Modeling and numerical simulation of the drawing of a dry woven reinforcement: Sensitivity of the shear angle to the parameters of the process

Modélisation et simulation numérique de l'emboutissage d'un renfort tissé sec : Sensibilité de l'angle de cisaillement aux paramètres du procédé

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Résumé : (16 gras)

Le présent travail a pour objectif de présenter une étude de sensibilité des modèles numériques réalisés avec le code ABAQUS, vis-à-vis la variation des paramètres du procédé d'emboutissage, l'effet d'orientation initiale du renfort, le type (coque ou membrane) et la taille du maillage. La simulation de la mise en forme est réalisée à l'échelle macroscopique en considérant le renfort comme un milieu continue. Cette approche continue s'appuie sur une loi de comportement hypo-élastique non orthogonale qui a l'aptitude à suivre la rotation des fibres (direction d'anisotropie) au cours de la mise en forme. Cette loi de comportement est implémentée dans le code de calcul des éléments finis ABAQUS/explicit en utilisant une subroutine VUMAT.

Abstract : (16 gras)

The present work aims to present a sensitivity study of the numerical models that are modelled with ABAQUS code, towards the variation of the process parameters, the initial orientation of fabric, type (shell or membrane) and size of mesh. Forming simulation has been realized at the macroscopic scale by considering the fabric as a continuum medium. The mechanical approach is based on non-orthogonal hypo-elastic behaviour that can track the rotation of fiber during the forming process. The constitutive model has been implemented in a commercial FE code (ABAQUS Explicit) via a user material subroutine VUMAT.

Keywords: hypo-elasticity / Continuous Approach / Textile Reinforcement

1. Introduction

Continuous fiber reinforced thermoplastic composites have been increasingly employed in several industrial fields such as aerospace, automotive, energy areas, defense and sports, due to enhanced and multi-functional material properties as compared to sheet metals, for instance their high specific strength and stiffness [1]. In recent years, the automakers are faced with two difficulties. The first one is the reduction of polluting emissions by decreasing the cars weight and the second challenge is about improving the cadence of production and mechanicals properties of the part [2]. In this context, the use of composite woven continuous glass fibers and thermoplastic matrix shaped by thermo-stamping, constitute the best compromise mechanical performance, cost and cadence of production [2]. Indeed the woven composite possess a good formability which results from the stretching of fibers in fiber direction and large amount of extension in diagonal direction. According these important characteristics, the textile composite can drape into fairly complex shape. In addition, the thermo-stamping process has a rapid cycle of fabrication (only seconds) regardless of the size and the complexity of the parts compared other process (LCM) which are very expensive with long time cycle [3]. The aim of this paper is to present a non-orthogonal hypo-elastic model that can track the fiber rotation during the forming step then to present a sensitivity study of the numerical models that are modelled with ABAQUS code, towards the variation of the process parameters

2. Computational implementation

2.1. Hypoelastic formulation: Constitutive model for woven fabrics

The hypo-elastic laws are widely used in FE codes to model the composite's behavior at large strain [4][5]:

$$\underline{\underline{\sigma}}^{\nabla} = \underline{\underline{\underline{\underline{C}}}} : \underline{\underline{D}} \tag{1}$$

Where $\underline{\underline{\sigma}}$ and $\underline{\underline{D}}$ are, respectively, the Cauchy stress and the strain rate tensors. $\underline{\underline{\sigma}}^{\nabla}$ is the objective derivative of the stress tensor. It can be seen as the time derivative for an observer which is fixed with regards to the material. The objective derivative is used to avoid stress change due to rigid body rotations [3][5]. It is written as:

$$\underline{\underline{\sigma}}^{\nabla} = \underline{\underline{Q}}\left[\frac{d}{dt}\left(\underline{\underline{Q}}^{t}.\underline{\underline{\sigma}}.\underline{\underline{Q}}\right)\right]\underline{\underline{Q}}^{t} \tag{2}$$

In literature, there are several objective derivatives that the main object is avoiding the stress change under rigid body rotations. Commercial FE codes, such as ABAQUS use generally two types of derivative objective [7]

- The Green-Naghdi GN stress rate, based on polar rotation, is used in ABAQUS/Explicit
- The Jauman stress rate, based on corotational frame rotation, is used in ABAQUS/Standard

