INFLUENCE OF THE FIBRE VOLUME FRACTION PARAMETER ON THE PREDICTIONS OF THE CURE-INDUCED DEFORMATIONS IN THERMOSET COMPOSITE PARTS

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Abstract

Manufacutring composite parts induces deformations within the part either due to handling the fibres and prepregs or the curing process itself. An important challenge for composite manufacturers is therefore to respect the tolerances imposed by the designers in order for the part to be assembled. An accurate prediction of the cure-induced deformations would help reduce the costly trial-and-error or empirical approach often used in mould design. One of the main challenges behind an accurate prediction of the residual stresses and deformations is the use of a model complexity level suited to the problem being studied. The fibre volume fraction gradient has often been shown to have a significant influence on the part deformation after curing [1,2]. The present study focuses on quantifying the influence of the fibre volume fraction parameter on the prediction of the cure-induced deformations in order to evaluate the level of refinement to introduce in the model. Results have shown the importance of a fine modelling of the resin location in the thickness of the part.

1. Introduction

The polymerisation reaction, or curing, which transforms the liquid thermoset resin to solid, induces internal stresses within the part being produced. During this change of state, the part deforms due to thermal expansion and chemical shrinkage of the resin. The contact conditions with the mould as well as the pressure exerted on the part prevent these deformations from developing freely resulting in a build-up of internal stresses. Upon demoulding, some of these internal stresses are released, resulting in the appearance of distortions. Being able to predict the cure-induced deformations is therefore a key point in order to avoid the costly trial-and-error or empirical approaches currently used in mould design. One of the main challenges behind an accurate prediction of the residual stresses and deformations is the use of a model complexity level suited to the problem studied. The fibre volume fraction gradient has often been shown to have a significant influence on the part deformation after curing [1, 2]. During processing, the resin can migrate internally in the part or externally through the bleeder which lead to variations in the fibre volume fraction (V_f) compared to the nominal value of the prepreg. The present study focuses on quantifying the influence of the fibre volume fraction parameter and its uncertainty on the prediction of the cure-induced deformations in order to evaluate the level of refinement to introduce in the model. Numerical simulations using both nominal and measured fibre volume fraction allowed to evaluate and quantify the importance of measuring accurately this parameter and the relevance of taking into account process variations. To quantify these cure-induced deformations, the spring-in angle $\Delta\theta$ is measured between the nominal geometry or mould geometry and the cured geometry. Fig. 1 illustrates the methodology used to compute the spring-in angle. Experimental measurements are compared to numerical predictions in order to evaluate the accuracy

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of the numerical tool. Based on the experimental observation of thicknesses and locations of resin or fibres rich regions, the numerical model has been refined to reflect the observations.

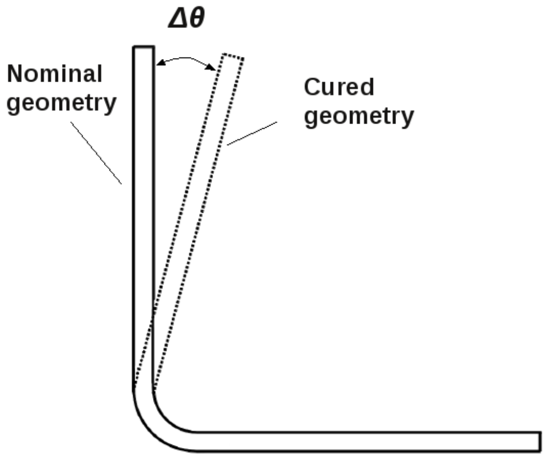

Figure 1. Definition of the spring-in angle.

2. Materials and method

The geometry of interest is a 150 mm long Z-shaped angle bracket with 100mm wide flanges. It is made of Hexcel AS4/8552 prepreg plain-weave fabrics (V_f=55%) and cured in an autoclave on an Invar tooling. The Invar tooling was chosen due to its low CTE. This lowers the mismatch between the coefficients of thermal expansion and limits the influence of the thermal dilatation of the mould and the tool-part interaction in the simulation. The stacking sequence is the following: 10 plies of carbon fabric prepreg, symmetric: $[(\pm45/0\text{-}90)_2/\pm45]_S$. The cure cycle applied is a cycle used by aeronautic companies while curing secondary structures. This part has been modelled and the comparison with experimental measurements evaluates the robustness of the numerical tool. Parts with a significant resin rich region were manufactured as well as parts with no visible resin rich region in order to compare the effect of such defect in the curvature radii.

