Forming simulation of a thermoplastic commingled woven textile on a double dome

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ABSTRACT: This paper presents thermoforming experiments and FE simulations of a commingled glass-PP woven composite on a double dome geometry, with the aim of assessing the correspondence of predicted and experimental shear angles. Large local deformations - especially in-plane shear, i.e. relative rotation between the two yarn families – occur when draping a textile on a three dimensional part and eventually unwanted phenomena like wrinkling or tearing may occur. The macroscopic drape behaviour of a weave is generally subdivided into: 1) The high tensile resistance along the yarn directions, expressed as non-linear stress-strain curves, and 2) The shear resistance, expressed as non-linear shear force versus shear angle curves. The constitutive model is constituted of a dedicated non-orthogonal hypo-elastic shear resistance model, previously described in [1, 2], combined with truss elements that represent the high tensile resistance along the yarn directions. This model is implemented in a user subroutine of the ABAQUS explicit FE solver. The material parameters have been identified via textile biaxial tensile tests at room temperature and bias extension tests at 200°. Thermoforming experiments are performed on a rectangular blank with the warp direction along the second symmetry plane of the tool, with a preheating temperature of 200°C, a constant mold temperature of about 70°C, and a blankholder ring. It was concluded that the shear angles were fairly well predicted for this particular case study, which could be expected in view of the fact that no wrinkles had formed during the thermoforming experiment.

KEYWORDS: thermoplastic, woven fabric, thermoforming, composite, finite element

1 INTRODUCTION

Automated manufacturing of textile composite shell-like products typically requires draping of dry or pre-impregnated textile sheets. Large local deformations occur in the blank in order to adapt to the curved shape and potentially flaws like wrinkling and tearing may arise. Process parameters like the membrane stresses introduced by a blankholder, the mold and preheating temperature, the blank shape and punch force can affect the drape behaviour, the occurrence of wrinkling, and the consolidation and impregnation quality.

The macroscopic mechanical in-plane behaviour is typically non-linear because the textile prepreg is of heterogeneous nature and deformation mechanisms at smaller scales affect the macro-scale behaviour. Typical of weaves is the extreme high tensile resistance along the yarn directions, since the yarns are fairly straight, apart from the out-of plane waviness due to the intermingled structure. Another important measure of in-plane drape behaviour is the resistance against the relative rotation of the two yarn families at the crossovers, produced by frictional forces and lateral compression between neighbouring yarns. The commingled thermoplastic matrix behaves like a viscous fluid that affects the friction between the fibres, making the drape behaviour sensitive to the temperature history. Various research groups try to develop suitable constitutive models to describe the complex (visco-)elastic drape behaviour of (preimpregnated) textiles, in order to support process optimization, by predicting the local fibre directions or the onset of flaws like wrinkling. Previously a dedicated non-orthogonal hypo-elastic model has been proposed and validated [1, 2]. This model was composed of a shear resistance and a tensile resistance part. Later the shear resistance was adapted in order to include shear rate dependency for viscous textiles [3]. In the rate dependant version of the hypo-elastic model the tensile resistance part was replaced by truss elements for reasons of numerical stability. This study applies the model to simulate a thermoforming experiment of a co-mingled glass-PP weave on a double dome geometry (proposed in a Woven Benchmark Exercise, initiated at ESAFORM in 2003) and compares the predicted shear angles with those obtained from a thermoforming experiment.

2 CONSTITUTIVE BEHAVIOUR

2.1 The shear model

The non-orthogonal hypo-elastic model, that accounts for the shear resistance when two yarn families rotate relatively with respect to each other has been well described in [1]. Consider a material frame in the reference state with base vectors $\underline{G}_1, \underline{G}_2$ aligned with the weft and warp yarn directions. Three frames are introduced that are linked to the overall deformation of the body.

