

# Modelling shape distortions in composite products

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**ABSTRACT:** Shape distortions often occur after the forming of woven fabric reinforced composite products. The thermomechanical behaviour of the product must be known in order to predict these product distortions. A two-step strategy is proposed to model the thermomechanical behaviour of a product. First, the fibre reorientation during processing is predicted, including the process induced fibre stresses. Secondly, a Classical Laminate Theory based model accounts for the locally changed thermomechanical properties of the composite. The strategy is demonstrated with a hemispherical product.

**Key words:** distortions, composites, draping, FE-modelling, composites forming

## 1 INTRODUCTION

Woven fabric reinforced composite materials are typically applied in plate or shell structures, such as ribs, stiffeners and skins. Products of this type can be manufactured with several processes. A few examples are compression moulding, diaphragm forming, matched metal die forming and Rubber Press Forming (RPF). Shape distortions can occur during manufacturing of composite products. During the development stage of the products these distortions often exceed the required dimensional accuracy in the aeronautical and car industry. Accounting for the occurring distortions by adapting the mould shape can meet the demanded dimensional accuracy. This procedure is based on costly trial and error methods. Development costs can be reduced by modelling the shape distortions on beforehand and subsequently adapting the mould shape.

To predict shape distortions, the mechanical properties (stiffness) and thermal expansion behaviour (shrinkage and warping), referred to as thermomechanical properties, of the product need to be included in the model. The distortions can be introduced by for example, thermal loading or stresses induced due to forming. Obviously, the materials used and the lay-up of the composite affect the resulting properties. However, due to process induced fabric reorientation, the thermomechanical properties of the composite change locally as a

function of the fibre reorientation. The fibre orientation and resulting local composite properties need to be taken into account in order to model the product distortions.

Only a few authors modelled process induced shape distortions of composites. Hsiao and Kikuchi [1] modelled the complete thermoforming process of thermoplastic composites in 1999. They account for fibre reorientation during forming and the evolution of the microstructure of the fabric weave in the non-isothermal simulation. In 2002, Sweeting [2] modelled the deformation of curved circular flanged thermosetting laminates due to thermoforming. Spring forward was incorporated in the model, while neglecting the effects of the microstructure of the weave. Hofstee [3] coupled a kinematical drape modeller to a woven fabric analysis in 2002 on a pyramid-shaped product. He accounted for the geometrical changes induced by forming.

The objective here is to model the shape distortions using a Finite Element method with computationally effective plate elements. A two-step strategy is proposed to model the thermomechanical behaviour of the product.

First, the fibre reorientation during processing is predicted, including the process induced fibre stresses. A previous contribution to the ESAForm conference [4] addressed the Finite Element (FE) modelling of draping during the RPF process.

The second stage accounts for the locally changed thermomechanical properties of the composite. A Classical Laminate Theory (CLT) [5] based solution is used to predict the local composite properties of fabric-reinforced laminates. Combining the results from draping with those for the local thermomechanical properties of fabric reinforced composites results in a prediction for the process induced distortions. Modelling of the shape distortions is also implemented in the FE model, in order to include geometrically non-linear effects.

The shape distortions of a woven fabric reinforced thermoplastic composite hemisphere are modelled. The hemisphere is a frequently used shape for modelling draping in the academic world.

## 2 FIRST STEP, FE DRAPING

A multi-layer drape material model was developed and implemented in the FE package DIEKA using membrane elements [4].

The multi-layer drape material model is based on an extension of Spencer's Fabric Reinforced Fluid model [6]. Finite fibre stiffness and compressible matrix behaviour are assumed in the model. The fibres are assumed to have only stiffness properties in the fibre directions and the matrix response is Newtonian viscous.

The multi-layer drape material model accounts for the through-thickness shear behaviour of multi-layered composite materials. A slip law, based on a resin rich layer between the woven fabric layers, allows the individual deformation of the fabric layers.

The implementation of the multi-layer material model involves an energy minimisation approach of the composite laminate for each element in the implicit FE scheme. Power contributions are formulated for each of the fabric layers and the interface layers within the laminate. A minimisation technique is used to find the individual fabric layer deformations, based on the average deformation of an element. The multi-layer drape behaviour thus requires only one element through the laminate thickness. As a result, the number of Degrees Of Freedom (DOF) remains the same for single- and multi-layer drape simulations. Solving of the FE

matrix-vector system is thus comparable for single- and multi-layer simulations.

