SPRING-FORWARD OF WOVEN FABRIC REINFORCED COMPOSITES

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INTRODUCTION

Continuous-fibre-reinforced plastic products are usually formed at elevated temperatures. They exhibit distortions when they are cooled to room temperature and released from the mould. For example, the enclosed angle of an L-shaped product decreases, see Fig. 1. This effect is known as spring-forward. It is mainly due to the anisotropic thermal shrinkage of the composite, which is small in the fibre direction and relatively large in the direction normal to the fibres.

The costs of forming a product with the demanded dimensions by trial and error are high. To reduce these costs, the objective of the research described in this paper is to develop a model, which predicts the occurring distortions.

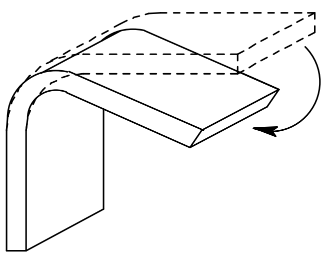

Fig. 1 Decrease of the enclosed angle of an L-shaped product after moulding

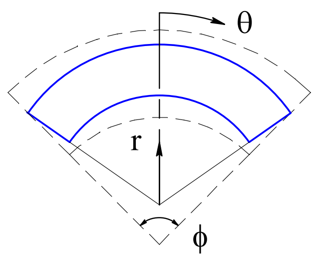

Fig. 2 Cylindrical segment after temperature deformation when inplane and through-thickness thermal expansion are not equal

MODELLING

Various researchers have reported on the modelling of spring-forward of composite panels. Spencer et al. (1) and Kollar and Springer (2) performed a three-dimensional thermo-elastic stress analysis on a laminated cylindrical segment. Wiersma et al. (3) extended this approach with a finite element analysis to account for cure shrinkage and the difference in thermal expansion between the mould and the composite product. Cure shrinkage of the matrix and residual stresses at the full cure temperature were also investigated by Nelson and Cairns (4). Here, the analysis is restricted to the effect of anisotropic thermal shrinkage of thermoplastic composites.

A simple, one-dimensional solution for the change in arc section enclosed angle can be derived geometrically by considering the arc lengths and arc thickness before and after thermal deformation, see Fig. 2. These depend on the tangential and radial coefficient of thermal expansion (CTE), respectively. The change in angle is then described by:

$$\Delta\phi = \phi\frac{(\alpha_r - \alpha_\theta)\Delta T}{1+\alpha_r\Delta T} \approx \phi(\alpha_r - \alpha_\theta)\Delta T \qquad (1)$$

where α_r and α_θ are the *effective* coefficients of thermal expansion in radial and tangential direction, respectively, and ΔT is the change from stress-free temperature to room temperature. When the contribution of $\alpha_r\Delta T$ in the denominator is neglected, then equation 1 agrees with the one-dimensional thermo-elastic solution proposed by O'Neill et al. (5).

The application of equation 1 on a laminated continuous-fibre-reinforced composite arc section requires the laminate effective CTE's. For laminates built up from unidirectional plies, the tangential CTE can be calculated using Classical Laminate Theory. But, the prediction of the radial CTE asks for a different approach, for example as presented by Goetschel and Radford (6) or Chen and Tsai (7), requesting the three-dimensional thermo-elastic properties of each ply. For woven fabric reinforced composites, a micromechanical analysis is necessary to predict them, taking into account the undulation of the fibre bundles.

Several models have been developed to calculate the elastic and thermal constants of woven fabric reinforced plastics. The larger part of them consists of a geometrical analysis to distinguish repetitive unit cells in the weave structure, after which these are described mathematically using shape functions. With this information, the laminate thermo-elastic properties are averaged under the assumption of uniform stresses or uniform strains throughout the laminate. Here, the two-dimensional analysis of Akkerman and De Vries (8), which is based on the work of Naik and Shembekar (9,10), is followed regarding the geometrical analysis and extended onwards to predict the three-dimensional thermo-elastic constants. A schematic representation of the analysis of a 5H satin fabric weave is shown in Fig. 3.

