MODELLING THE DISTORTIONS
OF SKewed Woven Fabric REINFORCED COMPOSITES

E.A.D. Lamers, S. Wijskamp & R. Akkerman
Composites Group, Department of Mechanical Engineering, University of Twente,
The Netherlands

INTRODUCTION
Woven textile structures are often used as reinforcements in composite materials. Their ease of handling, low fabrication cost, good stability, balanced properties, and excellent formability make the use of Woven Fabrics (WF) very attractive for structural applications in, for example, the automotive and aerospace industry. However, due to the process of draping the fibre orientation varies over the product. During production these inhomogeneous properties will lead to internal stresses, which lead to product distortions such as shrinkage and warpage. In order to predict these distortions, the thermo-elastic properties of the composite must be known.

Normally, WF-composites consist of multiple fabric layers. These layers are oriented and skewed differently, and each contributes to the overall composite properties. Therefore, in order to predict the overall thermo-elastic properties of the composite as a whole, the properties of each individual layer must be known. In this paper, the inplane thermo-elastic properties of a woven fabric reinforced composite with an arbitrary weave type are analysed as a function of the skew angle, using micromechanics.

Several models have been developed to predict the inplane thermo-elastic properties for various fabric weaves. Ishikawa and Chou (1,2) developed three one-dimensional models for various types of orthogonal woven fabric composites; the mosaic model, the crimp model, and the bridging model. The two dimensional model of Naik and Shembekar (3,4) describes the full geometry of plain weave fabric laminates. The model predicts the inplane elastic properties in the load direction, based on the Classical Laminate Theory (5) and assuming a mixed parallel-series arrangement of infinitesimal pieces. Based on this model, Falzon and Herzberg (6) considered the effect of laminate configuration on the strength and stiffness properties. Akkerman and De Vries (7) developed a two-dimensional model for orthogonal fabric weaves. The model presented here is based on their work.

Here, the objective is to develop a model for the prediction of the inplane thermal and elastic properties of skewed woven fabric composite laminates. The method is verified with thermomechanical tests on orthogonal and skewed 5H satin weave laminates.

MODELLING
Three different levels of material structure are modelled, the micro-, the meso- and the macro level. The inplane thermo-elastic properties of four different basic elements are determined at the micro level, using geometrical shape functions and a two-dimensional thermo-elastic model. The inplane properties of one fabric layer are determined at the meso level, using the fabric pattern and the properties of the basic elements. At the macro level the homogeneous properties and warpage of woven fabric composites are considered. Here the composite structure and the properties of the individual layer are used.
In the weave (the geometrical structure of the fabric), two of the three structural levels are determined, the meso- and micro level. Repetitive units, called unit cells, are distinguished at the meso level. These unit cells are the smallest regions that still can represent the overall weave. They are found in any regular two-dimensional weave. Unit cells consist of fabric elements, which are characteristic for each weave type. The fabric elements are composed of basic elements. These basic elements are the building blocks for any two-dimensional fabric weave type. For each weave type, the unit cell and the fabric elements are different.

In Fig 1 a satin 5H unit cell with most warp yarns on top is shown. The unit cell, marked with the dotted line, is composed of twenty-five fabric elements. Three different types of fabric elements can be distinguished, each consisting of four basic elements.

Fig 1: Unit cell of Satin 5H weave, with fabric elements 1, 2, 3 and basic elements A, B, C, D

In the basic elements, regions of warp yarns, fill yarns and pure resin are separated by geometrical shape functions, similar to the work of Naik and Shembekar (3,4). The size of these regions determines the average fibre volume fraction in the yarn regions, when the overall fibre volume fraction is known. By means of a geometrical transformation, the shape of the skewed and non-skewed fabric elements is modelled. In Fig 2, the four different basic cells are shown.

With the geometrical description of the basic elements, the thermo-elastic properties are modelled. Assuming that the CLT is applicable to the basic elements, the constitutive equation for the inplane elastic properties for the basic elements is:

\[
\begin{bmatrix}
N_i \\
M_i
\end{bmatrix} = \begin{bmatrix}
A_y(x,y) & B_y(x,y) \\
B_y(x,y) & D_y(x,y)
\end{bmatrix} \begin{bmatrix}
\varepsilon^0_j \\
\kappa_j
\end{bmatrix}
\]

\[(i,j = 1,2,6)\]  \[1\]

and

\[
(A_y(x,y), B_y(x,y), D_y(x,y)) = \int_{h_0^k}^{h_t^k} (1, z, z^2) Q_\theta dz
\]

\[2\]

