One-step Method for Tri-axial Carbon Fiber Reinforced Composites in LS-DYNA®

Houfu Fan[1], Danielle Zeng[2] and Xinhai Zhu[1]

(1 Livermore Software and Technology Corporation, Livermore, CA 94551, USA)

(2 Ford Motor Company, Dearborn, MI 48121, USA)

Abstract

In this paper, an algorithm for one-step analysis approach of carbon fiber reinforced composites (CFRC) modeling is introduced and successfully implemented in LS-DYNA. Local fiber rotations during the forming process of fiber reinforced composites are almost inevitable. These rotations have significant effect on the material behaviors of the composite, especially for composites with tri-axial carbon fibers embedded in. In the current work, rotation effects of the embedded fibers are considered and new implementation is capable of handling composites with tri-axial carbon fibers. The prediction ability of the algorithm is demonstrated through modeling of a double dome part with tri-axial carbon fiber composites. Good agreement is obtained in the initial composite shape prediction as compared to experimental data.

Introduction

Carbon fiber reinforced composites are drawing great attention in the automotive industry due to their lightweight, high stiffness/strength properties. Fiber reinforced composites in various fabric architectures are preformed into a designed part shape before a final compression molding of the parts. Currently, most numerical simulation methods are developed for woven composites that are fabricated with bi-axial fiber orientations. To the best of our knowledge, there is no modeling technique for composites with tri-axial fiber directions. In this paper, our previous work on bi-axial woven composites [1] is extended to model the tri-axial composites based on a one-step analysis approach. The algorithm developed for this analysis treats the matrix and fibers as different materials. Any material model in the commercial FEA software can define the matrix, while the fiber is modeled as an elastic material. The material deformation on the final formed part is obtained by using the minimum energy method. This feature has been successfully implemented in LS-DYNA and can be activated by the modified keyword *DEFINE_FIBERS.

This paper is organized as follows. One-step method for the modeling of carbon fiber reinforced composites are first discussed. After that, the keyword *DEFINE_FIBERS to defined composites with the tri-axial fibers embedded is illustrated. Simulations of a double dome part with tri-axial carbon fiber composites are then presented, whose results are compared to that of the corresponding experiment.

One-step method for the modeling of CFRCs

In this part, the method on the modeling of carbon fiber reinforced composites is presented. The key ingredient of the current method is by treating the fibers and its underlying matrix as two separated materials that couples with each other through the displacement field.

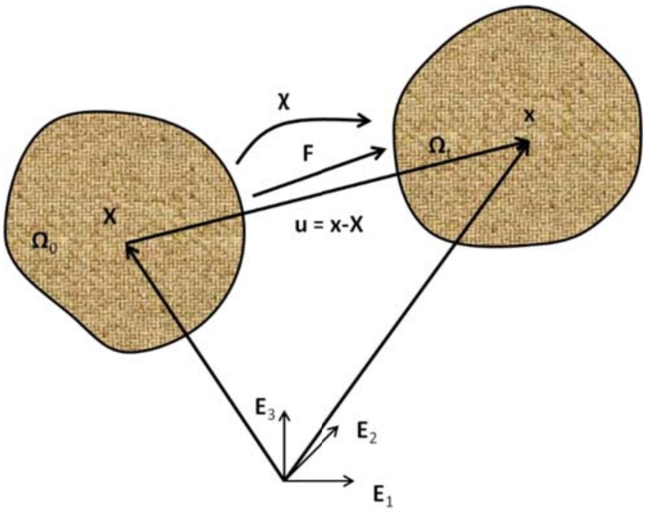


Figure 1, A carbon-fiber composite body deforms from Ω_0 to Ω_t, **F** is the deformation gradient tensor

As can be seen in Figure 1, a composite initially occupying domain Ω_0 deforms to Ω_t at current time t. The composite is subjected to two sets of boundary conditions: essential boundary condition $\mathbf{u} = \bar{\mathbf{u}}, \forall \mathbf{x} \in \Gamma_{\mathbf{u}}$ and natural boundary condition t=σn=$\bar{\mathbf{t}}$, $\forall \mathbf{x} \in \Gamma_{\mathbf{t}}$. It is assumed that a fiber is perfectly attached to its underlying matrix, which means the deformation of the fiber can be solely decided by the displacement field of the matrix. In this way, the coupled system (fiber and matrix) can be solved by finding the displacement field $\mathbf{u}$ within the matrix.