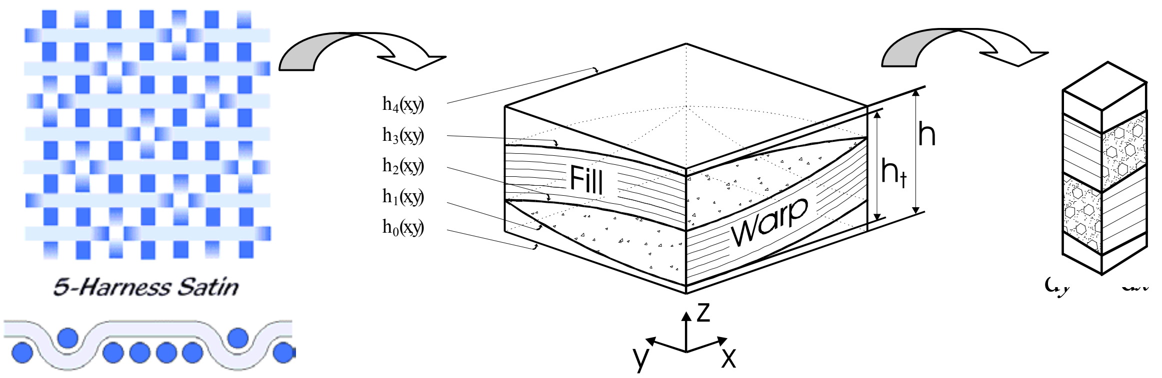

Fig. 3 Representation of the 5H satin fabric weave, one of its three repetitive elements and the infinitesimal piece of which the thermo-elastic properties are averaged over the thickness

Three repetitive elements can be discerned in the 5H satin weave. Within an element, the distribution of warp yarn, fill yarn and the pure matrix region can be mathematically described with the sinusoidal shape functions $h_i(x,y)$. This distribution is then used to average the three-dimensional thermal and elastic properties in an infinitesemal piece of laminate with size $dx \times dy$ under the assumption of uniform through-thickness stress and uniform inplane strain (6). Then, following Naik and Shembekar (9,10), these properties are averaged over the element surface by either applying a Series/Series (SS) scheme or a Parallel/Parallel (PP) scheme, assuming uniform inplane stress or strain, respectively.

EXPERIMENTAL

The micromechanical model was verified by measuring the inplane thermal and elastic properties with standard testing methods. An experimental setup was designed to measure the thermally induced spring-forward of curved strips. It consisted of a quartz glass dilatometer in a glycerin temperature bath, in which small temperature dependent displacements are measured by means of a micrometer. A sketch of the specimen and the test rig are shown in Fig. 4 and Fig. 5, respectively.

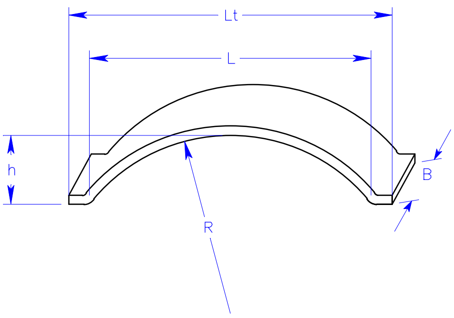

Fig. 4 Specimen for the spring-forward experiment

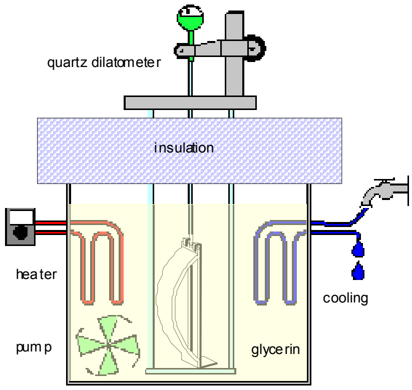

Fig. 5 Schematic representation of the quartz glass dilatometer set-up

The measurements were performed with specimens of woven fabric carbon reinforced poly-etherimide (carbon/PEI) with dimensions B = 30 mm, L_t = 85 mm, R = 48 mm and h = 17 mm. The dimensional changes of the arc end-to-end length L_t and arc height h were recorded as a result of the change in temperature.

