Advances in In Situ Inspection of Automated Fiber Placement Systems

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ABSTRACT

Automated Fiber Placement (AFP) systems have been developed to help take advantage of the tailorability of composite structures in aerospace applications. AFP systems allow the repeatable placement of uncured, spool fed, preimpregnated carbon fiber tape (tows) onto substrates in desired thicknesses and orientations. This automated process can incur defects, such as overlapping tow lines, which can severely undermine the structural integrity of the part. Current defect detection and abatement methods are very labor intensive, and still mostly rely on human manual inspection. Proposed is a thermographic in situ inspection technique which monitors tow placement with an on board thermal camera using the preheated substrate as a through transmission heat source. An investigation of the concept is conducted, and preliminary laboratory results are presented. Also included will be a brief overview of other emerging technologies that tackle the same issue.

Keywords: Automated Fiber Placement, Manufacturing defects, Thermography

1. INTRODUCTION

Large, complex composite structures have become common in the aerospace industry. 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 (Fig. 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 lines them side by side. The row of fiber tows are 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 increase tackiness and ensures the tow tape does not slip during deposition. In 2015 NASA Langley Research Center procured a multi-axis AFP system to use as a research platform for new manufacturing and inspection techniques (Fig. 2) . 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.

Composites constructed in AFP systems can be prone to manufacture defects. These defects can 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 tow line, gaps between tow lines and overlapping tow lines. 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, but this is partially due to the fact that lap and gap defects can sometimes correct themselves during the curing cycle[2] . The tendency of these defects to self correct, and their effects on structural integrity is currently being investigated through other efforts in the ACP.

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. This is especially notable on larger structures such as barrel fuselage sections, where some areas can reach up to 96 plies thick.

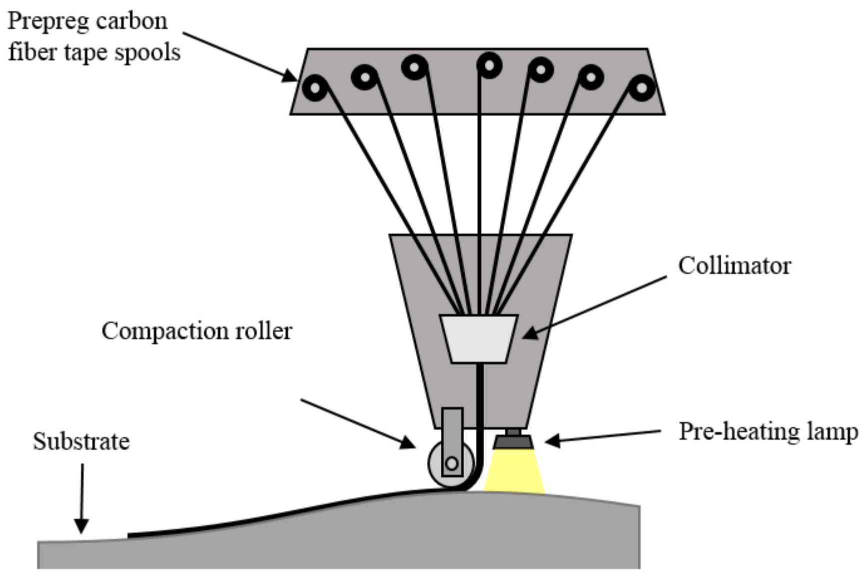

Figure 1. Simplified diagram showing the operating principles of Automated Fiber Placement (AFP) systems. In some designs the AFP head will remain stationary while the substrate translates and rotates on a spindle, such as during the construction of barrel fuselage sections.

Figure 2. The Integrated Structural Assembly of Advanced Composites, or ISAAC, was procured by NASA Langley Research Center as a research tool to investigate new and innovative manufacturing techniques.

Several technologies have been developed to detect these manufacturing defects. In 2007 an out-of-process system was patented[3] that essentially imitated the manual inspection process, but uses angled lights and a camera system to aid a technician in defect detection (such as missed defects and false calls). 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 finished. The use of laser profilometry is very robust to finding changes on the surface, and has found great success in experiments.[4] The shortcomings are that this is an out of process (ex situ) technique, the 3D profile of the part at each layup needs to be known ahead of time, and false positives can be generated from small surface perturbations that would be otherwise cleared in the subsequent debulking.

