Reinforced thermoplastic sheet composite deep drawing investigation

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Abstract

This paper covers numerical investigations of the deep drawing of a woven composite sheet into a “hat” shape, combining a hemispherical cup with a wide flat rim. A non-orthogonal constitutive model is proposed to characterize the anisotropic material behavior of woven composite fabrics under large deformation loadings. The non-orthogonal constitutive model has been developed as a set of user defined material subroutines and incorporated into commercial FEM packages, ABAQUS/Implicit (UMAT) and ABAQUS/Explicit (VUMAT) codes. A comparison of results is investigated and presented in this paper.

1. Introduction

Woven fabric reinforced composites have been widely used in the aerospace, automotive, and sporting goods industries due to a number of advantages such as high strength to weight ratio, ease of handling, and well developed weaving technology. As the use of these materials become more prevalent, automated manufacturing processes will be needed to replace the hand shaping of woven preforms. For the design of such automated manufacturing processes, the use of accurate numerical tools for simulating the deformation behavior of preforms becomes indispensable. In order to accurately reflect the material behavior in the simulation, constitutive equations need to be defined that take into account the mechanical behavior of the material. There have been several studies conducted for the constitutive modeling of woven preforms, with the majority of these focusing on the prediction of fiber angle change (angle between warp and weft fibers) due to the shear deformation [1–5]. Severe fiber angle changes in woven preforms have been shown to cause defects such as wrinkling and buckling during forming. There are two different approaches for the simulation of the draping of fabrics, the geometrical and the mechanical approach. The pin-joint model, or so-called kinematics approach, was one kind of approach applied to simulate fabric forming [6–8]. This method is fast and fairly efficient but this method does not account for the mechanical behavior of the fabric. The model was extended in Ref. [9]. The effects of boundary conditions, such as friction and binder force, on fabric deformation and loads generated during the forming process, however, were not considered. The effect of material properties is not generally included in the geometrical approach. The solid mechanics analysis of the draping of fabrics by using finite element methodology [10–13] takes into account the mechanical properties of the fabric and, hence, describes the physical process of draping. Compared to extensive literatures on the orthogonal material models for woven composites and fabrics [14–21], little efforts have been given to the non-orthogonal constitutive relations.

Peng and Cao [22] presented a systematic framework for predicting the effective nonlinear orthotropic elastic moduli of textile composites with the combination of the homogenization method and finite element analysis. No experimental test is needed to
obtain the effective material properties of textile composites. However, the accuracy of this approach mainly depends on the geometric description of the unit cell and the homogenized material properties imposed. Gaps between fiber yarns and fiber threads usually result in a much lower tensile modulus in the transverse direction than that modeled in the unit cell. No feasible approach is available to accurately evaluate the effect of gaps. To circumvent the difficulties involved in the purely numerical approach and to capture the anisotropic material behavior of woven composite fabrics during forming, a non-orthogonal constitutive model is developed by Peng and Cao [23]. They use the real material properties in their model. In this paper we use discrete layers of woven and viscous materials to model the thermoplastic reinforced composite sheet. Each ply of the viscous material is modeled as a transversely isotropic incompressible Newtonian fluid, also we use the experimental results and non-orthogonal constitutive model that developed by Peng and Cao [23] to model each ply of the woven material. The developed constitutive equation was implemented into the ABAQUS/Explicit and ABAQUS/Implicit codes using the user material subroutines VUMAT and UMAT [24]. By using these two codes the fiber orientation, logarithmic strain and the boundary profile of final part predicted and the results are compared. Also the CPU time require for simulation of the forming process using these two codes are compared.

2. Constitutive model for woven fabrics
To trace the rotation of fiber yarns in woven fabrics during deformation, we choose the two vectors, $g_1$ and $g_2$, to coincide with the current weft and warp directions of the fabrics, as shown in Figure 1.

