

# One-step Method for Tri-Axial Carbon Fiber Reinforced Composites in LS-DYNA<sup>®</sup>

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## Abstract

*In this work, an algorithm for one-step analysis approach of tri-axial 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.

## Modelling Carbon-Fiber Reinforced Composites

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.

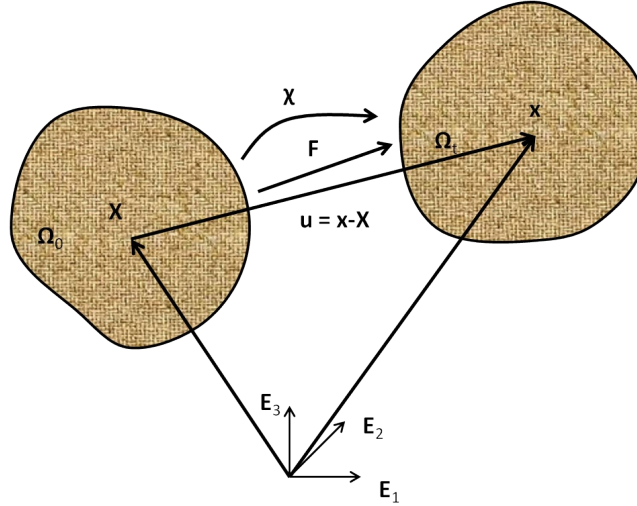


Figure 1, A carbon-fiber composite body deforms from  $\Omega_0$  to  $\Omega_t$ ,  $\mathbf{F}$  is the deformation gradient tensor

As can be seen in Figure 1, a composite initially occupying domain  $\Omega_0$  deforms to  $\Omega_t$  at current time  $t$ . The composite is subjected to two sets of boundary conditions: essential boundary condition  $\mathbf{u} = \bar{\mathbf{u}}, \forall \mathbf{x} \in \Gamma_u$  and natural boundary condition  $\mathbf{t} = \bar{\mathbf{t}}, \forall \mathbf{x} \in \Gamma_t$ . 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,

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

where

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

and

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

where  $\Psi(\mathbf{F}(\mathbf{u}))$  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.,

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

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:

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

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

$$\delta \Pi_{\text{int}} = \int_{\Omega_t} \boldsymbol{\sigma}_m : \nabla \delta \mathbf{u} d\Omega + \int_{\Omega_t} \boldsymbol{\sigma}_f : \nabla \delta \mathbf{u} d\Omega$$

and

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

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

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

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

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

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

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

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

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

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 Figure 2, 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

$$\mathbf{V}_o = \frac{\mathbf{F}_c^{-1} \mathbf{V}_c}{\|\mathbf{F}_c^{-1} \mathbf{V}_c\|}$$

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

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

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.

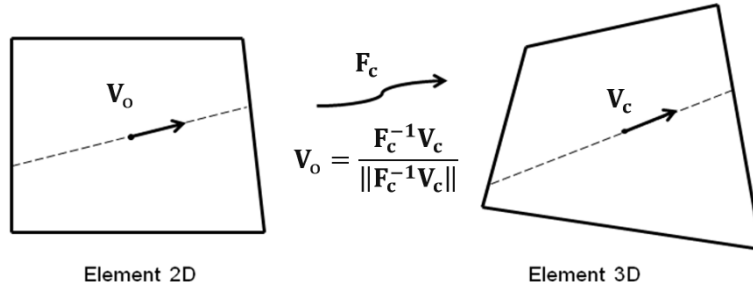


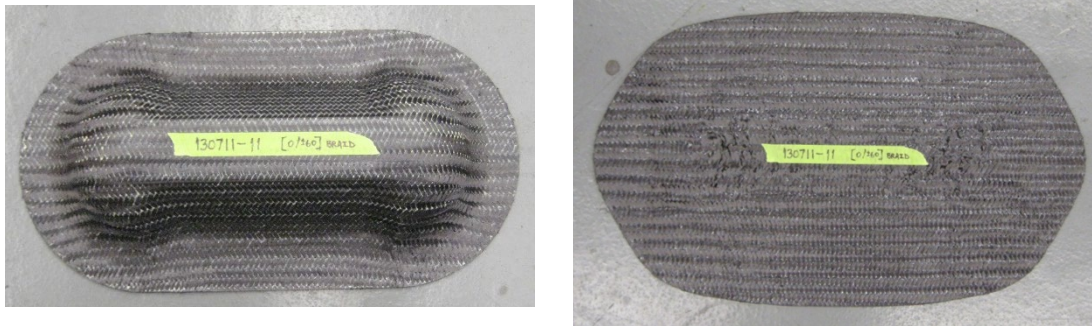
Figure 2, Mapping of a generic fiber element from the original configuration to the current configuration:  $\mathbf{F}_c$  is the element deformation gradient,  $\mathbf{V}_c$  and  $\mathbf{V}_o$  represent the local fiber in the current and reference configuration correspondingly.

