DRAPE MODELLING OF MULTI LAYER FABRIC REINFORCED THERMOPLASTIC LAMINATES

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INTRODUCTION

The Rubber Press Forming process (RPF) is a relatively fast process for fabric-reinforced thermoplastics. Typically, the production cycle is in the order of a few minutes and consists of infrared heating of a multi-layer preform above melt or glass transition temperature, hot pressing of the preform and cooling the preform below the glass transition temperature of the thermoplastic matrix. The negatively shaped rubber upper mould presses the hot preform on a positively shaped steel lower mould. During pressing the rubber deforms nearly hydrostatically, proving a good way to consolidate the laminate. Heating, pressing, cooling and removing the product from the press are automated, ensuring reproducibility. Due to the good draping characteristics of the fabric material, the processing forces are low and the tools are relatively inexpensive.

However, production may lead to shrinkage and warpage, resulting in unacceptable dimensional changes of the products. Fibre re-orientation is one of the major factors causing these distortions. Especially when producing doubly curved parts, the process of draping causes the angle between the warp and weft yarns to vary over the product with this double curvature. Since the properties and the orientation of the fibres dominate the composite's material behaviour, the properties of the fabric-reinforced thermoplastic show a corresponding distribution. Obviously, the resulting fibre orientations must be predicted accurately to predict the overall properties of the product.

Here, a multi layer fabric reinforced fluid was implemented in DIEKA, a Finite Element (FE) package used for modelling forming processes, such as e.g. deep drawing of metals. Using different lay-ups, drape experiments were performed on a double dome geometry. Finally, the results of the FE-model are compared with experimental results.

FE DRAPING

Several authors [1,2] modelled the draping process using FE methods. One of the main reasons for this was the incapability of the geometrical method to incorporate the composite properties and processing conditions during draping. However, as shown at the ESAForm 2002 conference, the inter-ply composite behaviour can have a dominant effect on the drape properties.

To describe this phenomenon, de Luca *et al*. [1] developed a multi-layer drape approach using "specialized viscous-friction and contact constraints" between the shell elements of the drape material. This method leads to huge FE simulations, since the number of Degrees of Freedom (DOF) increases dramatically with the layers in the composite. Here, a material model is presented incorporating the inter-ply composite behaviour. With this model, only one sheet element is required for modelling the drape of multi-layered composites.

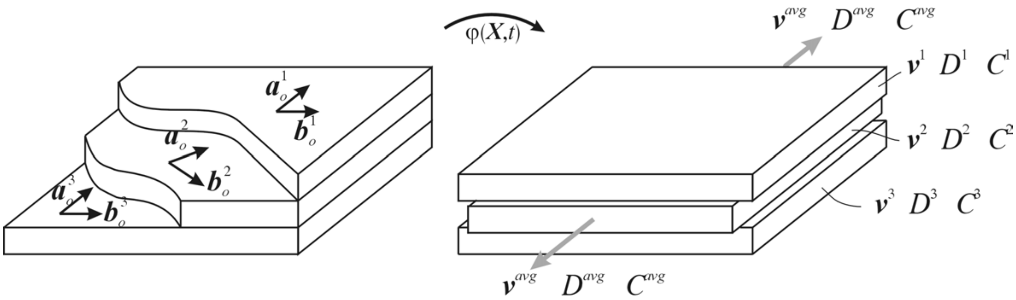

Figure 1: Individual and averaged deformations of a three layer laminate

Single layer drape material model

For single layer composites, a material model similar to the model developed by Spencer [3] was implemented. In his work, Spencer assumes the fibres to be inextensible, while the matrix material is incompressible. These rather strong conditions were adapted for the FE simulation by assuming a finite fibre stiffness in the fibre direction, and compressible matrix properties. The fibres are assumed to have no stiffness properties in the other directions while the matrix response is Newtonian viscous. The total Cauchy stress is hence expressed as:

$$\boldsymbol{\sigma} = -p\boldsymbol{I} + S_a V_{f1}\boldsymbol{A} + S_b V_{f2}\boldsymbol{B} + V_m \boldsymbol{\tau}(\boldsymbol{D},\boldsymbol{a},\boldsymbol{b}) \quad (1)$$

where

$$\boldsymbol{\tau}(\mathbf{D},\mathbf{a},\mathbf{b}) = 2\eta\mathbf{D} + 2\eta_1(\mathbf{A}\cdot\mathbf{D} + \mathbf{D}\cdot\mathbf{A}) + 2\eta_2(\mathbf{B}\cdot\mathbf{D} + \mathbf{D}\cdot\mathbf{B}) + 2\eta_3(\mathbf{E}\cdot\mathbf{D} + \mathbf{D}\cdot\mathbf{E}^T) + 2\eta_4(\mathbf{E}^T\cdot\mathbf{D} + \mathbf{D}\cdot\mathbf{E})$$

and

$$\mathbf{A} = \mathbf{aa},\ \ \mathbf{B} = \mathbf{bb},\ \ \mathbf{E} = \mathbf{ab}$$

