A SYSTEMATIC APPROACH TO TRANSFORMING COMPOSITE 3D IMAGES INTO MESO-SCALE COMPUTATIONAL MODELS

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Abstract

High performance polymer matrix composites (PMC) have a high specific stiffness and can be used to easily manufacture highly complex components. Many types of defects can occur during molding. Flaws and damage degrade the resulting mechanical properties of the composites material. It is difficult to assess the actual stiffness, strength and fatigue limit of flawed and damaged structures. Among these the fatigue limit is the most difficult to predict. Through a combination of modern imaging techniques and finite element analysis of in-situ fiber bundles, it is now becoming possible to estimate fatigue limits for polymer matrix composites structures with flaws or damage. Composite materials can be imaged with 3D X-ray Computed Tomography (CT) in a sufficient detail to view 3D fiber bundle matrix interfaces. These images can then be directly imported into physical models to be used in finite element analysis. The process of converting these images into computer models for analysis is currently extremely time consuming, difficult and subjective. The method presented here has been developed to bridge this gap.

1. Introduction

Polymer matrix composite materials continue to be used in even higher percentages of primary structure materials in aerospace, wind turbine and other high-performance applications where the size to strength ratio is an important metric. This is due to the light weight nature of the material and the ease in manufacturability of highly complex components. There are a number of defects, molding problems, and damage that can occur during processing and molding. Many of these issues can degrade the properties of composite material. It can be difficult to assess and predict the actual strength, stiffness and fatigue limit of the component due in part to the differences that can occur in manufacturing Unless an extensive experimental study bas been conducted testing many different effects of defects. Fatigue reduction caused by flaws and defects can be particularly difficult to assess. Experimental fatigue tests can also be quite time consuming, particulary for full structural components. Using finite element analysis to help predict the effects of defects is of interest to reduce this time. It may be possible to predict these fatigue limits though a combination of imaging and finite element analysis of the in-situ fiber bundles. This is of particular interest in the aero-engine [1] and wind turbine [2] industries.

2. Background

Imaging technology continues to advance and it is becoming easier to obtain clear 3D images of micro and meso level polymer matrix composite specimens. In particular, there is the ability to visibly capture fiber bundles in relatively large samples, which can then be used to characterize a representative volume element (RVE) or larger volume of the sample. A systematic approach must be developed in order to interpret these images in a consistent integrated computational materials engineering method for finite element analysis.

There is some research available for developing a composite microstructure model from 3D image data. Sharma [3] interpreted composite microstructure from images for carbon-carbon composites. However, carbon-carbon composites have limited fiber bundle undulation. This approach does not capture fiber bundle undulation or deal with bundle proximity issues, which are relevant for the majority of polymer matrix composites. More recently, Liu et al. [4] developed a method to model a Jacquard woven polymer matrix composites. The approach is repeatable, but is limited by the 3D binarization utilized for discretizing fiber material from matrix material. This binarization appears voxelated and creates irregularities along the bundle surfaces which leads to artificial stress concentrations. Naouar et al. [5] used a commercial software to create stepped bundle surfaces which limit these surface based artificial stresses. However, this method is limited to a tetrahedral mesh for the fiber bundle [5]. A Hexahedral mesh may be more desirable for continuous bundles geometries. It is desirable for the type of continuous fiber bundles discussed here to be able to create a swept mesh in the axial direction of the bundle. In addition to research conducted at the meso scale (bundle and weave level), there has also been several image-based formulations at the micro scale (fiber level). For example, Sencu et al. [6] have developed an approach using CT images to develop FE models. Many of these methods have limitations in bundle geometry separation and can be labor intensive for complex laminates.

3. Approach

In this paper we present a systematic approach to interpreting 3D images and verify the methodology with comparisons to experimental test data which have been conducted for different high-performance composite samples. An example can be seen in Fig. 1 where the 3D image was used to section and trace the exterior fiber bundles at each discrete layer (a), loft the closed loops (b), and mesh the resulting solid bundle structures (c). There are two material systems involved in this study. Both glass (GF) and carbon fibers (CF) used as continuous fiber reinforcement in a polymer matrix are included. Non-crimp fabric (NCF), discrete tow bundles and off axis fiber orientations are included in the investigation. The experimental mechanical tests used for validation include both tension-tension fatigue and compressive failure. This array of materials and testing conditions should provide a substantial range of results for initial quantitative verification of the proposed method. The materials included in this study are designed to be used in aeroengine structures [1] and wind turbine blade structures [2], but the methodology is applicable to many structural composite applications.

