Shape Distortion of Carbon/Epoxy Composite Parts During Fabrication

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Summary: The accurate modelling of residual stress in thermoset composites requires comprehensive consideration of all the phenomena contributing to its formation. These include: chemical shrinkage of matrix due to cross linking of molecules, mismatch of thermal expansion or contraction among fibres and matrix and viscoelastic relaxation during the fabrication. Thermo-physical and thermo-mechanical properties are altered during the curing process due to an exothermic chemical reaction. Since all the phenomena causing residual stress are strongly coupled, the solution procedure is a complex task. In this study, spring-in angle of carbon/epoxy woven composite bracket with three different thicknesses are calculated by simultaneously solving the thermo-kinetics and thermo-mechanics coupling by a finite element code COMSOL Multiphysics. Properties of composites required for numerical simulation are obtained using an analytical method. The spring-in angle values obtained by numerical simulation are also compared with the results of the analytical model.

Keywords: residual stress; spring-in; woven composite

Introduction

The use of carbon/epoxy composites has significantly increased in the aircraft and automotive industries in recent years by virtue of their high performance and many other advantages over the conventional metallic materials. Certain problems such as shape distortion, matrix cracking, fibre bucking, delamination of plies and reduced mechanical strength of composite part which are associated to the manufacturing process, however, are still critical issues.

A major source of such problems is the process-induced residual stress, which is caused due to the heterogeneous nature of composite materials. Matrix undergoes the chemical, thermal and viscoelastic phenomena during the fabrication. Resin curing process involves crosslinking of molecules in the matrix that leads to the change of its thermo-physical and thermo-mechanical properties, exothermic reaction, and chemical shrinkage.[1] Tool-part interaction is another source of residual stress. For the accurate prediction of residual stress in thermoset composites, the correct consideration of all of these phenomena is essential.

Many studies have been conducted to model the residual stress and to predict the final shape of composite parts. In early studies conducted by Hyer,[2] only thermal effect was considered for such modelling. Later on, viscoelasticity was also taken into account along with thermal effects. Effect of

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curing shrinkage and related phenomena have been included in the modelling in recent years.[2–4] This effect is significant, especially in the composite parts having complex geometries.

The prediction of final shape of the fabricated composite part is of great significance in the industry. In general, analytical solutions[4] have been used for this purpose. However, these solutions are only applicable to simple geometries such as rectangular plates and angled brackets with simple stacking sequences.

For example, we can consider an angled bracket made of composite material as shown in Figure 1. If such a bracket is subjected to chemical shrinkage during resin curing and a thermal contraction due to a temperature change ΔT during cooling, the external angle will change from θ to $\theta + \Delta\theta$.

Radford and Rennick presented a simple analytical model[5] to calculate a spring-in angle ($\Delta\theta$) for such components:

$$\Delta\theta = \theta\left[\left(\frac{(CTE_1 - CTE_3).\Delta T}{(1 + CTE_3.\Delta T)}\right) + \left(\frac{(CS_1 - CS_3)}{(1 + CS_3)}\right)\right] \quad (1)$$

where CTE_1 and CS_1 are the thermal expansion and chemical shrinkage coefficients along length (in-plane), and CTE_3 and CS_3 are the thermal expansion and chemical shrinkage coefficients in the through-thickness direction.

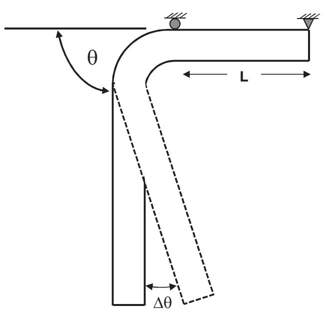

Figure 1.
L-shaped composite part.

For complex geometries, numerical simulation is used to simultaneously solve the thermo-kinetics and thermo-mechanics coupling for obtaining a realistic solution.

Determination of properties of composites during and after cure is a pre-requisite for modeling of residual stress. In general, multi-scale modeling has been used in literature for predicting the average elastic properties of woven composites. Homogenization schemes can be categorized in two major groups:[6] Analytical engineering models[7–11] are based on the material mechanics approach by semi analytical and/or analytical expressions to calculate the effective composite properties from the properties of constituents and known morphology.[12] Several authors[13,14] also used FEM for the same objective. Since the analytical models are simple and provide good results with minimal calculations, they are often preferred.