![Figure 1: Schematic of a deformed plain weave structure with shear deformation.](image)

The vectors $\{g_i\}$ construct a non-orthogonal coordinate system which reflects the fiber reorientation during deformation. Experimental studies on the biaxial tensile tests of woven composite fabrics have verified that the shear stress and the direct stresses can be treated as uncoupled. Hence, it should be reasonable to assume that in the non-orthogonal coordinate system $\{g_i\}$ the elastic matrix, which relates the stresses to the strains, has an orthotropic format. Consequently, we can rewrite the constitutive relation in a rate form as

$$
\begin{bmatrix}
\dot{d}\sigma^{11} \\
\dot{d}\sigma^{22} \\
\dot{d}\sigma^{12}
\end{bmatrix} =
\begin{bmatrix}
\tilde{D}^{11}(\varepsilon) & \tilde{D}^{12}(\varepsilon) & 0 \\
\tilde{D}^{21}(\varepsilon) & \tilde{D}^{22}(\varepsilon) & 0 \\
0 & 0 & \tilde{D}^{12}(\varepsilon)
\end{bmatrix}
\begin{bmatrix}
\dot{d}\varepsilon_{11} \\
\dot{d}\varepsilon_{22} \\
\dot{d}\gamma_{12}
\end{bmatrix}
$$

(1)
3. Determination of the elastic matrix

In this section we will use experimental force–displacement curves [23] to obtain the elastic matrix \( \mathbf{D} \) in non-orthogonal coordinate system \( \{g_i\} \). The balanced plain weave fabric used is a fiber reinforced thermoplastic composite (glass fiber and polypropylene resin). The real tensile moduli \( D_{11} \) and \( D_{22} \) were determined by Peng and Cao [23] has the following formulation

\[
\begin{align*}
D_{ii}(\text{MPa}) = \begin{cases} 
0.1 & \epsilon_i < 0 \\
2000 & 0 \leq \epsilon_i < 0.022 \\
1200 & \epsilon_i \geq 0.022
\end{cases}
\end{align*}
\]

(2)

where \( i=1 \) or \( 2 \) and no summation for \( i \). Considering the weak interaction between the weft and warp yarns under tension, the term \( D_{12} \) is assumed to have a very small value \( D_{12} = \min(D_{11}, D_{22}) \)

The real shear modulus were determined by Peng and Cao [23] has the following formulation

\[
D_{33}(\text{MPa}) = 5.027\gamma_{12}^3 - 1.21\gamma_{12}^2 + 0.194\gamma_{12} + 0.075
\]

(4)

4. Implementation of user material subroutine UMAT

In user subroutine UMAT the basis system in which stress and strain components are stored is orthogonal and rotates with the material thus the components of stress and strain tensors must transformed from non-orthogonal coordinate system \( \{g_i\} \) to orthogonal coordinate system \( \{e_i\} \).

4.1. Converting the components of the stress and strain tensors from non-orthogonal coordinate system to orthogonal coordinate system

We first determine the elastic matrix in the non-orthogonal coordinate system, and then transform it to the orthogonal system. To consider the non-orthogonality of woven fabrics caused by the fiber reorientation during shear deformation, we need to express the stress tensor \( \sigma \) and the strain tensor \( \epsilon \) in the non-orthogonal coordinate system. we can obtain the relation between \( \{d\epsilon\} \) and \( \{\tilde{d}\epsilon\} \) in a matrix format as:

\[
\begin{bmatrix}
\tilde{d}\epsilon_{11} \\
\tilde{d}\epsilon_{22} \\
\tilde{d}\epsilon_{12}
\end{bmatrix} =
\begin{bmatrix}
\cos^2\alpha & \sin\alpha & \sin\alpha\cos\alpha \\
\cos\alpha & \sin^2\alpha & \sin\alpha\cos\alpha \\
2\sin\alpha\cos\alpha & 2\sin\alpha\sin\alpha & \sin^2\alpha
\end{bmatrix}
\begin{bmatrix}
d\epsilon_{11} \\
d\epsilon_{22} \\
d\epsilon_{12}
\end{bmatrix}
\]

