3D MODELING AND PRINTING OF AUTOMATED FIBER PLACEMENT DEFECTS

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ABSTRACT

Automated Fiber Placement (AFP) is a composite manufacturing technique used to fabricate lightweight air and space vehicles. AFP uses tows, or strips of composites, laid side by side to build plies and laminates. A major consequence of this technique is the defects induced via the AFP process. Knowledge and detection of defects requires some expertise on the size, shape, and significance of the considerable number of possible defects. Detection then becomes increasingly difficult due to the substrate and incoming material both being a dark black color. The inability to detect defects leads to a part with poor quality. This report aims to provide some education on these defects using 3D modeling and 3D printing to visualize each defect. To ease visualization, the model can be printed in three different colors as follows: First, the tool surface is printed in one color, then the tows are printed in a second color. The contrast of these two colors can then be used to visualize defects such as boundary coverage or tow drops. Defects associated with single tows such as gaps, overlaps, and twist can be modeled and printed using a third color. This method creates 3D models with easily identifiable defects that can be used to educate or train AFP personnel.

Keywords: 3D modeling, 3D printing, Automated Fiber Placement, Defects
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1. INTRODUCTION

The applications for composite materials are continuously growing as research in design and manufacturing advances. With these advancements comes a need to produce the composite structures. Automated fiber placement (AFP) is a composite manufacturing technique often used to produce large aerospace structures. In this process strips of composite material, referred to as tows, are laid onto a tool surface at various fiber angles using a robotic/gantry platform and a fiber placement head. A heating mechanism attached to the head is used to ensure proper tackiness of the substrate. Directly after the heat is applied to the substrate, a compaction roller runs over the tows to adhere the tows to the substrate. Successive passes create plies, and the combination of the plies produces the overall structure.

Even with the constant improvements of AFP machines and the AFP process, it is far from perfected. One of the main side effects of this process is unavoidable defects that occur due to tool geometry, fiber steering, and material imperfections [1]. Even with recent developments in automated inspection technologies [2] [3], a majority of ply inspection is done by a human. AFP defects such as wrinkling caused by steering [4] can lead to up to a 36% decrease in overall strength of a structure [5]. Two of the most common defects present are gaps and overlaps due to the imperfect placement of tows [6]. Gaps tend to leave a resin rich area where a decrease in strength at the site can occur while overlaps behave oppositely by creating fiber rich areas where the local strength increases [7] [8]. Due to the large effect of defects to the structure, a thorough understand of each defect and its significance is crucial. Defects can be broken into 4 main categories: (1) positioning defects, (2) bonding defects, (3) tow defects, (4) foreign bodies [9]. A complete list of the defects and their category is presented in Table 1, and a complete description of each can be found in [1]. The identification of the defects requires a great deal of manufacturing experience and expertise. Noticing the defects becomes especially difficult due to the black-on-black nature of the composite substrate and current ply. This project aims to ease the difficulty of defect identification by using 3D models of each defect to learn the characteristics of each. All modeling was accomplished using Dassault Systemes' CATIA V5. These models will allow training of personnel on detecting defects before having any AFP experience, while also further spreading AFP knowledge.

Table 1: List of defects and their associated category

Defect	Category
Gap/overlap	1
Twist	1
Missing tow	1
Boundary coverage	1
Angle deviation	1
Wandering tow	1
Position error	1
Fold	2
Pucker	2
Wrinkle	2
Bridging	2
Loose tow	2
Splice	3
Foreign object detection	4

2. MODELLING

Modelling of the defects was done in multiple steps. First the tool was created for the tows to be placed onto. After the tools was created, a set of 5 tows was modeled with each one being a separate body. The tows can be modeled with or without defects to demonstrate good and bad quality layups. Each of the defects in modelled in its own file and then combined into a single model for printing. The process is detailed in the sections below.

2.1 Tool Surface Modeling

To begin modelling, a tool was created with a length and width of 100 mm and 75 mm respectively and was termed “Base Model” (Figure 1). The name of each model is embossed on the side of the tool to quickly know which model is in hand. A tool refers to the surface that the AFP head will place the tows onto. The geometry of the tool surface was created to demonstrate what would typically be seen on a complex tool. Complex tools have curvatures of varying values at each point along the tool. Such a geometry makes fiber placement difficult due to the defects it induces. The tool surface is then projected straight down to create the base of the tool where it is mounted to a flat surface or mandrel.

