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Investigation into a robust finite element model for composite materials

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ABSTRACT

Two models for completing structural analyses of cured fabric-reinforced composites that link back to a forming simulation are investigated. The objective of each model is to seamlessly use the predicted geometries of the textile plies to generate a finite element model of the cured structure. The first is a beam-shell model, where beam elements represent the fibers and shell elements represent the matrix. The beams are imported directly from the forming model to capture the deformed fabric geometry. The second approach is a double-orthotropic shell model where two shells, each representing a set of fibers, i.e. warp or weft, are superimposed. The material orientation in each shell is aligned with the respective fiber directions. To investigate the capabilities of the models for unidirectional-fiber reinforced composite plates with multiple fiber orientations and loading configurations, the two models are compared to classical laminate theory (CLT). To explore the models' ability to represent a plain-weave textile reinforced composite plate with various shear angles in the fabric reinforcements, the two proposed models are compared to experimental data. The double orthotropic shell model is found to be a better option for linking the mechanical behavior of the formed composite back to the simulation of the manufacturing process than the beam-shell model.

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1. Introduction

Composite materials are attractive for their high specific strength and high specific stiffness properties as compared to traditional metals [1–3]. While composites have the potential to create fuel-efficient vehicles, automotive companies are reluctant to replace metals with composites due to the higher costs and longer production cycle times [4] and the lack of reliable models for predicting the response of these materials during a crash situation. Researchers are currently investigating ways to reduce cycle times by automating the forming process through manufacturing techniques such as thermoforming of textile-reinforced composites [5–8], thereby making the composite manufacturing process to be competitive with metal forming cycle times. Complementary research is being pursued to develop simulation models of these automated composite manufacturing processes [8–18]. These models can be used to guide the design of the manufacturing process (e.g. selection of textiles, size and shape of the textile blanks, induced in-plane tension to reduce wrinkling) and can provide a direct link to build a high-fidelity model of the cured composite structure which can subsequently be used for structural analyses (e.g. stiffness, vibration and crash). Before such models can be widely accepted for use by industry, they must first be shown to provide credible predictions for structural performance.

Finite element modeling provides one option for a virtual design tool that can link the output of a simulation of the manufacturing process to a structural model of the composite component. Such a tool provides composite designers with the ability to model the manufacturing process, to identify if and where defects may manifest and to assess whether they will have a significant detrimental effect on the structural integrity of the part. By identifying unfavorable features of substantial influence, efforts can be focused on removing critical defects from the part instead of the overwhelming task of attempting to create a completely defect-free structure [19].

This paper will review existing design tools that can potentially link the manufacturing process to the resulting stiffness and quality of the composite part. In addition, two new modeling techniques will be introduced: the beam-shell model and the double orthotropic-shell model. Each of these models will address shortcomings that exist in current technologies by including the ability to represent the reinforcement fabric that has sheared during manufacturing. The feasibility of each model will be examined in a numerical study. Both structural modeling approaches will be compared to classical laminate theory (CLT) for

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a hypothetical unidirectional fiber-reinforced composite. The models will be assessed for a range of typical fiber orientations. Currently, there is no universally-accepted modeling technique for woven fabric-reinforced composites. Therefore, both modeling schemes will be compared to experimental data for a woven-fabric reinforced composite. The pros and cons of each model are reported.

2. Current models for fiber reinforced composites

The existing modeling techniques for fiber-reinforced composites will be reviewed. Methods for modeling unidirectional fiber reinforced composites are well established but generally do not account for deformations of the fibers during manufacturing. Woven-fabric reinforced composites are not as easily modeled as non-crimp fabric reinforced composites. Current techniques are presented and the existing shortcomings are discussed.

