COVER SHEET

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Title: **Advances in In-Situ Inspection of Automated Fiber Placement Systems**

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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 present is the uniformity of the deposited prepreg tape layers, which are prone to laps, gaps, overlaps and twists. The current detection modus operandi 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 idea was proposed to use the preheated base layer as a through transmission heat source and to inspect the newly added tape layer using a thermographic camera. As a preliminary study of this concept a laboratory proof of concept device was designed and constructed to simulate the through transmission heat source. Using the proof of concept device, we inspected an AFP-built uncured composite specimen with artificial manufacturing defects. This paper will discuss the results of this preliminary study and the implications involved with deploying a full-scale AFP inspection system.

Introduction

To keep up with the manufacturing demands of the aerospace industry, Automated Fiber Placement (AFP) systems were developed as a faster more repeatable automated composite construction technique to replace traditional hand layup. 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. Spool fed pre-impregnated carbon fiber epoxy tape strips (tow tape) are fed to the AFP 'head' which houses the compaction roller that deposits and compacts 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, consolidates previously deposited layers, 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

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Integrated Structural Assembly of Advanced Composites (ISAAC), this multi-axis robot is similar to other AFP systems used in the aerospace industry.

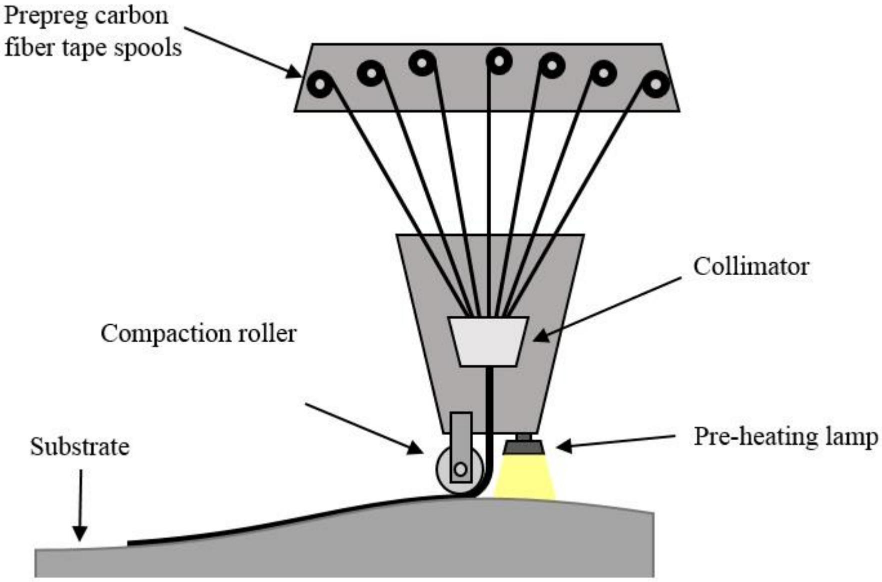

Figure 1. Simplified diagram showing the operating principles of Automated Fiber Placement (AFP) systems. In some designs the AFP head will remain stationary while the substrate translates and rotates on a spindle, such as during the construction of barrel fuselage

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.

Most rapid manufacturing process are prone to defects that must be monitored or mitigated, and composite AFP systems are no exception. Stress concentrations caused by tow tape defects during manufacturing can cause a weakening or failure of the constructed part. Many types of tow tape defects exist, but 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 as part of NASA's Advanced Composites Project (ACP).

Figure 1. Current industry method of tow tape defect detection is manual visual inspection. This is an image of a technician using magnifying optics to inspect the tape layer on a composite wing section

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 (Fig. 3) [12]. Reducing the time and cost associated with ply-by-ply visual inspections is an area of active interest across the aerospace industry. This is especially notable on larger structures such as barrel fuselage sections, where some areas can reach up to 96 plies thick. Though several technologies have been developed to detect these manufacturing defects, most are out-of-process inspection techniques, some rely on a priori knowledge of the shape of the layup, and some only have marginal improvements in inspection times [3] [4].

