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Simulation of the hemispherical forming process of a woven fabric with two different material models

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Abstract

The anisotropic hyperelastic model (MAT_249) and Non-Orthogonal Model (MAT_293) are the material models developed recently to simulate the forming process of dry fabric and fabric-reinforced thermoplastic prepregs. In this study, the prediction capabilities of these two models in terms of shear angle distribution and boundary profile of the deformed fabric are compared over a hemispherical forming simulation of a plain weave E-glass fabric reinforcement. According to the results, in the simulation performed with MAT_293, it is seen that excessive distortions occur in the meshes at the advanced stages of the deformation in the fabric. In addition, after a certain punch stroke, the shear angle distribution obtained with MAT_293 starts to deviate rapidly from realistic results. MAT_249 produces consistent results even in large deformations.

Key words: Woven fabrics, fabric forming, hyperelastic model, hypoelastic model, non-orthogonal model

1. Introduction

Finite element method (FEM) is an effective approach to predict the forming behavior of dry fabric and fabric-reinforced thermoplastic prepregs. The aim of the forming simulations performed by FEM is to evaluate whether a shape can be formed without defects. On the other hand, if the forming goes well, the local deformations that happen during forming should be known since they determine the mechanical response of the formed product. The final goal is to create a tool that allows optimization in the virtual world and thus to reduce or even to eliminate the time-consuming and costly "trial and error" approach [1].

One of the most critical factors that affect the prediction capability of a numerical simulation is the material model. There are two methods for choosing a suitable material model in finite element analysis. One of the options is to develop a user-defined material model. Many of researchers have been trying to develop a more accurate material model for the fabric reinforced composites. Another option is to use a built-in material model available in the library of a finite element software.

LS DYNA offers many options for modelling of dry fabrics or fabric reinforced thermoplastic prepregs. MAT_249 and MAT_293 are the latest models to simulate such processes in LS DYNA. The success of MAT_249 in terms of prediction capability has been tested in previous studies [2-4]. However, the suitability of MAT_293 for forming simulations of dry fabrics needs to be tested.

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This study aims to evaluate the prediction capabilities of these two material models through the simulation of the hemispherical forming of dry woven fabric.

2. Materials and Method

Fabric forming simulations are performed in order to compare two material models, MAT_249 and MAT_293, using LS DYNA solver in this study. Parameters which are necessary for the finite element analysis are taken from an experimental study in the literature [5].

2.1. Material

Plain weave type E-glass woven fabric is used in the hemispherical forming simulations. The main properties of the fabric are given in Table 1.

Table 1. Properties of the woven fabric [5]

Fabric thickness (mm)	0.58
Areal density (kg/m^2)	0.529
Ends/10 mm	1.1
Picks/10 mm	1.2

The axial stress vs. axial strain curve obtained from the uniaxial tensile test is given in Figure 1.

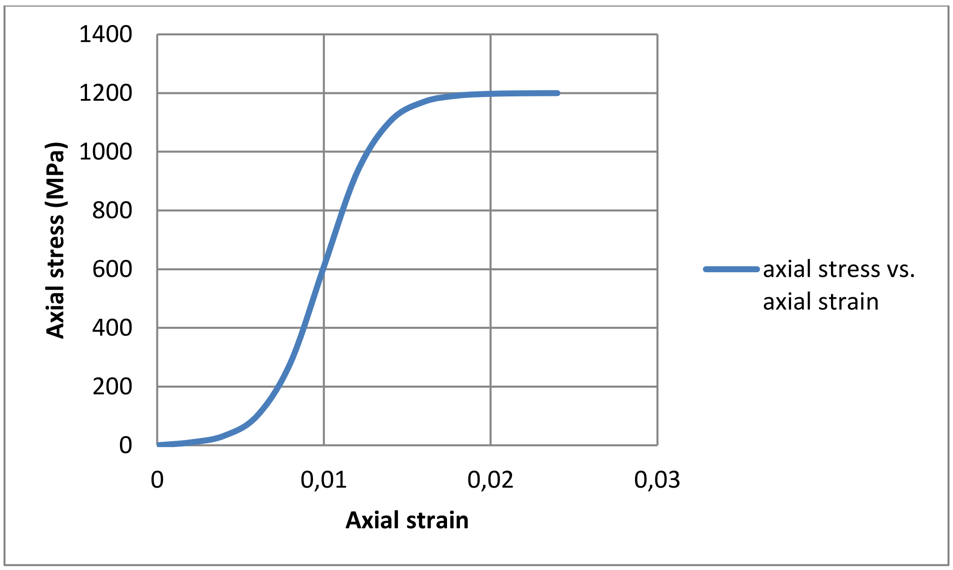

Figure 1. Axial stress vs. axial strain curve of the fabric reinforcement

The shear stress vs. shear angle curve obtained from the picture frame test is given in Figure 2.

