Development of a One-Step Analysis for Preforming of Woven Carbon Fiber Composites

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Abstract

Carbon fiber reinforced composites are drawing great attention in automotive industry due to their lightweight, high stiffness and strength properties. Carbon fiber prepregs with resin material pre-impregnated in various architectures of fiber fabrics are preformed to a designed part shape before final compression molding of the parts to reduce production cycle time and achieve high product quality. The current numerical simulation techniques are based on the phenomenological models which have difficulty to capture the large shear deformation during the preforming process, and based on the models for incremental simulation which requires long computation time and tooling design information.

In this paper, a one-step analysis approach is developed to reduce the simulation time without sacrificing the prediction accuracy. The new algorithm developed for this analysis treats the matrix and fibers as different materials. The matrix can be defined by any material model in the commercial FEA software; while the fiber is modeled as elastic material. The material deformation on the final formed part is obtained by using minimum energy method.

*This model has been successfully implemented in LS-DYNA® and can be activated by the new keyword: *DEFINE_FIBERS. No tooling information is needed for model setup. The initial prepreg shape and size can be obtained based on the final part geometry. The prediction accuracy and computational efficiency of the developed one-step analysis are demonstrated through modeling the preforming of a double dome part. The predicted deformation and fiber orientation change during the preforming process are compared to physical test data as well as the predictions. Good agreement is obtained among those comparisons.*

Introduction

Carbon fiber reinforced polymer (CFRP) composites have been gaining interests in automotive industry due to their lightweight, high stiffness and strength properties. Compression molding process is one of the major manufacturing methods to produce high strength structure components. Due to its good geometric conformability, woven CFRP is one of the most suitable materials for compression molding a complex part. In the compression molding process, woven prepregs, which have been pre-impregnated with resin matrix, are placed in a mold cavity and compressed and molded to produce a low void content and high fiber content finished part.

Preforming process is a critical step in compression molding of woven composite. In this step, the woven prepregs with a specific number of plies and a certain ply layout with a designed fiber orientation are cut into a desired shape. The material is softened under certain temperature and formed into a desired shape. A large number of trial and error experiments are required to find the optimal manufacturing process conditions such as forming temperature, ply layout orientation, and forming rate as well as the initial prepreg shape to produce a defect-free part. The large amount of material waste and long experimental time could result in high developing cost and long product development cycle, which hinders the wide application of woven CFRPs for automotive design.

Numerical methods that can simulate the behavior of the woven composites during preforming process are developed to address this issue. The pin-joint net (PJN) model [1] is a widely used purely kinematic based phenomenological model to simulate the woven composites, with the assumption that the composites hold only pure shear deformation and the fibers can rotate freely at the tow joints during preforming process. This approach is computationally efficient. However, the ignorance of the mechanical properties of the woven fabric and the resin matrix could result in inaccurate prediction of fiber orientation and wrinkling behavior.

The mechanical properties of woven composite are highly dependent on the fiber orientations in the material. During the preforming process, the woven yarn angle will change when the material experiences large shear deformation, which will result in the change of material properties in the formed parts. Thus, accurate prediction of yarn angle after preforming is important. Recently, more physical based material models have been developed to accurately simulate the fiber orientation, and wrinkling behavior during the preforming process [2-3]. Hamila [4] and Boisse [5] developed a semi-discrete shell elements approach to describe the textile material as a continuum material in one hand and to discretely model all the yarns and their contacts in the other hand. Peng [6] and Xue [7] proposed a non-orthogonal material model to consider the coupling of tensile and shear behavior. However, the prediction of wrinkling and fiber orientation with this model could be inaccurate when the material subjects to large shear deformation. An improved non-orthogonal model with appropriate material parameter characterization method was developed by Zhang [8-10] has been successfully implemented in LS-DYNA as MAT_293 (MAT_COMPRF). The predicted material deformation and fiber orientation from this model showed great agreement with physical testing data through a double dome part trial.

