and Space Administration (NASA)



(*) Radius anchored outside the plot.

Figure 3. The MDU tow-steered hanger plies in an unfolded view.

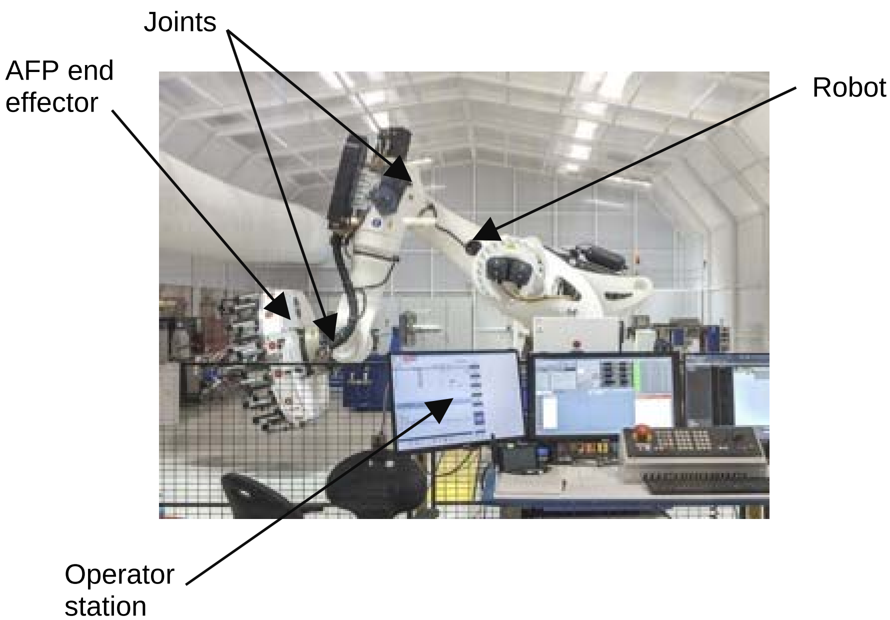


Figure 4. Components of the ISAAC system in the clean room at LaRC.