In order to follow the rotation of fiber yarns in woven fabrics during deformation, we construct two vectors which are coincided with the current directions of warp and weft. In reality, the two vectors are no orthogonal and no unit but for simplicity they are chosen to be unit vectors. In the current configuration, the fiber directions are obtained from the deformation gradient tensor $\underline{\underline{F}}$. By default the stress and strain are expressed in the GN base. So it must define the vectors $\left(\underline{e}_1, \underline{e}_2\right)$ that defined the GN basis. In the current configuration, $\left(\underline{e}_1, \underline{e}_2\right)$ are obtained using orthogonal rotation tensor $\underline{\underline{R}}$.

$$\underline{f}_k = \frac{\underline{\underline{F}}.\underline{e}_k^0}{\left\|\underline{\underline{F}}.\underline{e}_k^0\right\|} \quad ; \quad \underline{e}_k = \frac{\underline{\underline{R}}.\underline{e}_k^0}{\left\|\underline{\underline{R}}.\underline{e}_k^0\right\|} \tag{3}$$

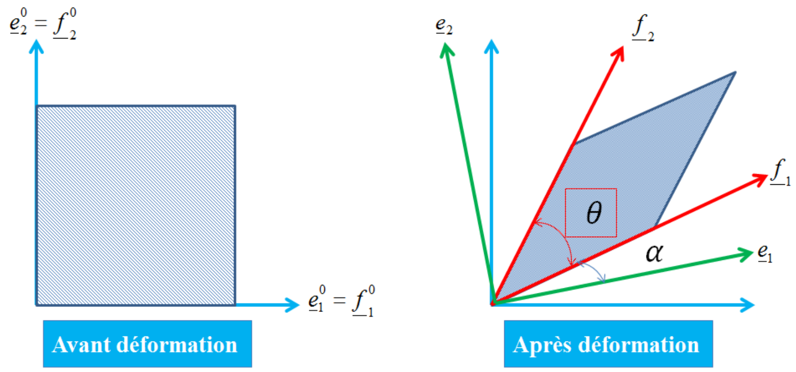

Figure 1: Schematic of a deformed plain weave structure with shear deformation

Initially, the initial vectors of the two bases (Fiber and GN) are assumed coincided. Let θ denotes the angle between the two current vectors of fiber frames and α defines the angle between the two independent fiber frames and the orthogonal GN axes (see figure1). To take into account the non-orthogonally of woven fabrics after forming the dry woven composite, we need to give the expression of the stress and deformation tensors in the non-orthogonal frame. In order to express the stress and strain in the fiber frame we need to construct a transformation matrix that is used to convert the different tensors between the two frames. The components of the transformation matrix are calculated using the sine and cosine of θ and α. The strain expressed in fiber base is related to the GN strain by the following relation [8][9].

$$\begin{bmatrix} d\overline{\varepsilon_{11}} \\ d\overline{\varepsilon_{22}} \\ d\overline{\varepsilon_{12}} \end{bmatrix} = \begin{bmatrix} \cos^2\alpha & \sin^2\alpha & \sin\alpha\cos\alpha \\ \cos^2\phi & \sin^2\phi & \sin\phi\cos\phi \\ 2\cos\alpha\cos\phi & 2\sin\alpha\sin\phi & \sin\phi \end{bmatrix} \begin{bmatrix} d\varepsilon_{11} \\ d\varepsilon_{22} \\ d\varepsilon_{12} \end{bmatrix} \tag{4}$$

Or, we can write

$$\{d\bar{\varepsilon}\} = [T]\{d\varepsilon\} \tag{5}$$

Similarly for the stress

$$\{d\bar{\sigma}\} = [T]\{d\sigma\} \tag{6}$$

In the non-orthogonal coordinate system, we can assume that the elastic matrix has an orthotropic format. Thus, in this frame, the stress is relied to the strain by:

$$[H] = \begin{bmatrix} \dfrac{E_{11}}{1-\nu_{12}\nu_{21}} & \dfrac{\nu_{21}E_{11}}{1-\nu_{12}\nu_{21}} & 0 \\ \dfrac{\nu_{12}E_{22}}{1-\nu_{12}\nu_{21}} & \dfrac{E_{22}}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12}(\gamma) \end{bmatrix} \tag{7}$$