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. The tape layup process can be monitored by attaching an infrared camera to the AFP head and imaging the area immediately behind the compaction roller. As the heat is conducted from the substrate and through the most recently applied tape layer, non-uniformities in the tow will cause temperature differences that can be measured with the infrared camera.

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 a homogeneous 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.

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. 4). 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. 5). 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).

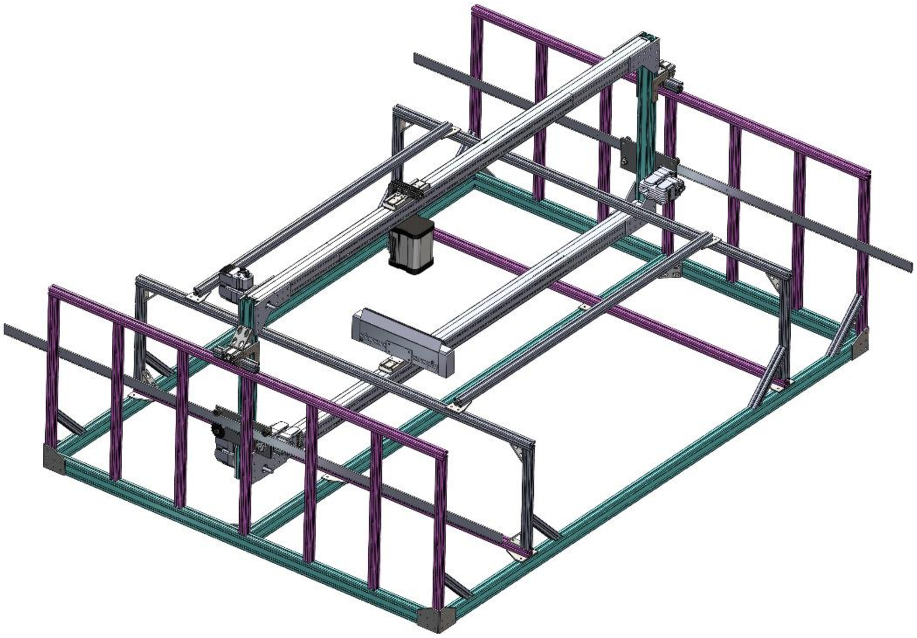

Figure 4. A model of the proof of concept setup for thermographic inspection. Two independent linear rails carried a thermal camera and line heat lamp above and below a sample that would be suspended between them. The two rail frame was indexed on a rack-pinion guide

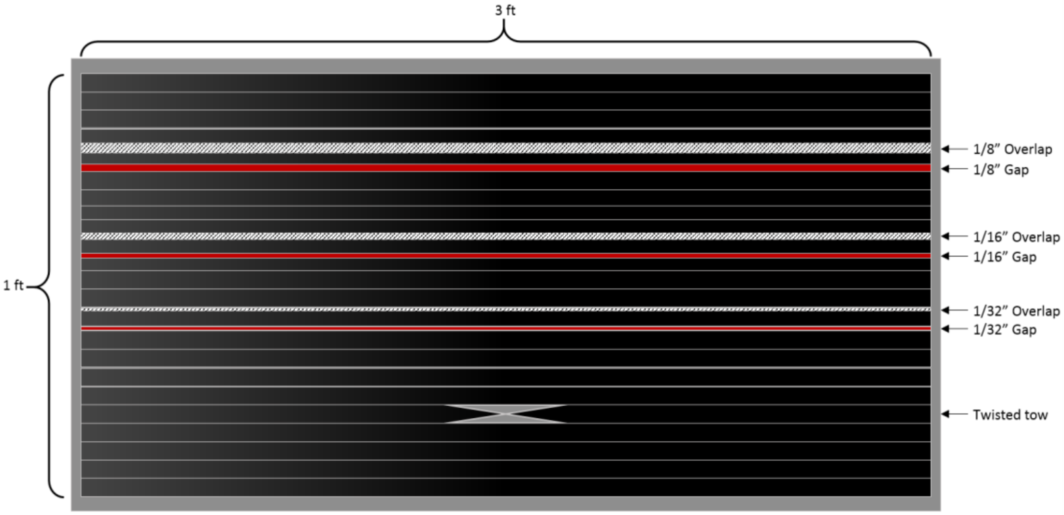

Figure 5. Diagram of the uncured defect panel made by ISAAC. Defects and locations are approximate and not to scale.

