An Integrated Computational Materials Engineering Method for Woven Carbon Fiber Composites Preforming Process

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Abstract. An integrated computational materials engineering method is proposed in this paper for analyzing the design and preforming process of woven carbon fiber composites. The goal is to reduce the cost and time needed for the mass production of structural composites. It integrates the simulation methods from the micro-scale to the macro-scale to capture the behavior of the composite material in the preforming process. In this way, the time consuming and high cost physical experiments and prototypes in the development of the manufacturing process can be circumvented. This method contains three parts: the micro-scale representative volume element (RVE) simulation to characterize the material; the metamodeling algorithm to generate the constitutive equations; and the macro-scale preforming simulation to predict the behavior of the composite material during forming. The results show the potential of this approach as a guidance to the design of composite materials and its manufacturing process.

INTRODUCTION

Woven carbon fiber composite materials have received increasing attractions because of their high strength-to-weight ratio and excellent corrosion resistance [1]. Replacing conventional metals with composite materials in the transportation area can realize weight reduction for better fuel economy and higher corrosion-resistant ability [2], making them attractive to industries. Woven composites have been utilized in the aerospace industry, however, requires a significant cost reduction to be applicable in the automobile industry. Such cost reduction can come from process optimization.

To manufacture woven composite material parts in mass production, the first step is to stack several layers of uncured woven composite prepregs in proper fiber orientations; then these 2D plane layers are formed into a 3D part shape via a preforming process on a press; after this, the shaped parts are cured to harden the epoxy and fix shapes; finally some trimming and polish work are conducted to provide fine finished parts. The application of the preforming process replaces the time consuming hand-lying work for the composite layers in the conventional process, leading to a much higher production rate.

The current necessary techniques to design and perform composite materials preforming rely on the numerous tests and prototypes for the material characterization and part manufacturing processes design [3]. The production of the composite materials parts is limited due to the high cost and long development period to perform the experiments. To solve this challenge, numerical methods that can precisely capture the behavior of the composite materials during preforming are essential [4].

The previously widely used simulation method for the composite preforming process is the pin-jointed net (PJN) approximation [5]. It focuses on the kinematic behavior of the material with the pure shear and the freely rotating tow joints assumption. The approach is computational efficient, however, the ignorance of the mechanical properties of the fabric and the resin leads to increasingly inaccuracy during the non-uniform deformation simulation [6]. As an alternative approach, the finite element analysis that is capable of modeling the composite material mechanical behavior attracts lots of investigations, and some suitable methods for the preforming process have been proposed [2, 4, 6-8]. All of these models require material properties measurement via several kinds of tests. As a result, the development of the manufacturing process is still affected by the cost and time to conduct the physical tests.

The goal of the integrated computational materials engineering (ICME) method for woven carbon fiber composites preforming process is to reduce the cost and time needed for the mass production of the composite material parts. A systematic method based on the simulation is proposed and applied to the composite materials from the micro-scale to the macro-scale model in the preforming process simulation. This method contains three parts. The first one is the representative volume element (RVE) simulation. This RVE simulation will lead to accurate stress-strain predictions of the composite materials because of the highest level of details in mechanical aspect [9]. The second one is the metamodeling algorithm. This algorithm will generate the constitutive equations in the large and continuous strain space based on the limited and discrete data from RVE simulations in a reliable way [10]. The third one is the macro-scale preforming simulation to predict the behavior of the composite material during forming. The non-orthogonal model [11] is applied to capture the material response in a more efficient way. The detailed process will be introduced separately in the following content.

RVE MICRO-SCALE MODELLING

In the RVE modelling and simulation process, the material structure and the corresponding mesh are generated by the open source software TexGen®. The script is flexible and the structure parameters can be easily modified based on the material used. The one layer plain woven structure, as shown in Fig. 1, is selected in the RVE modeling process for demonstration. After the structure and mesh are built, the mechanical properties of the material are assigned to elements.

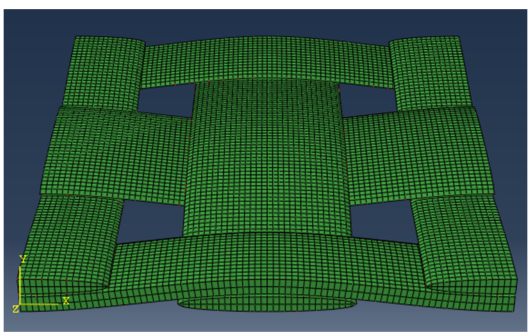


FIGURE 1. Plain woven structure and mesh in the RVE model.

