IN SITU THERMAL INSPECTION OF AUTOMATED FIBER PLACEMENT OPERATIONS FOR TOW AND PLY DEFECT DETECTION

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ABSTRACT

The advent of Automated Fiber Placement (AFP) systems have aided the rapid manufacturing of composite aerospace structures. One of the challenges that AFP systems pose is the uniformity of the deposited prepreg tape layers, which complicates detection of laps, gaps, overlaps and twists. The current detection method used in industry involves halting fabrication and performing a time consuming, visual inspection of each tape layer. Typical AFP systems use a quartz lamp to heat the base layer to make the surface tacky as it deposits another tape layer. The innovation proposed in this paper is to use the preheated base layer as a through-transmission heat source for inspecting the newly added tape layer in situ using a thermographic camera mounted on to the AFP hardware. Such a system would not only increase manufacturing throughput by reducing inspection times, but it would also aid in process development for new structural designs or material systems by providing data on as-built parts. To this end, a small thermal camera was mounted onto an AFP robotic research platform at NASA, and thermal data was collected during typical and experimental layup operations. The data was post processed to reveal defects such as tow overlap/gap, wrinkling, and peel-up. Defects that would have been impossible to detect visually were also discovered in the data, such as poor/loss of adhesion between plies and the effects of vacuum debulking. This paper will cover the results of our experiments, and the plans for future versions of this inspection system.

1. INTRODUCTION

1.1 Overview

Automated Fiber Placement (AFP) systems were developed to transition composite construction from a manual hand layup technique to a faster more repeatable automated technique. Several variants of AFP systems exist, but all operate on the same basic design principle (Figure 1). A stationary or moving substrate is used as an inner mold for the composite part to guide the final shape. Preimpregnated carbon fiber epoxy tape strips (tow tape) are spool fed to a collimator that aligns them side by side. The row of fiber tows is then fed to the AFP 'head' which houses the compaction roller that travels along the surface of the substrate, depositing the tows onto the substrate. The substrate or the roller (or both) move and rotate so that the tows are deposited on a preset path. Traveling ahead of the roller is a heat source (usually a quartz lamp) that preheats the substrate to aid the adhesion of the ply onto the previous ply or substrate.

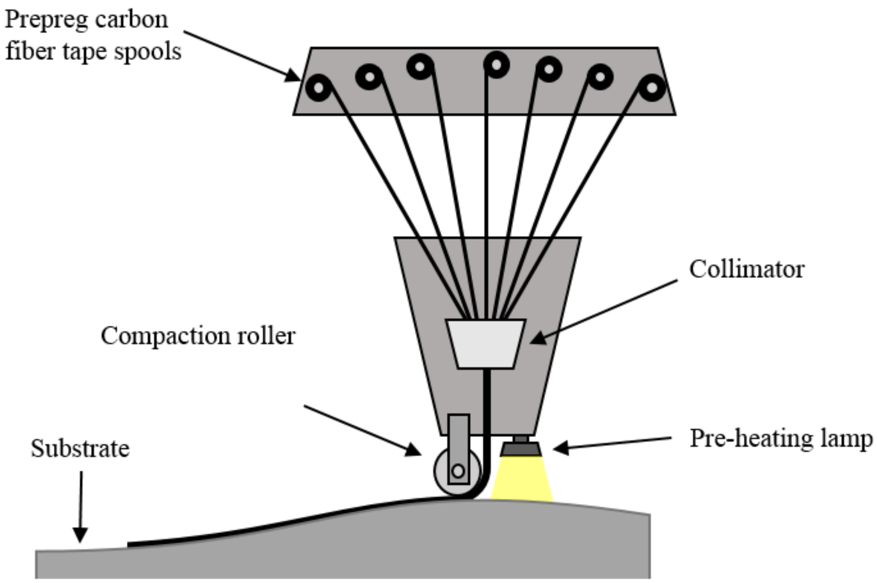


Figure 1: Simplified diagram of a typical AFP robotic platform

Composites constructed with AFP systems can be prone to manufacturing defects that may severely compromise the structural integrity of the part by creating stress concentrations that can lead to failure. The primary defects of interest are twists in the tows, gaps between tows, overlapping tows, reduced ply adhesion quality, and Foreign Object Debris (FOD). In order to detect and mitigate the effects of these manufacturing defects, the standard procedure in aerospace manufacturing environments is to conduct a full visual inspection of each layup. This usually involves the use of multiple technicians with lights and magnifying optics combing over the entire structure after each ply layer is deposited. Not surprisingly, this adds labor and time costs to the manufacturing process.

