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Java application for springback analysis of composite plates

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Dedicated to Professor Zdeněk Bittnar in ocassion of his 70th birthday

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ABSTRACT

The use of hi-tech thermoplastic matrices (e.g. PEKK, PEEK or PPS) in carbon fiber-reinforced composites is growing, mainly in the aircraft industry. The manufacturing process is carried out at higher temperatures, which leads to residual stresses and dimensional changes of the manufactured part. Our work is focused on making an analytical prediction of the springback angle of C/PPS laminate with textile reinforcement. Better prediction will make the manufacturing tool more precise. Our analytical model took into account the temperature change, the moisture change and resin shrinkage during the cure cycle (which is crucial for semi-crystalline matrices). The analytical model is based on classical lamination theory (CLT) and an equation for through thickness characteristics. The description of the model was written in Matlab code, which was subsequently transformed into Java with GUI for easier input of the characteristics of the composite (lay-up, materials, angle of the layer, radii, volumetric fiber fraction and characteristics of the textile reinforcement-number of threads in warp and weft direction, thickness, type of weave, etc.) The results from our program were compared with the results measured by the manufacturer, and good agreement was achieved.

1. Introduction

Thermoplastic materials have significant advantages during fabrication and allow the application of optimized metalworking technology (stamping). However, the high temperature at which the thermoplastic composite must be processed implies that there will more significant thermally induced stresses and distortions in the finished product. For this reason, the dimensional changes (i.e. springback, warpage, etc.) need to be predicted in order to make the final part more precise. Changes in the dimensions of the composite are related to many parameters: part angles, thicknesses, lay-ups, flange length, and also tool materials, tool surface or cure cycles [1]. When an L-shaped (or U-shaped, see Fig. 1) composite in the shape of L (or U) section is extracted from the mold after it has been cooled down to room temperature, the change in the angle of the part can be observed. Tool angles have to be modified to deal with this problem. The design of the tool is based either on either the "rules of thumb" from past experience, or on a trial-and-error approach. For angular parts, the compensation is normally between 1° and 3°. The most common problem that is found, using a standard factor, is that the springback may vary with the lay-up, material, cure temperature, etc. Therefore, what worked once does not necessarily work next time.

2. Springback phenomenon

Springback is the angular change in a composite which occurs after the laminated part is released from the mold and cools down. This effect is influenced by many parameters, which have been mentioned above. The main causes used in analytical computation are thermal expansion in the laminate, shrinkage of the resin during the curing process (this effect is relevant only in semi-crystalline matrices which change from amorphous to crystalline phase during the cure cycle), and moisture absorption.

The total change in angle can be written as

$$\Delta\gamma = \Delta\gamma_t + \Delta\gamma_h + \Delta\gamma_c = \gamma\frac{\varepsilon_y^t - \varepsilon_z^t}{1+\varepsilon_z^t} + \gamma\frac{\varepsilon_y^h - \varepsilon_z^h}{1+\varepsilon_z^h} + \gamma\frac{\varepsilon_y^c - \varepsilon_z^c}{1+\varepsilon_z^c} \quad (1)$$

where $\Delta\gamma_t$ is the change in the angle due to temperature, $\Delta\gamma_h$ is the change in the angle due to the hygroscopic effect and $\Delta\gamma_c$ is the change in the angle due to shrinkage effect during the cure cycle. Strains (from temperature, moisture absorption and shrinkage-superscripts t, h and c) marked with y subscripts stand for longitudinal directions and coefficients marked with z stand for transversal (through thickness) direction [4]. The strains can be computed

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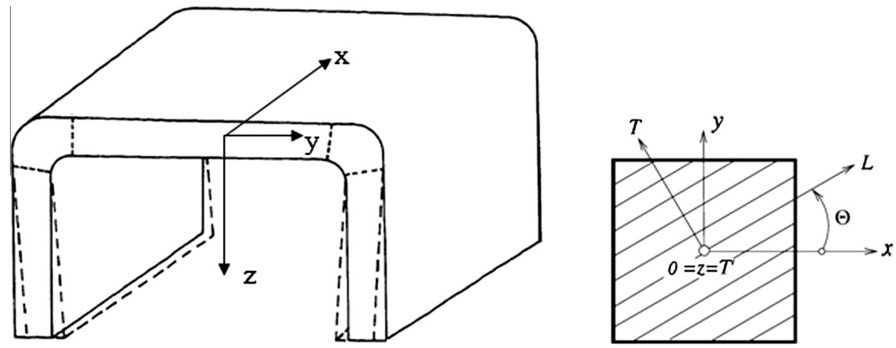

Fig. 1. Distortion of molded U-section.

using equations based on CLT combined with equations for the through thickness characteristics [2]. The final equations are

$$\begin{Bmatrix} N_x^{thc} \\ N_y^{thc} \\ N_{xy}^{thc} \\ M_x^{thc} \\ M_y^{thc} \\ M_{xy}^{thc} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{21} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^{0,thc} \\ \varepsilon_y^{0,thc} \\ \gamma_{xy}^{0,thc} \\ \kappa_x^{thc} \\ \kappa_y^{thc} \\ \kappa_{xy}^{thc} \end{Bmatrix} \tag{2}$$

where A_{ij}, B_{ij} and D_{ij} are the generally known elements of membrane stiffness, bending-extension coupling stiffness and bending stiffness matrices, and quantities N_i^{thc}, M_i^{thc} are defined by the equations

$$N_i^{thc} = \int Q_{ij}\varepsilon_j^{thc}\,dz \tag{3}$$

$$M_i^{thc} = \int Q_{ij}\varepsilon_j^{thc}z\,dz \tag{4}$$

with the fact that integration boundaries are from $-H/2$ to $H/2$. N_i^{thc} and M_i^{thc} have the same dimension as N_i and M_i and they are called the resultants of the thermo-hygro-crystallic unit internal forces and moments and $\varepsilon_{ij}^{0,thc}$ and κ_{ij}^{thc} are strains and curvatures. Q is the 2D plane stress matrix in the L, T coordinate system (see Fig. 1).