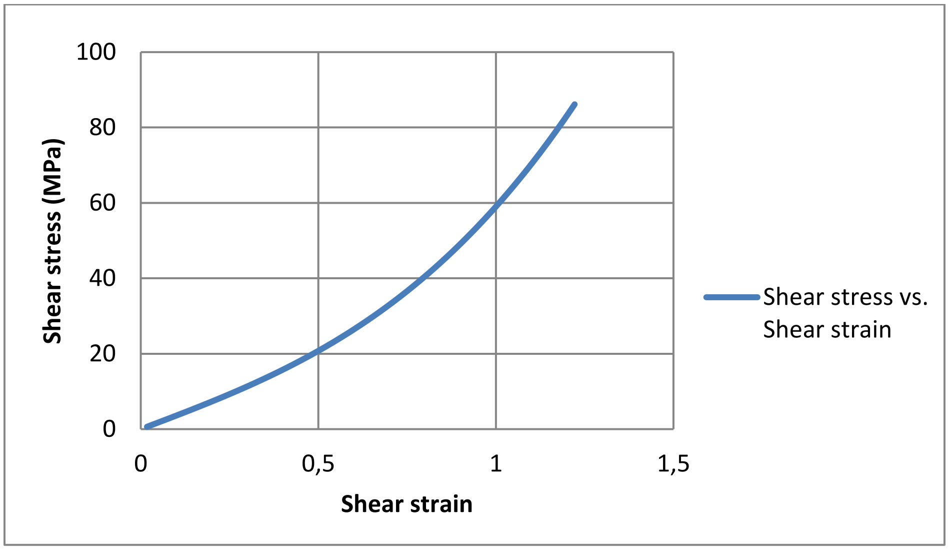

Figure 2. Shear stress vs. shear strain curve of the fabric reinforcement

2.2. Finite element modelling

The model created to simulate the hemispherical forming process consists of four parts: the hemispherical punch, blank holder, die, and woven fabric as seen in Figure 3. The diameters of the hemispherical punch and die cavity are 194 mm and 200 mm, respectively. The size of the square shaped fabric is 320 × 320 mm. It is taken advantage of the symmetric boundary condition to decreasing the computation time in the model. The fully integrated deformable shell elements are used in the fabric, while the tool parts consist of rigid shell elements. The friction coefficient between the tool and fabric is selected as 0.2 to be compatible with the literature [6]. A blank holder force of 97 N is applied to prevent the wrinkling problem during the process.