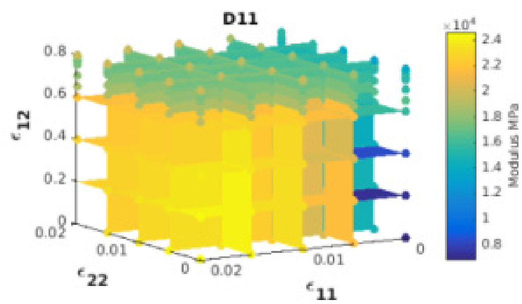


FIGURE 2. Contour of D11 of the constitutive equation at different strain states.

The three components of the in-plane strain tensor are chosen as the independent descriptors for the constitutive equations. During the simulation, the RVE is deformed to some specific strain states. The selections of strain states are optimized to decrease the number of necessary data points and reduce the computational cost. At each strain state, three different strain perturbations are applied separately so that the nine components of the constitutive matrix at this strain state can be calculated. The contour of the D_{11} of the constitutive matrix at different strain states is shown in Fig. 2 as a demonstration. Once the RVE simulations are finished, the constitutive matrices data obtained is saved with the corresponding strain states and fibers orientations as the input for the following metamodeling algorithm to get the constitutive equations for the entire strain state space.

METAMODELING OF CONSTITUTIVE EQUATIONS

During the material deformation in the macro-scale preforming simulation, the resulting strain states and fiber orientations will be different from one element to another. This will lead to huge computational cost if the RVE is directly implemented into the macro-scale model to run the simulation. As an alternative approach, the metamodeling method is applied to construct an efficient surrogate model of the material constitutive equations in the entire strain space. It will analyze the results from the RVE and capture a good range of mechanical properties as functions of fiber orientations and strain states.

Figure 3 shows the flowchart about how to use the metamodeling method to obtain the constitutive equations from the RVE data. A set of strain states are selected as the inputs to the RVE to obtain the constitutive equations under different deformation conditions. Then the metamodeling algorithm will utilize these limited data to predict the constitutive equations through the entire strain state space. The constitutive equations are determined by multiple highly correlated parameters, i.e., the components of the plane strain tensor. Due to its excellence in handling the highly nonlinear responses, the Kriging techniques are applied to generate the constitutive law in the entire strain space [12]. This technique enables the user to reduce the necessary number of RVE data points while ensuring the accuracy and certainty of the constitutive equations.

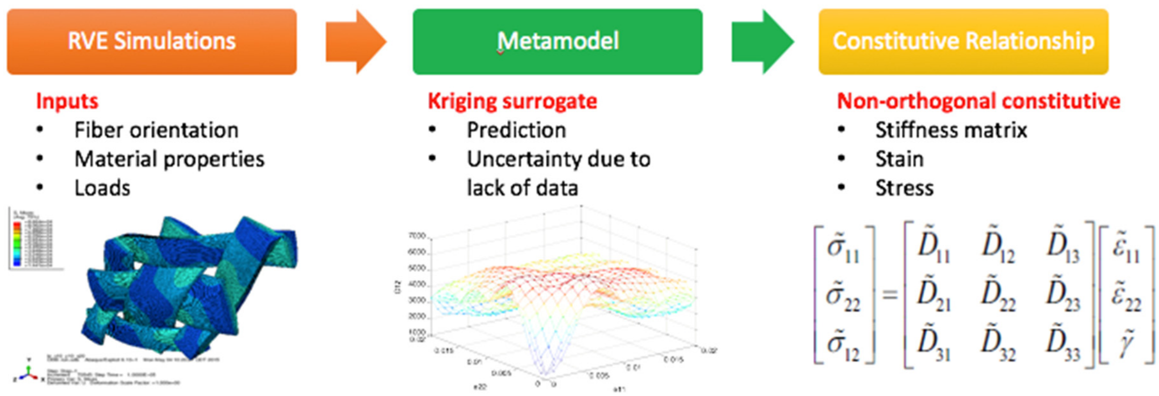


FIGURE 3. Co-Kriging metamodeling for woven composite constitutive equations.

MACRO-SCALE PREFORMING MODELLING

The in-plane stress-strain constitution equations from the metamodeling method are implemented to the macro-scale model as functions of the strain states for the preforming simulation. When the woven composite materials are deformed, the tows share most of the tension load while the fiber-fiber and fiber-resin interactions at the joints of the warps and wefts largely determine the shear stress. The mechanical behavior of the woven composite materials is highly dependent on the directions of fiber tows, hence, a non-orthogonal macro-scale model was proposed in [8]. The model can be used in the fully coupled situation. Nevertheless, as the first step in the ICME approach, we used the model that describes the material behavior in the fabric coordinate to decouple the tension and shear behavior of the composite materials. This decoupling reduces the number of unknown parameters in the constitutive equations, resulting a shorter time calculation in the RVE modeling and metamodeling. It will also simplify the expression of the constitutive equations: the tension behavior is a function of the tension strain, and the shear behavior is mostly a function of shear strain. This eases the implementation work of the constitutive equations to the commercial FEA software.