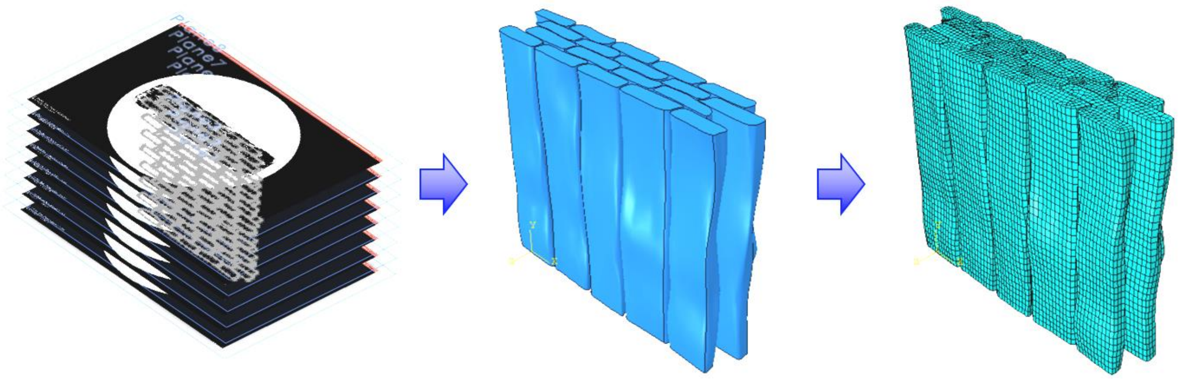

Figure 1. a) 3D images slices, b) 3D spline based solids, c) FE mesh

The image sample shown was part of a collection of testing conducted by Jespersen et al. [2] for wind turbine blade structures. The test sample includes four layers of unidirectional fiber bundles and two layers of bias fiber bundles. The method of taking the image files and interpreting them for finite element analysis involves 15 steps, 9 of which have been automated. First, the waviness of the bundles is characterized. Then the image is segmented at no more than one half the resulting wavelength. In the next step the images segments are binarized using a threshold. The images are then imported into a computed aided design (CAD) software and the bundles are traced in each image and two edge splines are created for each bundle to assist in one of the following steps for automated mesh generation. The splines are then lofted to create spline-based solid bundle geometries. Those geometries are then exported from the CAD software to a computer aided engineering (CAE) software. Once all the bundles are imported, an automated interference check and mitigation script is run. Next, an orientation spline is created at the central axis of each bundle. In practice this artificially gives all the fibers in one bundle the same orientation. The material is then defined and set to the orientation. In the next step the matrix object is made by an automated object subtraction. The fiber bundles are then meshed via a script. The matrix is currently meshed with a semi-automated approach using tetrahedral elements. Further effort is required to automate this step. The surfaces of the bundles and the matrix are then tied in a corresponding way using an automated script. The last steps are to apply the desired boundary conditions and run the desired analysis.

In order to demonstrate the capabilities of the method, a model was created using this method for one of the samples involved in this study, seen in Fig. 1. Using this model, a virtual axial tension test was run. The base of the specimen was constrained in the vertical direction and displacement was applied to the top of the specimen. The fiber considered was a glass fiber and the matrix considered was an epoxy matrix where the stiffness properties set is listed in Table 1. The regions of the matrix object in the simulation were modeled as neat matrix properties. The volume fraction of the bundels was calculated using the fiber area weight and corresponding thickness fraction of the sample. For simplicity the material was assumed to have no voids. The fiber volume fraction of the bundles was also verified with the experimental resulting overall volume fraction for the composite. The error between the calculated total volume fraction and the experimental total volume fraction of the fibers was 0.2%. A more accurate value of the fiber volume fracture could be obtained using segmentation of a 3D image of the bundle, similar to the method used by Lenz [8]. Using the previously described calculated intrabundle fiber volume fraction and the properties from Table 1, the composite properties of the bundles were determined. The micromechanics method used was the method developed by Goldberg and Stouffer [7]. The resulting intrabundle stiffness properties can be seen in Table 2.

Table 1. Fiber and Matrix Properties.

Material	E_1 (GPa)	v_{12}
Fiber	79	0.2
Matrix	2.8	0.3

Table 2. Intrabundle Properties.