In the present study, spring-in occurred in a thick composite part is simulated using finite element analysis. All the gradients of temperature, of degree of cure and of properties are taken into account. The properties of resin during and after the curing are taken from the literature. Properties of composite laminate are modelled by analytical methods using the properties of resin and fibre. Spring-in angle of fully cured part is also calculated by numerical simulation and the results are compared with the analytical model predictions.

Materials and Part Geometry

Right angled composite brackets (Figure 1) made of carbon/epoxy (AS7/RTM6) with three different thicknesses equal to 4mm, 20mm and 40mm were studied. RTM6®, furnished by Hexcel, is an epoxy resin commonly used in the aerospace industry for composites manufacturing using resin transfer moulding. The reinforcement AS7 is a five harness woven satin fabric made from carbon tows.

All the plies were stacked with the ply angle of 0°. The fibre volume fraction (V_f)

was equal to 57%. The length (L) of each branch is equal to 20cm. A following thermal cycle was used for composites curing: heating from room temperature until 185 °C at the rate of 3 °C/min, maintaining at this temperature for two hours and then cooling to room temperature at the rate of 3 °C/min. It was assumed that the outer and inner faces were in contact with mould surfaces whose temperatures were maintained according to the above given thermal cycle. The part was assumed to be mechanically free except at constraints on two nodes (Figure 1) to avoid rotation of model.

Results and Discussion

Cure Kinetics and Temperature Gradients

In general, significant temperature gradient in thickness direction is induced in the thermoset composite parts during curing due to exothermic chemical reaction and low thermal conductivity of polymer. Since degree of cure depends on local temperature in the part, the temperature gradient induces the gradient of degree of cure and that of cure dependent mechanical properties.

To calculate these gradients, it is needed to solve the heat transfer equation (Eq 2) coupled with cure kinetics (Eq 3).

$$\rho\left(Cp(T,\alpha)\frac{dT}{dt} - (1 - v_f)\Delta H\frac{d\alpha}{dt}\right) = \nabla.(\lambda(T,\alpha)\nabla T) \quad (2)$$

where ΔH is the enthalpy of reaction of resin, λ is the thermal conductivity of composites, ρ is the density of composites, C_p is the specific heat of composites, α is the degree of cure and V_f is the fibre volume fraction.

Cure kinetics model proposed by Kamal and Sourour[15] has been used successfully in the literature to calculate the reaction kinetics of RTM6 resin:

$$\frac{\partial\alpha}{dt} = [K_1 + K_2\alpha^m](1 - \alpha)^n \quad (3)$$

where K_1 and K_2 are temperature dependent Arrhenius functions which can be described as: $K_i = A_i\exp\left(-\frac{E_i}{RT}\right)$ with A_i being the reaction rate constants, E_i the activation energies, R the ideal gas constant, and m and n are the reaction orders. It is assumed that the cure kinetics and the thermal properties are independent of pressure or shear stress. The model parameters were taken from literature.[6,7]

Equation 2 was solved in heat transfer module of commercial finite element analysis software COMSOL Multiphysics. Exothermic heat source depends on time dependent reaction kinetics. Therefore, reaction kinetics (Eq 3) was determined locally solving a transient ordinary differential equation. The degree of cure was treated as an internal variable of the thermal behaviour of composites. Its evolution over time was calculated locally at each integration point, taking into account the local temperature evolution.

Calculated temperature and degree of cure at the mould surface and in the core (half thickness) of composites of the three samples are plotted in Figures 2 and 3, respectively.

For 4mm thick part, the core (half thickness) and surface temperatures overlap. This shows that temperature gradient through the thickness was negligible. The same can be observed for degree of cure of this sample as shown in Figure 3.

For 20mm and 40mm samples, the surface temperature ($T_{surface}$) was higher than the core temperature (T_{core}) at the early stage of curing, as expected for the

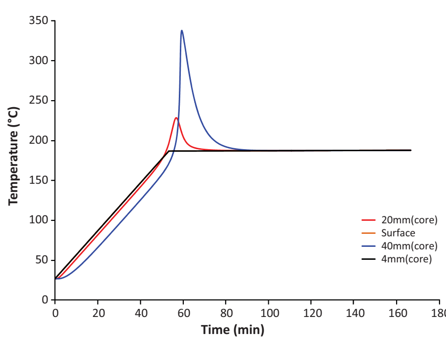

Figure 2.
Simulation results of temperature profile in composite part.

