THERMAL AND MECHANICAL BEHAVIOR OF THE ANGLE SECTION OF COMPOSITES WITH A SINGLE AND DOUBLE CURVATURE

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1 Introduction

Incorporating thermoplastic matrices (PEEK etc.) in carbon fiber-reinforced composites results considerably in higher toughness and impact resistance than have traditional thermoset based composites. In addition, the thermoplastic materials have significant advantages during fabrication and allow applying optimized metal working technology (stamping). However, the high temperature at which the thermoplastic composite must be processed does suggest an increased significance of thermally induced stresses and distortions in a product finished. Therefore it is desirable to be able to predict distortions accurately, reducing the trial and error time when producing a new component.

2 Analytical and numerical investigation

2.1 Springforward phenomenon

Residual stresses which set in the fiber reinforced composites during curing of laminate in closed form, lead to dimensional changes of composites after extracting from the form and cooling. One of these dimensional changes is so called "springforward" (also called in literature "spring-in" or "springback") of angle sections. Other dimensional changes are for example the warpage of flat sections or the displacement of singe layers of composite.

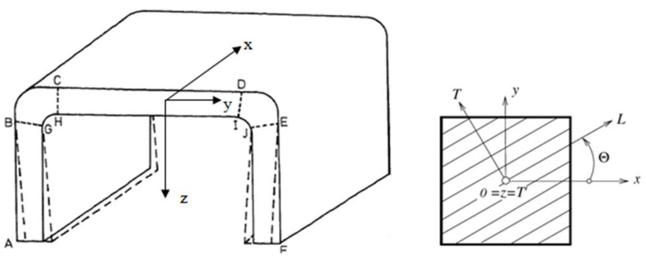

Fig.1. Distortion of moulded U-section

2.2 Analytical approach

Temperature change of dimensions is related to many parameters like angle of the composite part, laminate thickness, lay-up, flange length but also tool material, tool surface or cure cycle [1], [2], [3]. Published papers usually describe the springback effect on a behavior of composite L (or U) section, extracted from the form which was cooled to the room temperature; see Fig.1 [3]. The analytical model which covers temperature change, chemical shrinkage during curing and moisture change was used to describe the change of the angle section. It can be seen in the next equation,

$$\Delta\gamma = \Delta\gamma_t + \Delta\gamma_h + \Delta\gamma_c = \gamma\frac{(\alpha_x-\alpha_z)\Delta T}{1+\alpha_z\Delta T} + \\ +\gamma\frac{(\beta_x-\beta_z)\Delta c}{1+\beta_z} + \gamma\frac{(\phi_x-\phi_z)}{1+\phi_z} \quad (1)$$

where $\Delta\gamma_T$ is the temperature part of angle change, $\Delta\gamma_h$ is the change in angle due to a hygroscopic effect and $\Delta\gamma_C$ is the change in angle due to a shrinkage effect during the cure cycle [1]. A single curvature of the section shape is usually simulated in literature and its verification was published by the authors in [4]. However, dies often have very complex shapes, including surfaces with double curvature. The analytical solution and the numerical program for such a problem will be presented in this paper. The temperature term of Eq. (1) can be re-written into the equation describing the springback as a relative change in the section angle

$$\text{springback} = \Delta\gamma/\gamma_T = \frac{(\alpha_y-\alpha_z)\Delta T}{1+\alpha_z\Delta T} = \frac{\varepsilon_y^T-\varepsilon_z^T}{1+\varepsilon_z^T} \quad (2)$$

For the unsymmetrical lay up, an additional term must be included in Eq. (3)

$$\text{springback} = R\kappa_y^T + \frac{\varepsilon_y^T-\varepsilon_z^T}{1+\varepsilon_z^T} \quad (3)$$

where κ_Y^T is the change in curvature and R is the radius which affected the straight part of the plate. The change in curvature is given by:

$$\begin{Bmatrix} \varepsilon_x^{0,T} \\ \varepsilon_y^{0,T} \\ \gamma_{xy}^{0,T} \\ \kappa_x^T \\ \kappa_y^T \\ \kappa_{xy}^T \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{12} & a_{22} & a_{26} & b_{12} & b_{22} & b_{26} \\ a_{16} & a_{26} & a_{66} & b_{16} & b_{26} & b_{66} \\ b_{11} & b_{12} & b_{16} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{26} & d_{21} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{16} & d_{26} & d_{66} \end{bmatrix} \begin{Bmatrix} N_x^T \\ N_y^T \\ N_{xy}^T \\ M_x^T \\ M_y^T \\ M_{xy}^T \end{Bmatrix} \tag{4}$$