The total potential energy of the system is given as the sum of the internal and external potential energy,

$$\Pi(\mathbf{u}) = \Pi_{\mathrm{int}}(\mathbf{u}) + \Pi_{\mathrm{ext}}(\mathbf{u})$$

where

$$\Pi_{\mathrm{int}}(\mathbf{u}) = \int_{\Omega_0} \Psi\big(\mathbf{F}(\mathbf{u})\big) d\Omega$$

and

$$\Pi_{\mathrm{ext}}(\mathbf{u}) = -\int_{\Omega_t} \rho \mathbf{b} \cdot \mathbf{u} d\Omega \; - \int_{\Gamma_t} \bar{\mathbf{t}} \cdot \mathbf{u} \mathrm{d}\Gamma$$

where $\Psi\big(\mathbf{F}(\mathbf{u})\big)$ is the strain-energy function per unit volume, $\mathbf{F}(\mathbf{u})$ is the deformation gradient.

From the principle of the stationary potential energy, we know that the equilibrium of the system in the deformed configuration can be found by requiring the first variation of the total potential energy, denoted $\delta\Pi$, vanishes, i.e.,

$$\delta\Pi(\mathbf{u}, \delta\mathbf{u}) = \frac{d}{d\alpha} \Pi(\boldsymbol{u} + \alpha\delta\boldsymbol{u})|_{\alpha=0} = 0$$

for any arbitrary vector field $\delta\mathbf{u}$ that is consistent with the conditions imposed on the body. Thus $\delta\mathbf{u}$ satisfies the homogenous essential boundary condition:

$$\delta\mathbf{u} = \mathbf{0}, \forall \mathbf{x} \in \Gamma_{\mathbf{u}}$$

For the current problem, the first variation of the internal potential and external potential energy can be expressed as

$$\delta\Pi_{\mathrm{int}} = \int_{\Omega_t} \boldsymbol{\sigma}_{\mathrm{m}} : \nabla\delta\mathbf{u} \mathrm{d}\Omega + \int_{\Omega_t} \boldsymbol{\sigma}_{\mathrm{f}} : \nabla\delta\mathbf{u} \mathrm{d}\Omega$$

and

$$\delta\Pi_{ext} = -\int_{\Omega_t} \mathbf{b}\rho\mathbf{b}\cdot\delta\mathbf{u}d\Omega - \int_{\Gamma_t}\bar{\mathbf{t}}\cdot\delta\mathbf{u}\,d\Gamma$$

where $\boldsymbol{\sigma}_m$ is the Cauchy stress in the matrix, $\boldsymbol{\nabla}$ is the gradient operator, $\boldsymbol{\sigma}_f$ is the Cauchy stress in the fiber, ρ is the mass density, $\mathbf{b}$ is the body force.

By substituting $\delta\Pi_{int}$ and $\delta\Pi_{ext}$ into the stationary of the total potential energy and reorganize, one can get

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

Without the loss of generality, one can 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

$$\boldsymbol{\sigma}_m = \frac{1}{J}\frac{\partial\Psi}{\partial\mathbf{F}}\mathbf{F}^T$$

and

$$\boldsymbol{\sigma}_f = \mathbf{E}\boldsymbol{\varepsilon}$$

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

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

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

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

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

where nf is the number of fiber orientations of the composites.

To better account for the effects of the embedded fibers, the rotation of a local representative 'fiber' within a generic element is considered. As shown in Fig. 1, using standard Finite Element formulation, the deformation gradient of the generic element can be obtained as $\mathbf{F_c}$. In one-step method, the 3D final part is always provided and the corresponding 2D part are to be obtained. So the unit vector $\mathbf{V_c}$ representing the direction of the generic fiber in the current configuration is given. In order to compute the internal forces due to this generic fiber, one needs to get the initial unit vector $\mathbf{V_o}$, which is proposed to be

$$\mathbf{V_o} = \frac{\mathbf{F_c^{-1}V_c}}{||\mathbf{F_c^{-1}V_c}||}$$

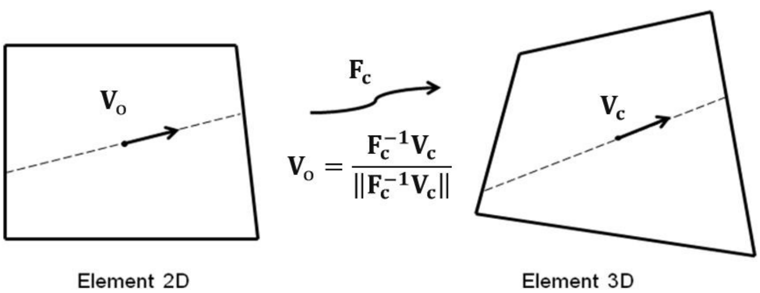


Fig 1: Mapping of a generic fiber element from the original configuration to the current configuration: $\mathbf{F_c}$ is the element deformation gradient, $\mathbf{V_c}$ and $\mathbf{V_o}$ represent the local fiber in the current and reference configuration correspondingly.