In this paper, we propose a solution for defect detection using a thermographic inspection technique. The quartz heating lamp that proceeds the tow placement, in an AFP system, can be used to make the substrate a through transmission heat source to inspect the deposited fiber layer. By attaching an infrared camera to the AFP head and imaging the area immediately behind the compaction roller, the heat conduction from the substrate to the outer surface (process monitoring) or from the outer surface into the composite (post process NDE) to assess the material state. The following sections will discuss the background of the problem that motivated this innovation; an overview of our research including experimental setup; and data from a subset of projects in which we have participated. We will then conclude with a summary of our intent for the future of this innovation.

1.2 Background and Theory

Detecting and mitigating AFP-related manufacturing defects has been one of the most challenging obstacles in the adoption of AFP systems in large-scale high-throughput manufacturing environments. The current use of 100% manual inspection of AFP-made safety-critical aerospace structures is due to the known (and, perhaps more importantly, the unknown) effects of AFP-related defects. It has been observed in simulations [1] that twist, lap, and gap defects reduced the mechanical strength of composite parts as much as 32%. Smaller strength reductions (7% to 12%) have been observed in experiments, partially due to lap and gap defects sometimes self-correcting during the cure cycle [2]. The tendency of these defects to self-correct, and their effects on structural integrity is currently being investigated in other efforts [3].

Several technologies have been developed to detect these manufacturing defects. In 2007 an out-of-process system was patented [4] that augmented the manual inspection process with angled lights and a camera system to aid a technician in defect detection. The technique suffers from the same limitations as the manual technique, and only benefits from an increase in inspection speed. In 2014, an automated laser profilometry system was developed to inspect each ply layer layup after the ply layer is complete. The use of laser profilometry has proven to be robust at finding changes on the surface [5]. However, this has only been implemented as an out of process (ex situ) technique. Additionally, this technique relies on changes in surface displacement to detect defects, so it is insensitive to defects such as loss of ply adhesion to the substrate or very thin Foreign Object Debris (FOD).

The innovation described in this paper can be employed in two ways. The first is an in situ method that monitors the tow tape as it is being laid up on the substrate, referred to hereafter as mode 1. Since the substrate is heated immediately prior to layup using a heat source traveling ahead of the roller, the state of the newly deposited tows can be assessed by monitoring how the heat from the substrate flows into the tow layer. Figure 2 graphically represents the heat flow in the specimen from through-transmission heating. Immediately after the tow is compacted into the substrate, the heat from the substrate begins to conduct through the cooler medium of the new tow layer. The temperature profiles will be different when observing heat transferring from (b) substrate to a tow layer (normal), (a) substrate through two tow layers (overlap), and (c) an exposed substrate cooling by itself (gap). Additionally, if the interface between the two layers is poor (i.e. the layers are not adequately bonded to each other) there will be an increase in the thermal resistivity and thus a decrease in the heat flow from the substrate to the new ply.

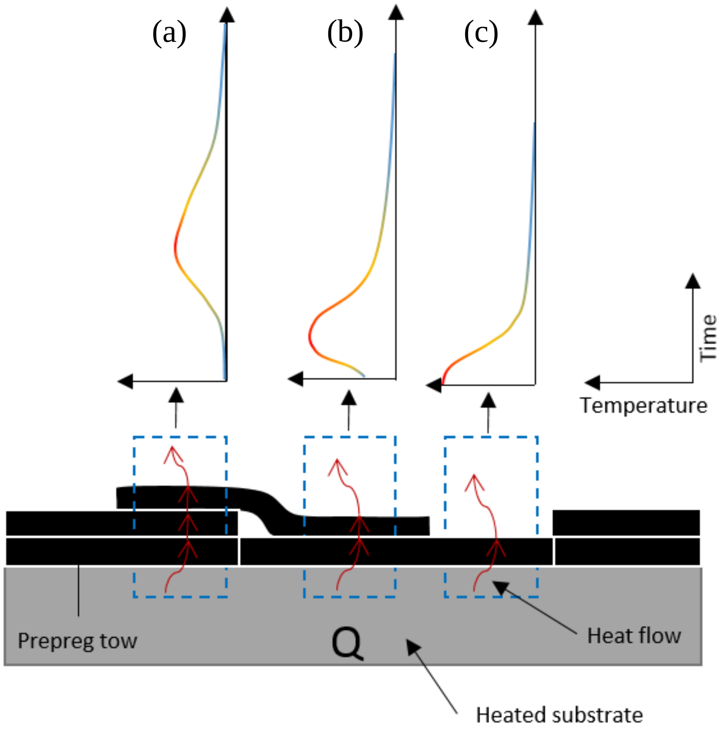


Figure 2: A depiction of the effect of defects on the temperature profile when the substrate acts as a through transmission conductive heat source.