Where $G_{12}(\gamma)$ is the in-plane shear rigidity which is a function of shear angle (radians). The shear rigidity of the of the glass/polypropylene BPW fabric is given by:

$$G_{12}(\gamma) = 8.48\gamma^4 - 12.0972\gamma^3 + 6.1275\gamma^2 - 0.83\gamma + 0.051$$

2.2. Stress computation

The aim of this section is to express the σ^{n+1} in the fiber basis. The integration of the equation between t_n and t_{n+1} (the time increment $\Delta t = t_{n+1} - t_n$ is assumed to be small enough) using the mid-point integration scheme gives us:

$$\underline{\underline{\sigma}}^{n+1} = \underline{\underline{\sigma}}^{n} + \Delta\underline{\underline{\sigma}} \tag{9}$$

Where

$$\Delta\underline{\underline{\sigma}} = \underline{\underline{\underline{\underline{H}}}}^{n+1/2} : \underline{\underline{D}}^{n+1/2}\Delta t \tag{10}$$

Thus, the stresses in the fiber frame are updated according to the Hughes and Winget [4] by the following expression

$$\underline{\underline{\sigma}}^{n+1} = \underline{\underline{\sigma}}^{n} + \underline{\underline{\underline{\underline{H}}}}^{n+1/2} : \underline{\underline{D}}^{n+1/2}\Delta t \tag{11}$$

2.3. Implementation of the hypo-elastic model

The hypo-elastic model described in the previous section has been implemented in a user material subroutine VUMAT using FORTRAN code [7]. The implementation is summarized in the following figure 2. According to figure 6, the following matrices and vectors are provided by the code at each time step expressed in the default basis of the code. The user subroutine has to return the stress state at the end of the step. Then, we compute the inverse matrix of the right stretch tensor. The last tensor is used to compute the polar rotation matrix. The current work basis and material basis are computed from the tensor F and R. These current vectors are used to calculate the passage matrices T. Then, we compute the material strain increment from the code's strain increment. We update the material stress tensor. Finally, we return the stress tensor in the work basis of the code.

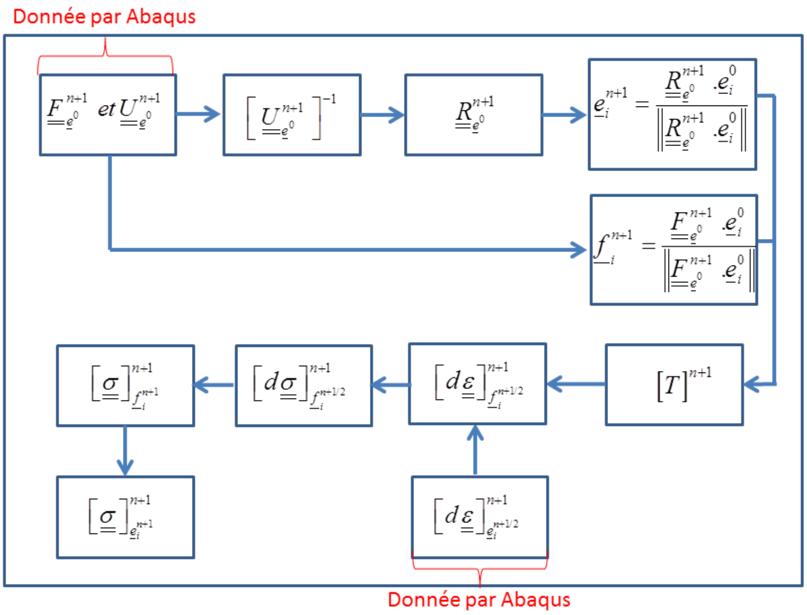

Figure 2: Scheme of stress computation in the developed user material subroutine.

3. Parametric Sensitivity Study

3.1. Stamping finite element model

Hemispherical stamping is one of the simplest references of forming woven composites. It has been the subject of several publications [11]. The FEM model development of hemispherical and the forming tests have been carried out using a commercial finite element code of ABAQUS Explicit using standard elements. The model consists of four elements: die, punch, holder and the sheet of composite (figure 3). In this FE model, the three forming tools are considered as rigid solids and are modeled as discrete rigid bodies and meshed with 3-D triangular rigid elements (R3D3). The reinforcement is considered is considered as a continuum material. Thus, it is modeled as four node membrane elements M3D4R.