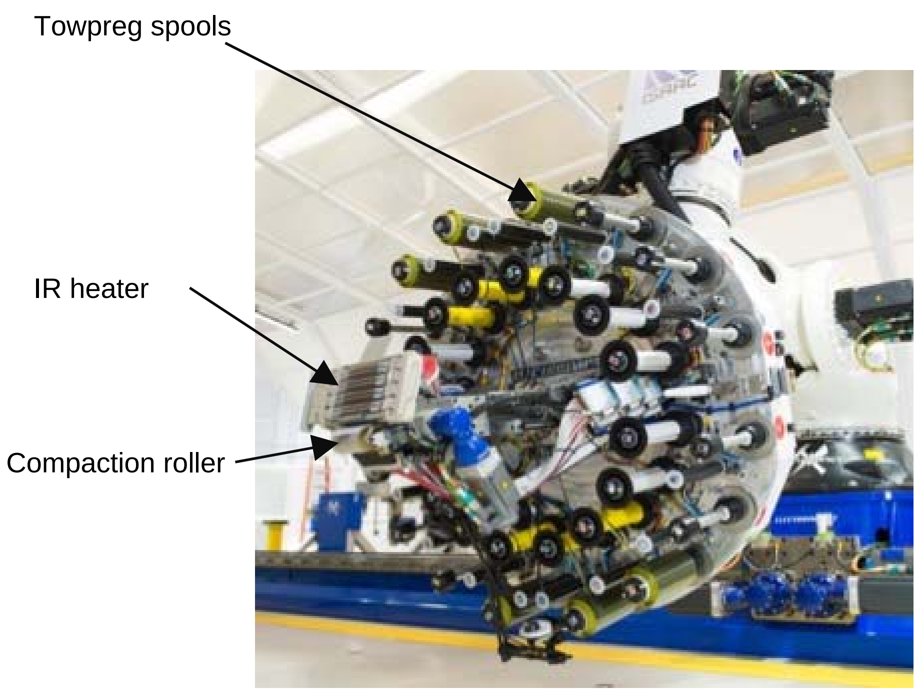
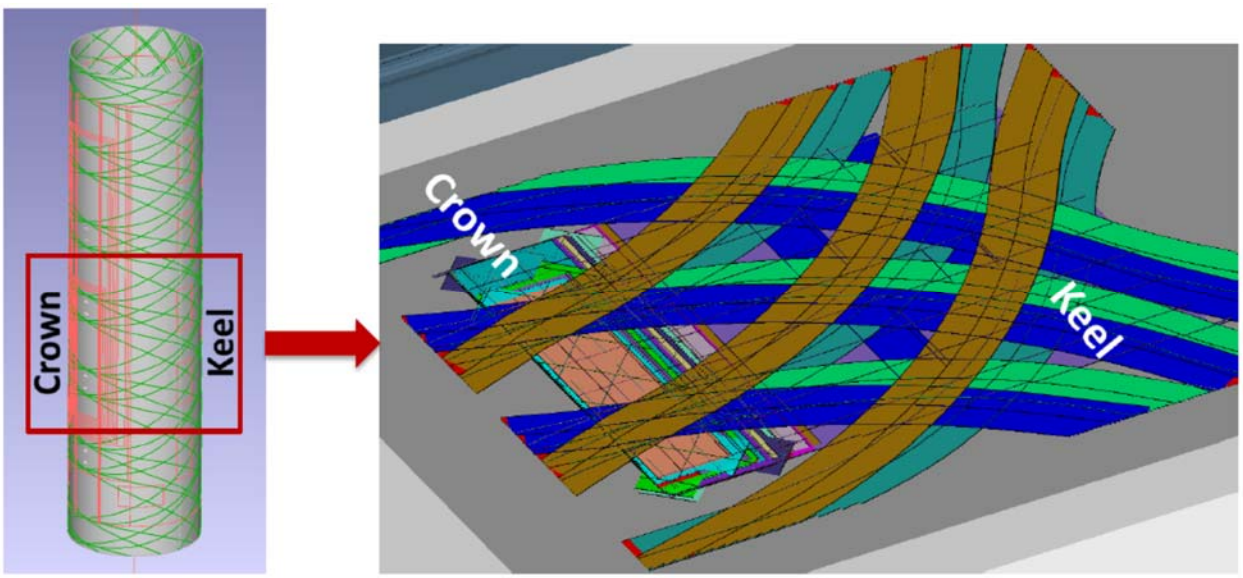


Figure 5. A view of the AFP end effector on ISAAC.

When placing the tow-steered plies, partial separation of those plies from the underlying material was encountered in form of tow peel-ups. Some of the peel-ups occurred almost immediately after fiber placement. Others occurred later when the top tow-steered layer was left unsecured. The risk mitigation activity proceeded by first removing the top steered ply with peel-ups, then re-applying tow-steered plies with several different speeds, IR heater power settings, and levels of compaction force on the roller. The iteration of this procedure led to the determination of settings that reduced ply separation to acceptable levels. Generally, straight-fiber layers were placed at a speed of 500 in/min to minimize peel-up at the beginning of tow placement with a compaction roller force of 100 lb. Tow-steered hanger plies peeled up at this speed, so the speed was reduced to 100 in/min. Although these settings did not completely eliminate the peel-up behavior, these settings reduced peel-ups to the point that individual tows would not encounter a complete separation across the entire width of the tow. This observation indicated that the positioning of each tow on the structure was uniquely determined, and that no displacement of the tows should occur in further processing. Nevertheless, establishing full contact between the steered tows and the substrate was still an issue to be resolved.

