

DE-LA-MO: A FRAMEWORK FOR STRUCTURAL ANALYSIS OF LAYERED COMPOSITES WITH DEFECTS

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ABSTRACT

Structural analysis of fiber-reinforced composite structures using finite element analysis (FEA) are usually performed using shells due to the complexity in modeling the layers of the composite structure with 3D elements. However, accurately modeling the residual strength of composites require incorporating concrete definition of defects into layered 3D models, which is not directly feasible with shells. In this work, we have developed an automated framework that can first be used to isolate a region of interest from a shell computer-aided design (CAD) model of a composite structure, model the individual layers in the region, incorporate defects such as delaminations and fiber breakage, and set up the model for structural analysis using FEA. This framework can be used to automatically set up structural analysis of a composite structure with defects and accurately assess the impact of manufacturing defects or service damage on its residual life.

INTRODUCTION

Multi-layer fiber-reinforced composite structures are being increasingly used in several high-strength, low-weight applications such as aircraft structures and wind turbine blades. Composite structures involve several steps in their layered manufacturing process and make use of expensive material such as carbon fibers [7]. As a result, composite structures are currently expen-

sive to manufacture, and are used only for mission-critical components. Computational structural mechanics models of composite structures can help reduce costs by allowing for optimization of the composite design. In addition, predictive damage models can be used to understand the effect of manufacturing and service defects on the remaining service life of composite structures [5].

Traditionally, composites are modeled using Kirchoff-Love thin shells for performing structural analysis. In thin-shell analysis, the composite laminate is modeled only using its mid-surface and the material properties are homogenized over the thickness. This allows for a simplified analysis using only a surface, which can be represented using standard surface representations such as non-uniform rational B-splines (NURBS) [1]. However, it is not possible to get interlaminar quantities of interest, such as interlaminar stresses and strains, using the thin shell analysis. In addition, special techniques are required to model common interlaminar defects such as delaminations using only thin shell analysis. Analyzing interlaminar phenomenon require explicit modeling of the laminar structure of the composites using solid elements.

We had previously developed an automated framework to model the composite structure using CAD modeling tools and incorporate defects measured using ultrasonic testing [2, 3]. The framework can then build a structural finite element (FE) model that can be used to assess the residual strength of the composite laminates (Figure 1). The framework consists of three customizable subcomponents: the CAD Model Builder, which creates the

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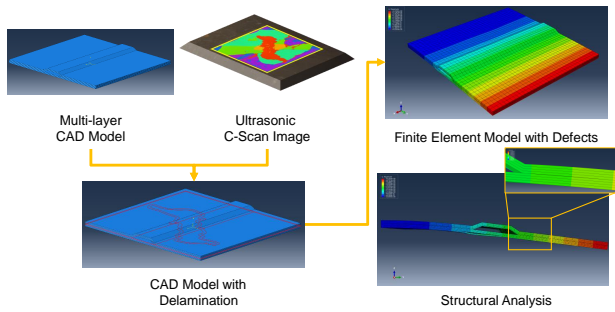


Figure 1. Workflow for automatic incorporation of defects into layered composite models and perform structural analysis. Our framework allows incorporation of defects such as delaminations and fiber-breakage into a layered composite model, apply appropriate boundary conditions, and perform structural finite element analysis.

solid model, the Finite Element Model Builder, which creates a corresponding finite element model, and the Model Builder API, which provides a flexible user interface to the CAD and Finite Element Model Builder APIs without exposing the details of the CAD and finite element model generation steps to the user. The CAD Model Builder is implemented using a commercial solid modeling kernel, 3D ACIS Modeler [8] and the Finite Element Model Builder is implemented using the ABAQUS FEA package [4].

In this work, we extend the framework to use open source solid modeling system, OpenCASCADE [6]. Using an open-source solid modeling system will allow for wide adoption of the framework without any licensing concerns.

CAD MODELING OF MULTI-LAYERED COMPOSITES

Performing FE analysis of the complete layered composite structure for large-scale components such as aircraft fuselage is prohibitively expensive. Hence, we focus on a small region of the composite structure to perform the layered FE analysis. This layered region can then be attached to the shell model of the entire structure using suitable boundary conditions. The modeling framework is a class library that can perform *virtual manufacturing* of small regions of laminated composite structures. It can create a detailed layer-by-layer CAD model and a corresponding script to preprocess the layers for FE analysis. In addition, it can insert flaws into the layer assembly to represent the structural significance of defects.