When the cylindrical shell of the diameter $D=2R_y$ is analyzed, this springback effect must be included in the thermal force-strain relationship of laminated plates. This is accomplished by making following replacement in Eq. (4).

$$\kappa_y^T \Rightarrow \kappa_y^T + \frac{1}{R_y}\left(\varepsilon_y^T - \varepsilon_z^T\right). \tag{5}$$

In the case of double curved shells (with two main curvatures radiuses R_x , R_y) we have to make also this replacement in Eq. (4)

$$\kappa_x^T \Rightarrow \kappa_x^T + \frac{1}{R_x}\left(\varepsilon_x^T - \varepsilon_z^T\right). \tag{6}$$

The hygroscopic and shrinkage terms of Eq. (1) can be modified in similar way. The calculation of ε_z^T is described in detail in [3]. In our case, the C/PPS springforward composite, with the fiber volume fraction $V_f = 49\%$ and $[[(0,90)/(\pm 45)]_4/(0,90)]_s$ lay-up, was investigated. The thermomechanical characteristics for unidirectional lamina is presented in Table 1. Table 2 shows the coefficients of thermal expansion and the coefficients of shrinkage for the whole composite.

E_L [MPa]	**E_T [MPa]**	**E_3 [MPa]**	**G_{LT} [MPa]**	**G_{T3} [MPa]**
114638	7961	7961	4372	4155
G_{L3} [MPa]	**ν_{LT} [-]**	**ν_{T3} [-]**	**ν_{L3} [-]**	**α_L [C^{-1}]**
4372	0,3306	0,916	0,3306	$5{,}05.10^{-7}$
α_T [C^{-1}]	**α_3 [C^{-1}]**	**Φ_L [%]**	**Φ_T [%]**	**Φ_3 [%]**
$2{,}44.10^{-5}$	$2{,}44.10^{-5}$	$2{,}536.10^{-4}$	0,4526	0,4526

Table 1. Thermoelastic properties for unidirectional lamina

α_x[C^{-1}]	**α_y[C^{-1}]**	**α_{xy}[C^{-1}]**	**α_z[C^{-1}]**
$2{,}49.10^{-6}$	$2{,}49.10^{-6}$	0	$4{,}36.10^{-5}$
Φ_x[-]	**Φ_y[-]**	**Φ_{xy}[-]**	**Φ_z[-]**
$3{,}77.10^{-4}$	$3{,}77.10^{-4}$	0	0,0087

Table 2: Coefficients of thermal expansion and coefficients of shrinkage for the whole composite

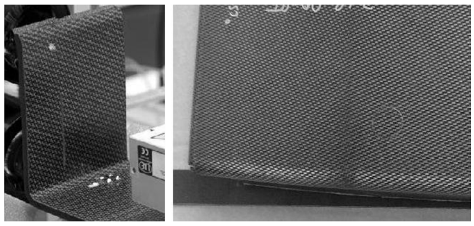

Fig. 2. Single and double curvature plate

In our case, the composite plate was analyzed with the single curvature of R_y=6 mm which corresponds to the laboratory measurement configuration of the springback angle for ΔT=60°C. The plate with the double curvatures of R_y=6 mm and R_x=2810 mm corresponds to a real moulding manufacturing process where the temperature change is ΔT=160°C. The section angle in the *y-z* plane (see Fig.1) is γ=90°. The calculated results for the flat plate, the single curvature plate and the double curvature plate can be seen in Tables 3, 4 and 5.

Temperature springback [-]	Recrystallization springback [-]	Total springback [-]
-0,00207	-0,0065	-0,00857

Table 3: Springbacks of the flat plate (ΔT=60°C)

Temperature springback [-]	Recrystallization springback [-]	Total springback [-]
-0,00415	-0,0081	-0,01225

Table 4: Springbacks of the single curvature plate (ΔT=60°C)

Temperature springback [-]	Recrystallization springback [-]	Total springback [-]
-0,001105	-0,010963	-0,012068

Table 5: Springbacks of the double curvature plate (ΔT=160°C)

Temperature springback [-]	Recrystallization springback [-]	Total springback [-]
-0,0041518	-0,0031246	-0,0072872

Table 6: Relative and absolute springbacks of the double curvature plate (ΔT=60°C)

$\Delta\gamma$ flat plate [°]	$\Delta\gamma$ single curvature [°]	$\Delta\gamma$ double curvature [°]
-0,77	-1,1033	-0,65487

Table 7: Absolute angles for all the analyzed plates (ΔT=60°C)

The single and double curvature springback results for the temperature change of ΔT=60°C are shown in the Tables above. The differences between the results for the temperature change under the point of recrystallization represent obviously the influence of the second curvature. The differences between the results of double curvature and temperatures ΔT=60°C and ΔT=160°C show how the recrystallization affects the resulting springback angle.