Two measures were exercised to improve the consolidation quality of the steered tows, namely the vacuum debulking process after placement of the steered ply, and covering a tow-steered ply with a subsequent straight-fiber ply. The debulking process involved application of release film directly on the top of the outermost steered ply, the addition of breather cloth to the laminate surface, and the installation of a vacuum bag over the surface. A vacuum of approximately 24 in-Hg (11.8 psi) was applied to the bag and the laminate for 30 minutes. Upon visual inspection after debulking, the vast majority, if not all, peel-ups were eliminated. Furthermore, the top tow-steered ply did not show a tendency to peel up again within approximately 10 to 15 minutes after completion of debulking, based on visual inspection. This observation instilled confidence that an aggressively tow-steered ply could be stabilized sufficiently to permit placement of subsequent plies, which would further stabilize the tow-steered layup. The latter measure was addressed earlier in the MDU design process by specifying that the outermost acreage ply would have a nearly circumferential fiber orientation.

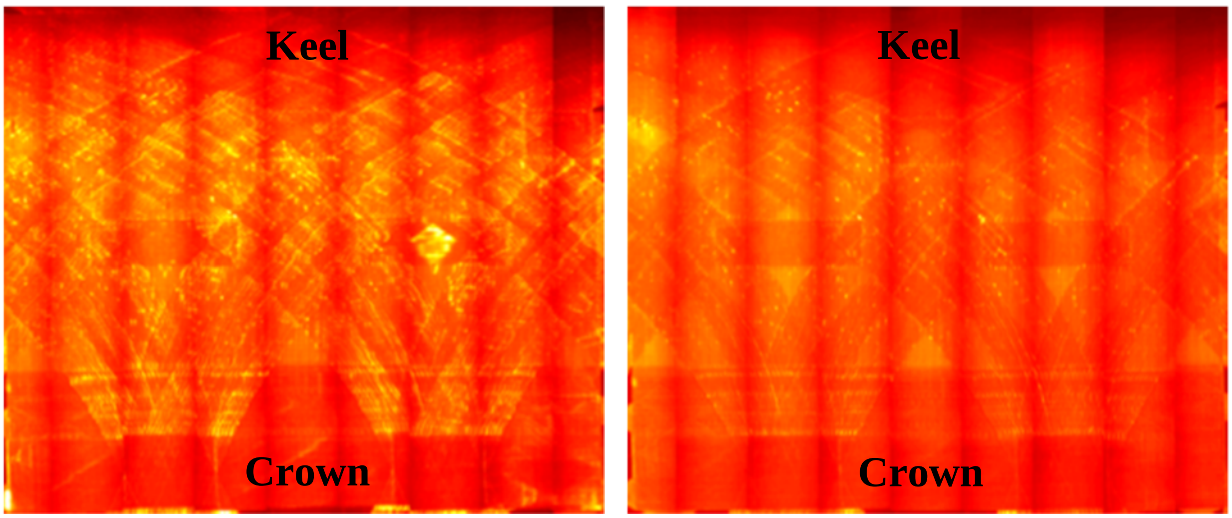


a) Full cylinder ply map **b) Unfold panel ply paths**

Figure 6. "Unfold" risk mitigation panel.

The limitations of visual inspection of the peel-up and debulking process became apparent early in the process of layup of the unwrap panel. Though an eye visual inspection can reveal gross separation between layers, that type of inspection reveals no information about the consolidation quality of the ply interfaces. The need to assess ply interface quality motivated the use of an in-situ thermal imaging technique currently under development at LaRC. Though the system was in early stages of its development, the system was exercised in this application in an attempt to provide objective data on the as-placed quality of the laminate, while providing a useful set of test cases for maturing the system. The system was based on an Ethernet-streaming thermal camera mounted on the ISAAC AFP end effector. This camera collected surface temperature images of the laminate immediately behind the compaction roller. The images were post-processed to compile them into an image which is analogous to a flash thermogram of the completed ply.