RESULTS AND DISCUSSION

A typical curve of the spring-forward measurement is shown in Fig. 6, where L_t is recorded during heating and cooling between room temperature and about 70 °C. Through the smooth cooling part, a linear curve was fitted of which the direction cosine was taken as the parameter for comparison with the theory. The results of the measurements of the changes of the arc height dh/dT and the length dL_t/dT are shown in Fig 7.

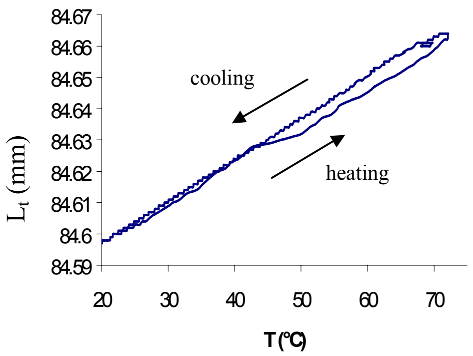

Fig. 6 Measured change in length of a crossply woven fabric carbon/PEI curved specimen as a function of the temperature

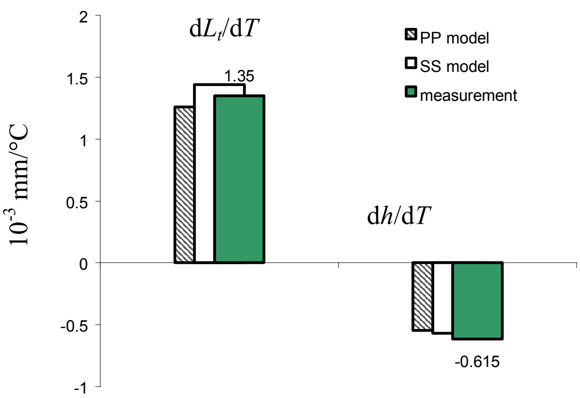

Fig. 7 Measured and predicted values of the temperature dependent dimensional changes of woven fabric carbon/PEI curved specimens

The analytical expressions of L_t and h as a function of the temperature can be formulated similar to equation 1. The coefficients of thermal expansion were calculated using the micromechanics algorithm with both the SS and PP scheme. It can be seen that the calculated and measured results agree very well.

The total spring-forward of the curved strips was also measured by comparing their dimensions with the dimensions of the mould. On average, the enclosed angle decreased 1.30° from stress-free temperature (T_g in the case of PEI) to room temperature. The theoretical decrease was calculated to be 0.96° and 1.0° with the SS and PP scheme, respectively. So, the thermally induced part of the total distortion is about 75%. Other causes that deserve further investigation are present for the thermoplastic composite tested in this research.

The curved panels, similar to many reinforced thermoplastic products, were pressed on a steel mould using a rubber press. Thus, the hot laminate is placed between a relative cold surface with a high heat conductivity and a relative cold surface with a very low thermal conductivity. This complicates the temperature profile in the laminate during the moulding cycle, which has its effect on the distribution of the residual stresses.

Another cause for the shape distortions can be the interply shear that occurs when the flat laminate is draped over the curved mould. The top and bottom ply are subjected to a tensile and compressive stress, respectively, causing changes in the weave geometry of the bottom layer. This results in a gradient of thermo-elastic properties over the thickness of the laminate, intensified by a gradient of the fibre volume fraction as a consequence of matrix bleed.

The analytical approach will most likely not succeed to take into account all of these effects, especially when more complicated product geometries are examined. The goal for further work is to design a finite element analysis (FEA) in which at least the temperature profile in the laminate is simulated during the moulding cycle, coupled to a (visco-elastic) thermomechanical model, incorporating the structure of the fabric weave composite.

CONCLUSIONS

A simple model for the prediction of the spring-forward of arc sections was developed. It requests the effective laminate coefficients of thermal expansion, which depend on the three-dimensional thermo-elastic properties of the plies. These were predicted for woven fabric reinforced composites by means of a micromechanical model. The temperature dependent spring-forward of single curved strips was measured and compared with the theory. They agreed very well. After comparison with the total spring-forward it can be concluded that it cannot be modelled with thermo-elasticity alone. Temperature and heat conductivity effects, interply shear and weave distortions will be examined using FEA.

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