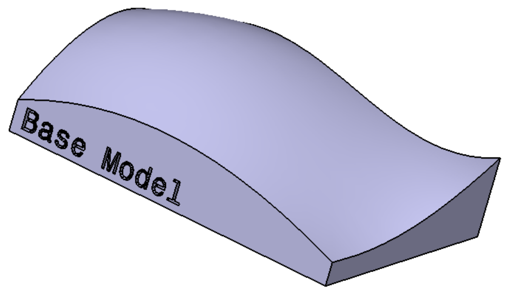


Figure 1: 3D model of the tool surface

Apart from the defect modeling, tool surface modeling can be used to teach personnel about the effects of geometry such as concavity or possible collision areas. Concave portions of a tool are prone to bridging defects, and severe curvatures are probable collision areas. Understanding the limits on tool geometry is the first step in producing high quality AFP structures.

2.2 Tow Modeling

As previously mentioned, tows are the strips of composite material that is placed onto the tool surfaced using the AFP machine and attached head. The tows are modeled following the geometry of the tool surface modeled in the last step. Five large tows are used instead of smaller ones to ease visualization of defect and non-defect tows. In a real manufacturing environment, between 8 and 32 tows are usually deposited at once. The tows “blend” together and it is challenging to decipher the appearance of minor defects. Learning what defects to look for and how to spot them on the larger models makes for an easier transition into locating defects in a real manufacturing environment.

2.2.1 Tows Without Defects

Defect free tows are created with equally sized small spaces between them to identify one tow from another, and these gaps are not to be interpreted as defects. To create each tow straight lines are projected onto the tool surface using reference points on the edge of the tool to define the beginning and end. Each tow is a closed curve, and therefore can be extruded to create the thickness of the tow. The tows can be created in the same file as the base, or they can be modeled in a separate file and combined with the base in a final model (Figure 2). The distinction between these two methods will become clear in Section 3 when the printing of the models is discussed.

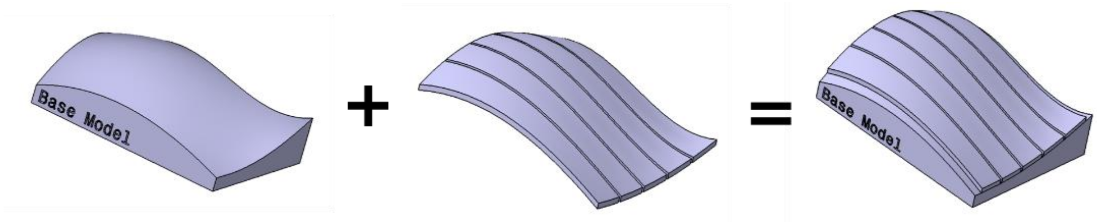
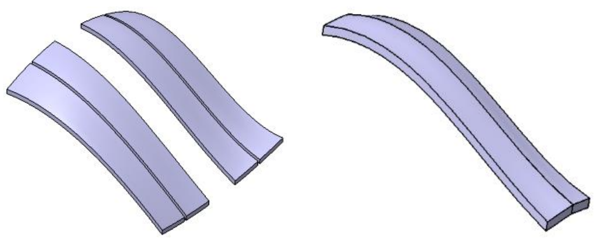


Figure 2: Explanation of combining the base model with the non-defect tows

2.2.2 Tows With Defects

Modelling tows with defects is a similar process to modelling tows without defects. The first step is deciding on which tow, or tows, are going to have the specific defect. The defect is then modeled using the geometry of the previously created tool surface and surrounding tows. This process is demonstrated in Figure 3 where a gap/overlap is modeled. In this model the center tow is modeled to have a gap on one side and a resulting overlap onto the tow on the opposing side. Combining the defect and the other tows with the base model creates the complete gap/overlap model. The benefit of creating the tool and each tow separately will be clear when the 3D printing methods are discussed (Section 3). Using the same method, any desired defect can be modeled.



(a) (b)

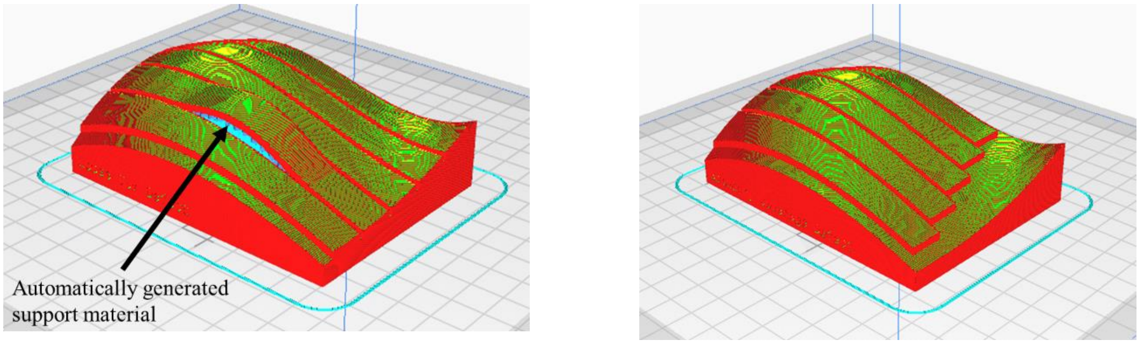
Figure 3: Example of modeling tows with a gap/overlap