In this paper, we propose a solution for defect detection using an in situ thermographic inspection technique. The quartz heating lamp that leads the tow placement, in an AFP system, can be used as 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 through the tape layer can be monitored.

An in situ method of detecting manufacturing defects will drastically increase AFP composite construction times and efficiencies. A recognition program based on the physics of heat conduction can be produced to continually monitor the tow placement. If an anomaly is detected, engineers can enact automatic repair methodologies.[5]

This preliminary study will also lay the groundwork for quantitative analysis of the inspection data. 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] showed with a line source moving at a constant speed that, in the limiting case, the surface temperature (T) is 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. 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 off or buildups occur.

2. EXPERIMENT

Prior to a full scale implementation on an AFP system, a laboratory proof of concept (POC) experiment was designed and fabricated to investigate the feasibility of this technique. The POC scanning gantry has two parallel independent scanning rails that are indexed on rack-pinion guides (Fig. 3) . The top scanning rail carriage carries an infrared camera (FLIR SC6000), while the bottom rail carriage carries a commercially available 3000-watt quartz heat lamp. The lamp is arranged with an elliptical reflector behind the quartz tube focusing the energy to approximate a line of heat 40.6 cm in length and 1.27 cm in width. Since the rails operated independently scanning can be performed so that the lamp leads the camera by any desired distance, which can be used to control the temperature transient in the specimen. A software package was developed to control the scanning system and to interface and record the thermal camera data.

Using ISAAC a two-ply unidirectional specimen was fabricated with manufacturer defects on the top ply (Fig. 4). The specimen was made from Hexcel IM7-8552-1 0.635 cm (0.25 in) prepreg tape, which is a standard aerospace grade composite material and was deliberately left uncured. Intentional defects were manually created at the top ply of the specimen. These defects consisted of a twisted tow, three overlaps and three gaps (each overlap creates an inherent gap in this instance), each of which nominally measured 0.32 cm (1/8 in), 0.16 cm (1/16 in), and 0.08 cm (1/32 in).

Fig. 5 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. In the transient, the heat going through the thickness of two tow layers (normal), three tow layers (overlap) and a single tow layer (gap) will exhibit different temperature profiles as the surfaces heat and cool.

Inspection was carried out by scanning both the top and bottom rail along the length of the uncured panel, in the tow layup direction at a constant speed. The line heat source led the center of the camera by approximately 10cm. The scanning speed was selected to easily allow the reduction of the acquired data into images at fixed times after heating. For each scan frame, the unit spatial measurement per pixel (p, measured in meters/pixel) can be calculated by focusing the camera on an object of known size and counting the pixels. The camera acquisition rate is set by the user (f, measured in frames/second). The velocity needed to advance camera the same distance as X number of pixels per frame acquired is calculated by:

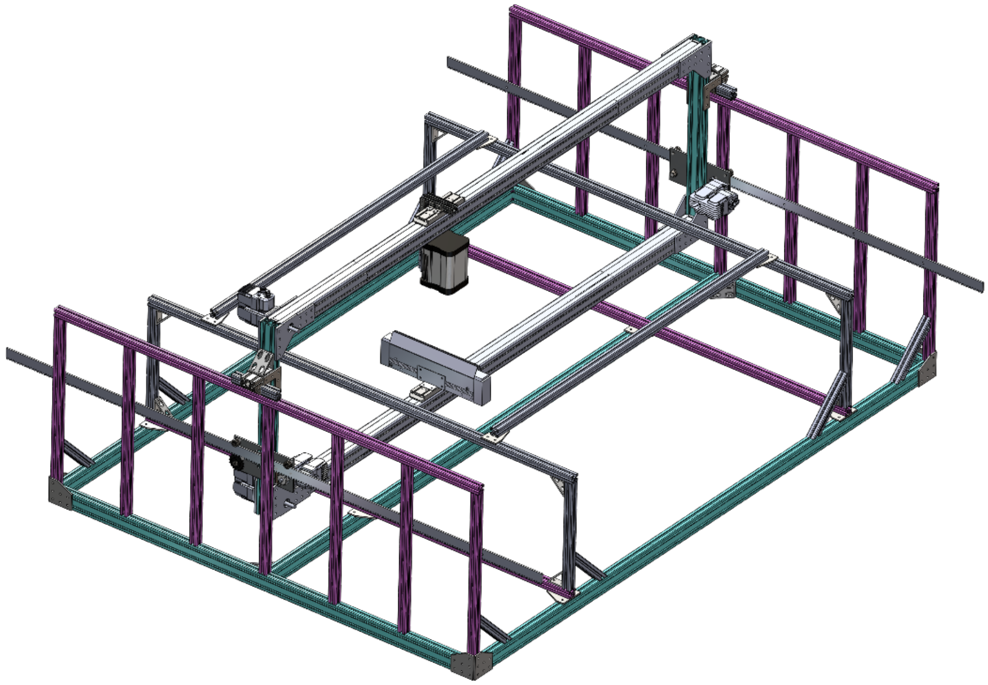

Figure 3. A SolidWorks model of the proof of concept setup for thermographic inspection. Two independent linear rails carried a thermal camera and line heat lamp above and below a sample that would be suspended between them. The two rail frame was indexed on a rack-pinion guide.

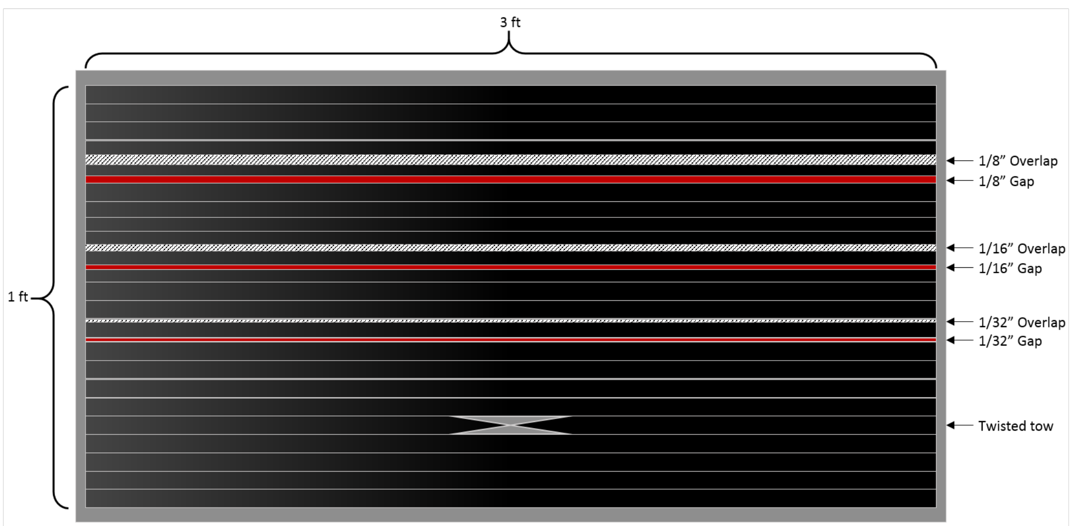

Figure 4. Diagram of the uncured defect panel made by ISAAC. Defects and locations are approximate and not to scale.

$$V\left(\frac{meters}{second}\right) = p\left(\frac{meter}{pixels}\right) * f\left(\frac{frames}{second}\right) * X\left(\frac{pixels}{frame}\right) \tag{1}$$

For this proof-of-concept experiment, each pixel covers a 0.33 mm field of view, the camera is capturing 120 frames per second, and it is desired to have the camera advance 1 pixel per frame, therefore the velocity selected was 0.04 m/s. While speeds of industrial AFP systems widely varies depending on the machine and application