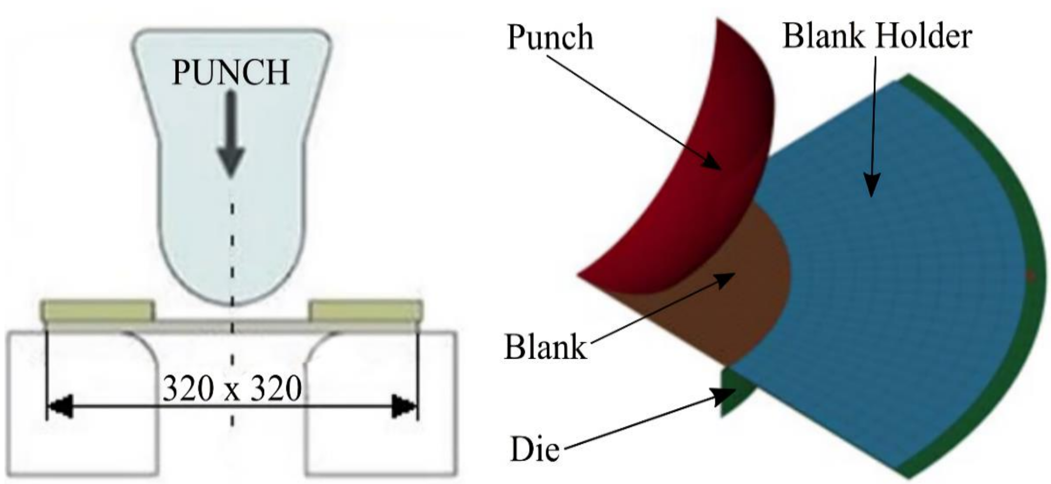

Figure 3. The simulation model of the hemispherical forming process

2.2.1. MAT_249 (Anisotropic hyperelastic model)

MAT_249 material model available in the LS DYNA material library was developed for thermoforming simulations of continuous fiber reinforced composites. The material behavior of the fiber reinforcement is represented by an anisotropic hyperelastic material model, while the thermoplastic resin is modelled with a simple thermal elastoplastic material formulation. Although this model was actually developed for thermoplastic composites, it also enables the forming processes of dry reinforcements to be modelled. MAT_249 allows the modeling of three types of reinforcement, unidirectional, woven and non-crimp fabric, respectively. The stress calculation procedure of the model is given in the user manual as the following [7]:

-The total stress response of the model is calculated by summation of the matrix stress and the fiber stress as follows:

$$\sigma = \sigma^m + \sigma^f \tag{1}$$

-Fiber reinforcement is considered a hyperelastic material since it is subjected to significant angular distortions during the process. The initial orientation of fiber families is defined by a unit vector m_i^0. The current fiber configuration is obtained by using the deformation gradient F as follows

$$m_i = F\, m_i^0 \tag{2}$$

-The elastic stresses within the yarns resulting from tension or compression are computed with the following equation

$$\sigma_T^f = \sum_{i=1}^{n} \frac{1}{\det F} f_i(\lambda_i)\, F(\, m_i^0 \otimes m_i^0) F^T \tag{3}$$

where the function f_i of the fiber strain λ_i corresponds to the stress-strain curve obtained from a uniaxial tensile test.

-The shear stresses resulting from the interaction between the yarns are obtained from the following equation [101]:

$$\sigma_S^f = \sum_{i,j} \frac{1}{det\, F} g_{ij}\big(\alpha_{ij}\big)\, F\big(\, m_i^0 \otimes m_j^0\big) F^T \tag{4}$$

where the function g_{ij} of the shear angle a_{ij} corresponds to the stress-strain curve obtained from a picture frame test.

-The matrix material in the MAT_249 material model is assumed that the material is isotropic, and Young’s modulus $E = E(T)$ and Poisson’s ratio $v = v(T)$ is temperature-dependent values. von Mises yield criterion is used in the model of the matrix material. The yield criterion can be stated as the following:

$$\varphi(\boldsymbol{\sigma}, \sigma_y) = |\boldsymbol{\sigma}| - \sigma_y(\varepsilon^P, T) \leq 0 \tag{5}$$

2.2.2. MAT_293 (non-orthagonal model)

MAT_293 material model is a new model based on hypoelasticity in LS DYNA material library. It was developed to model thermoforming simulation process of woven fabric reinforced composites. It is easier to determine material model constants in MAT_293 than in MAT_249 since it does not require testing the matrix and reinforcement separately. The stress calculation procedure of the MAT_293 material model is given in the user manual as the following [7]:

-Like MAT_249, this model uses the deformation gradient tensor F to trace the yarn directions and stretch ratios during the process. It can be stated by the following equation:

$$g = F.G \tag{6}$$

where g and G are the final and initial orientations of the yarns, respectively.

-Stress is divided into two components: stress caused by the yarn stretch, σ_f, and stress caused by the yarn rotation, σ_m, as shown in Figure 4.