Two means of acquiring the images were evaluated. In the first technique, images were obtained during AFP operations. In the second technique, a post-layup pass was conducted in which the AFP head moved the heater over the laminate surface along the fiber paths with placing material. This approach was similar to a thermal line scan process described in Ref. [18]. The composite thermal image of the panel just after a steered-tow placement is shown in Figure 7(a) and the thermal image for the same area of the panel after a 30 minute-long debulking process is shown in Figure 7(b). In both images, brighter colors (shades of yellow) indicate higher temperatures and darker colors (dark red to burgundy) indicate lower temperatures. The initial panel image contains many areas with higher surface temperatures. The image after debulking has fewer "hot spots," and a more uniform temperature distribution. Hot spots are associated with a reduction in through-the-thickness thermal conductivity due to entrainment of air at the ply interfaces. The more uniform temperature field in the post-debulk image indicates that the debulk process improved the consolidation quality of the surface ply and the outermost ply interface. The thermography measurements and their interpretation were consistent with the visual inspections of the "unfold" panel tow-steered plies before and after debulking. These measurements served as a useful semi-quantitative validation of the visual inspection results, and increased confidence that the vacuum debulk approach was providing value in improving the consolidation quality of the layup.



(a) Immediately after layup **(b) After a 30 minute debulk**

Figure 7. Thermal images of the same area of the "unfold" panel.

C. Cylinder MDU

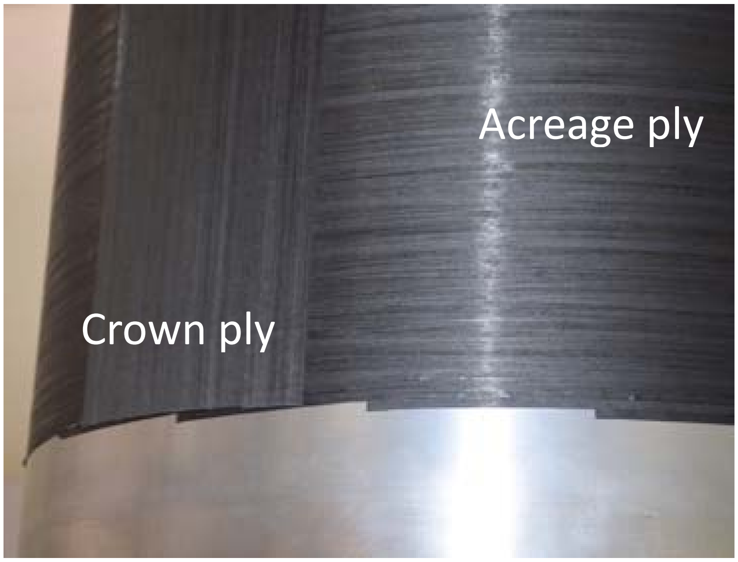
After the risk mitigation activity on the "unfold" panel was complete, the parameters such as the speed of tow placement, tow tensioning, IR heat setting, and force applied to the compaction roller were reviewed and conservative (known reliable) values were selected for the cylindrical MDU fabrication. The settings varied between the three groups of plies, i.e., acreage, patch, and hanger plies, with the last group characterized by the most conservative approach to improve adhesion of the hanger plies to the underlying plies. For example, 50 lb of compaction force was used for the first two plies which were placed directly on the tool (one acreage and one patch ply), while 100 lb compaction force was used on all other plies including all hanger plies. A feed rate of 100 in/min was used to enable the first tow plies to stick to the tool while rates 200 in/min and 500 in/min were used on the remaining straight-fiber plies. A rate of 100 in/min was used for the hanger plies.

For the cylinder fabrication, an aluminum tool was mounted to the rotary turntable, as shown in Figure 1. The small diameter and vertical orientation of the unheated cylindrical tool posed additional challenges. The contact area between the tool and the compaction roller is reduced when the fiber path deviates from the circumferential direction because of the tool curvature and the finite compliance of the compaction roller. To accommodate this constraint, the width of the course was reduced to assure that all placed tows would experience adequate compaction pressure. Hanger plies in particular were limited to a 10-tow (2.5 in.) course width to minimize peel-up. Multiple coats of tackifier and the use of double-sided tape at the ends of the laminate were required to get the first ply to stick to the tool. Both of these methods added significant time to the overall AFP process. Two cylindrical MDUs were manufactured using these processes and both MDUs have undergone ultrasound NDE. Photographs showing the sequence of tow-placement in the fabrication of MDU 2 are shown in Figures 8 through 12.