In these equations, $\boldsymbol{\sigma}$ and $\boldsymbol{\tau}$ are stresses, $\boldsymbol{D}$ is the rate of deformation tensor, $S_{a,b}$ are the fibre longitudinal stresses (which depend on the fibre longitudinal strains and moduli only), while the vectors $\boldsymbol{a}$ and $\boldsymbol{b}$ represent the fibre directions. η, η_1, η_2, η_3 and η_4 are matrix viscosities that depend on the angle between the fibre directions. V_{f1}, V_{f2} and V_m are the volume fractions of the constituents.

Multi layer drape material model

To incorporate inter-ply deformation of multilayered composites, the individual plies in the material must slide with respect to each other and deform individually. Figure 1 illustrates the deformation of a three layer laminate. In the original configuration, the layers have independent fibre orientations $\boldsymbol{a}^i$ and $\boldsymbol{b}^i$ (where i is the layer index). For a given average deformation, the layers will deform individually, conforming to their individual orientations.

The velocity and the rate of deformation will, generally, be non-uniform over the laminate thickness. The deformation and rate of deformation are assumed to be piecewise constant for each ply i in an element (respectively $\boldsymbol{C}^{\mathrm{i}}$, $\boldsymbol{D}^{\mathrm{i}}$) The element through-thickness averages are denoted as deformation $\boldsymbol{C}^{\mathrm{avg}}$, rate of deformation $\boldsymbol{D}^{\mathrm{avg}}$ and a velocity $\boldsymbol{v}^{\mathrm{avg}}$. These averaged values correspond to the nodal displacement increments of the element. A virtual power method is applied per element to solve for the individual layer deformations.

Layer deformations

For each layer, under the assumption of plane stress, an inplane displacement field is assumed as:

$$\begin{aligned} \Delta u_x^i &= a_1^i + a_2^i\Delta x + a_3^i\Delta y \\ \Delta u_y^i &= b_1^i + b_2^i\Delta x + b_3^i\Delta y \end{aligned} \quad (2)$$

where Δu_x^i and Δu_y^i are the displacement increments in *x*- and *y*-direction, a_1^i, a_2^i, a_2^i, b_1^i, b_2^i, b_2^i are constant in each layer and *i* is the layer index. Discretising in time *t* leads to:

$$\begin{aligned} v_x^i &= (a_1^i + a_2^i \Delta x + a_3^i \Delta y)/\Delta t \\ v_y^i &= (b_1^i + b_2^i \Delta x + b_3^i \Delta y)/\Delta t \end{aligned} \qquad (3)$$

resulting in the velocity components v_x^i and v_y^i.

From equations (2,3), the deformation increments, the rates of deformation and the velocities can be derived. Using the material model (1), and applying the rule of virtual power, the energy per layer can be derived in terms of a_j^i and b_j^i.

Velocity difference between layers

Since the individual plies in the laminate can have different velocities, the interface between these plies must deform correspondingly. Assuming resin rich layers between the individual plies in the laminate, the interlaminar behaviour is assumed to be viscous, leading to a viscous slip law expressed in the velocity differences between subsequent layers. This can be elaborated to the corresponding energy in terms of a_j^i and b_j^i.

Stresses acting on plies

The edges of the individual plies will be subjected to an external stress from the adjacent elements. These stresses are assumed act in the fibre directions $\boldsymbol{a}^i$ and $\boldsymbol{b}^i$ of each ply. The resulting tractions act as a prescribed load which, incorporated in the usual manner, appears in the right hand side of the resulting system of virtual power relations.

Implementation of the FE model

Linear triangular membrane elements with one integration point were used to implement the material model in DIEKA. Contact between both sides of the composite and the moulds was modelled using six node wedge contact elements. On the steel face, the normal contact stiffness was high, while on the rubber face, the normal contact stiffness was relatively low. Viscous sliding friction was used with a constant slip coefficient.