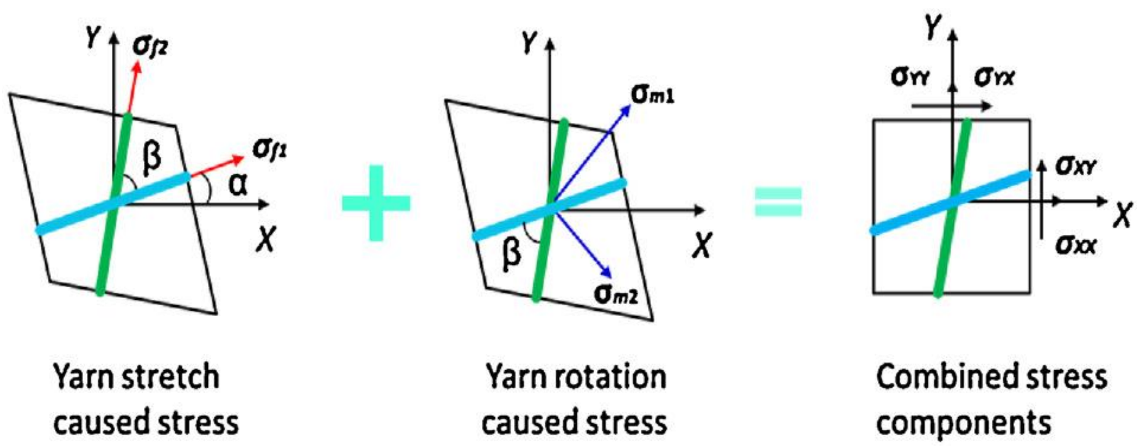

Figure 4. Schematic representation of the total stress calculation

-The stress components, σ_f and σ_m, are transformed into the local corotational X-Y coordinate using the following equations.

$$\sigma_{XX}^{f} = \sigma_{f1}.cos^2\alpha + \sigma_{f2}.cos^2(\alpha+\beta) \tag{7}$$

$$\sigma_{XY}^{f} = \sigma_{YX}^{f} = \frac{1}{2}\sigma_{f1}.sin2\alpha + \frac{1}{2}\sigma_{f2}.sin2(\alpha+\beta) \tag{8}$$

$$\sigma_{YY}^{f} = \sigma_{f1}.sin^2\alpha + \sigma_{f2}.sin^2(\alpha+\beta) \tag{9}$$

$$\sigma_{XX}^{m} = \frac{\sigma_{m1}+\sigma_{m2}}{2} + \frac{\sigma_{m1}-\sigma_{m2}}{2} cos(2\alpha+\beta) \tag{10}$$

$$\sigma_{XY}^{m} = \sigma_{YX}^{m} = \frac{\sigma_{m1}-\sigma_{m2}}{2} sin(2\alpha+\beta) \tag{11}$$

$$\sigma_{YY}^{m} = \frac{\sigma_{m1}+\sigma_{m2}}{2} - \frac{\sigma_{m1}-\sigma_{m2}}{2} cos(2\alpha+\beta) \tag{12}$$

$$\sigma_{XX} = \sigma_{XX}^{f} + \sigma_{XX}^{m} \tag{13}$$

$$\sigma_{XY} = \sigma_{YX} = \sigma_{XY}^{f} + \sigma_{XY}^{m} \tag{14}$$

$$\sigma_{YY} = \sigma_{YY}^{f} + \sigma_{YY}^{m} \tag{15}$$

-If the angle between the warp and weft yarns reaches the shear locking angle, the shear components of the yarn rotation-caused stress is calculated using the following equation.

$$d\sigma_{XY}^{m} = d\sigma_{YX}^{m} = E.d\varepsilon_{XY} \tag{16}$$

where E is the transverse compression modulus of the yarns and $d\varepsilon_{XY}$ is the shear strain increment after shear locking.

3. Results

Hemispherical fabric forming simulations are performed using the two material models. According to the mesh sensitivity analysis applied for each material model, optimum mesh sizes for MAT_249 and MAT_293 are determined as 4 mm and 3.2 mm, respectively. MAT_249 and MAT_293 results obtained for punch stroke of 97 mm, which corresponds to the punch radius, are shown in Figure 5. As seen in Figure 5, the MAT_249 result is more compatible with the experimental results since wrinkle formation is not noted in the experimental study. However, it is seen that many wrinkles occur in the simulation performed with MAT_293.

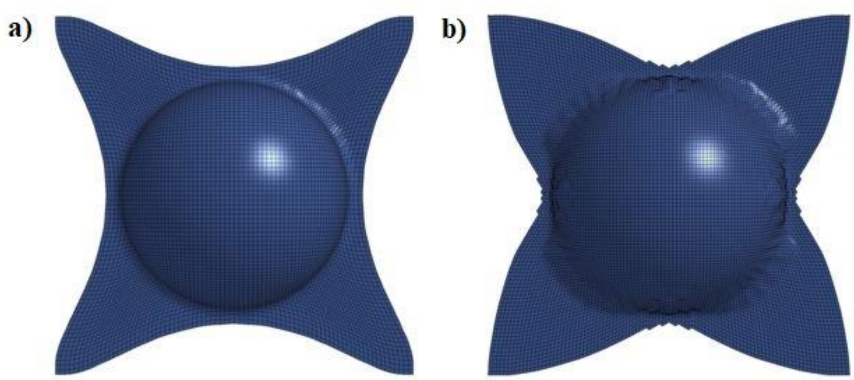

Figure 5. Deformed shapes obtained with 97 mm punch stroke: a) The MAT_249 material model b) The MAT_293 material model

Although MAT_293 leads to unrealistic results for punch stroke of 97 mm, it is highly compatible with MAT_249 up to punch stroke of 61.5 mm, as seen in Figure 6. After the punch stroke of 61.5 mm, it is observed that meshes begin to distort rapidly, and wrinkles appear on the deformed fabric. Although many trials are applied by changing the contact or material card parameters to prevent the mesh distortions, they do not have any positive effect on the results.