Due to the arbitrariness of $\delta\mathbf{u}_i^I$, one may get

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

This is a set of nonlinear equations about the displacement field $\mathbf{u}$, which can be solved iteratively by using the Newton-Raphson method. This model has been implemented in LS-DYNA the keyword *DEFINE_FIBERS.

The keyword *DEFINE_FIBERS

In order to activate the new feature, aside from the existing keyword *CONTROL_FORMING_ONESTEP, a new keyword named *DEFINE_FIBERS is to be used, as shown below:

```
*CONTROL_FORMING_ONESTEP
         7
*DEFINE_FIBERS
$       IDF       IDP      NUMF        N1        N2       EFB       SHR     HRGLS
          1         4         3     19128     19156      &efb     -1011       0.0
$    ALPHA1    ALPHA2    ALPHA3
        0.0      60.0     120.0
$        X1        Y1        Z1        X2        Y2        Z2
        &x1       &y1       &z1       &x2       &y2       &z2
```

IDF is the unique fiber ID; IDP means the matrix part ID; NUMF denotes the number of fiber orientations; N1 and N2 are user IDs of nodes that defines the reference direction for the fiber orientations; EFB is the effective fiber stiffness (>0) or the curve ID (absolute value) that defines the effective fiber stiffness versus the normal strain; SHR is the shear stiffness (>0) or curve ID (absolute value) that defines shear stiffness versus the shear strain; HRGLS is a coefficient that helps stabilize the material behaviors at the fringe of the composite (default is 0.0); ALPHA1, ALPHA2 and ALPHA3 defines the orientation of the fibers (two or three) in degrees. Points (X1,Y1,Z1) and (X2,Y2,Z2) define the reference direction for the fiber orientations when N1 and N2 are not defined.

One-step analysis validation

We are considering the preforming of a double dome part with a tri-axial carbon fiber reinforced composite. The experimental setup is shown in Fig. 2. The lower punch and binder of a compression molding tools shall enable the forming of the specimen into a double dome shape. The upper matching mold cavity at the top is not shown in the picture and the initial flat composite are laid over the binder before the preforming process. There are generally two steps. First the upper mold goes down to the set on the binder surface to clamp the composite. Then the lower punch goes up to form the double dome part.

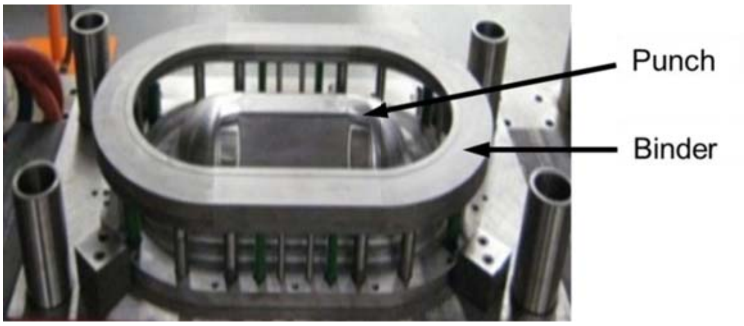
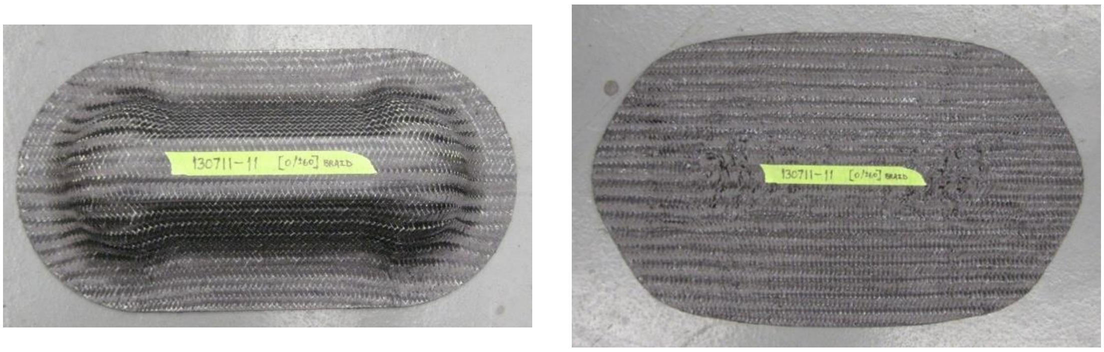


Fig 2: Experiment setup for the double dome test.