(5)

or \( \{\tilde{d}\epsilon\} = T \{d\epsilon\} \)

Similarly, we can obtain the relation between \( \{d\sigma\} \) and \( \{\tilde{d}\sigma\} \) in a matrix format as

\[
\begin{bmatrix}
\tilde{d}\sigma_{11} \\
\tilde{d}\sigma_{22} \\
\tilde{d}\sigma_{12}
\end{bmatrix} =
\begin{bmatrix}
\cos^2\alpha & \cos\alpha & \cos\alpha\cos\alpha \\
\sin^2\alpha & \sin\alpha & \sin\alpha\cos\alpha \\
\cos\alpha & \sin\alpha & \sin\alpha\cos\alpha
\end{bmatrix}
\begin{bmatrix}
d\sigma_{11} \\
d\sigma_{22} \\
d\sigma_{12}
\end{bmatrix}
\]

(7)

or \( \{\tilde{d}\sigma\} = T \{d\sigma\} \)
Where \( \{d\tilde{e}\} , \{d\tilde{\sigma}\} , \{d\sigma\} \) are the component of the strain and stress tensors in non-orthogonal and orthogonal coordinate systems. And \( \alpha \) and \( \theta \) are indicated in Figure 1. Substituting Eqs. (1) and (6) into (8) yields

\[
\{d\sigma\} = [T]^T \tilde{[D]} (e) [T] \{d\tilde{e}\} = [D] \{d\sigma\} \\
(9)
\]

Consequently, the elastic matrix \([D]\) in the orthogonal Cartesian coordinate system can be transformed from the non-orthogonal elastic matrix \(\tilde{[D]}\) by

\[
[D] = [T]^T \tilde{[D]} [T] \\
(10)
\]

4.2. Model validation
To verify the model a multi-element model is built to simulate the bias extension test of sample size of \(167 \text{mm} \times 334 \text{mm}\). In Figure 2 the numerical load–displacement curve obtained from the FEM simulation is compared with experimental results. As can be seen from Figure 2, a very good agreement between the numerical bias extension load and the experimental results is obtained.

4.3. Geometrical finite element model and basic set up of deep drawing simulations
The simulations were performed using the geometrical model, shown in Figure 3, includes a rigid punch, a die and a holder and the woven composite blank. To reduce computation time only one quarter of the specimen was modeled. The punch is a hemispherical mould with a radius of 97 mm joined with a cylindrical flange at the upper end. The die is a hemispherical hat shape mould with a radius of 100 mm in the hemisphere and a radius of 250 mm in the flat disc part. The holder is a flat ring to hold the fabric during draping. The blank material is a composite sheet of thickness of 1 mm. Four-node shell elements SR4 are used to model the composite blank. This type of element is of bilinear finite strain and is designed to handle large deformations and large rotations. The holder, die and punch are represented by analytical rigid bodies. The initial shape of elements is chosen to be squares.

4.4. Numerical results
Simulation was done by using the non-orthotropic constitutive equation. Different mesh sizes were employed for the composite blank, namely \(8 \times 8\), \(10 \times 10\) and \(16 \times 16\) shell elements. The material directions of the undeformed woven fabric coincide with the sides of the initial mesh and we didn’t refine the mesh during the simulation so that
the finite element mesh was used to represent the fiber yarns in the composite part. Figure 4 shows deformed mesh with contour of Logarithmic strain in forming simulation. Figure 5 shows edge profile of the deformed woven preform for different mesh sizes.

Figure 4: Deformed mesh with contour of Logarithmic strain.

Figure 5: Edge profile of the deformed woven preform for different mesh sizes.