It was shown that the drape behaviour of multi-layered woven fabric composites depends on the lay-up of the laminate. Drape simulations of the RPF process were performed successfully. The drape model results were compared with experiments and confirm the clear dependency between the drape behaviour and the laminate lay-up. The model provides a computationally attractive tool to model draping of multi-layered composites.

## 3 SECOND STEP, LOCAL PROPERTIES

Drape simulations predict the fibre rearrangement within the product after pressing. This rearrangement results in non-orthogonal weaves within the laminate. Therefore, a model is required to predict the thermomechanical properties of laminate built from non-orthogonal woven fabrics.

Combining the results from draping with the resulting properties of laminates built from non-orthogonal weaves results in the thermomechanical properties of the product.

### 3.1 *Local composite properties*

A contribution to the ECCM 9 [7] conference addressed the CLT based modelling of non-orthogonal, or skewed, weaves.

The repetitive units in biaxial weaves were geometrically modelled using basic elements. Any biaxial weave can be modelled with these basic elements. Areas of yarns and matrix were distinguished in these basic elements.

The thermomechanical properties of the basic elements were predicted using micromechanics. An averaging technique was used to determine the resulting unit cell properties of skewed weaves. Thermally induced forces and moments of the laminates are based on the properties at room temperature, assuming temperature independent properties of matrix and fibres.

The model was validated on skewed 5H satin carbon fibre reinforced poly(phenylenesulphide) (PPS) laminates.

### 3.2 Combining local properties and drape results

The drape simulation predicts the fibre orientations and fibre stresses per layer in each element. This information is stored for all integration points of the elements, together with the other state variables. All state variables are updated incrementally during the simulation and stored for the next step.

Normally, when stopping the FE simulation, the nodal information is stored for post processing purposes. Here, additional to the nodal information, the element information is stored in a file. The simulation can restart by reading the element and nodal data from this file.

Manipulating this restart-file can effectively change the type of simulation. The thermomechanical module presented in section 3.1 computes the CLT based solution, including thermal and mechanical loads, per element integration point. The state variables from the drape simulation are then replaced by the state variables required for a CLT based simulation.

The CLT based simulation uses Discrete Kirchhoff Theory (DKT) triangular elements in order to account for bending. The resulting mesh from draping used as a reference mesh for the cooling simulation. A second simulation is then started with the 'new' state variables and DKT elements. The shape distortions during cooling are predicted with this simulation.

## 4 SIMULATIONS

Draping and subsequent cooling of 8H satin glass fibre reinforced PPS laminates on a hemispherical shape is simulated in the RPF process. The simulation strategy is similar to the real production process. First draping is simulated, closing the mould, using the FE model described in section 2. Then, cooling is simulated using the CLT based model (section 3), while keeping the mould closed. Finally, the product is released by opening the mould.

The initially square blank of  $360 \times 360 \text{ mm}^2$  is formed over a hemisphere with a radius of  $80 \text{ mm}$ . A structured mesh of 1600 triangular elements modelled a quarter of the square blank using two

lines of symmetry. Figure 1 depicts the meshes used for modelling.

The press velocity during draping was set at  $500 \text{ mm/s}$ , further input parameters for the drape simulations can be found in [4]. The initial fibre directions of the 8H satin weave  $[0^\circ/90^\circ]_s$  composite were parallel to the sides of the blank.

The temperature at which the matrix material was able to sustain stresses was assumed at  $180^\circ\text{C}$ . The density of the satin weave was  $300 \text{ g/m}^2$ , while the warp-count was  $2280 \text{ m}^{-1}$  and the fill-count  $2200 \text{ m}^{-1}$ . The additional parameters for the model are the modulus, Poisson's ratio and thermal expansion coefficient of the constituents,  $72 \text{ GPa}$ ,  $0.2$  and  $5 \text{ ppm/K}$  for the glass fibres and  $4.4 \text{ GPa}$ ,  $0.2$  and  $51 \text{ ppm/K}$  for the PPS matrix.