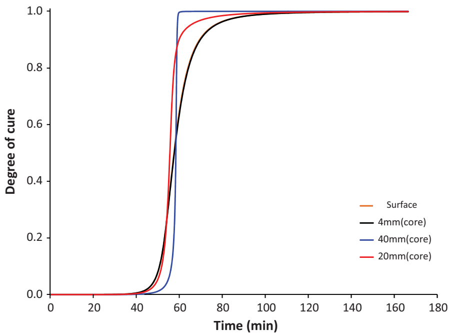

Figure 3.
Simulation results of degree of cure in composite parts.

heating and curing process of thin polymer and composite parts. Due to exothermic reaction, however, T_{core} began to become greater than $T_{surface}$ (Figure 2) as the curing process continued. Because of the smaller thickness, the exothermic peak in the 20mm thick sample appears earlier than in the 40mm sample. The same trend can be observed in the plot of degree of cure in Figure 3.

Since degree of cure is strongly dependent on temperature, its evolution is also non-uniform through the thickness direction of thick (20mm and 40mm) composite parts (Figure 3). There is a significant difference in the calculated degree of cure between at the surface and at the core of part. This difference also creates the gradients of cure dependent properties (CTE, CS, Young's modulus, shear modulus, etc.) in the part which cause residual stress in the part in addition to other factors.

Since temperature gradient is negligible in thin composite parts, degree of cure gradient is also negligible. This is evident from overlapping of degree of cure curves at surface and at 4mm core in Figure 3. Therefore, it can be concluded that contribution of thermal gradient to residual stress is negligible in thin composites.

Modelling the Woven Composite Properties

A code mmTEXlam[8,9] was used to obtain the homogenized properties of composites from the properties of fibre and resin. This code is based on the model proposed by Naik et al.[19] (a modified version of Ishikawa's model). They considered the yarn cross-sections as a lenticular shape, and discretely modelled the yarns' centreline paths within a RUC (representative unit cell) by assuming sinusoidal undulation. They used a yarn discretization scheme together with a 3D stress averaging procedure to compute overall stiffness properties. Yarn count, crimp, and spacing were considered to be the same for both the warp and weft. Yarn cross-section was considered to be the same for both the warp and weft yarns and assumed constant over the whole yarn length.

The resin properties were taken from the literature.[17] The homogenized properties of composites during curing were obtained for several values of degree of cure. Using this data, polynomial functions were defined to represent each property in terms of degree of cure (e.g. $E_{22} = f(\alpha)$). The objective was to use these functions in COMSOL to find the local properties for the calculated degree of cure.

Calculation of Spring-in Angle by Solving the Coupled Problem

Calculation of the residual stress or strain is a strongly coupled problem. Here, this problem is solved in the form of two simultaneous sub-coupled problems: reaction kinetics and heat transfer coupling, and thermo-kinetic and mechanical coupling.

The part was constrained at two points (Figure 1) to avoid rotation of model. The temperature and degree of cure profile within the composite part was obtained as described in the previous section. This data was used further as input data for determination of temperature and cure dependent properties and chemical shrinkage and thermal expansion strains.

Simulation of chemical reaction kinetics coupled with heat transfer equation using transient ordinary differential equation and heat transfer module in COMSOL yielded for each integration point the local evolution of temperature and degree of cure versus time (section 3.1). This data was used as input for structural mechanics module which was fully coupled with the other two modules. An elastic constitutive relation was used for the mechanical stress analysis:

$$\overline{\overline{\sigma}} = \overline{\overline{C(T,\alpha)}}\left(\overline{\overline{\varepsilon}} - \overline{\overline{CTE(T,\alpha)}}\Delta T - \overline{\overline{CS(T,\alpha)}}\Delta\alpha\right) \quad (4)$$

The rigidity matrix C, the coefficient of thermal expansion (CTE) and the coefficient of chemical shrinkage (CS) depend either linearly or nonlinearly on the degree of cure (α) and temperature (T). The rigidity matrix C can be calculated using the values of Young's moduli, shear moduli and Poisson's ratios. These values also change as a function the degree of cure (α) and temperature.