2.1. Unidirectional fiber-reinforced composites

The popular method for the modeling of unidirectional fiber-reinforced composite materials is Classical Lamination Theory (CLT), which is the universally accepted analytical approach [2]. Commercially available finite element packages, such as Abaqus, ANSYS, and LS-DYNA, have composite layup features with material properties formulated using CLT. This feature allows the user to define multiple layers with multiple materials, orientations, and layer thicknesses [20,21]. Programs such as CATIA and FiberSIM can interface with these FEA platforms to offer designers the ability to include fabric reorientation due to manufacturing processes in their analyses. These interfacing programs use a fishnet algorithm to predict how the fabric will deform to conform to the shape of the mold. Once the deformation of the fabric has been predicted by the interface, the fiber orientations are fed into the composite layup feature of an associated finite element package. While such software offer a quick solution for capturing variations in effective fiber orientations within each ply as it conforms to the tool geometry, the fishnet algorithm is limited in its ability to simulate the forming process. For example, effects due to boundary conditions are not considered by the fishnet algorithm. Therefore, two simulations performed on the same geometry with different binder pressures would yield the same results. Additionally, the fishnet algorithm does not consider the mechanical behavior of the fabric. Consequently, the simulations are unable to capture manufacturing defects such as in-plane and out-of-plane buckling that can be incurred during the forming process [11]. Therefore, these models would not be able to study the relationship between the processing parameters and the formation of manufacturing defects. Without knowing if and where defects occurred, their subsequent influence on structural performance could not be explored. Thus, users should limit the use of fishnet-based programs to geometries with gentle smooth surfaces. For more complex geometries, the fabric deformation needs to contain not only the kinematics (as are captured by fishnet algorithms) but also consider the mechanical behavior of the specific fabrics.

2.2. Woven fabric reinforced composites

The modeling of woven fabrics does not lend itself directly to a CLT analysis because a single ply of woven fabric contains two sets of fiber orientations (warp and weft) within the same plane. While CLT is commonly used to analyze laminates with multiple fiber orientations, the plies within the laminate are considered to be discrete unidirectional fiber layers. Analytical models exist that attempt to capture the woven mechanical behavior using CLT derivations such as the “mosaic” model, the fiber undulation model, and the bridging model [22,23]. Other models use a micromechanical approach to homogenize the fabric repeating unit cell and derive orthotropic properties of the composite [16,24]. However, once the fabric has sheared, it is no longer an orthotropic material as the warp and the weft tows reorient from their initial mutually perpendicular configurations as is shown in Fig. 1. This shearing poses an additional challenge to modeling the behavior of a woven-fabric reinforced composite.

While modeling strategies exist to represent woven-fabric reinforced composites, these models always assume that the tows are mutually perpendicular. However, for a woven fabric to conform to a compound-curvature surface, the tows must become non-orthogonal. Thus, such an orthogonality assumption compromises the solution for any composite with a compound-curvature surface. The two techniques examined in this paper offer the ability to model a composite in which the fiber tows have sheared and are no longer mutually perpendicular.

3. Proposed model descriptions

Brief descriptions of the methodologies used for the beam-shell model and the double orthotropic-shell model are presented in the following sections.

3.1. Beam-shell model

The beam-shell model is a discrete mesoscopic finite element model. The model employs a mixed-mesh unit cell approach to represent a woven-textile, as shown in Fig. 2. The unit cell of the fabric is represented by a two-dimensional shell element (S4) surrounded by four one-dimensional beam elements (B31). The beam elements represent the tensile and flexural behaviors of fiber tows, while shell elements capture the shear behavior of the fabric.

This methodology has been implemented in Abaqus/Explicit [8,12,15,25] and successfully used to model the forming of composite structures. The discrete modeling of the fibers by the beam

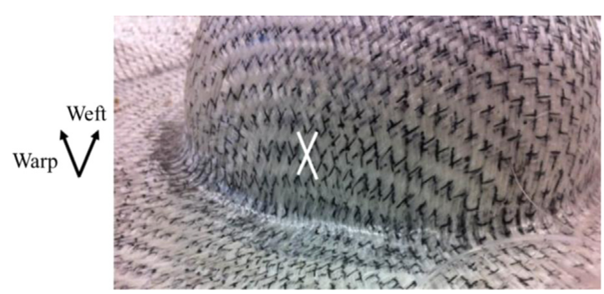

Fig. 1. Deformation of textiles due to forming processes (a) fiber reorientations and (b) manufacturing defects.

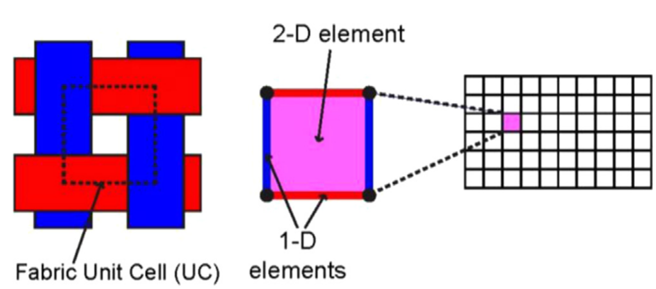

Fig. 2. Fabric unit cell methodology utilized within the beam-shell model.

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