The through thickness strain can be computed as

$$\varepsilon_z^{thc} = \frac{\Delta H^{thc}}{H} \tag{5}$$

where H is the total thickness of the composite part and ΔH^{thc} is the change in the thickness due to the thermo-hygro-crystallic effect

$$\Delta H^{thc} = \Delta H^t + \Delta H^h + \Delta H^c \tag{6}$$

The thermal, hygral and crystallic thickness change can be computed as

$$\Delta H^t = \sum_{k=1}^{N}\left\{[S_{12}S_{23}S_{36}][T_q]_k\left(z_k - z_{k-1}[\overline{Q}]_k\left(\begin{bmatrix}\varepsilon_x^0\\ \varepsilon_y^0\\ \gamma_{xy}^0\end{bmatrix} - \Delta T\begin{bmatrix}\alpha_x\\ \alpha_y\\ \alpha_{xy}\end{bmatrix}_k\right)\right.\right.$$
$$\left.\left. + \frac{z_k^2 - z_{k-1}^2}{2}[\overline{Q}]_k\begin{bmatrix}\kappa_x\\ \kappa_y\\ \kappa_{xy}\end{bmatrix}\right) + (z_k - z_{k-1})(\Delta T(\alpha_3)_k)\right\} \tag{7}$$

$$\Delta H^h = \sum_{k=1}^{N}\left\{[S_{12}S_{23}S_{36}][T_q]_k\left(z_k - z_{k-1}[\overline{Q}]_k\left(\begin{bmatrix}\varepsilon_x^0\\ \varepsilon_y^0\\ \gamma_{xy}^0\end{bmatrix} - \Delta c\begin{bmatrix}\beta_x\\ \beta_y\\ \beta_{xy}\end{bmatrix}_k\right)\right.\right.$$
$$\left.\left. + \frac{z_k^2 - z_{k-1}^2}{2}[\overline{Q}]_k\begin{bmatrix}\kappa_x\\ \kappa_y\\ \kappa_{xy}\end{bmatrix}\right) + (z_k - z_{k-1})(\Delta c(\beta_3)_k)\right\} \tag{8}$$

$$\Delta H^c = \sum_{k=1}^{N} = \left\{[S_{12}S_{23}S_{36}][T_q]_k\left(z_k - z_{k-1}[\overline{Q}]_k\left(\begin{bmatrix}\varepsilon_x^0\\ \varepsilon_y^0\\ \gamma_{xy}^0\end{bmatrix} - \begin{bmatrix}\Phi_x\\ \Phi_y\\ \Phi_{xy}\end{bmatrix}_k\right)\right.\right.$$
$$\left.\left. + \frac{z_k^2 - z_{k-1}^2}{2}[\overline{Q}]_k\begin{bmatrix}\kappa_x\\ \kappa_y\\ \kappa_{xy}\end{bmatrix}\right) + (z_k - z_{k-1})((\Phi_3)_k)\right\} \tag{9}$$

where N is the number of layers, S_{ij} are elements of the compliance matrix, T_q is the transformation matrix, z is a coordinate of the layer, $\overline{Q}$ is the 2D plane stress matrix in the x, y coordinate system (see Fig. 1), ΔT is change in temperature, Δc is change in moisture, α_{ij} is the coefficient of thermal expansion, β_{ij} is the coefficient of moisture absorption and Φ_{ij} is the coefficient of chemical shrinkage during recrystallization.

For parts with single curvature (which are analyzed in our case) there is a modification of Eq. (2)

$$\kappa_y^{thc} \Rightarrow \kappa_y^{thc} + \frac{1}{R_y}\left(\varepsilon_y^{thc} - \varepsilon_z^{thc}\right) \tag{10}$$

where R_y is the radius of the analyzed part in the y direction.

2.1. Representation of the weaving geometry

Because of the regular structure of the woven composite, the thermo-elastic properties of the whole composite are similar to the properties of the typical element. In order to calculate these properties we have to know.

- the mass of the fabric M (g/m^2),
- the number of threads n (1/cm),
- the thickness of the fabric h (mm),
- the warp and weft materials and geometry,
- the type of weave.

The most common weave types are: plain weave, twill weave and satin weave (see Fig. 2). In each type of weave there is an area that is regularly repeated. After analyzing this area we obtain three types of elements which characterize the weave (see Fig. 3). The dimensions of the element are described in Eqs. (13)–(16).

Element I has both fibers undulated (typical for plain weave), element II has both fibers straight and element III has at least one fiber curved. It can be shown that twill weave and satin weave can be composed from elements I and II [1]. Element I is the basic type, because the other are special cases of it. In order to calculate the properties of element I we have to accept some presumptions.

- the whole thickness of the element is the sum of the fabric thickness and the matrix thickness,
- the weave of the fabric is tight,