3. 3D PRINTING

3D printing of these educational models creates a hands-on experience for personnel. Printing can be accomplished with any available printer and in two methods: (1) single print and (2) multiple prints. The single print method combines the tool and the tows into a single model for printing. Although this method is faster and easier, it results in the entire model being one color. Using method 2 the model can be printed in multiple colors with the base, non-defect tows, and defected tows each being a separate color. Printing with multiple colors allows for the defects to be highlighted for easy detection. The method chosen in solely based on the desired appearance.

3.1 Single Print Method

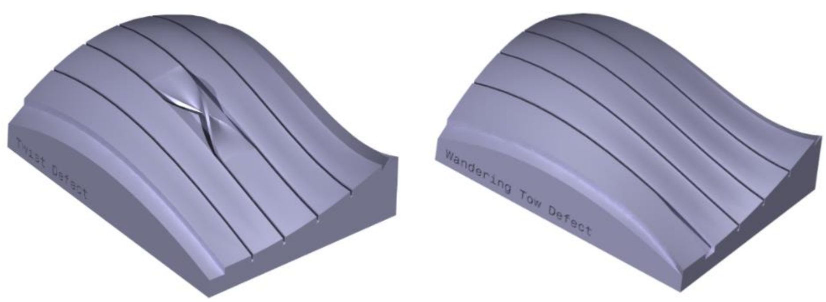
In this method, the tows and tool will be combined into a single STL file for printing. Depending on how the model was created, this may require creation of an assembly before exporting the model. Once exported the STL model is imported into the desired slicer software that will create the individual layers and G-code for the printer to follow. The authors used the Ultimaker Cura slicer and have provided an example of two sliced models in Figure 4. Specific printer configuration properties such as nozzle diameter, layer height, infill, etc. are not required. The chosen properties should be based on the knowledge of the printer's performance. If there is not a lot of experience with the printer, the default options will provide a quality print.



(a) (b)

Figure 4: Sliced models of a (a) loose tow and (b) boundary coverage defect

A major advantage of this method is that no support material is required, except for the defects that are not in contact with the tool surface (Figure 4.a). Support structures are not a part of the model and are generally created through a slicer software. These are generally used in places where the model is not supported by any underlying material, therefore the printer has nothing to deposit the material onto. With the ability to use one continuous print with minimal support material, this method will be faster and more efficient. A depiction of the final printed model using the single print method is shown in Figure 5.



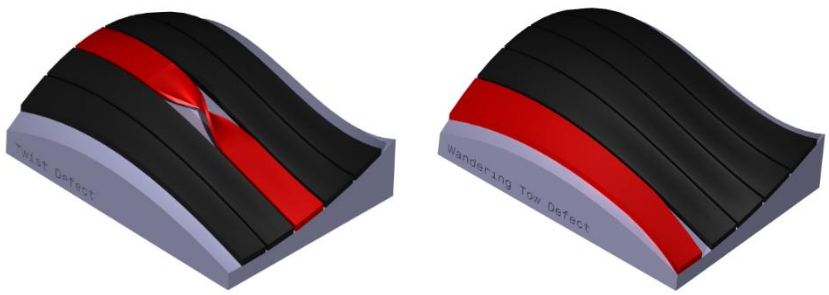
(a) (b)

Figure 5: Example of a (a) twist and (b) angle deviation using the single print method

3.2 Multiple Prints Method

Observing the angle deviation defect in Figure 5.b, it is apparent that some defects are hard to notice in a model printed using a single color. To create a more visually appealing printed model, multiple prints, or a dual nozzle 3D printer, can be used with various colors to highlight the defect. However, this method will be more time and labor intensive due to the amount of prints and assembly that is required. To begin the base with the desired defect name embossed on the side should be printed. Once the base is printed, each tow associated with that defect should be printed separately. Depending on the tows being printed and the placement on the printer bed, support material will be required. If the printer's capabilities allow for multi-color printing it may be possible to print all the tows in the two desired colors at one time.

After the base and each tow are printed, they can be assembled to create the final model. The assembly is accomplished by using an adhesive to attach the tows to the tool. Each tow should fit precisely in place due to the matching curvature of the tool and the tow. Once assemble, the model should present a series of tows with a highlighted defected tow as it was modeled. Figure 6 shows a twist and angle deviation defect using this method. Comparing Figure 6.b with Figure 5.b demonstrates the benefit of simpler defect detection using multiple colors.