The simulation result of spring-in angle change (global) in the 4mm thick part, during the whole curing cycle is plotted in Figure 4. Surface temperature and degree of cure are also plotted on the same figure. As shown earlier in Figures 2 and 3 the temperature gradient was negligible in the thin part and the properties of sample were assumed to be uniform throughout the thickness of the sample.

Since the properties, such as stiffness, of resin and composites began to build up from the gel point ($\alpha = 0.5$), no deformation was observed before this point. Spring-in due to chemical shrinkage became significant from $\alpha = 0.85$ and reached the maximum value of 0.2° in the cured state ($\alpha = 1$) at $T = 185\,°C$.

It was assumed that there was no stress relaxation stress after curing and before cooling. Therefore, spring-in angle induced due to chemical shrinkage maintained at maximum level. During the cooling, spring-in increases as a linear function of temperature to reach a maximum value of 1.05°.

Temperature gradients were present in the 20mm and 40mm parts during curing (Figure 3 and 4). Therefore, they also contributed to the residual stress formation. That is why the evolutions of spring-in angle of three samples were not the same (Figure 5). However, the extended curing caused the properties to become uniform and the final values of spring-in angle for all three samples were almost the same. It should be also noted that the in-plane tensile-compressive residual stresses can remain in the final thick composite parts due to the different thermal hysteresis between the surface and the core. Hence, this heterogeneous internal stress state in the part can eventually decrease the mechanical performance of final composite structures.

The spring-in angle predicted using analytical model was equal to 1.1° which was very close to numerical solution.

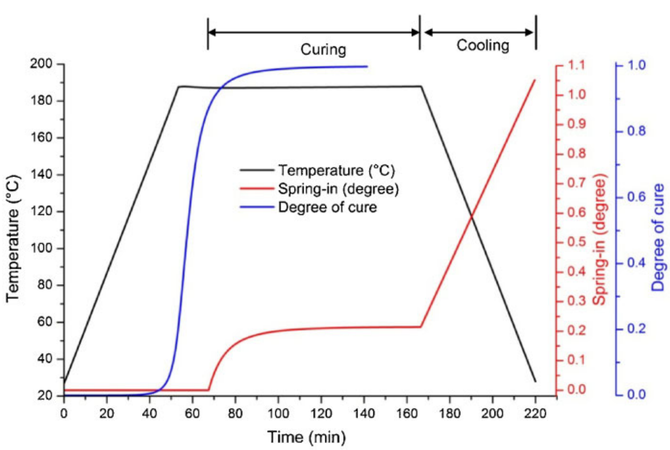

Figure 4.
Evolution of spring-in angle during curing and cooling.

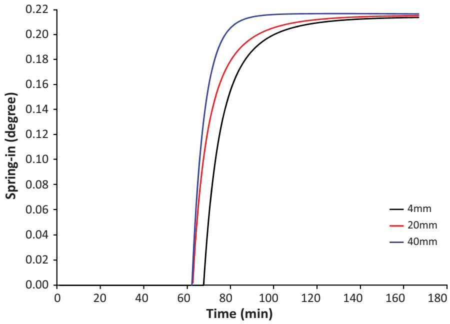

Figure 5.
Evolution of spring-in angle during curing of three samples with different thicknesses.

Experiments will be conducted on composite parts studied in this paper to validate the model. However, the experimental results of similar carbon/epoxy composites found from the literature[20,21] show that the model results are reliable.

Conclusion

In this article, the spring-in angle of three composite angled brackets was obtained using analytical and numerical methods. The analytical method provided a quick estimation of spring-in angle but the consideration of whole manufacturing process needed numerical methods. The homogenized properties of composites were calculated using an analytical method from the properties of resin and fibre. These properties were then used to calculate the residual stress and spring-in angle of composite parts using COMSOL Multiphysics while solving simultaneously the thermo-kinetics and thermo-mechanics coupling. Temperature, degree of cure and material properties were then calculated. It was found that temperature gradient in the thin composite part (4mm thick) was negligible and its contribution to the residual stress formation could be ignored. However, non-uniform temperature gradient affected the evolution of spring-in of thick composite parts.

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