The Green-Naghdi frame: This orthonormal frame is the standard objective frame, used by ABAQUS to update the constitutive tensors. This frame follows the average rigid body rotation of the element, i.e. the rotation of the eigenvectors of the deformation. Its base vectors are obtained as: ${}^t\underline{e}_i = {}^t\,\underline{\underline{R}} \cdot \underline{G}_i$.

Orthonormal bisector or X"Y"-frame: This orthonormal frame remains always $-45°$ rotated with respect to the bisector frame of the warp α and weft γ fiber.

Covariant normalized frame or $\underline{g}_i$: A material line that was parallel to the $\underline{G}_i$ base vector in the reference state, will always remain parallel to the $\underline{g}_i$ base vector in the deformed state. Furthermore, the base vectors have a normalized length: ${}^t\underline{g}_i = \frac{\underline{\underline{F}}\cdot\underline{G}_i}{|\underline{\underline{F}}\cdot\underline{G}_i|}$

These frames can be unambiguously defined in each deformed state, based on the deformation gradient $\underline{\underline{F}}$, and unambiguous transformations exist that map the frames onto each other.

First a theoretical derivation between the shear stress increment and the shear angle increment is derived in the covariant normalized frame, for a pure shear deformation, assuming that σ^{12}, σ^{21} are the only stress components different from zero. This can be interpreted as assuming that the shear resistance and the fibre tensile resistance are uncoupled, since a shear increment does not lead to a stress component σ^{ii} in the fibre directions, and elongations in the fibre directions do not cause shear stresses.

$$\underline{\underline{\sigma}} = \sigma^{12}\underline{g_1} \otimes \underline{g_2} + \sigma^{21}\underline{g_2} \otimes \underline{g_1} \quad (1)$$

$$\sigma^{12} = \sigma^{21} = \frac{F_s}{c} \quad (2)$$

Here c is the thickness of the blank, in the current study considered to be constant and equal to the fully consolidated thickness, $F_s(\gamma)$ represents the nonlinear shear force (i.e. shear force per initial width [N/m]) versus shear angle curve [deg], as identified in a picture frame or bias extension test, or calculated with a meso-scale material model.

Consequently this expression is analytically differentiated with respect to the shear angle and mapped onto the X"Y"-frame, leading to an explicit formula (for derivation see [1]):

$$\Delta\sigma_{xx} = \frac{\Delta\gamma}{c}\left(\frac{dF_s}{d\gamma}tan\gamma + F_s((tan\gamma)^2 + 1)\right) \quad (3)$$

$$\Delta\sigma_{yy} = \Delta\sigma_{xx} \quad (4)$$

$$\Delta\sigma_{xy} = \frac{\Delta\gamma}{c}\left(\frac{dF_s}{d\gamma}\frac{1}{cos\gamma} + F_s\frac{sin\gamma}{(cos\gamma)^2}\right) \quad (5)$$

Furthermore it is assumed that for an arbitrary deformation (where fibre elongation may occur) the explicit relations (3-5) still hold in the X"Y" frame, and the X"Y"-frame will always remain $-45°$ rotated with respect to the bisector frame of the fibres. Finally these stress increments are transformed to the Green-Naghdi frame, since this is the only frame in which ABAQUS can update the stress state in a subroutine.

2.2 Shear parameters

The shear curve assigned to the elastic shear model is derived from bias extension tests at 200°C, published in [4], and can be expressed as:

$$\begin{aligned} F_s = 5.463^{-2} + 2.466\gamma^1 + -2.566^{-1}\gamma^2 + \\ 1.427^{-2}\gamma^3 + 1.427^{-2}\gamma^4 + 7.273^{-6}\gamma^5 + \\ -6.145^{-7}\gamma^6 + 2.054^{-10}\gamma^7 \end{aligned} \quad (6)$$

with F_s the shear force per initial width in [N/m], and γ the shear angle in [deg].