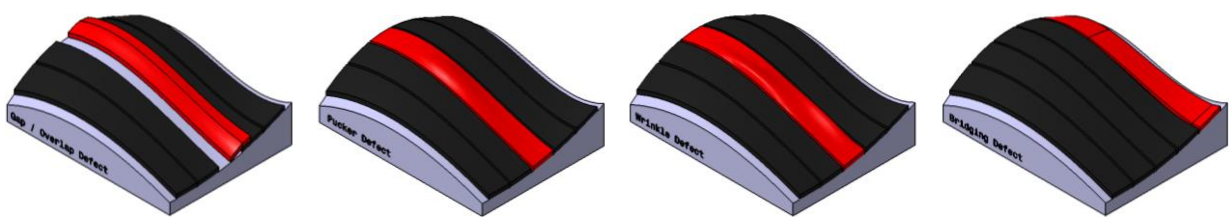


(a) (b)

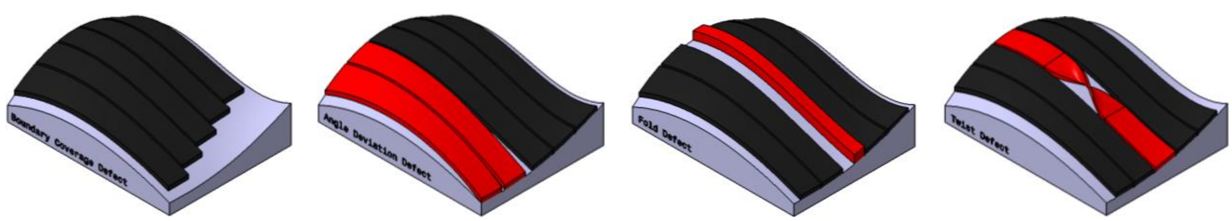
Figure 6: Example of a (a) twist and (b) angle deviation using the multiple prints method

3.3 Completed Defect Models

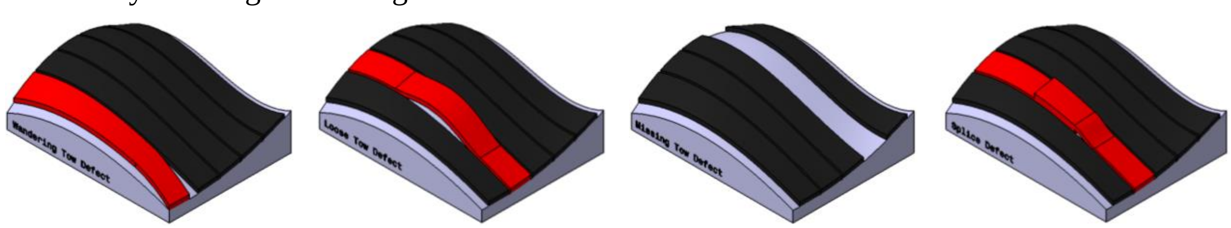
Following the modeling, printing, and assembly procedures outlined above, each defect presented in Table 1 was modeled and printed using 3 different colors. Gray was used for the tool, black was used for normal tows, and red was used to highlight defected tows. Each model has been presented below in Figure 7 for reference.



Gap/overlap Pucker Wrinkle Bridging



Boundary Coverage Angle Deviation Fold Twist



Wandering Tow Loose Tow Missing Tow Splice

Position Error FOD

Figure 7: 3D models of each defect

4. MODEL DISSEMINATION

The main goal of the creation of these models is to share them with the public. This will allow for anyone to view and print the models seen above in Figure 7. With open access to these models, AFP knowledge can be spread to anyone wanting to learn. For reference, some models previously printed by the authors are shown in Figure 8. The models were printed using the multiple prints method described in Section 3.2 above. Visiting the following link will provide downloadable files of each defect model that can be printed on most 3D printers: link

Figure 8: Examples of some 3D printed defect models

5. CONCLUSIONS

The presented methods for 3D modeling and printing of AFP defects can play an integral role in spreading the knowledge associated with these defects. This knowledge is typically gained through experience with inspecting numerous AFP manufactured plies. Exposing personnel to these models introduces the types of AFP defects seen during manufacturing along with their geometry without having any prior experience. Identification of defects is just a small step in a complete understanding of the AFP process. Combining the education gained from modeling and printing the defects with their actual effects and significance will bring a broad knowledge of the process of inspecting and reworking tows.

6. REFERENCES

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