We make use of a NURBS surface that can be input as a mold and follow the composite manufacturing process to build the multi-layered model (Figure 2). We make use of the the NURBS surface offset functionality in OpenCASCADE to construct thin layers. We first offset the mold surface to create the

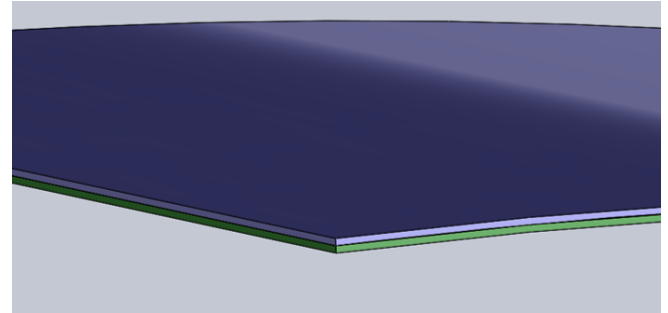


Figure 2. Creating multi-layered composite structures using offset operations.

offset surface. We then construct a solid model of the layer by constructing the side faces. The offset surface can then be used as a mold for the subsequent layer.

INCORPORATING DEFECTS

After creating the intact CAD model of the composite structure, we can modify it based on measured NDE data to incorporate defects. We focus on delaminations in our current implementation.

The delamination outline is segmented from an ultrasonic c-scan of composite in the region of interest. This outline is then projected to the correct lamina boundary using automatic projection algorithms. We then use this projected curve to split the lamina boundaries into two pieces, intact and delaminated regions (Figure 3).

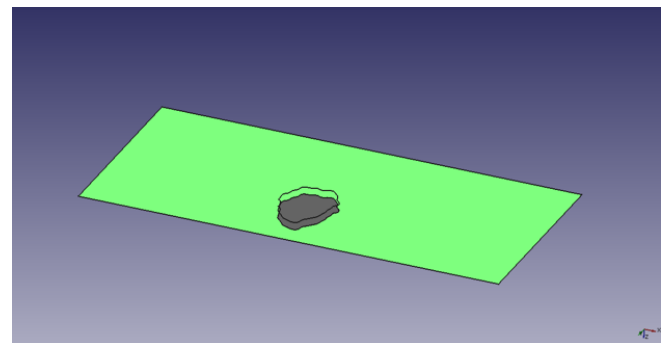


Figure 3. The delamination outline is projected to the lamina boundary and is used to split the surfaces into intact and delaminated pieces.

STRUCTURAL FE ANALYSIS OF COMPOSITES WITH DEFECTS

Once the defects have been incorporated into the CAD model, our framework can automatically set up the model for structural analysis by applying the appropriate boundary conditions to the lamina interfaces. Cohesive boundary condition is applied to the lamina interfaces and contact boundary condition is applied to the delaminated regions.

In addition, external boundary conditions and forces can also be applied to the composite structure. Our framework also has the ability to automatically mesh the structure and set it up for structural analysis bases on user-defined input. All the pre-processing commands are created as a Python input file to ABAQUS, which can then be run inside the ABAQUS CAE interface. Figure 4 shows the structural analysis results (in-plane shear stress) of a curved 8-layer composite structure with delamination defects. The composite structure was bent by fixing it on one end and applying a force to the bottom surface.

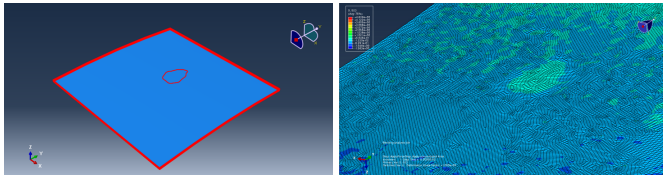


Figure 4. Left: Structural analysis of a 8-layer curved composite with delamination defect between one of the lamina interfaces. Right: In-plane shear stress of the composite around the delaminated region.

CONCLUSIONS

We have developed an automated framework for building composite laminates with defects for structural analysis. The framework automates the model setup process, thereby removing tedious operations needed for setting up the boundary conditions in the model before analysis can be performed. In addition, the framework can incorporate complicated delamination shapes obtained from ultrasonic testing of the composite between the corresponding layers of the laminate. The framework then automates the process by generating a CAD model and a corresponding script that can correctly set up the boundary conditions to perform structural analysis. The use of open-source tools for creating the solid model will enable widespread adoption of our framework.

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