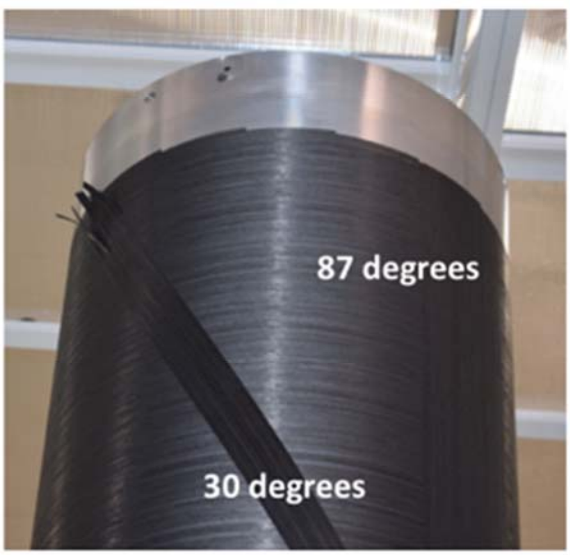
The experience in building the MDUs lead to guidance for future cylinder builds. Specifically, to enable the material to stick to the tool surface, tackifier should be applied one day before application of the first ply; double sided tape must be placed at the cylinder edges; release coat should not be applied beyond the part boundary since this causes the sealant tape to peel up during vacuum bagging creating an inadequate vacuum pressure during debulking; and two rows of sealant tape must be used. Tow steering on the cylinder produced peel ups on the inner radius of the tow. The initial assessment suggested that the severity of the peel-up would cause the tow to fall off the cylinder, so debulks were performed. During manufacturing, it was determined that debulking after each hanger ply was unnecessary, but that alternating the layup direction of the hanger plies and applying the compaction force from the AFP roller helped reattach the peel-ups in prior plies. Additionally, the in-situ flash thermography was helpful to qualitatively determine the compaction of the tow steered hanger plies. Both visual inspections and in-situ thermography supported a conclusion that debulking was an effective technique in eliminating mild tow-steered ply peel-ups, i.e., peel-ups that do not extend over the entire width of the tow.

(a) Starting fabrication **(b) Ply 1, crown patch at 0 degrees**

Figure 8. First ply of MDU begin applied by ISAAC.



(a) Ply 2, acreage at 87 degree and ply 3, crown patch at 0 degrees



(b) Starting ply 4, acreage at 30 degrees **(c) Completed ply 7, acreage at -30 degrees**

Figure 9. Acreage plies of MDU laid down by ISAAC.