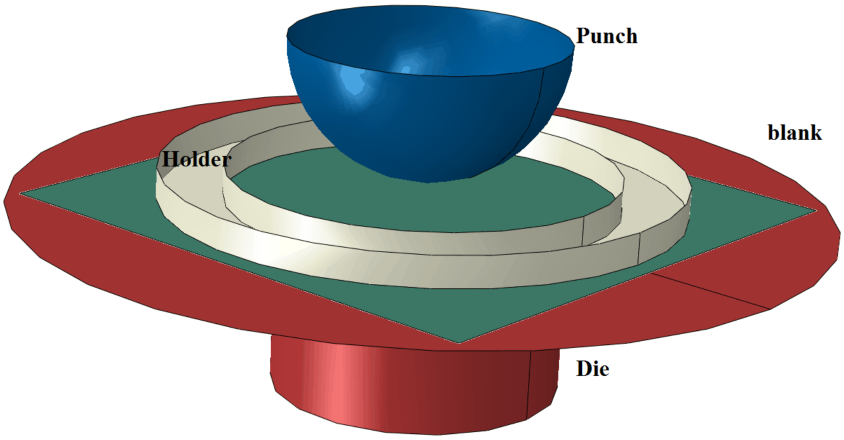

Figure 3 : Schematic of a deformed plain weave structure with shear deformation

In the initial configuration, the directions of warp and weft coincide with the two perpendicular edges of the membrane element. The material characteristics and process parameters used in this study are fixed as [5]:

- E_{11}=35400MPa
- E_{22}=35400MPa
- $\nu_{12} = 0$
- Mass density, ρ = 0.00253 g/mm3
- Blank holder force F=100N
- Punch velocity V=90 mm/s
- Coefficient of friction μ = 0.3

3.2. Effect of variation of the Punch Velocity

The final state of composite piece is influenced by the process parameters such us velocity of punch, binder force, blank holder shape…This section described the effect of the variation of the velocity punch on the distribution of the shear angle. In order to control the apparition of many defects like plies, wrinkling and buckling, it must select the optimized parameter of punch velocity. The figure 4 shows a comparison between two punch velocities.

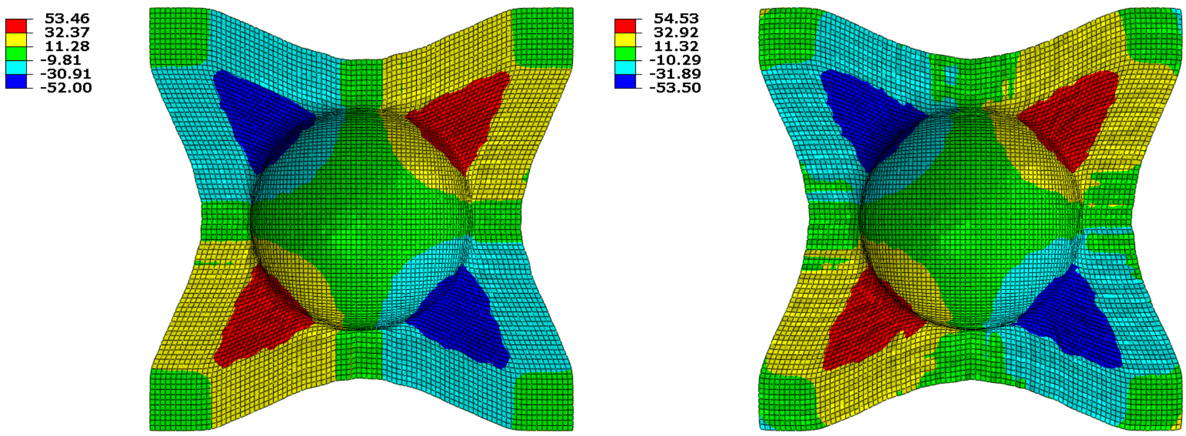

Figure 4: Forming results of shear angle in degrees (SDV71) with punch velocities