The second way this innovation can be employed is ex situ by using a line-scan methodology, referred to hereafter as mode 2. During traditional a thermographic line scan a heat source is scanned across the surface and the heat flow (as indicated by the surface temperature) is monitored as it conducts through the full thickness of the material. We replicate this maneuver by using the AFP machine to execute an existing full coverage acreage ply with zero tow feed and a small surface offset so that it will run the same path without laying down material. During this operation, we collect data while the surface is being heated with the onboard heat source. This has the benefit of assessing the entire part at the end of layup instead of just the most recently applied layers. Our research has shown that this method can detect defects undetectable by current visual inspection techniques.

Previous work [6-10] has shown that moving a heat source across the surface of a stationary specimen not only detects defects in a specimen, but can also be used to quantify thermal diffusivity and thickness. For example, Winfree [7] observed that constant velocity line source heating produces a surface temperature inversely proportional to the thickness of the specimen. Therefore, it should be possible to not only detect defects during the manufacturing process, but also classify the type of defect based on the measured temperature response and defect shapes. Additionally, the analytical relationship between surface temperature and thickness will become especially important when inspecting ply layers on parts that have a substrate with intentional variable thicknesses. A qualitative approach alone may not be suitable for defect detection in regions where ply drop-offs or buildups occur.

2. EXPERIMENTATION

2.1 Experimental Setup and ISAAC

In 2015, NASA Langley Research Center (LaRC) acquired a multi-axis AFP system to use as a research platform for new manufacturing and inspection techniques. Known as the Integrated Structural Assembly of Advanced Composites (ISAAC), this multi-axis robot is similar to other AFP systems used in the aerospace industry and was developed by ElectroImpact, Inc. ISAAC is used for prototyping of parts as well as AFP technology research and development. All the data presented in this paper was generated by our thermal system installed on the ISAAC AFP platform.

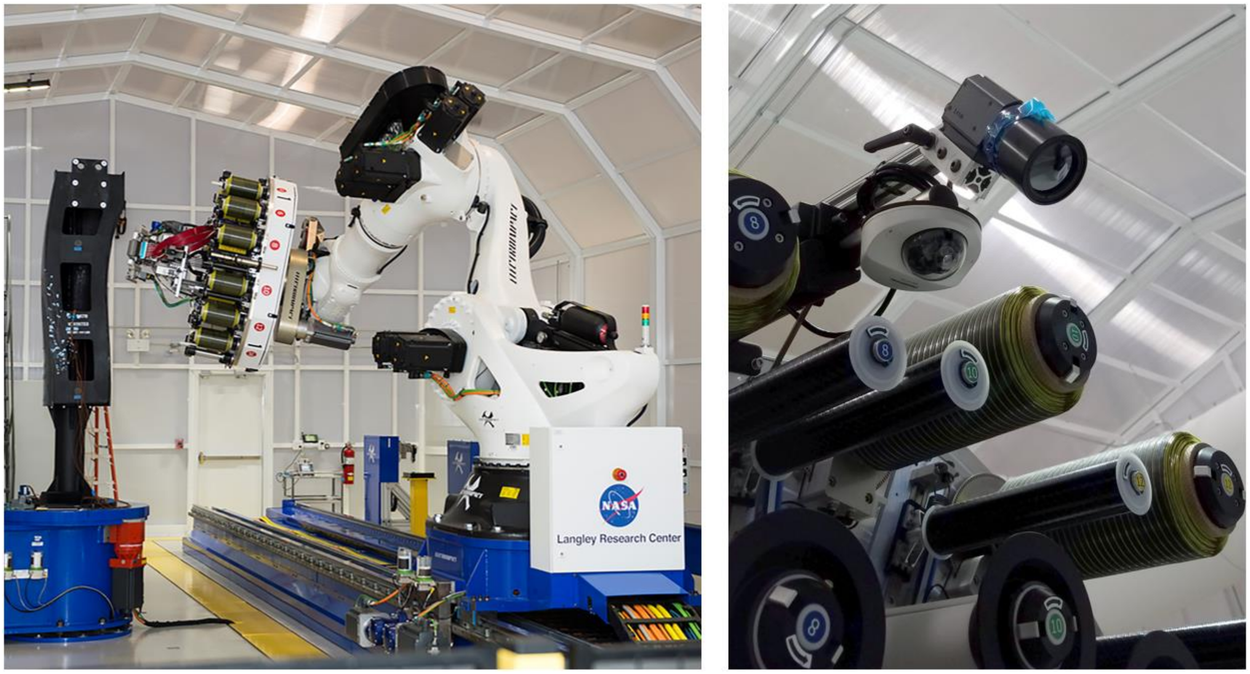


Figure 3: (left) Photo of ISAAC during an AFP operation (right) close up of the thermal imaging camera mounted on ISAAC's AFP end effector