2.3 *The fibre tensile behaviour*

The high tensile stiffness along the warp respectively weft yarn direction is introduced via truss elements that connect the nodes of the membrane element. A constant Young‘s modulus and zero Poisson coefficient are assigned to the truss elements, corresponding to the tensile stiffness, measured beyond the stretching an crimp interchange phase in biaxial tensile tests with warp/weft strain velocity ratio of 1 [5]. The Young‘s modulus in warp direction is $E_{warp} = 1.57GPa$, and that in weft direction $E_{weft} = 10.6GPa$.

3 THERMOFORMING STUDY

The thermoforming study is performed at the K.U.Leuven on an industrial press equipped with a separate infrared heating unit, and an automated transport band to transfer the material to the press unit within 2-5s. A rectangular blank of 190*270 mm with the warp direction along the second symmetry plane of the tool is preheating to 200°C. The female mold is actively heated via a temperature control unit that circulates heated water through canals in the mold, the male mold and blankholder are heated through contact with the female mold before the test. During thermoforming the female respectively male mold have a constant temperature of 73 respectively 65°C. The maximum punch velocity is 180 mm/s, with constant acceleration and deceleration, and a total translation of 150 mm/s in ca. 2 s. A blankholder ring enforces a constant force of 186 N before the punch contacts the blank, and the gap between the molds is 1 mm. It was estimated that the temperature remained above 165°C during the forming stage, based on a temperature measurement with a thermocouple that was co-consolidated with the blank region that contacts with the blankholder.

The local fibre directions are tracked on the part via a 3D-digital image correlation technique that assesses the intersections of a raster pattern that is painted on the pre-consolidated blank along the yarn directions [6]. No wrinkles were observed on the thermoformed part.

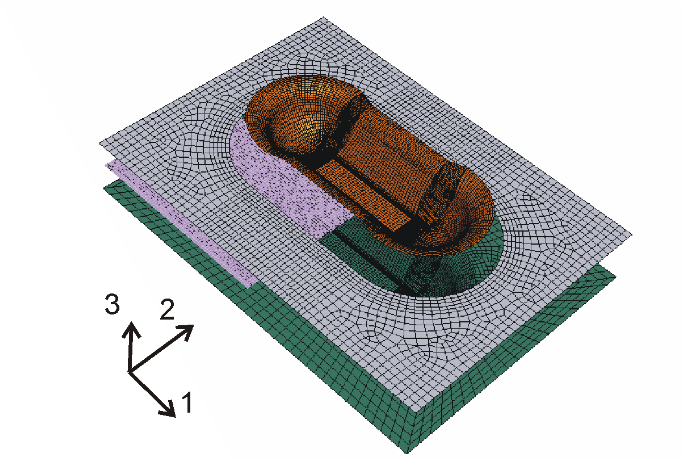

Figure 1: Assembly of tools and blank in the double dome simulations

4 FORMING SIMULATION

The forming simulation has been performed in ABAQUS Explicit using rigid tools, and symmetry conditions for the blank. As mentioned before the shear resistance model is assigned to reduced membrane elements, and truss elements parallel to the membrane edges represent the high tensile stiffness in the yarn direction. The blankholder tool geometry is such that the exterior dimensions fully cover the blank (see figure 1). A friction coefficient of 0.3 is assigned between tools and blank, corresponding to data in literature.