Most of the models mentioned above are developed based on the incremental method. It calculates every step of the forming process from flat prepreg to the design shape in "incremental" time steps. The results predicted from this method is usually accurate as long as the material models can capture the material deformation behavior. The complete tooling surfaces and detailed manufacturing process information are required to build up the simulation models. When the geometry of the tools, the blank shape and the loading path during the forming process are not available, the incremental method cannot be used in this circumstance anymore. One-step method [11] was developed to quickly and effectively assess sheet metal formability during stamping process. It inversely computes the deformation potential of a finished part geometry to the flattened blank. The primary input is the part final geometry; no tooling geometry is needed. However, the application of the one step method for modeling the preforming of woven prepregs is very limited.

In this paper, a new algorithm is developed to assess the part formability and predict the fiber orientation of woven prepregs during the preforming process. The new algorithm treats the matrix and fibers as different materials. The matrix can be defined by any material model in the commercial FEA software; while the fiber is modeled as elastic material. The material deformation in the final formed part can be obtained with the use of minimum energy method.. No tooling information is needed for model setup. The shape and size of the initial prepregs are obtained based on the final part geometry. The prediction accuracy and computational efficiency of the developed one-step analysis is demonstrated through modeling the preforming of a double dome part.

One Step Model Development

Recently, a completely new algorithm for the modeling of woven composites is successfully developed and implemented in LS-DYNA. Unlike any pre-existing method, a hybrid constitutive model is proposed. In particular, the fiber and its underlying matrix are treated as two separate materials, while at the same time are coupled with each other.

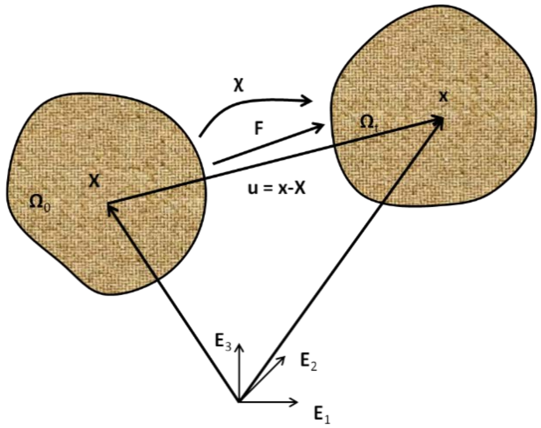


Figure 1: A carbon-fiber composite body deforms from Ω_0 to Ω_t
(F is the deformation gradient tensor)

As shown in Figure 1, we are considering a carbon-fiber composite body Ω_0 in the reference configuration. Subjected to both essential ($u = \bar{u}, \forall x \in \Gamma_u$) and natural ($t = \sigma n = \bar{t}, \forall x \in \Gamma_t$) boundary conditions, the body Ω_0 deforms to Ω_t at time t in the current configuration. The finite element method is employed to find the displacement field u within the composite.
For a virtual displacement δu, the external virtual work can be expressed as

$$\delta W_{ext} = \int_{\Omega_t} b\rho b \cdot \delta u d\Omega + \int_{\Gamma_t} \bar{t} \cdot \delta u d\Gamma \tag{1}$$

where ρ is the mass density and b is the body force.
Also the internal virtual work due to the virtual displacement δu can be written as

$$\delta W_{int} = \int_{\Omega_t} \sigma_m : \delta\varepsilon d\Omega + \int_{\Omega_t} \sigma_f : \delta\varepsilon d\Omega \tag{2}$$

where σ_m is the Cauchy stress in the matrix, $\delta\varepsilon = \frac{1}{2}\left(\frac{\partial \delta u}{\partial x} + \left(\frac{\partial \delta u}{\partial x}\right)^T\right)$ is the virtual strain tensor and σ_f is the Cauchy stress in the fiber. The virtual work of the carbon fibers can be expressed as

$$\int_{\Omega_t} \sigma_f : \delta\varepsilon d\Omega = \sum_{i=1}^{nf} A_i \int_{S_{it}} \sigma_f : \delta\varepsilon \, ds \tag{3}$$

where A_i is the cross-section area of fiber i, which is assumed to be a constant A_0.
The principle of virtual work states that the external virtual work δW_{ext} due to the virtual displacement δu equals to the internal virtual work δW_{int},

$$\int_{\Omega_t} \rho b \cdot \delta u d\Omega + \int_{\Gamma_t} \bar{t} \cdot \delta u d\Gamma = \int_{\Omega_t} \boldsymbol{\sigma}_m : \delta\boldsymbol{\varepsilon} d\Omega + A_0 \sum_{i=1}^{nf} \int_{S_{it}} \boldsymbol{\sigma}_f : \delta\boldsymbol{\varepsilon} \, ds \tag{4}$$