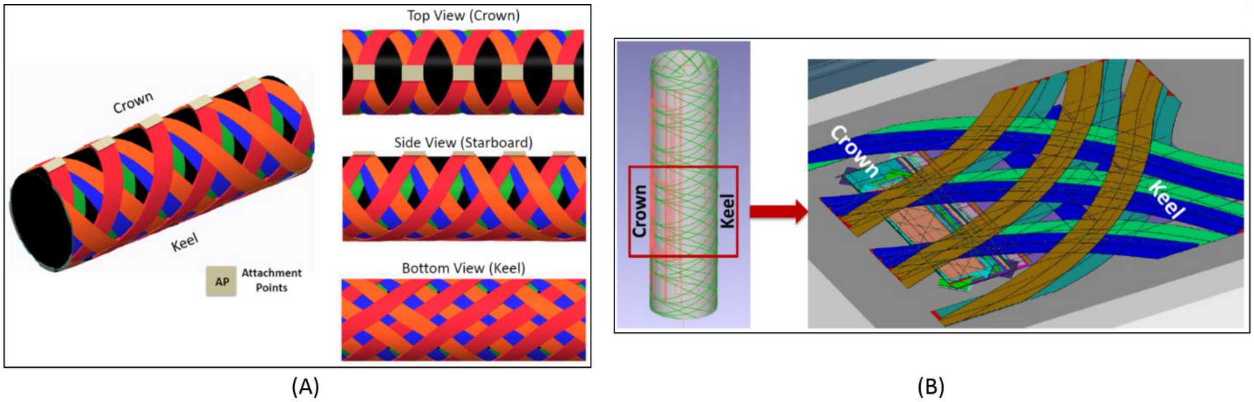
Figure 3 shows the integrated thermal camera and its location on the ISAAC AFP head. The thermal camera used in this study is the FLIR A65, which uses an uncooled microbolometer sensor to capture 14-bit linear temperature data across a 640 x 512 array and at a rate of up to 30Hz. It is powered and communicates with the controller via gigabit ethernet connection using the industry standard GigEVision protocol. The camera communicates to a data acquisition computer at the operator's station via an ethernet switch on the AFP head itself, which then passes the ethernet through the slip ring/tool changer assembly at the end effector of the robot. The thermal camera is mounted near the existing visible light camera, which is used by the operators to monitor the roller. Both cameras point to a region directly behind the compaction roller to observe the material right after lay up as it passes underneath the roller. The placement of the camera coupled with the installed 50 mm lens enabled the capture of a 7.62 cm x 10.16 cm region behind the roller, giving a 4232 pixel/cm^2 density.

2.2 Tow Steered Composite Experiments

NASA LaRC collaborated with Generation Orbit Launch Services (GO) to investigate the feasibility of fabricating reduced-mass composite rocket bodies using AFP tow-steering. Tow steering is a method with which design engineers can efficiently tailor the strength of a structure by orienting the fibers in the direction of loading. Tow steering is performed by rotating the direction of the AFP roller during the layup of individual courses, instead of keeping a straight path as is seen in traditional layups. Normally these types of rocket bodies are built with a quasi-isotropic stacking sequence to produce a composite with a strength that is uniform throughout the cylinder. By steering the fiber direction to where it is most needed the overall amount of material needed can be reduced. The collaborative project designated GO-1 designed the tow-steered cylinder seen in Figure 4A. The strength of the structure is tailored to a series of mounting hard points on the crown of the cylinder. This was to ensure the hard points could support the entire launch vehicle, enabling the rocket to be mounted and launched from the wing hard point of an aircraft [11]. The final cylinder designed was 1.85 m tall with a 0.61 m diameter.

Despite the potential mass savings of tow steering, uptake in aerospace applications have been limited. Intuitively we see that, during a tow steer, the tows at the outer edge of the curve will cover more distance than tows at the inside edge of the curve. This is accounted for in the tow feed rates during a tow steer; however, each tow has a finite width. Thus, it is difficult to make a tow bend about its width (in plane) without the edge peeling up from the ply or buckling on the respective sides of each tow. Tow misalignment leading to overlaps and gaps is also a concern, as tows may slip out of place due differences in tow tension and loss of adherence [11].

To investigate the likelihood of these defects and how well they could be mitigated through process control, the GO-1 team designed a tow steered panel based on the design of the GO-1 cylinder (Figure 4B). We acquired thermography data during both the panel and the subsequent cylinder builds. The results generated from testing on the tow steered panel contributed directly into the process development and build plan of the cylinder.



(A) (B)

Figure 4: (A) Design of the GO-1 tow-steered cylinder. (B) Diagram of the tow steered panel used for risk mitigation study, and the section of the cylinder it was built to imitate

Additionally, we recently rebuilt the GO-1 cylinder using a modified stacking sequence and process parameters. The intent was to characterize the effects of sub-optimal compaction on the thermal data acquired during the build. This work is still on going, but preliminary results will be presented in the following section.