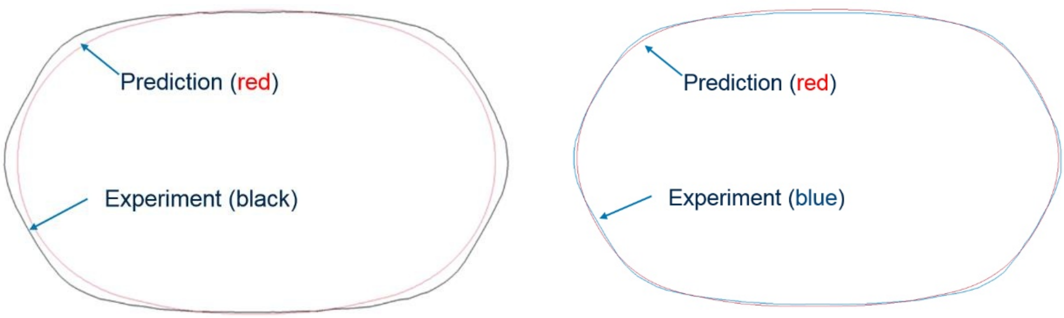
The 3D composite has an initial fiber orientation of -60/0/60 degree, with respect to the defined direction. Fig. 3(a) and (b) shows the final 3D part and initial 2D part of the preformed double dome, respectively.



(a) Final 3D part (b) Initial 2D part

Fig. 3 Results from the double dome preforming experiment.

By using the LS-DYNA one-step analysis approach, without and with the rotation effects, the predicted initial shapes of the flat composite are shown in Fig. 4. One can see that the predicted initial blank shape obtained from the method without rotation effect is some way off the experiment result (see Fig. 4(a)), while the current implementation with the rotation effect produces much better prediction (see Fig. 4(b)).



(c) No rotation effect (Original) (d) With rotation effect (Current)

Fig. 4 Predicted initial blank shapes from the one-step simulations using LS-DYNA, as compared to the corresponding experiment result.

Aside from the initial 2D shape prediction, the current method can also provide the angles between different fibers in the composite, as shown in Fig. 5.

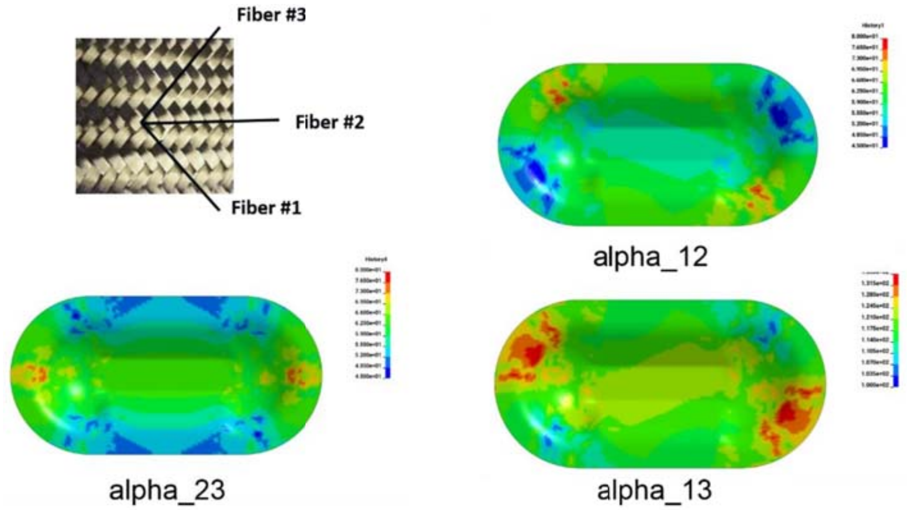


Fig 5: Contours of angles between different fibers

Conclusion

In this work, an algorithm considering the fiber rotation effect is proposed and implemented for the one-step method in LS-DYNA. It is shown that the proposed algorithm in LS-DYNA can provide much better accuracy in predicting the initial shape for tri-axial carbon fiber reinforced composites.

Reference

[1] Danielle Zeng, Xinhai Zhu, Li Zhang, Jeff Dahl, Houfu Fan, Development of a One-Step Analysis for Preforming of Woven Carbon Fiber Composites. 15-th International LS-DYNA Users Conference, June 10-June 12, 2018, Michigan, USA.