The lower punch velocity (9mm/s) predicts the shear angle in the final state as 53, which is 1.5 less than high speed (90mm/s) shown in Figure 4

3.3. Effect of variation of Binder force

The binder or blank holder plays a very important role in the forming processes of composite materials like of metallic materials. Mainly, the blank holder is used to ensure a homogeneous flow of the material. Thus, it prevents the appearance of manufacturing defects, especially the wrinkling. In order to clearly observe the effect of blank holder force on the draped part, two concentrated forces have been applied on the binder. The figure 5 shows the results of shear angle with these two different forces. The magnitude of the binder force determines correct execution of the forming step. It has a little effect on the maximum shear angle for axisymmetric configuration. In fact, the effect of the blank holder force is well shown in an asymmetric repartition of force.

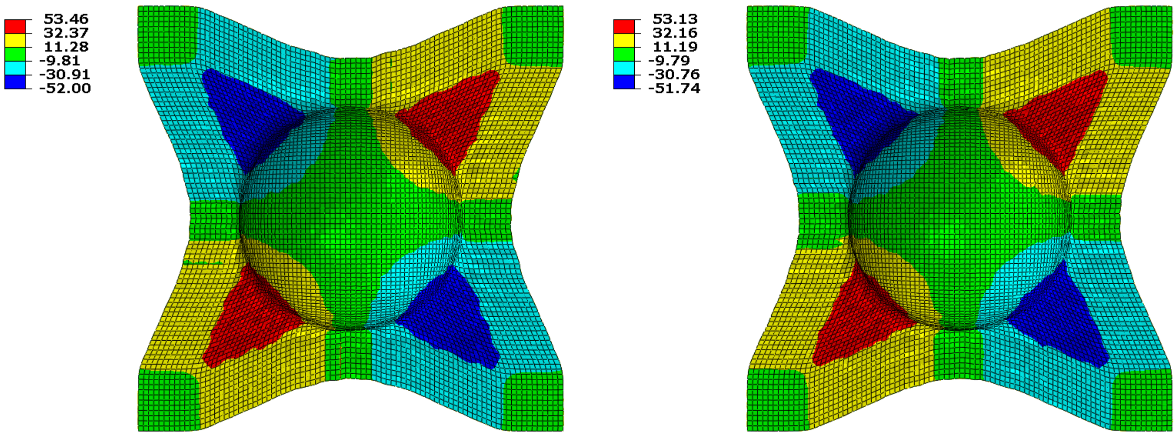

Figure 5: Forming results of shear angle in degrees (SDV71) with punch velocities

The figure 6 shows the significant role of the force on the formability results of a composite .In this case of configuration, the shear-angle distribution has shown a great variation in the final part.