3. RESULTS

3.1 Data Processing and Analysis Notes

In the following section and subsequent figures, the interpretation of the data will greatly depend on the method of processing and analysis. We employ several methods of data processing and analysis to interpret the thermal data we collect. A selection of these methods is presented here, but we have seen success using other methods such as expected value analysis [12]. Which method we utilize is dependent on what we are investigating and which mode of data collection we are using (i.e. mode 1: during layup or mode 2: post layup line scan). Since mode 1 data is captured during layup the darker/lower temperature regions indicate less heat flow from the substrate to the new course, which is indicative of loss of adhesion, peel up/buckling, overlapping tows, etc. Lighter/ higher temperature regions in mode 1 data are indicative of gaps between tows revealing the heated substrate underneath. In mode 2 data, since heat is flowing from the surface down through the thickness, the opposite is true: hotter regions show lack of heat flow indicative of loss of adhesion, peel up/buckling, overlapping tows, etc. while colder regions show greater heat flow through the composite into the tooling surface.

Raw and processed data will differ in interpretation as well. In a raw frame of thermal data, the material closest to the roller has less time for heat flow to occur than the material on the opposite side of the image (since the roller is in the direction of the layup). As the heat flows through the material, the indication of defects will diffuse due to natural convection and thermal conduction in different directions. We can take advantage of this process to generate temporal information of how the heat flows through the material. Once we isolate the individual courses in the frame and align all the courses in space, we can use data manipulation (described in detail in [6, 12, 13]) to align all the spatial coordinates in time. This allows us to view the entire ply layer at a single time after the application of heat. We refer to this as heat-time alignment.

3.2 Tow Steered Panel

Figure 5 shows the raw mode 1 data captured during the layup of the tow steered panel. Figure 5A is an example of a relatively pristine layup, which exhibits a uniform temperature profile across the width of the course. The field of view of our thermal camera allows us to capture the previous course as well, which exhibits buckling on the inside of the tow steer. Figure 5B was collected as the course was steered over a ply build up. When a course goes over a steep stair-stepped ply build up bridging can occur. Bridging is when the tows create gaps by lying flat across the stair-steps instead of tucking into each step. Figure 5B also shows that the buckling of the tow steer may be partially alleviating some of the bridging, as the tow edges on the inside of the curve buckled into the stair step, leaving only half the tow bridged. Figure 5C shows that although the tows all have adequate adhesion to the substrate there are steer-induced overlaps and gaps in the tow. This indicates that tow-misalignment is occurring at the nip-point of the roller.

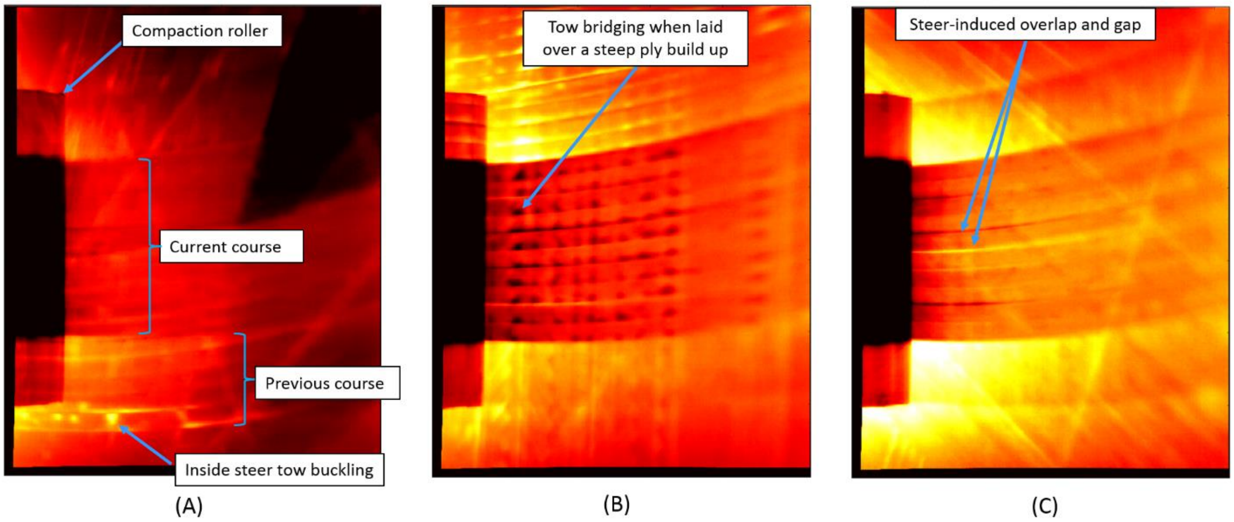


Figure 5: Mode 1 thermal images during three separate courses demonstrating various defects and features of note during the layup of the GO-1 tow steered panel