5. Implementation of user material subroutine VUMAT

In user subroutine VUMAT, tensor quantities are defined in the non-orthogonal coordinate system that rotates with the material point so that we directly use the components of the stress and strain tensors in our non-orthogonal constitutive equation and we don’t have to convert the components of stress and strain tensors from non-orthogonal coordinate system to orthogonal coordinate system.

5.1. Simulation of composite sheet forming using VUMAT subroutine

Simulation was done using the non-orthotropic constitutive equation, geometrical model and the non-orthogonal elastic matrix \( [\bar{D}(\epsilon)] \) used in previous sections. The mesh size was \( 16 \times 16 \). Investigations were carried out for different punch speeds, \( v \), from \( 0.0085 \) to \( 85 \, \text{m/s} \). Figure 6 shows edge profile of the deformed woven preform for different punch speeds. Figure 7 displays the predicted punch force for different punch speeds. The predictions for punch force and boundary profile with \( 85 \, \text{m/s} \) and \( 8.5 \, \text{m/s} \) punch speeds seem not to be accurate and result in large oscillations whereas the accuracy is much improved for speeds lower than \( 8.5 \, \text{m/s} \).

Figure 6: Edge profile of the deformed woven preform for different punch speeds.

Figure 7: The predicted punch force for different punch speeds.
From the results presented in Figures 6 and 7 the precision regarding punch force and boundary profile converges with decreasing punch speed while the computation time increase.

6. Results and discussion

Figure 8 shows the comparison between the predicted boundary profiles of the formed preforms from user subroutines UMAT and VUMAT with mesh size of $16 \times 16$ and punch speed of $0.085 \text{m/s}$. Also Figures 9 and 10 display the predicted Logarithmic strain and grid element angle along the diagonal line of the formed preform from user subroutines UMAT and VUMAT with mesh size of $16 \times 16$ and punch speed of $0.085 \text{m/s}$. Figure 11 shows the comparison between the CPU times that require for simulation of deep drawing process using different mesh sizes from user subroutines UMAT and VUMAT.

As can be seen, the simulation results from these two subroutines are identical but the CPU times required for simulation using UMAT subroutine is about twenty times greater than the CPU times required for simulation using VUMAT subroutine because:
1- The explicit time procedure requires no iterations and no tangent stiffness matrix. When the problem size is large and the discontinuous effects dominate the solution, the explicit dynamics approach is often less expensive computationally and more reliable than an implicit quasi-static solution technique.

2- UVMAT user subroutine must do the following jobs in each iteration in each integration point:
   a) Update the vectors \( \{ e_i \} \) (rigid-body rotation of orthogonal coordinate system)
   b) Update the vectors \( \{ g_i \} \)
   c) Compute the angles \( \alpha \) and \( \theta \)
   d) Compute the elastic stiffness matrix in non-orthogonal coordinate system
   e) Compute the matrix \( [r] \)
   f) Compute the elastic stiffness matrix in orthogonal coordinate system
   g) Compute the Jacobian matrix of the constitutive model
   h) Update the stress tensor

   but VUMAT user subroutine do the following jobs in each integration point:
   a) Compute the elastic stiffness matrix in non-orthogonal coordinate system
   b) Update the stress tensor

   As can be seen the UMAT user subroutine must do the eight jobs in each iteration for each integration point but the VUMAT user subroutine must do the two jobs for each integration point.

7. Conclusions
A non-orthogonal constitutive model to characterize the anisotropic material behavior of woven composite fabrics under large deformation is proposed. By using the developed non-orthogonal constitutive model, user defined material subroutines are coded for commercial FEM packages ABAQUS/Implicit (UMAT) and ABAQUS/Explicit (VUMAT) codes. The simulation results from these two subroutines are identical but the CPU times required for simulation using UMAT subroutine is about twenty times greater than the CPU times required for simulation using VUMAT subroutine. This shows that in simulation of the complicated parts implementation of VUMAT code is reliable and is faster than UMAT code.

References