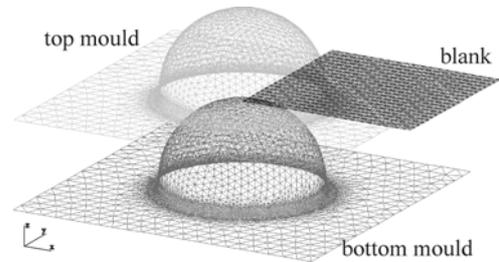


Fig 1: Set-up for the hemispherical product

The deformed mesh after cooling is shown in figure 2. Significant fibre re-orientation occurred in zone A. The angle between the fibres reached a minimum of  $30^\circ$ . A relatively high stiffness and low thermal expansion results in the global  $45^\circ$  direction from these fibre directions. Very little shearing occurred in zone B. The enclosed fibre angle remains  $90^\circ$ , resulting in a more evenly distributed thermomechanical properties.

The mesh resulting from draping is used as a reference for the distortions of the product. The in-plane deformations due to cooling are quite small, only up to  $0.1 \text{ mm}$ .

The out-of-plane deformations are shown in grey shades in the mesh after cooling. Significant out-of-plane deformations occur in the flange of the released product. A wave develops in the flange. The maximum negative out-of-plane displacement is approximately  $-1.3 \text{ mm}$  and occurs at positions D. The maximum positive out-of-plane displacements occurs at position C and is  $0.9 \text{ mm}$ . Zone A also has of positive out-of-plane displacement.

The thermomechanical properties change locally due to fibre orientation. The mismatch in stiffness and thermal expansion during cooling in the areas with little shearing *B* and significant shearing *A* results in membrane stresses. The out-of-plane displacements develop from the membrane stresses built-up during cooling.

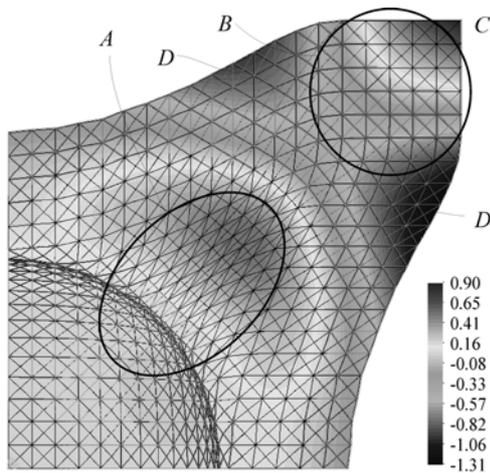


Fig 2: Deformed mesh of the hemispherical product after cooling. Out of plane displacement of the product relative to the mesh after draping.

The maximum predicted fibre stress by the drape simulation was  $220 \text{ MPa}$  and occurred in the spherical part of the product. Fibre stresses are very small in the flanges, only up to  $7 \text{ MPa}$ . Incorporating or neglecting the drape predicted fibre stresses in the cooling simulation resulted in a maximum difference of  $0.013 \text{ mm}$  in the out-of-plane displacement. This difference occurred at position *C* in figure 2. The fibre stresses have an insignificant effect on the shape distortions in this example since the geometric stiffness in the hemispherical part of the product is high.

The time used for modelling the shape distortions of the product was 9 minutes on an Athlon XP2000+ PC. Draping was simulated in 5 minutes; the remaining time was used for the cooling simulation.

## 5 CONCLUSIONS

A two-step method was presented to model the shape distortions of woven fabric reinforced composite materials. It incorporates the fibre re-orientation due to draping and the subsequent effect on the local thermomechanical properties of the product.

Incorporating the fibre direction into the model is required to find the shape distortions of the woven fabric reinforced products. Mismatch in thermal expansion in the product can result in out-of-plane distortions when membrane stresses can develop. Incorporating fibre stresses results in small changes in product distortions for the hemispherical product.

## 6 FUTURE WORK

Currently, the product distortions of a wing leading edge stiffener are evaluated. The stiffener is depicted in figure 3. The experimental results will be compared with the results from modelling.



Fig 3: Wing leading edge stiffener

The current model does not account for spring-forward, the change of the enclosed angle in bent flanges. This effect is primarily caused by the difference between the in-plane and through-thickness expansion in composites. Research focuses on incorporating spring-forward in the model.

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