After all the tow steered plies were laid up, we conducted a line scan to collect mode 2 data. This data was then aligned in space and heat-time as described in section 3.1. Shown in Figure 6A, we can see many hot-spot indications of tow peel up and buckling throughout the panel. Many of these indications were also visible from the surface, since the tow lifted off of the substrate a measureable amount. One notable exception is the bright diamond-shaped feature in the middle right region of Figure 6A. Prior to the layup of the tow-steered plies, 4 small rectangular patches were laid up on the surface as per the design of the cylinder. During the layup of the tow steered plies, the turning motion of the steering caused this patch to completely disbond from the surface. Subsequent tow-steered plies came near enough to this patch to re-compact most of it, but left a diamond shaped region of material unbonded. This defect was not visible during the visual inspection conducted between each ply, and was only discovered in the post processing of the thermal data.

After the line scan, the panel was subjected to a debulking cycle. Debulking is a common procedure in composite layup where the part is bagged and a vacuum is pulled. This is used to help eliminate trapped air and to increase compaction. After debulking, a second line scan was performed and analyzed. The data from this analysis is shown in Figure 6B. Here we see that a majority of the defects have been corrected, including the debonded patch. The majority of the defects that remain are under the intersection of multiple tow steers and other ply buildup features. This suggests that frequent debulking cycles between sets of tow steered plies may help avoid these defects.

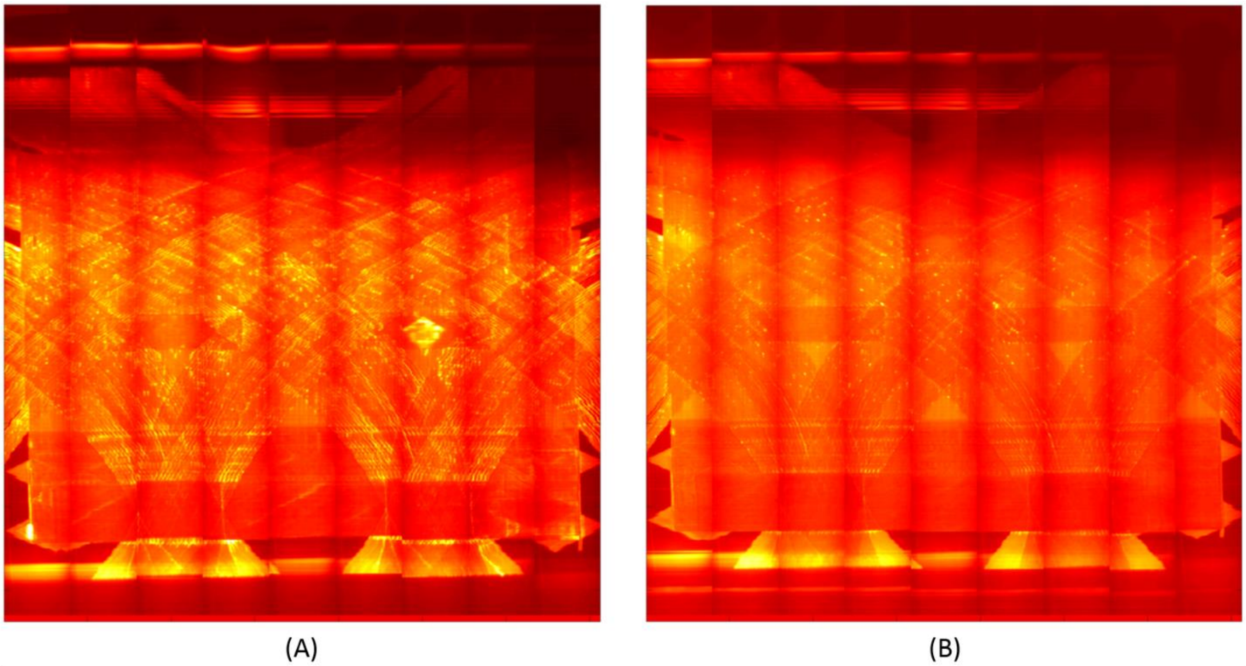


Figure 6: Mode 2 data that has been aligned in space and heat-time for the GO-1 tow steered panel (A) after final ply prior to debulking and (B) after 30 minute debulking. Both data sets are alligned to the earliest point in heat-time

3.3 GO-1 Cylinders

The data from the build of the GO-1 cylinders produced results similar to the tow steered panel. We performed a line scan after the tow steered plies. We then unwrapped and aligned in space and heat-time to produce the image seen in Figure 7A. The vertical lines are due to the lower lamp heat output towards the edges of the course. The slant in the image is due to the line scan being performed using an 87° helical pattern. The bridging effects were still present in the ply build-up approaching the crown, but were less pronounced due to a shorter incline. Despite using higher heat settings on the AFP system during the cylinder build (versus the panel build) significant tow peel up still occurred. Figure 7B shows the line scan data collected after a 30-minute debulking cycle was performed. We can see that the tow steered plies responded well to the debulking, as there is little evidence of tow peel up. The consolidation of the ply layers is sufficient to allow embedded features to show through the upper plies, such as the rectangular patches and crown build up. These features were previously obscured due to the lack of heat transfer from the top most plies. After debulking, the composite was consolidated enough to allow for heat transfer into those lower layers, revealing their geometry due to the changes in local thickness.