Without the loss of generality, we assume that the matrix is a hyper-elastic material with energy function $\psi(\mathbf{F})$ and the fiber is a linear elastic material with Young's modulus $\mathbf{E}$, from which the stresses can be obtained as

$$\boldsymbol{\sigma}_m = \frac{1}{J}\frac{\partial \Psi}{\partial \mathbf{F}} \mathbf{F}^T \text{ and } \boldsymbol{\sigma}_f = E\boldsymbol{\varepsilon} \tag{5}$$

With a finite element discretization $\delta u_i = \mathbf{N}^I \delta \mathbf{u}_i^I$ (implied summation on nodal index I), one can rewrite all the terms as

$$\int_{\Omega_t} \rho \mathbf{b} \cdot \delta \mathbf{u} d\Omega = \left[\int_{\Omega_t} \rho b_i \mathbf{N}^I d\Omega\right] \cdot \delta \mathbf{u}_i^I \tag{6}$$

$$\int_{\Gamma_t} \bar{\mathbf{t}} \cdot \delta \mathbf{u} d\Gamma = \left[\int_{\Gamma_t} \bar{t}_i \mathbf{N}^I d\Gamma\right] \cdot \delta \mathbf{u}_i^I \tag{7}$$

$$\int_{\Omega_t} \boldsymbol{\sigma}_m : \delta \boldsymbol{\varepsilon} d\Omega = \int_{\Omega_t} \frac{1}{J} \frac{\partial \Psi}{\partial \mathbf{F}} \mathbf{F}^T : \frac{\partial \mathbf{N}^I}{\partial \mathbf{x}} \delta \mathbf{u}_i^I d\Omega = \left[\int_{\Omega_0} \frac{\partial \Psi}{\partial \mathbf{F}} \frac{\partial \mathbf{N}^I}{\partial \mathbf{X}} d\Omega\right] \cdot \delta \mathbf{u}_i^I \tag{8}$$

$$A_0 \sum_{i=1}^{nf} \int_{S_{it}} \boldsymbol{\sigma}_f : \delta \boldsymbol{\varepsilon}\, ds = A_0 \sum_{i=1}^{nf} \int_{S_{it}} \boldsymbol{\sigma}_f : \frac{\partial \mathbf{N}^I}{\partial \mathbf{x}} \delta \mathbf{u}_i^I\, ds = A_0 \left[\sum_{i=1}^{nf} \int_{S_{it}} \boldsymbol{\sigma}_f \frac{\partial \mathbf{N}^I}{\partial \mathbf{x}} ds\right] \cdot \delta \mathbf{u}_i^I \tag{9}$$

Due to the arbitrariness of $\delta \mathbf{u}_i^I$, we have

$$\underbrace{\int_{\Omega_t} \rho b_i \mathbf{N}^I d\Omega + \int_{\Gamma_t} \bar{t}_i \mathbf{N}^I d\Gamma}_{\text{external force}} = \underbrace{\int_{\Omega_0} \frac{\partial \Psi}{\partial \mathbf{F}} \frac{\partial \mathbf{N}^I}{\partial \mathbf{X}} d\Omega}_{\text{matrix}} + \underbrace{A_0 \sum_{i=1}^{nf} \int_{S_{it}} \boldsymbol{\sigma}_f \frac{\partial \mathbf{N}^I}{\partial \mathbf{x}} ds}_{\text{fiber}} \tag{10}$$

This is a nonlinear equation about the displacement field **u**, which can be solved iteratively using the Newton-Raphson method.