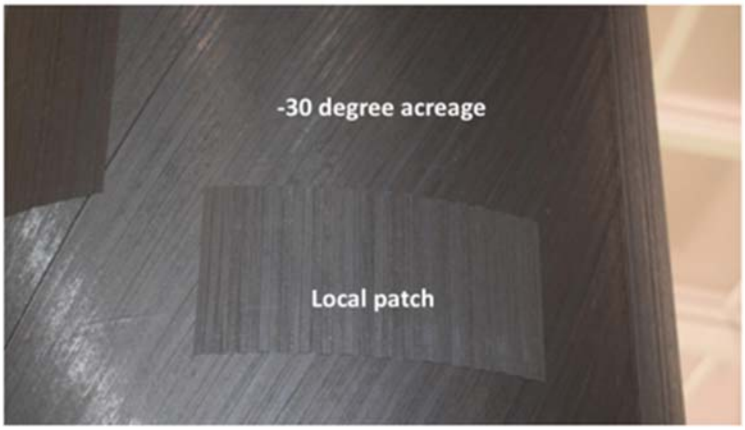
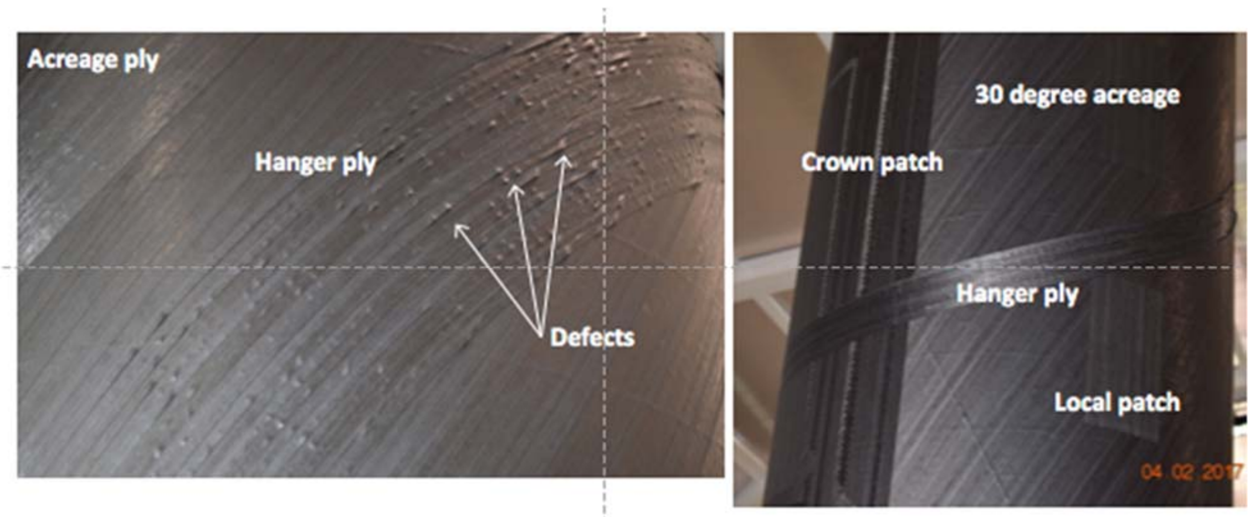


Figure 10. Local patch ply of MDU.



(a) Close up showing peel-ups **(b) Hanger ply over patch and acreage plies**

Figure 11. First Hanger ply of MDU laid down by ISAAC.

(a) Completed cylinder keel **(b) Completed cylinder crown**

Figure 12. All tows completely placed using ISAAC.

V. Concluding Remarks

GO partnered with LaRC to design, analyze, optimize, and fabricate a tow-steered MDU of a LO_x tank. fabrication of the tow-steered MDU was performed using the ISAAC system at LaRC. One flat panel and two cylindrical MDUs were fabricated using AFP of a carbon-epoxy material system. The AFP involving the cylindrical structure used a metallic constant-bore tool placed on a vertical rotator. A complex, small-radii tow-steering pattern incorporated into the MDU design was motivated by a relatively small cylinder diameter and specific load paths from the captive carry flight conditions. Such a design presented manufacturing challenges. Initial trial layups were conducted on the flat panel to determine the most favorable AFP process parameters for fabrication of the cylindrical MDU design. In addition to a subjective visual evaluation, in-situ thermography NDE was used to evaluate the quality of placement of the tow-steered plies. Both visual inspections and in-situ thermography supported a conclusion that debulking was an effective technique in eliminating ply peel-ups that do not extend over the entire width of the tow.

References

[1] Hyer, M. W., and Charette, R. F., "Innovative Design of Composite Structures: The Use of Curvilinear Fiber Format in Composite Structure Design," NASA-CR-186453, 1989.

[2] Hyer, M. W., and Charette, R. F., "Use of Curvilinear Fiber Format in Composite Structure Design," *AIAA Journal*, Vol. 29, No. 6, 1991, pp. 1011-1015.