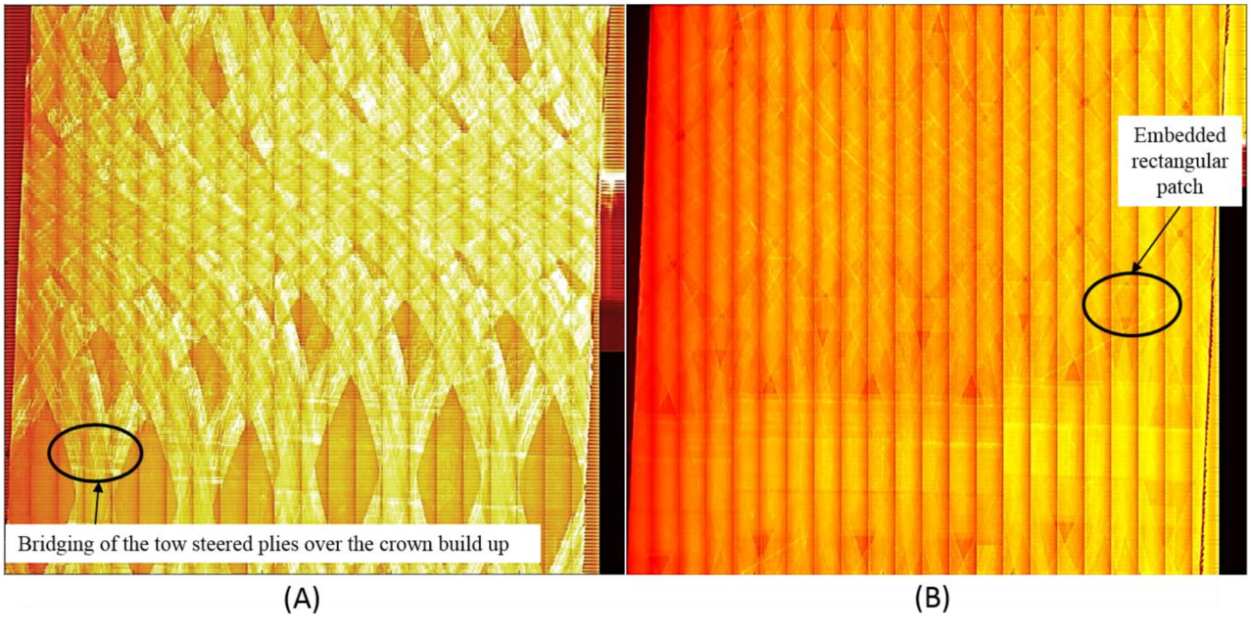


Figure 7: Mode 2 data that has been aligned in space and heat-time for the GO-1 tow steered cylinder (A) after final ply prior to debulking and (B) after 30 minute debulking

The final cylinder was built to test the effects of suboptimal compaction on the thermal signature. On several crown patch layers the roller compaction was varied to as little as 25% of the design specifications. Because these patches were laid up along the length of the cylinder, rather than the circumference, the effects of this lower compaction was exacerbated by the roller conforming to a cylindrical surface (Figure 8). We collected mode-1 data and aligned it spatially to create Figure 9. The lower compaction settings produce a noticeable lack of adhesion between the course ply and the substrate, which also correlates with the darker/colder regions in the thermal image due to lack of heat flow. We are still investigating the sensitivity of thermal signature to varying adhesion between prepreg layers.