One Step Analysis Validation

<u>Preforming of a double dome part with a specified prepreg shape</u>

The present approach is first applied to preform a double dome part to evaluate the applicability and effectiveness of the develop method. Figure 2 shows the lower punch and binder of a compression molding tool with a double dome shape. The upper matching mold cavity at the top is not showing in the picture. The flat prepregs are laid on the binder before the preforming process. There are two actions. In the first action, the upper mold goes down to set on the binder surface to clamp the prepreg. Then the lower punch goes up to form the double dome part.

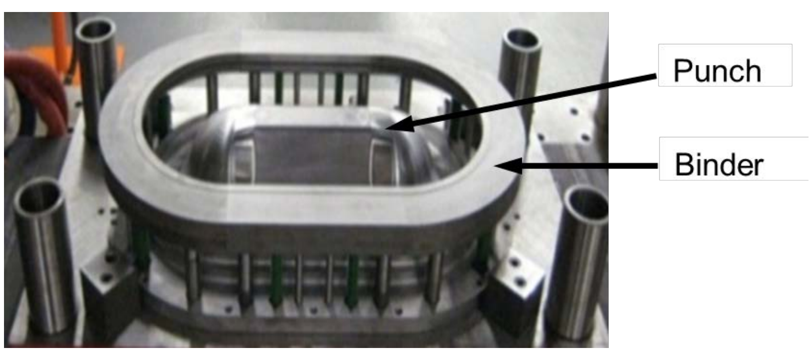


Figure 2: Experimental setup for the double dome test

The initial blank is a 0.7mm thick single layer twill woven prepreg. The angle between the yarn direction and the global coordinates is defined as the prepreg layout orientation. As shown in Figure 3, the prepreg is initially laid out at a ±45° direction. The yarn angle, defined as the angle between the woven warp and weft direction, is 90° initially. Figure 4 shows the final shape of the preformed double dome. It can be clearly seen that the yarn angle deviates from 90° in the final part. There are large change in the angles at certain locations, especially at large curvature regions. The yarn angles at the twelve points marked on the part are measured to provide experiment data for one step analysis prediction to compare later.

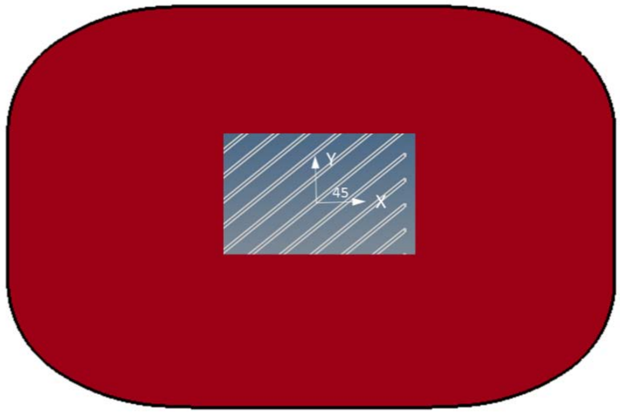


Figure 3: The initial blank shape with ±45º prepreg layout

Figure 4 Preformed double dome part with initial yarn direction of ±45º

Next, the part is scanned to provide geometry input to build up the one step analysis model. The elastic-to-plastic material model MAT_24 in LS-DYNA is chosen for the matrix material with a low Young's Modulus since the prepreg is heated up to 60ºC to be softened for better formability before laying on the binder. The new keyword *define_fibers is used to define the fiber properties, and the prepreg layout. The Modulus of the fiber is 240Gpa and the fiber volume fraction is 50%. Shear property is the most important material input for this material since shearing between the warp and weft yarn is the major deformation mode during preforming process. Bias extension test can be used to characterize the shear stress-strain relation. In this paper, the shear stress-strain characterized by Ren [12] is used.

The initial prepreg shape and the fiber orientation distributions after preforming have been predicted. Figure 5 shows the comparison of the initial prepreg shape between the experiment and prediction. We can see that the one step analysis gives good prediction in both the blank shape and size.

As we know, the yarn angle, initially set to be 90º, will change as the prepreg deforms into the mold cavity. Figure 6 shows the predicted yarn angle distributions on the finished part. Figure 7 shows the comparison of the predicted yarn angles at the selected locations with the measurement data on the finished part. It can be seen from the plot that there are some variations among the measurement data. The predicted angles are within the measurement data range. Thus, the simulation results show that the developed one-step analysis is capable of accurately predicting the physical experiments regarding the yarn angle distribution and initial blank shape.