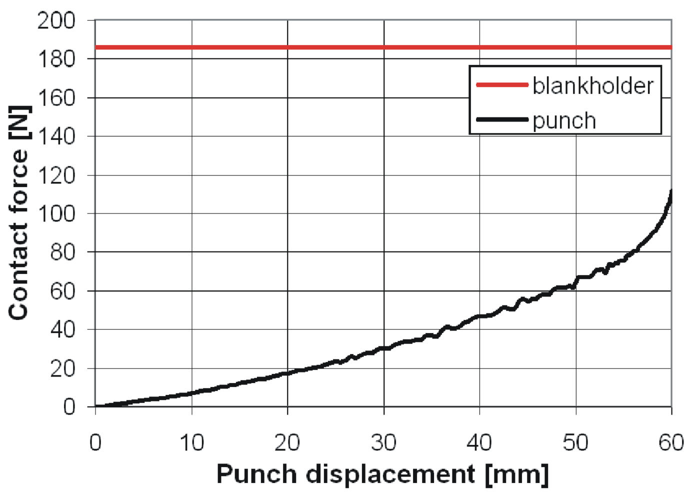

Figure 2: Contact force during the forming simulation

Figure 2 demonstrates the smooth contacting forces between the blank and the rools during the simulation. The shear angle field at maximum depth is illustrated in figure 3.

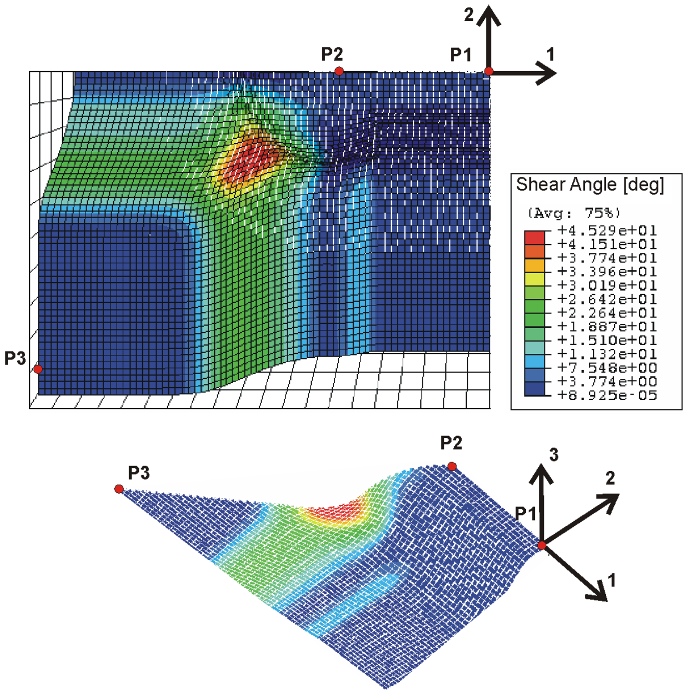

Figure 3: Shear angle field at maximal punch depth

Finally the absolute shear angle values are compared along the path $P2$ to $P3$ through the maximum shear zone (see figure 3). This path results from cutting the part with a vertical plane rotated 45° with respect to the first symmetry plane. The correlation between the experimental and predicted shear angles (see figure 4) learns that both trends are very similar. In the range between 70–80 mm from the apex point $P2$, the predicted shear angles are 2–5° degrees higher.

5 CONCLUSIONS

For this particular case study the predicted and experimental shear angles match quite closely. This could be expected considering the soft curvatures of the mold, the symmetric loading condition and the fact that no wrinkles had formed on the part during the thermoforming.

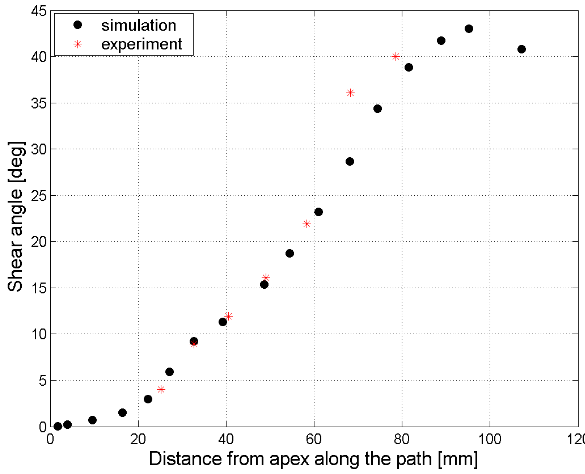

Figure 4: A comparison between experimental and simulated shear angles

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