The drape simulation is displacement controlled by moving the steel mould towards the rubber mould in small steps. For each displacement step, the system is solved using a predictor-corrector scheme (implicit). Only the draping part of the pressing cycle is simulated, since it is assumed that this part of the pressing cycle does not influence the fibre re-orientation and therefore this final step is not simulated here.

EXPERIMENTS

Rubber press experiments on a double dome geometry (see ESAForm 2002 [2]) were performed at Stork/Fokker Special Products using Ten Cate Advanced Composites Cetex® materials. The product shape consists of two intersecting hemispheres with different radii.

Three configurations of Satin 8H glass fibre reinforced PolyPhenylene Sulfide (PPS) laminates were pressed, a 0°/90°, 45°/-45° and a quasi-isotropic (QI) 0°/90°/45°/-45° lay-up.

The experimental results are shown in Figure 2. It is obvious from the experiments that the main fabric (shear) deformation occurs for both the $0^o/90^o$ and the $45^o/-45^o$ lay-up in the directions marked with an ***S*** in Figure 2. However, the QI lay-up behaves completely different. This laminate wrinkles (black arrows in Figure 2) and shows far less shear deformation than the other two laminates.

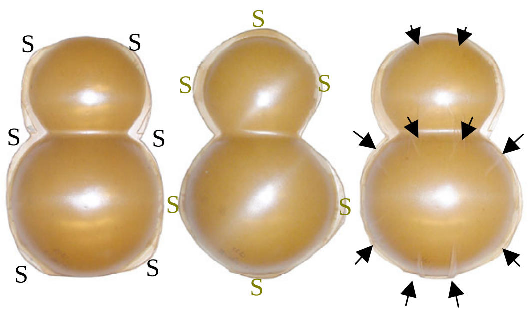

Figure 2: Rubber pressed laminates, with 0°/90°, 45°/-45° and a QI lay-up

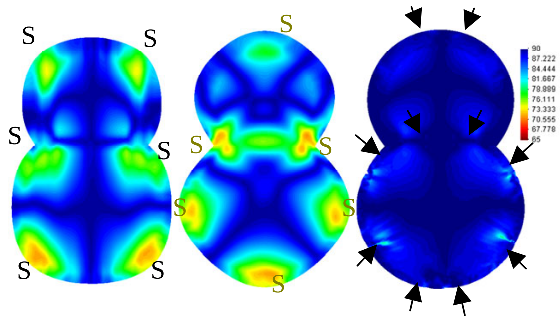

Figure 3: Enclosed fibre angle for FE drape simulation (perspective and top view)

SIMULATIONS

In the FE simulation, draping was simulated using an unstructured mesh of 4098 membrane elements. The average element size was approximately 4 mm. The longitudinal modulus of the glass fibres (65 GPa) was used as an input parameter for the Satin 8H glass fabric. The estimated input parameters for the PPS polymer matrix were: $\eta = 100$, $\eta_1 = 30$, $\eta_2 = 30$, $\eta_3 = 10$ and $\eta_4 = 10$ Pa·s. The fibre volume fraction was 50%. The initial fibre directions were the same as in the experiments and the contact friction coefficient was set at 33 m/(Pa·s).

RESULTS AND DISCUSSION

From the experiments it is clear that draping in the RPF process depends heavily on the lay-up of the fabric material. Draping $0^o/90^o$ and $45^o/-45^o$ laminates resulted in smooth products. Wrinkles occurred in QI laminates during draping, as the different the deformability of the separate layers is restricted by the interlaminar transverse shear stiffness of the laminate.

For the $0^o/90^o$ and $45^o/-45^o$ products, the model predicts large shear deformation of the fabric material at regions (denoted with an in ***S*** in Figure 4) between the fibre directions, which is in good agreement with the test specimens. For the QI lay-up the FE drape simulations predict the wrinkles in the areas observed in the experiments.

CONCLUSIONS

A multi layer drape material model was developed and implemented in the FE package DIEKA. It incorporates a biaxial fabric in a Newtonian viscous like matrix material. Drape simulations of the Rubber Press Forming process were performed successfully. The results were compared with experiments and show a clear dependency between the drape behaviour and the laminate lay-up. Quasi Isotropic lay-ups drape significantly worse than 0°/90° and 45°/-45° lay-ups. The simulations confirm this observation.

REFERENCES

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