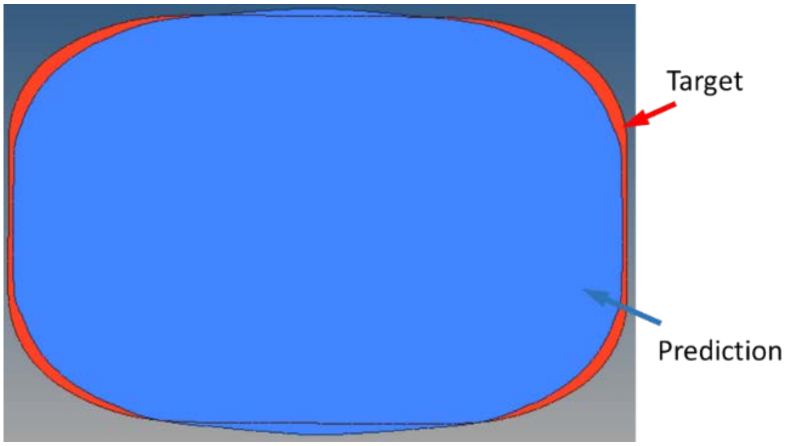


Figure 5: Comparison of the initial blank shape between the experiment and prediction

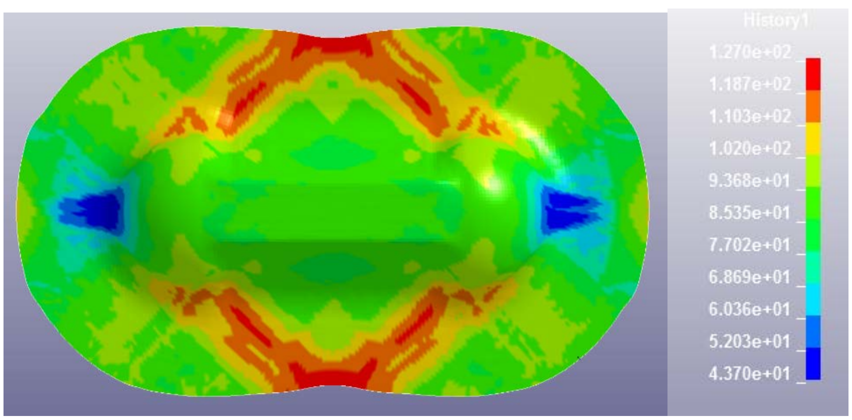


Figure 6: Predicted yarn angle distributions after preforming

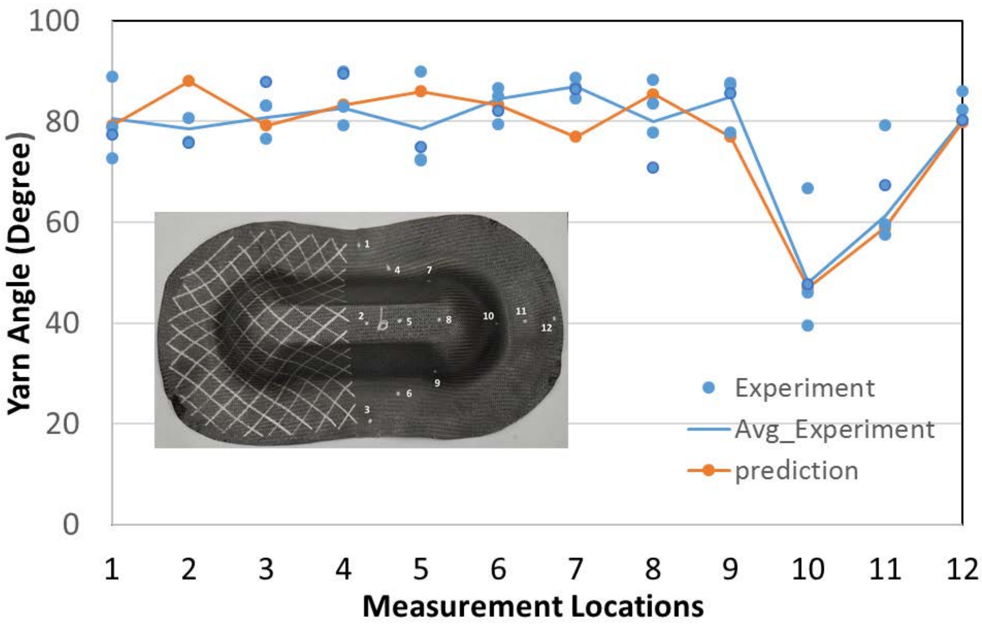


Figure 7: Comparison of experiment and predicted yarn angle at selected locations

Preforming of a double dome with an oval shape prepreg

In this section, the one-step analysis is applied to preform of prepregs with different layouts. No physical molding trial is conducted, Instead, an incremental simulation is performed to obtain the part shapes based on the oval shape prepregs as illustrated in Figure 8 at layout of 0/90º and ±45º, respectively.

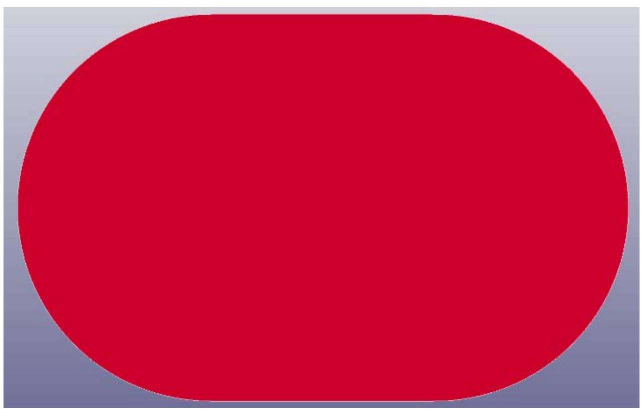


Figure 8: The designed initial blank shape