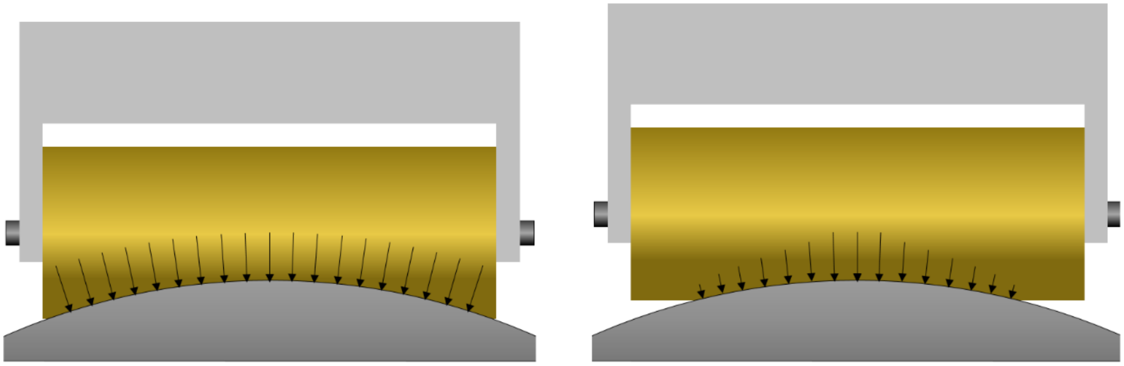


Figure 8: Visualization of the optimal (left) vs. suboptimal (right) compaction using a conformal roller on a cylindrical surface. Black arrows are a representation of compaction pressure. All dimensions are exaggerated for clarity.

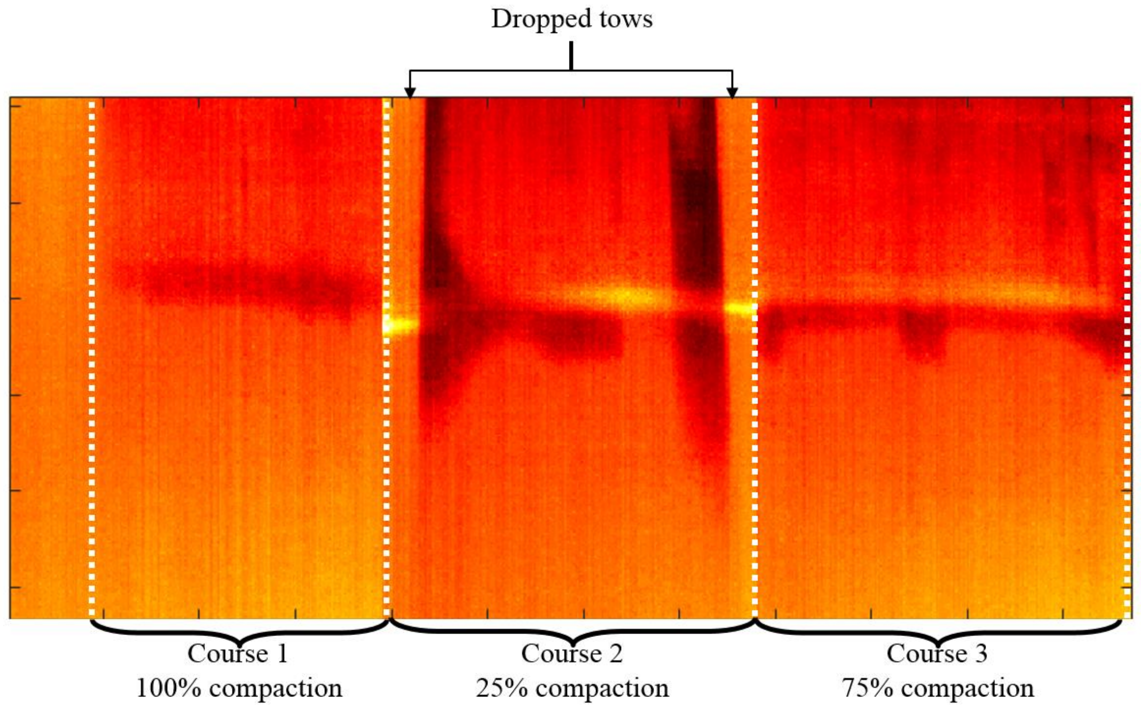


Figure 9: Mode 1 data of the sub-optimal compaction tests. Course 2 failed to place the ¼” tows at the far left and right side of the course due to insufficient compaction.

4. CONCLUSIONS

We have shown that in situ thermal imaging has detected defects of interest in AFP without the need for visual inspection of each ply layup. We have also shown the benefit of a post layup line scan in understanding the final material state prior to curing. Both in situ and ex situ thermal imaging has the potential to create more efficient production environments, as well as enhancing the process development for new material systems and structural designs. The thermal system implemented in this study is also low cost, with the thermal camera procured for under $9,000.

The next steps in our research will be to perform simple modifications to the ISAAC platform to allow the synchronous triggering of the thermal camera based on part coordinates. Currently part coordinates are inferred from knowing the starting point of the course and the time it takes to get to the end, which works for most cases. The ability to have a 1:1 comparison of thermal image to part coordinate will allow us to overlay our processed data into a three-dimensional model of the part. The second task will be to employ machine-learning algorithms for data reduction. The idea is to reduce the results to operator-friendly images and reports so that the operator can make a decision on repair necessity. We are also in the process of installing a small but powerful pre-processing computer (Intel NUC) on the AFP head of ISAAC itself to aid in data throughput. The on-board computer will handle the data reduction algorithms while saving the raw data simultaneously. This will enable faster data acquisitions and eliminate any data bandwidth limitations.

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