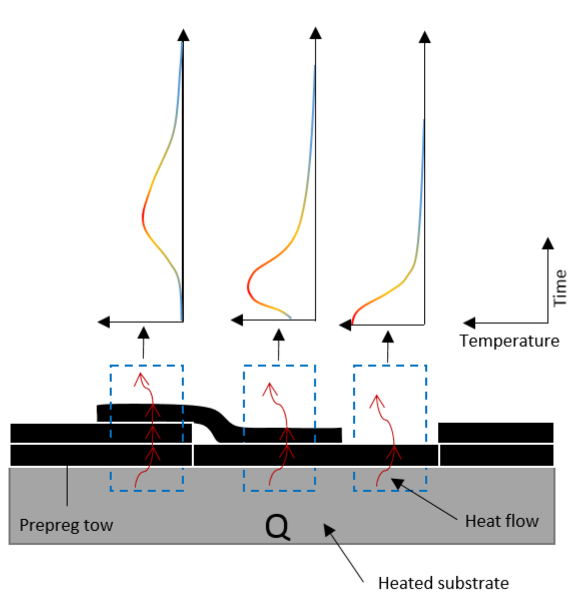

Figure 5. A depiction of the effect of defects on the temperature profile when the substrate acts as a through transmission conductive heat source. From the perspective of the thermal camera, gaps will immediately appear as a higher temperature and cool more rapidly, while overlaps will heat up much more slowly and may never reach the same maximum surface temperature as the normal layup.

(sometimes reaching as fast as 1 m/s) but generally stay around 0.17 m/s.[11] So for this POC experiment we are operating slower than a normal AFP speeds, due primarily to geometric limitations of the scanning setup.

3. RESULTS

Fig. 6 shows a single frame acquired from the infrared camera during a scan across the specimen. Even in this unprocessed image all of the defects are visible. Gaps show up as bright, high temperature regions and overlaps show as darker, low temperature regions. Because both the camera and heat source are moving relative to the specimen, Fig. 6 shows a significant variation in the spatial temperature distribution. Thus the left side of the image shows the temperature transient at early times after heating, while the right side shows later time in the temperature transient. At the edge of the heat lamp on the left of Fig. 6 many other darker spots and partial lines can be seen. These are not complete overlaps of adjacent tow tape, but instead are small imperfections in the flatness of the tape itself. Since they are the same thickness as the normal layup these features are evident in early times after heating, but quickly fade into the mostly uniform temperature of the defect free regions, seen in the middle of Fig. 6, while the temperature response of defects of interest persist even at later times..

Fig. 7 is a reconstructed image where all points represent the temperature at a fixed time (approximately 0.6 seconds) after heating. A number of different fixed time images can be reconstructed from the data acquired, only one is shown in this example. The camera optics and standoff distance were altered to achieve the desired spatial resolution, but as a result the full width of the sample was not acquired, thus the 0.32 cm (1/8 in) overlap/gap is not captured in this figure. This process technique not only reduces processing resources (such as cpu usage, memory, etc.), but also allows for an number of standard time-based analysis algorithms, typical of flash thermography, to be applied to the data.

4. CONCLUSION AND FUTURE DIRECTION

A proof-of-concept method of in-situ inspection of AFP systems was demonstrated. The new method involves thermographic inspection of individual ply layers as they are deposited, using the preheated substrate as a through transmission heat source. The preliminary study was carried out and a lab based POC device that was

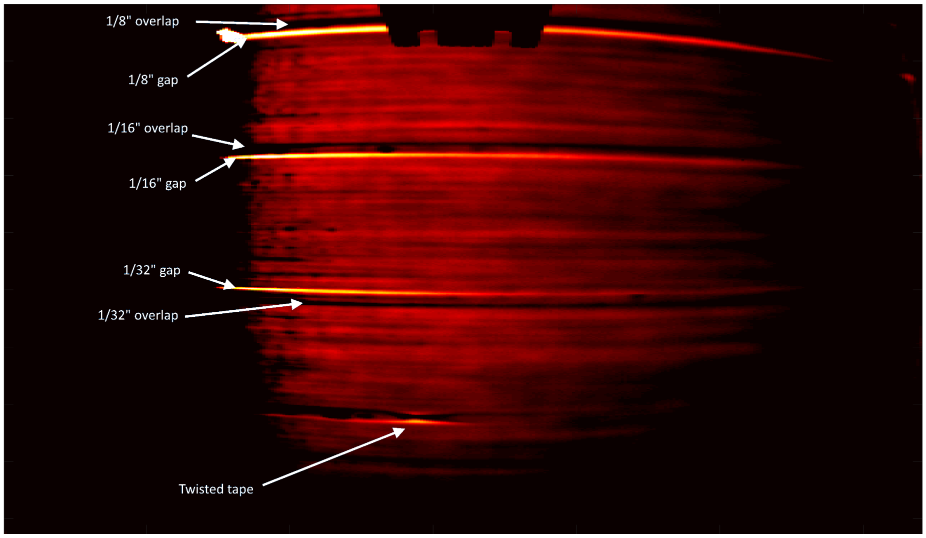

Figure 6. First results of the thermographic scan of the uncured panel.