The incremental simulation model is built up based on the molding tool shown in Figure 2. Figure 9 illustrates the FEA model setup. The prepreg is modeled by reduced integrated shell elements, while the punch, binder and die are modeled using rigid shell elements. The non-orthogonal model MAT_293 in LS-DYNA developed by Zhang et al. [8-10] is chosen with the same material property input. The material properties were calibrated using the uniaxial tension test, bias extension test and the bending test at 60ºC. Figure 10 shows the predicted part shapes from the incremental simulation for the two prepreg layout: 0/90º and ±45º, respectively. This tells us, the final formed part shape does not only dependent on the initial preperg shape and size, but also the prepeg layout.

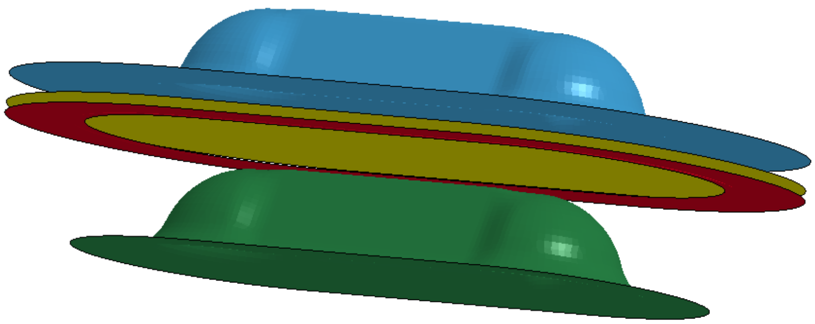
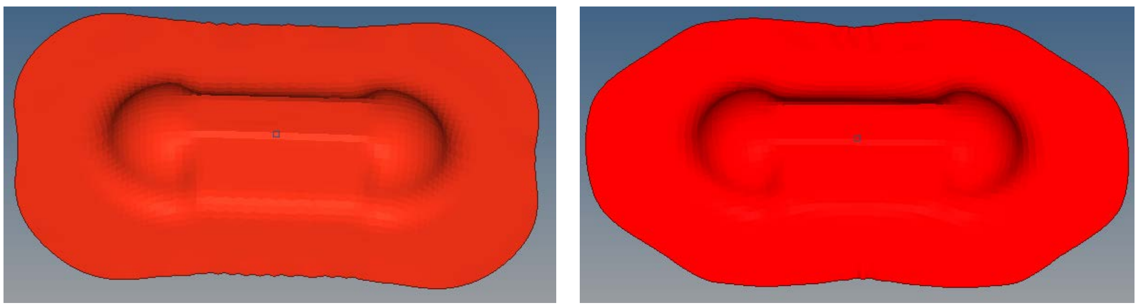