2.3 Numerical approach

A finite element model was created and analyzed for thermo-elastic deformations using ABAQUS solver. The results of FEM analysis are compared with the analytical spring-forward model as well as the experimental results. The spring-forward angle is the angle difference between the original mold angle and the angle of de-molded part as described in the analytical procedure chapter. An agreement between the predicted spring-forward angle from the analytical model and the finite element analysis is examined to define input parameters, which mean a practical tool for the engineers and designers of composite manufacturing.

The FEM model and solved deformation fields of the composite L section (of the single curvature) after a cooling are shown in Fig. 3 and correspond to the springback experimental configuration. The lay-up of composite was also $[[(0,90)/(\pm45)]_4/(0,90)]_s$. The deformation fields of the FE approximation of the moulded component with double curvature, that correspond to the molding manufacture process where temperature crosses over the recrystallization matrix point (*ΔT = 160°C),* are presented in Fig. 4. All the models were solved with hexahedron incompatible mode elements and for two types of material properties. The first one calculates the stiffness of laminate on the base of classical laminate theory. The thermal expansion properties of an orthotropic linear elastic material, used for one unidirectional lamina of composite section definition, are presented in Table 1. The second solution came from the experimental measurements of linear elastic properties of the entire laminate [5], [6]:

- AIMS 05-09-002 - $[(0,90)]_{3s}$
  E(Warp/Weft) = 58/58±3 GPa
- VZLU experimental report - $[0,(0,45)_2]_s$
  E= 37 GPa, ν= 0.272 in tensile test direction

The thermal expansion material behavior of the entire laminate is calculated by classical laminate theory and presented in Table2.

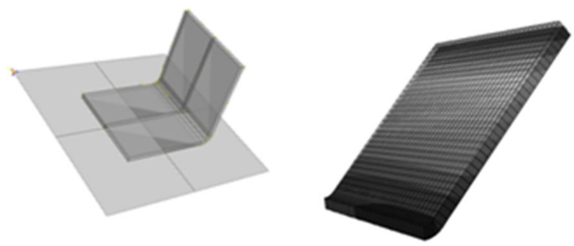

Fig. 3. FEM simulation of the springback effect of single curvature

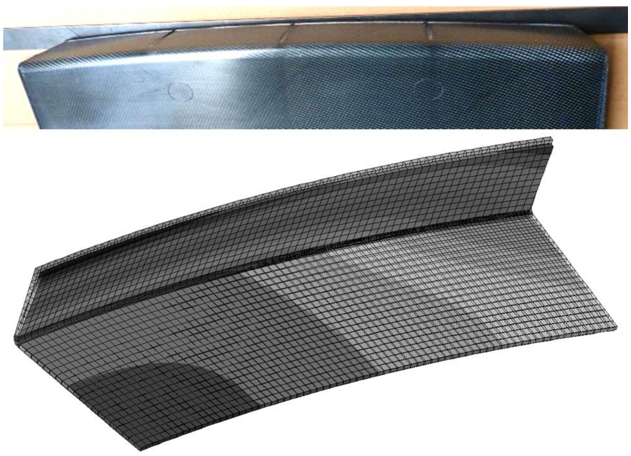

Fig. 4. Real moulded component, with double curvature of R_y=6mm, R_x=2800mm, and FEM simulation of springback (one half of the part)

3 Experimental investigations

The principal aim of measuring was to capture thermal deformation of C/PPS specimen. The springforward of C/PPS composite with $[[(0,90)/(\pm 45)]_4/(0,90)]_s$ lay-up was investigated. The measuring equipment, which was used, was temperature sensor PT100, CRZ Platinium thin film element, contactless infrared thermometer FLUKE 574, laser profilometer ScanControl LLT 2800-25 and optical distance measurement CHRocodile M4. Specimens were warmed in an oven and then cooled at the room temperature. At first, the measurements in the temperature range under the shrinkage effect were evaluated. The relative displacement between points, scaned by laser, was evaluated as an angular displacement at each time step. Then the springback values were calculated and compared with the analytical and numerical solutions.

4 Results and conclusion

The dog-bone specimen displacements [6], measured by a tensile testing machine, were compared with FEM results, Fig. 5. The difference between the experimental results and numerical solution is typical for this type of output and shows the good agreement of used FE material models.