Material	E_1 (GPa)	E_2 (GPa)	v_{12}	G_{12} (GPa)
Composite	71	11	0.21	16

The window of the specimen measured approximately 11.3 mm in the vertical direction (Fig. 2). The resulting stress in the vertical direction when 0.08 mm displacement is applied can be seen in Fig. 2. These three images are the same sample with slices three different depths though the thickness to visualize the internal stresses of the fiber bundles. The stresses displayed in Fig. 2 range from 0 (blue) to 500 MPa (red). Nearly all the stress is imparted to the axial fiber bundles, as can be seen in Fig. 2. There is also some interaction occurring between the axial fiber bundles and the bias fiber bundles (Fig. 2, far right image). This occurs despite the bundles being separated by matrix material. It should be noted that while the bundles are constrained by ties to the matrix, the bundles are not constrained to one another. It can be observed that stress is accumulating where the surfaces of the axial fiber bundles and bias fiber bundles are in close proximity. This fits well with the damage regions observed by Jespersen et al. [2]. In the findings reported the fiber fractures were located in regions where the proximity of the axial fiber bundles and the bias (outer layers) fiber bundles were close.

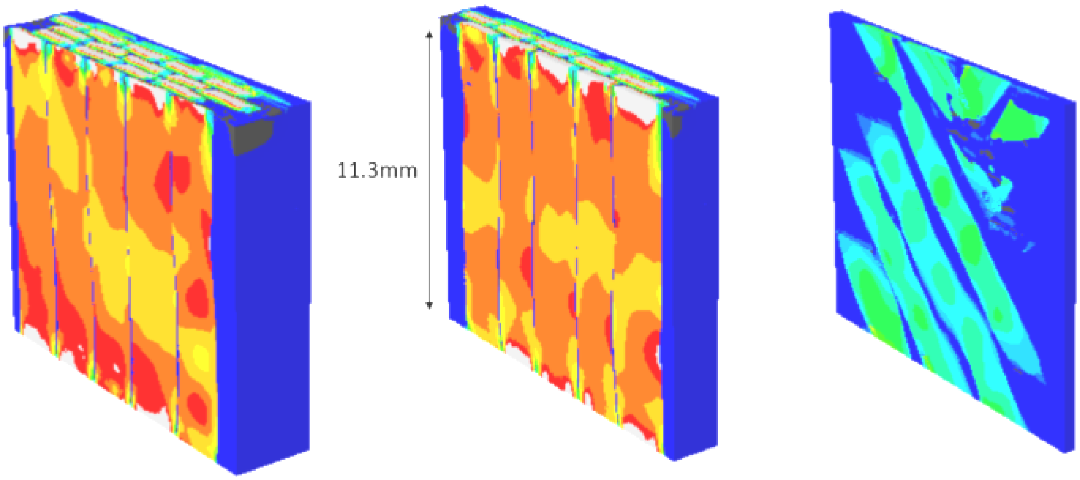

Figure 2. Global stress plotted in the vertical direction at discrete slices though the section thickness

Using this method, the NCF backing layers are excluded. These are the small bundles layers that stitch the NCF material together in such a way as to prevent significant movement of the fibers during assembly and processing. These backing layers cannot be included with the current method as they run parallel to the intersecting planes in the initial step. However, it is theorized that bundle undulations are the more dominate cause of failure initiation. By this reasoning, the proposed method should yield a good approximation of the meso structure. Further analysis including the backing bundles should be conducted to validate this assumption.

3. Conclusion

As fiber reinforced polymer matrix composites are adopted by more industries, it is becoming more important to be able to accurately assess and predict the actual strength, stiffness, and fatigue limit of composite components. A method has been developed to provide a tool to predict these material properties though a combination of imaging and finite element analysis of the in-situ fiber bundles. The preliminary capabilities of the method have been demonstrated. It can be seen that this method captures the undulations in the fiber bundles with sufficient resolution to cause plausible variations in the bundle stress when under axial tension loading. Further, the semi-automated approach can be used to model in-situ composite samples that have been imaged using 3D X-ray Computed Tomography. The models created using this method can then be utilized to conduct virtual experiments for correlation of various mechanical properties that can be difficult to derive by testing alone. Such as internal deformation, bundle-bundle interactions, and interfacial properties. This method can also be used to design experimental test procedures including loading conditions and specimen geometry. The primary limitation of this method is the insufficient automization of meshing the matrix material object. In many composite materials with continuous fiber bundles, the bundle proximity is very close. Matrix meshing can be done currently, but can be very time intensive. Automization of this mesh procedure is needed and requires further investigation.

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