Fig. 6 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.

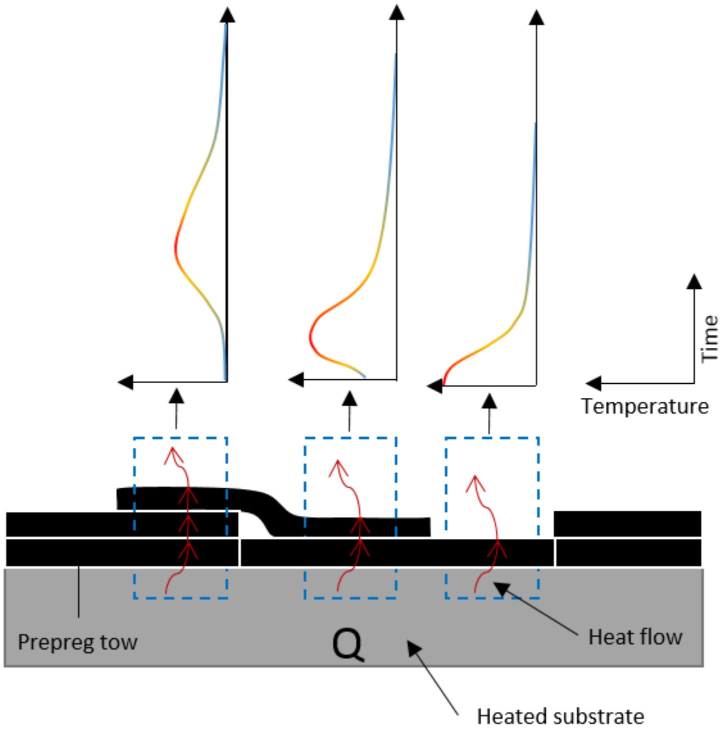

Figure 6. A depiction of the effect of defects on the temperature profile when the substrate acts as a through transmission conductive heat source. From the perspective of the thermal camera, gaps will immediately appear as a higher temperature and cool more rapidly, while overlaps will heat up much more slowly and may never reach the same maximum surface temperature as the normal layup.

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 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 (sometimes reaching as fast as 1 m/s), they 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.

Results

Fig. 7 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. 7 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. 7 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. 7, while the temperature response of defects of interest persist even at later times.