The macro-scale model is coded as a user-defined material subroutine during the implementation of the constitutive equations to the commercial FEA code. Single dome preforming simulation tests were conducted using the Abaqus explicit algorithm with this subroutine, as shown in Fig. 4. The punch, the binder and the die are treated as rigid bodies. The composite blanks are simulated with 4-node shell elements. The initial fiber directions in the composite blanks are along the local coordinate axes, which can be setting freely by the user.

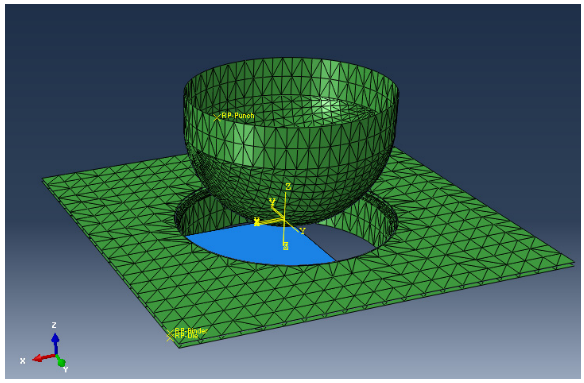
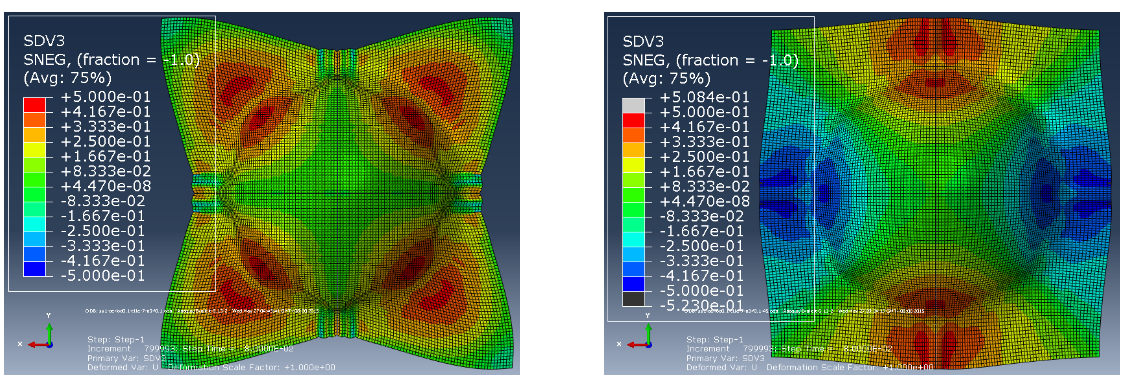


FIGURE 4. Single dome preforming simulation using the non-orthogonal model.

The simulation results are shown in the figures below. The contours use the shear component of the Green-Lagrangian strain as an indication of the angle change between the warp and weft fiber tows, because these two parameters are positively related to each other. Fig. 5 (a) is the preforming result when the fibers are along the global coordinate axes. Fig. 5 (b) is the result when the fibers are initially aligned at +45/-45 degrees from the global coordinate axes. This non-orthogonal model obviously is able to capture the impact of initial fiber orientations and the results and their influences can be included in the following simulation.

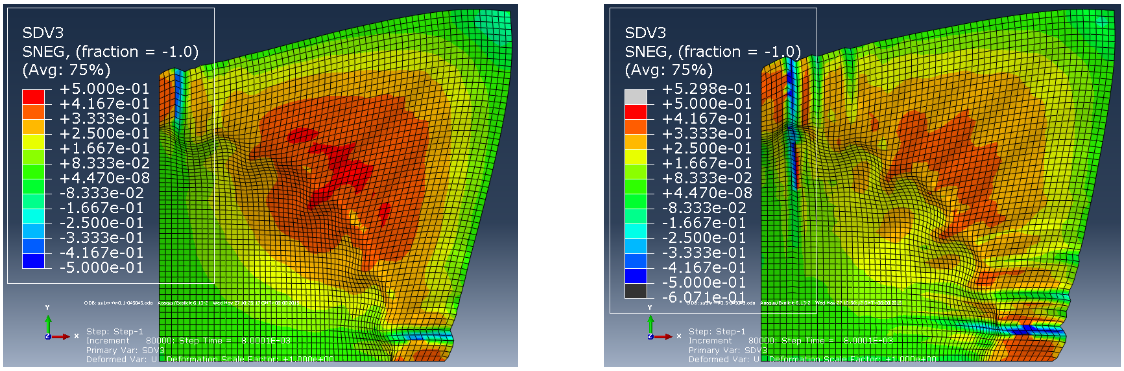
The friction during the preforming process will affect the deformation behavior of the woven composite materials, resulting in different wrinkling patterns and fiber orientation distribution. In order to obtain some preliminary results about how the interactions between the composite blanks and between the composite blanks and the tool affect the preforming result, the Coulomb friction law with the friction coefficient as 0.1 and 0.3 is used in the interaction setting in different cases.