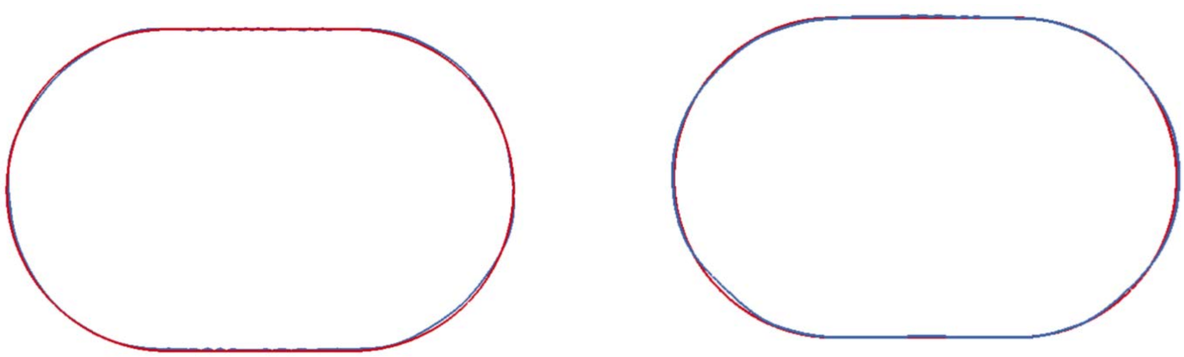
Figure 9: Double dome model setup



a) 0/90° preperg layout b) ±45° prepreg layout

Figure 10: The part shape predicted from the incremental simulation

Once obtained the final part shape from incremental simulation, a one-step analysis model is build up to inversely calculate the initial prepreg shape. The same one-step model setup and material parameters as in the previous example are used. Figure 11 shows the comparison of the initial prepergs between the designed shape and the predicted shape for both 0/90° and ±45° layout. This comparison shows that the one step model works well for different prepreg layout. Moreover, the prediction accuracy is as good as incremental simulation method.



a) 0/90° prepreg layout b) ±45° prepreg layout

Figure 11: Comparison of the designed and predicted prepreg shapes from one step analysis (The target blank shape is in red color; the predicted blank shape is in blue color)

Computational Efficiency

The following table provides a comparison of CPU time between one-step simulation and incremental simulation, on the 0/90° pregreg layout. Similar CPU times are seen for the ±45° pregreg layout as well. All simulation are conducted on Intel Xeon E5645 with 1 CPU and with SMP. As seen from the table, one-step simulation is 89% faster than incremental simulation.

Method	Incremental	One-step
CPU time	29 min. 50 sec.	3 min 20 sec.

Conclusions

A one-step analysis approach is developed to simulate woven prepreg preforming process. It has been successfully implemented in LS-DYNA with the new keyword *define_fibers to inversely calculate the initial prepreg shape, predict the strain and yarn angle distributions on the formed parts. No tooling information is needed for model setup. The initial preprege shape and size are obtained based on the final part geometry. The prediction accuracy and computational efficiency of the developed one-step analysis is demonstrated through modeling the preforming of a double dome part. The predicted material deformation and fiber orientation change during the preforming process using the developed model are compared to the measurements from physical tests. Good agreement is obtained among those comparisons. Thus, the proposed one-step method is applicable to the analysis of woven prepres preforming process. With reasonable expenditure of computing time and sufficient accuracy, this method can really help the engineers in the prepreg blank development, formability assessment and yarn angle prediction for the design of woven composite parts.

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