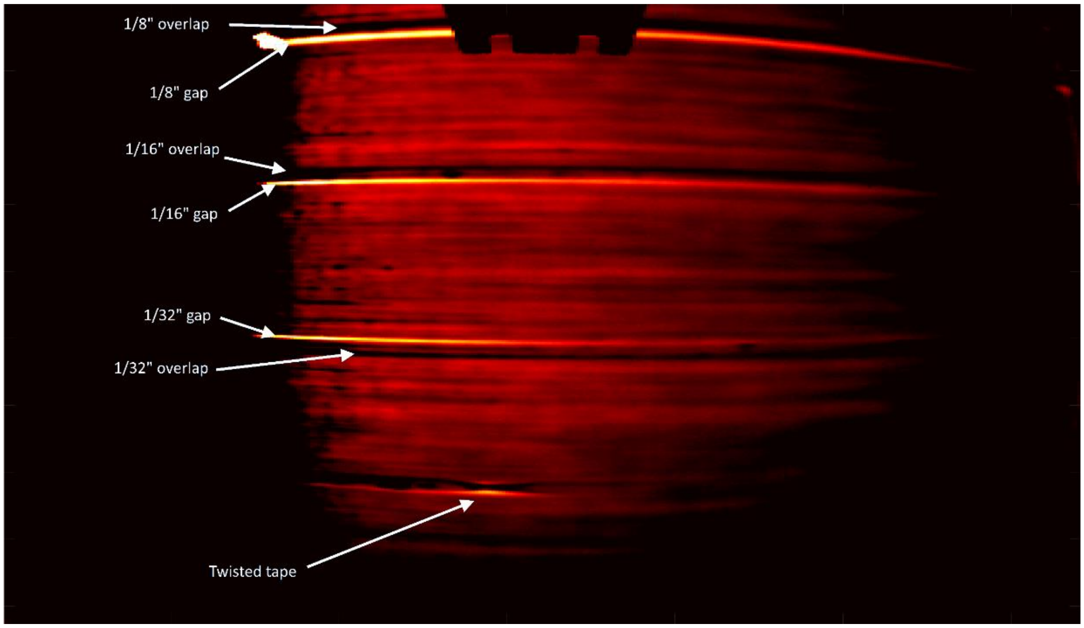

Figure 7. First results of the thermographic scan of the uncured panel.

Fig. 8 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. Because the camera moves a distance of one pixel per frame acquired, it is also possible to reconstruct a sequence of images after heating at the frame rate of the camera (120 Hz in this example). This reconstructed sequence is analogous to data acquired during conventional flash thermography. 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 a number of standard time-based analysis algorithms, typical of flash thermography, to be applied to the data (the reconstructed sequence).

Additional post processing was explored to aid in extraction of the relevant defect data. Quadtree decomposition is a technique often used in compressive algorithms to

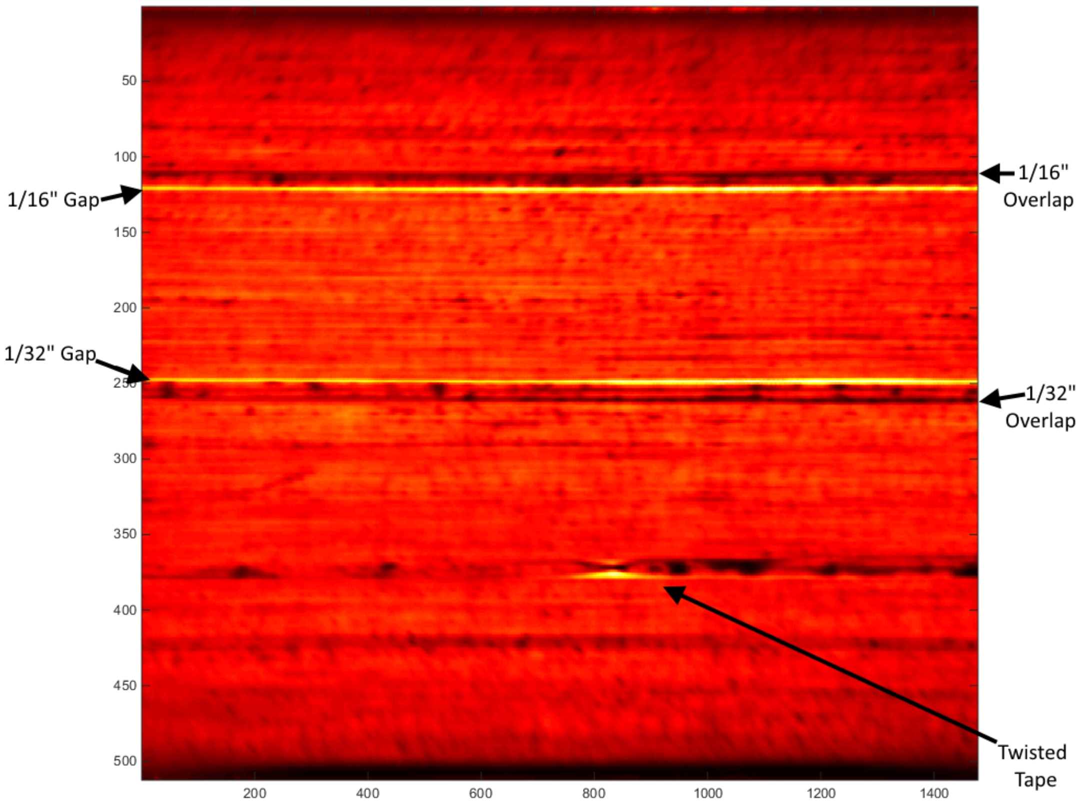

Figure 8. Image of all scanned spatial points at the same time in the heating/cooling process. Column data is gathered from a point that is approximately 0.6 seconds after the heat source has passed.