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
```

where 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.

## Validations



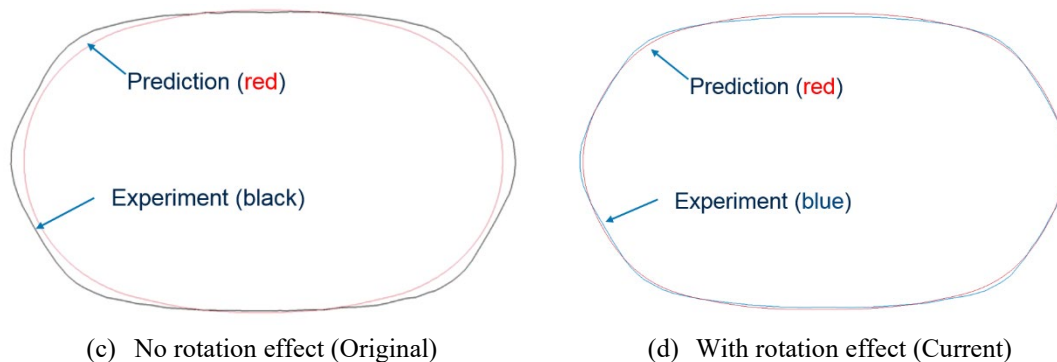
(a) Final 3D part

(b) Initial 2D part

Figure 3, Results from the double dome preforming experiment.

We are considering the preforming of a double dome part with a tri-axial carbon fiber reinforced composite. The 3D composite has an initial fiber orientation of  $-60/0/60$  degree, with respect to the defined direction. Figure 3(a) and (b) shows the final 3D part and initial 2D part of the preformed double dome, respectively.

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 Figure 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 Figure 4(a)), while the current implementation with the rotation effect produces much better prediction (see Figure 4(b)).



(c) No rotation effect (Original)

(d) With rotation effect (Current)

Figure 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 Figure 5.

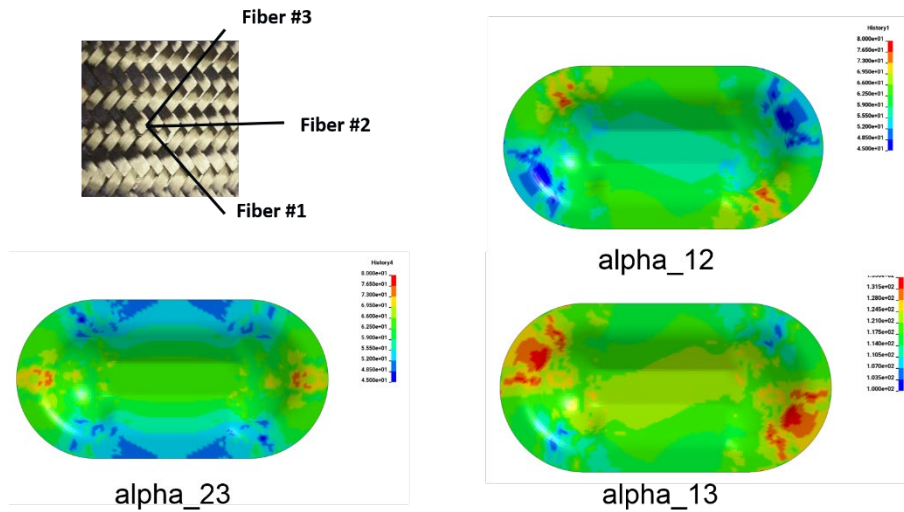


Figure 5, Contours of angles between different fibers

## Summary

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.

## References

[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.