Fig. 6 (a) shows the quarter result of the preforming simulation when the fibers are +45/-45 degree from the global coordinate axes, and the friction coefficient is 0.1. Fig. 6 (b) shows the quarter result of the preforming simulation when the friction coefficient is 0.3. From these results it can be seen that as the friction increases, the fiber angles difference at different location will be less, and the wrinkling on the composite material blanks will be more obvious. Although it may be invalid to assume the interactions between the materials and the tools to be Coulomb friction, these results can serve as a qualitative analysis for the current manufacturing parameter design that needs to consider the wrinkling prevention and the fiber orientation prediction.



(a) (b)

FIGURE 5. Green strain shear component after preforming when (a) the fibers are along the global coordinate axes; (b) the fibers are +45/-45 degree from the global coordinate axes.



(a) (b)

FIGURE 6. Green strain shear component after preforming when friction coefficient is (a) 0.1; (b) 0.3.

CONCLUSION

In this paper, the integrated computational materials engineering (ICME) method, which is made up with the RVE micro-scale model, the metamodeling algorithm, and the non-orthogonal macro-scale model, is proposed and developed for the preforming process of the woven composite materials. This method utilizes computational method from micro-scale to macro-scale to address the work such as material characterization and preforming simulation. In this way the high cost and time consuming experimental tests in the conventional manufacturing process could be avoided, benefitting the implementation of the light weight and high strength composite materials in the mass production area such as the automobile industry.

In the future, more work needs to be conducted before this method becoming a really practical design guidance for the manufacturing process. First, the RVE model used currently only takes the dry fabric into consideration. Resin should also be included in the real simulation case. Second, some in-plane stress-strain tests are necessary to validate and calibrate the RVE micro-scale model. The composite-composite and composite-tool interactions also require further study to make the macro-scale preforming simulation have more accurate results. All these things above worth being investigated to improve the ICME method in the future.

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REFERENCES

1. Che D, Saxena I, Han P, Guo P, Ehmann KF. Machining of Carbon Fiber Reinforced Plastics/Polymers: A Literature Review. Journal of Manufacturing Science and Engineering. 2014;136(3):034001-.
2. Jauffrès D, Sherwood J, Morris C, Chen J. Discrete mesoscopic modeling for the simulation of woven-fabric reinforcement forming. Int J Mater Form. 2010;3(2):1205-16.
3. ten Thije RHW, Akkerman R, Huétink J. Large deformation simulation of anisotropic material using an updated Lagrangian finite element method. Computer Methods in Applied Mechanics and Engineering. 2007;196(33–34):3141-50.
4. Hamila N, Boisse P, Sabourin F, Brunet M. A semi-discrete shell finite element for textile composite reinforcement forming simulation. International Journal for Numerical Methods in Engineering. 2009;79(12):1443-66.
5. van West BP, Pipes RB, Keefe M. A Simulation of the Draping of Bidirectional Fabrics over Arbitrary Surfaces. The Journal of The Textile Institute. 1990;81(4):448-60.
6. Sharma SB, Sutcliffe MPF. A simplified finite element model for draping of woven material. Composites Part A: Applied Science and Manufacturing. 2004;35(6):637-43.

7. Lee W, Cao J. Numerical simulations on double-dome forming of woven composites using the coupled non-orthogonal constitutive model. Int J Mater Form. 2009;2(1):145-8.
8. Peng XQ, Cao J. A continuum mechanics-based non-orthogonal constitutive model for woven composite fabrics. Composites Part A: Applied Science and Manufacturing. 2005;36(6):859-74.
9. Bai X, Bessa MA, Melro AR, Camanho PP, Guo L, Liu WK. High-fidelity micro-scale modeling of the thermo-visco-plastic behavior of carbon fiber polymer matrix composites. Composite Structures. 2015;134:132-41.
10. Wang Z, Wang P. A Maximum Confidence Enhancement Based Sequential Sampling Scheme for Simulation-Based Design. Journal of Mechanical Design. 2013;136(2):021006-.
11. Lee W, Um M-K, Byun J-H, Boisse P, Cao J. Numerical study on thermo-stamping of woven fabric composites based on double-dome stretch forming. Int J Mater Form. 2010;3(2):1217-27.
12. Ying X., Chen W., Apley D., Ding X. A non-stationary covariance-based Kriging method for metamodelling in engineering design. International Journal for Numerical Methods in Engineering 71, no. 6 (2007): 733-756.