in which \(Q_\theta\) is the elastic inplane stiffness matrix, \(z\) the height coordinate of the geometrically defined region in the fabric layer, \(h_0^k\) is the bottom co-ordinate of the region, and \(h_t^k\) is the top co-ordinate of the \(k^{th}\) region. The effective inplane elastic constants of the yarns can be described using their undulation angle. The elastic and thermal properties in the principal directions for UD yarn composites are calculated using the Composite Cylinder Assemblage (CCA) and Shapery models (8,9). The resulting inplane stiffness matrices are determined.
using the 2D WF model (3,4). The model can predict an upper and lower limit for the stiffness by assuming uniform inplane strain or stress conditions, respectively called the Parallel-Parallel (PP) and the Series-Series (SS) configuration. The thermal properties of the basic elements are determined under the same assumptions and method as the elastic properties of the basic elements. The integrals are evaluated numerically, using Gaussian quadrature.

By averaging the properties of the basic elements, the thermo-elastic properties of the fabric elements are determined. Averaging again leads to the unit cell properties.

To determine the laminate properties, the contribution of each fabric layer to the laminate properties must be taken into account. If $h_0$ is the distance of the midplane of the fabric layer to the midplane of the composite, the contribution of each individual layer to the ABD stiffness matrix is:

$$
A_{ij}^C = \sum_{k=1}^{m} A_{ij}^k \\
B_{ij}^C = \sum_{k=1}^{m} h_0^k A_{ij}^k + B_{ij}^k \\
D_{ij}^C = \sum_{k=1}^{m} h_0^{k^2} A_{ij}^k + 2 h_0^k B_{ij}^k + D_{ij}^k
$$

where $C$ denotes composite and $m$ is the number of fabric layers in the composite. The thermal properties of the composite are derived similarly.

**EXPERIMENTAL**

Experiments were performed on single layer laminates of satin 5H fabric reinforced thermoplastic layers. The fabric weave consisted of Toray T 300 JB carbon fibres and was produced by Ten Cate Advanced Composites. The matrix material is thermoplastic Poly Phenylene Sulfide (PPS, Hoechst). PPS is a semi-crystalline thermoplastic material with a melting temperature of 285 °C, a crystallisation temperature of 210 °C and a glass transition temperature of 90 °C.

Satin 5H fabric is unsymmetric to its midplane and due to thermally induced stresses single fabric layers will distort after production. The laminates were skewed to different angles up to the locking angle to investigate the effect of skewing on the resulting curvatures. The modelled $B$ and $D$-matrices can be quantified by measuring the curvatures after manufacturing.

Typically, the specimen size was $80 \times 80$ mm$^2$, with a thickness varying from 0.29 mm for unskewed fabric up to 0.33 mm for skewed fabric laminates. In the experiments, the warp yarns were skewed from –30 up to 30 degrees. The specimens exhibited a bi-stable thermally induced cylindrical shape, requiring the use of non-linear theory.

The finite element program ANSYS was used to account for the non-linear effects. In ANSYS, the curvatures are determined by using the SHELL99 elements with direct $ABD$-matrix input. Using the processing conditions, the PPS crystallisation kinetics and the Avrami (10) model, the temperature of maximum crystallinity of 170 °C is predicted. In ANSYS, this temperature is used as the stress free temperature.

**RESULTS AND DISCUSSION**

The results obtained from the experiments and modelling are shown in Fig 3, Fig 4 and Fig 5. Each of the figures shows a modelled and measured curvature for the composite plates as a function of the skew angle.
The experimental values for $\kappa_x$ show a larger absolute curvature as a function of the skew angle than the predicted values. The largest difference between the predicted and experimental curvatures occurs at the skew angles of 10 and 20 degrees. The experiments show a very large negative curvature for these skew angles. The dimension of the specimens explains this behaviour. They were close to the bifurcation point, resulting in a very size dependent behaviour of the curvature.

For $\kappa_y$, the measured and modelled curvatures agree well. As with $\kappa_x$, the largest difference between experimental and modelled curvatures is at the skew angles of 10 and 20 degrees. The dimension of the specimens explains this behaviour.

For $\kappa_{xy}$ the experimental and the modelled curvature agree well.

CONCLUSION
A model was developed to predict the inplane thermo-elastic properties of skewed woven fabric composites. Using the predicted properties and an FE-program to take non-linear effects into account, curvatures were modelled and compared with experiments. The model gives quantitatively good predictions of the properties of skewed satin 5H weave. In order to obtain less size dependent results for the resulting curvatures, the dimensions of the specimens should exceed the sizes used here.

REFERENCES