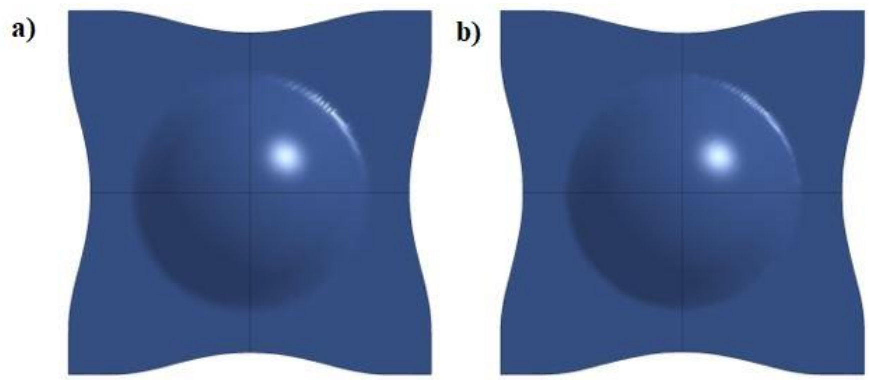

Figure 6. Deformed shapes obtained with 61.5 mm punch stroke: a) The MAT_249 material model b) The MAT_293 material model

The following figure shows the shear angle contour plot for the punch stroke of 61.5 mm. The results are highly compatible with each other. The maximum shear angle on the deformed fabric is predicted as 28.07 degrees with MAT_249, while the maximum shear angle is computed as 29.56 degrees with MAT_293.

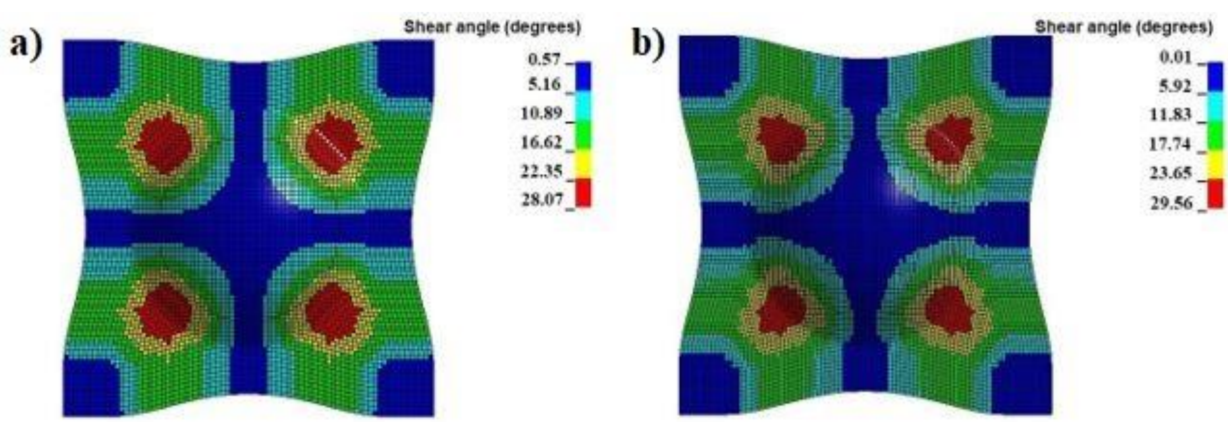

Figure 7. Shear angle contour plots obtained with 61.5 mm punch stroke: a) The MAT_249 material model b) The MAT_293 material model

Conclusions

In this study, hemispherical forming simulations of a plain woven fabric are performed using the MAT_249 and MAT_293 material models available in the LS DYNA material library. Both models produce similar results up to a certain punch stroke regarding the boundary profile and shear angle distribution. However, after a certain punch stroke is reached, high mesh distortions are observed, and then the wrinkling formation begins in the simulation performed with MAT_293. In addition, as a result of the analysis, it is seen that MAT_293 is more sensitive to mesh size than MAT_249. For this reason, smaller-sized meshes are used in simulations performed with MAT_293.

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