locate the structure of an image. This technique first starts by dividing the input image into 4 equal squares and tests each square for homogeneity according to a user specified test criteria. Should a square pass the test it is left as is, should a square fail it is divided into 4 smaller squares and the test is run again on the new regions. This is repeated until a minimum square size is reached or when all squares pass the test criteria. The quadtree decomposition method is very fast and has great potential to be parallelized to enable real time monitoring of simplified data.

To test quadtree decomposition, a section of the result was converted to grey scale and decomposed using a test criteria of 25%. This means that the maximum value in any square must be within 25% of the minimum value for the square to pass the test. The result is shown in Fig. 9, and the lap/gap/ twist defects are easily identifiable. Since this technique tests on the basis of image homogeneity, it is independent of temperature and can be used even if the heat lamp output is changed.

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- was designed and constructed. The POC device simulated the AFP in situ scanning by heating the

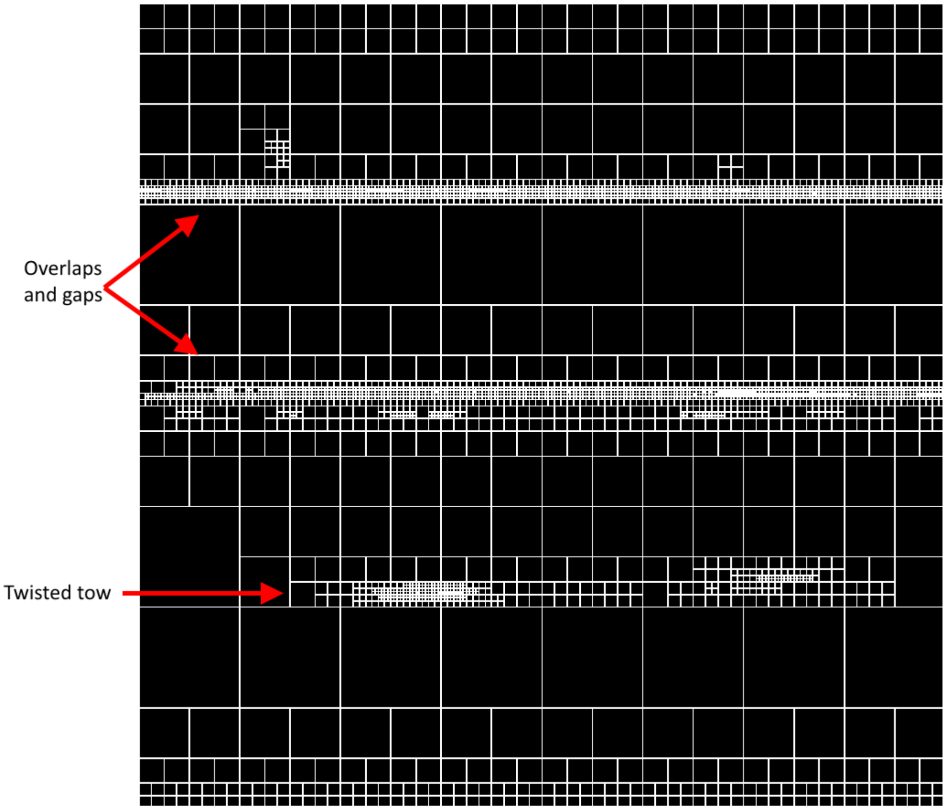

Figure 9. Thermal data after Quadtree decomposition. The tow tape defects are easily identifiable from the background. The twisted tow shows up as a solid region, as well as an out of plane wrinkle to the right of the twist, which was caused by the twist itself.

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 to the proposed technique, it is not exactly equivalent. For example, while the speed of inspection and the quartz lamp used are similar to those in AFP systems, they are not exactly the same. Therefore, one of the first goals for future work 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 previous 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. Post process algorithms are now being developed to downselect the data enabling faster processing and real time analysis.

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