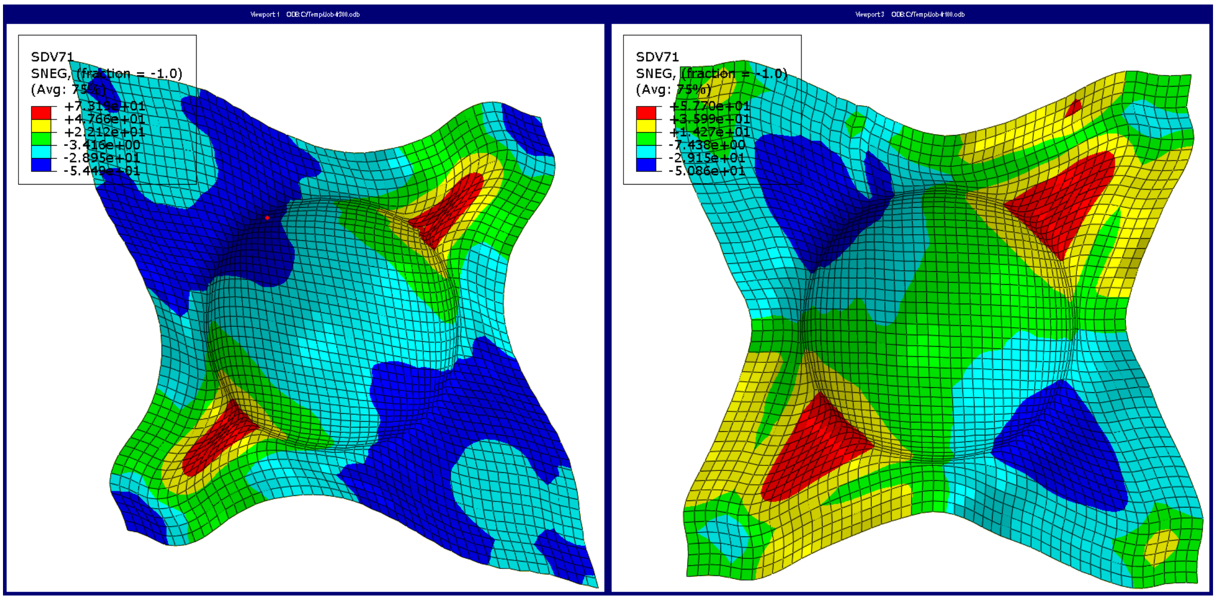

Figure 6: The evolution and distribution of the shear angle (deg) in the hemisphere model with non-axisymmetric configuration of the holder

There is also a high value of positive shear angle (73°) along the two free diagonals and (-52°) along the two other diagonals

3.4. Effect of variation of the friction coefficient

Other process parameter which can significantly affect the final geometry is the coefficient of friction tools/blank. In this model, there are three interactions: punch/blank, die/blank and holder/blank. These interactions are defined by a coefficient of friction introduced in the form of Coulomb friction. In reality, the coefficients of friction are different but in this study they are fixed as 0.3. In order to show the effect of the friction coefficient over the evolution of the shear angle different values were used. Figure shows the sensitivity of this parameter over forming results of two coefficient i.e. 0.3 and 0.5. The evolution of positive shear angles is affected by just about 2 but negative shear-angle values differ at maximum by almost 3° (Figure 7)

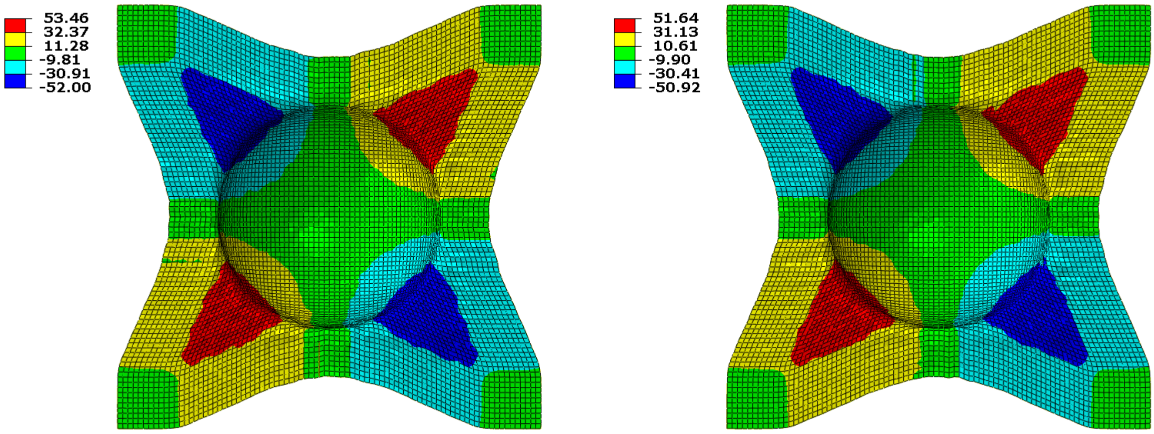

Figure 7: The evolution of the shear angle (degrees) in the two models with two different coefficients of friction

If the friction coefficient is more than 0.5 the results deteriorate largely and are no more presentable

4. Conclusions & outlook

In this study, numerical simulations of stamping on a dry woven reinforcement have been released using a non-orthogonal behavior law which is developed in a non-orthogonal frame (fiber directions) in order to keep tracing fiber reorientation during deformation. The hypo elastic model is implemented in a commercial FE code (ABAQUS/Explicit) via an user material subroutine VUMAT. In this work, we analyses the sensitivity of the shear angle to the process parameters. This parametric study gives results that have a good agreement with what is found in the literature.

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