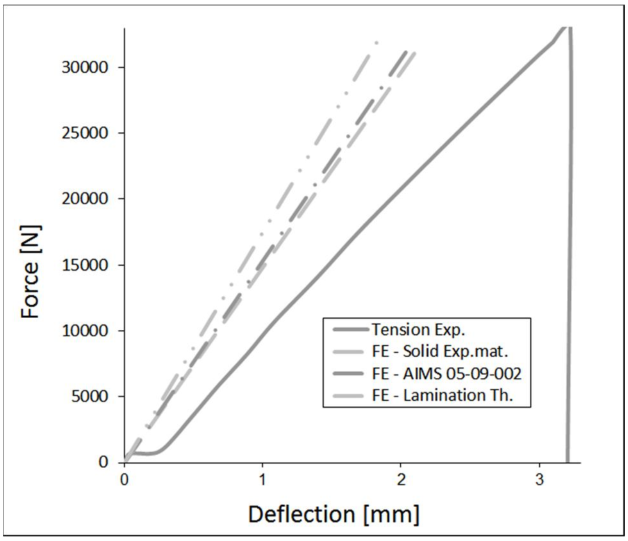

Fig. 5. Typical shift of loading beam during the bone specimen tensile test and the FEM model results

The comparison of theoretical, experimental and FEM simulation results for the corner (single curvature) section of C/PPS composite is depicted in Fig. 6. The results show a large range of experimental data and a very good agreement of the analytical solution with the FE results in the temperature range under the matrix recrystallization temperature point. Moreover, there was confirmed that the results of FE material model with coefficients calculated by classical lamination theory (Tab. 1) are conservative.

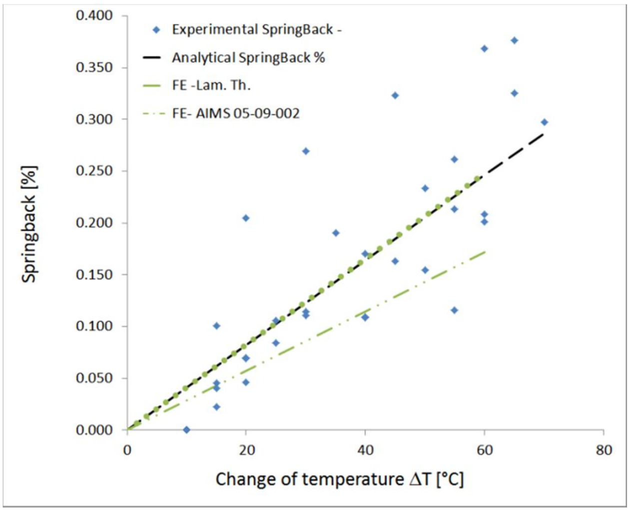

Fig. 6. Comparison of the theoretical, experimental and FE results of springback effect in the corner section of C/PPS composite.

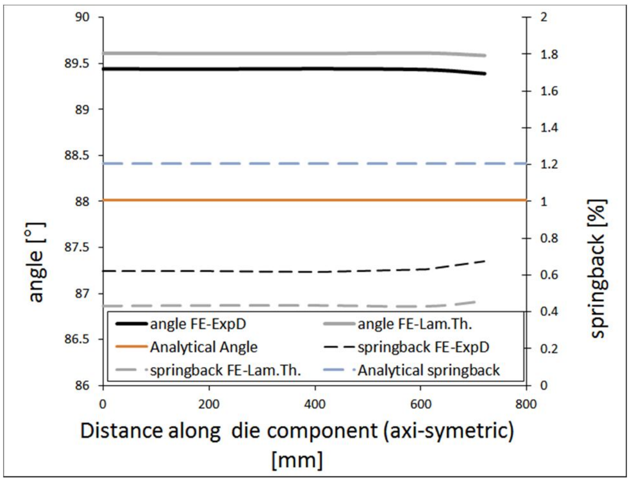

Fig. 7. FE results of moulded component with double curvature

The FE double curvature model (Fig.4) is only the first approximation of the real moulded component but confirms that the second curvature brings bending stresses into the structure and have a significant influence on the springback angle. The resulting angle, along the component after the manufacturing process at the temperature of $\Delta T = 160°C$. is shown. in Fig.7. The original angle is 90°C and the FE simulation corresponds to the real moulded component measurement in the meaning that the springback is increasing in the direction to the free part end. However, the analytical solution takes into account the matrix shrinkage effect during the warming and cooling process, but not the changing of springback along the component to the free end. A nonlinear behavior of the matrix thermal expansion is not yet implemented in the FE material model. The achieved results are depicted in Fig. 7 where these facts can be seen.

Single and double curvature modeling allows, in final, to product a more precise shape of a complete part. The next steps will be focused on the experimental measurement of single curvature specimens under the temperature that crosses over the matrix recrystallization point and on the shrinkage effect implementation into the FE material model.

Acknowledgements
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