[3] Hyer, M. W., and Lee, H. H., "The Use of Curvilinear Fiber Format to Improve Buckling Resistance of Composite Plates with Central Holes," *Composite Structures*, Vol. 18, 1991, pp. 239-261. doi: 10.1016/0263-8223(91)90035-W

[4] Olmedo, R., and Gürdal, Z., "Buckling Response of Laminates with Spatially Varying Fiber Orientations," AIAA Paper No. 1567, April 1993. doi: 10.2514/6.1993-1567

[5] Nagendra, S., Kodiyalam, A., Davis, J. E., and Parthasarathy, V. N., "Optimization of Tow Fiber Paths for Composite Design," AIAA Paper No. 1275.
doi: 10.2514/6.1995-1275
[6] Waldhart, C. J., Gürdal, Z., and Ribbens, C., "Analysis of Tow Placed, Parallel Fiber, Variable Stiffness Laminates," AIAA Paper No. 1569, 1996
doi: 10.2514/6.1996-1569
[7] Gürdal, Z., and Olmedo, R., "In-Plane Response of Laminates with Spatially Varying Fiber Orientations: Variable Stiffness Concept," AIAA Journal, Vol. 31, No. 4, 1993, pp. 751-758.
doi: 10.2514/3.11613
[8] Jegley, D., Tatting, B. F. and Gürdal, Z., "Optimization of Elastically Tailored Tow Placed Plates with Holes," AIAA Paper No. 1420. April 2003.
doi: 10.2514/6.2003-1420
[9] Weaver, P. M., Potter, K. D., Hazra, K., Saverymuthapulle, M. A. R., Hawthorne, M. T., "Buckling of Variable Angle Tow Plates: from Concept to Experiment," AIAA paper 2009-2509, May 2009.
doi: 10.2514/6.2009-2509
[10] Lopes C.S., Gurdal Z., Camanho P.P., "Variable-Stiffness Composite Panels: Buckling and First-Ply Failure Improvements over Straight-Fibre Laminates," *Computers and Structures*, Vol. 86, 2008, pp. 897–907.
doi: 10.1016/j.compstruc.2007.04.016
[11] Wu, K. C., Tatting, B. F., Smith, B. H., Stevens, R. S., Occhipinti, G. P., Swift, J. B., Achary, D. C., and Thornburgh, R. P., "Design and Manufacturing of Tow-Steered Composites Shells using Fiber Placement," AIAA Paper 2009-2700, May 2009.
doi: 10.2514/6.2009-2700
[12] Smith, B., "Evaluation of Tow-Steering Effects – Mechanical Coupon Testing," *Proceedings of the 31st American Society for Composites Meeting*, Williamsburg, VA, September 2016.
[13] Kennedy, G. J., Brooks, T. R., and Martins, J. R., "High-fidelity Aerostructural Optimization of a High Aspect Ratio Tow-steered Wing," AIAA Paper No. 2016-1179, January 2016.
doi: 10.2514/6.2016-1179
[14] Dillinger J. K. S., Klimmek T., Abdalla M. M., and Gürdal Z, "Stiffness Optimization of Composite Wings with Aeroelastic Constraints," *Journal of Aircraft*, Vol. 50, No. 4, 2013, pp. 1159-1168.
doi: 10.2514/1.C032084
[15] Wu, K. C., Turpin, J. D., Stanford, B. K., Martin, R. A., "Structural Performance of Advanced Composite Tow-Steered Shells with Cutouts," AIAA Paper 2014-1056, January 2014.
doi: 10.2514/6.2014-1056
[16] Wu, K. C., Stewart, B. K., Martin, R. A., "ISAAC – A Testbed for Advanced Composites Research," *Proceedings of the 29th American Society for Composites Meeting*, San Diego, CA, September 2014.
[17] NASA ISAAC Fact Sheet, FS-2016-12-273-LaRC.
[18] Cramer, K. E., Winfree, W. P., "Application of the Thermal Line Scanner to Quantify Material Loss Due to Corrosion," *Proceedings of SPIE 4020*, Thermosense XXII, March 2000.
doi: 10.1117/12.381553