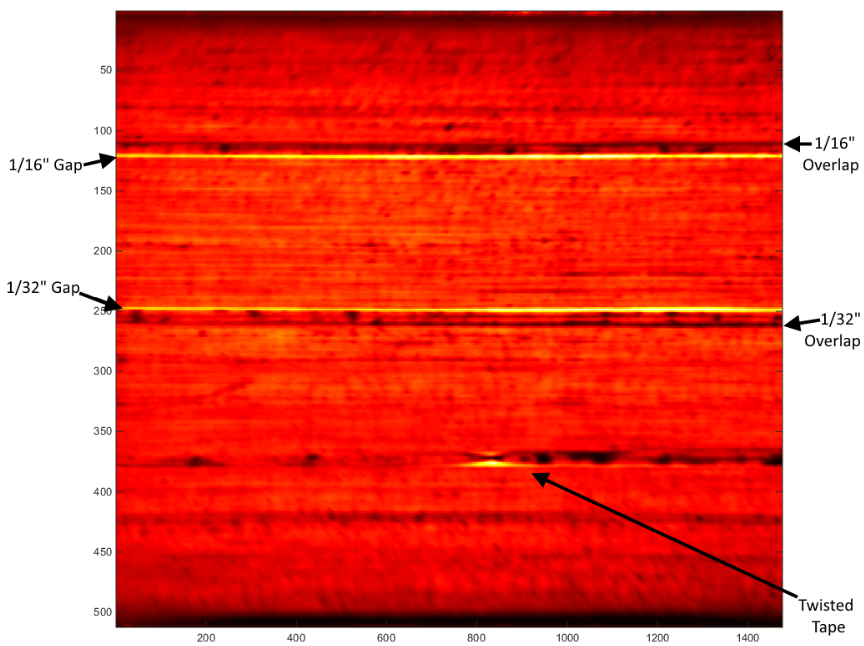

Figure 7. Image of all scanned spatial points at the same time in the heating/cooling process. Column data is gathered from a point that is approximately 0.6 seconds after the heat source has passed.

designed and constructed. The POC device simulated the AFP in situ scanning by heating the underside of a 2 ply uncured intentionally defective panel with a line heat lamp. Analysis of the line scan data indicates that the intentional manufacturing defects were qualitatively visible with no post processing.

While the experiment is analogous of the proposed technique, it is not exactly equivalent. For example, while the speed of inspection and the quartz lamp used is similar to those in AFP systems, they are not exactly the same. Therefore, one of the first goals for future work of will be to quantify and replicate exact heat flux rates experienced during AFP operations. Additionally, in the AFP process, the heat lamp is heating up the substrate in the path of the compaction roller prior to tow layer deposition; sometimes the substrate is the tooling surface (as it is for the first layer) and sometimes the substrate will be the last tow layer that was deposited, along with any prior layers under that. The prior ply layers underneath the substrate can influence the temperature profile at the surface of the newly deposited tow layer. Further, the proposed technique uses the heat of the surface of the substrate to heat the new tow layer for inspection, while the POC experiment is heating the bottom of a two-ply uncured layup and monitoring the top ply. The temperature profile of these two situations are different: in the former situation, a high temperature at the surface of the substrate is conducted further into the substrate and then into the newly deposited tow layer, and the latter situation a high temperature on the back end of the substrate propagates through the thickness of the substrate and then into the top ply layer. Differences notwithstanding, the experiment still serves as a representation of the overall concept: as heat conducts away from the higher temperature substrate surface into the new tow layer, the observed temperature profile will be an indicator of the state of the individual tow strips.

The ultimate goal of this investigation includes instrumenting the AFP system with an infrared camera that can measure surface temperatures during tow placement to confirm POC test results. Additionally, the post processing algorithms will be developed to conduct a feature recognition routine. This first involves passing the data through targeted filters and thresholds to enhance the contrast of the feature data. The parameters of the filters and thresholds can be arbitrary or based on the physics given the thermal properties and energy throughput. If needed additional derivative filters can be applied, and standard feature and edge detection algorithms[12] will be implemented to extract the defect indications and relay those to the AFP operators for corrective action.

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