The distortions of the parts are measured using a Nikon MMDx100 laser scanner mounted on a 7-axis Metrology-grade MCA II arm. The declared accuracy is 54 µm which leads to an uncertainty of 0.1° on the spring-in angle measured. The two angles of the Z-shape have been measured and abbreviations A1 and A2 in the following represent the male and the female angle of the tool, respectively. The angles were measured along the part length and the presented spring-in is the average of 10 measurements per part and per angle. The experimental error bars represents the measurement uncertainty of 0.1° on Fig. 2 in the following section.

The numerical prediction methodology used consists of performing coupled chemical-thermal-mechanical Finite Elements (FE) calculations using ABAQUS with the help of user material subroutines. It was assumed that the temperature gradient across the thickness of the part was negligible due to the low thickness of the part. As a result, a transient thermal analysis was not performed and the temperature was considered to be uniform throughout the part. The details of the model follow the approach suggested by Svanberg and Holmberg [3] who consider a simplified linear viscoelastic behaviour of the material where time-temperature-degree of cure superposition is invoked. Three of the main assumptions made are: (i) the stresses and strains are assumed to be zero until gelation, (ii) the thermal expansion is assumed to be linear within each material state, and (iii) the material properties are kept constant for each relevant state, rubbery or glassy, of the resin.

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The material properties have been characterized to determine their evolution along the cure cycle. Dynamic Mechanical Analysis (DMA) and tensile tests were performed in order to obtain the evolution of Young's and shear moduli along the cure cycle. Thermomechanical Analysis (TMA) was also performed to characterise the thermal and chemical dilatation or shrinkage coefficients which have been considered to be constant for each material state. The transition from the rubbery to glassy state occurs when the resin temperature reaches its glass transition temperature T_g which is assumed to depend only on the degree of cure X. The model used to predict the glass transition temperature T_g as a function of the degree of cure X and the kinetic model are those used in [4] for the 8552 resin. The characterisation campaign allowed the determination of the properties of the material at the nominal fibre volume fraction and of the neat resin. In order to get the properties at the modified fibre volume fraction, the following steps are computed :

- the targeted fibre volume fraction and the properties of both constituents, resin and fibres, are introduced into micromechanical equations to compute the properties of a UD ply of the material;
- the Classical Laminated Theory is applied to compute the equivalent properties of a ply of balanced fabric, considering the superposition of two UD plies;
- A ratio between the computed properties at the nominal V_f and the modified V_f is calculated in order to get the importance of the V_f on the computed properties. This ratio is then applied to the characterised prepreg properties to compute the properties at a modified V_f, keeping the trend of the characterised curves.

The autoclave process is modelled by applying boundary conditions intended to be close to those encountered experimentally in the autoclave. A pressure is applied on the free surface of the part to account for the effect of the autoclave, and the tool is modelled as a rigid body. This last assumption is relevant since the tool is made of Invar which exhibits a low coefficient of thermal expansion (CTE). The autoclave pressure contains the part against the mould and the mould prevents the angle to close during cure. The influence of the boundary conditions and mechanical properties on the numerical predictions have already been discussed in [5].

Based on the experimental observation, the influence of the fibre volume fraction on the numerical prediction is studied through four different situations modelled with an increasing refinement.

3. Results and discussion

The observations of the parts manufactured showed variations of thickness in the two curvature radii: During the upload you will be also asked to provide the following information:

- In the outward facing angle of the Z part, referenced as A1 in the following, a reduction of thickness is observed. This is explained as the plies are pinched between the vacuum bag and the tool. The resin is therefore pushed out of the curvature radius and a fibre rich region appears due to the thickness decrease;
- in the inner facing angle A2, an increase of the thickness has been constantly reported: the vacuum bag and the prepreg cannot fit closely the tool and the compaction of the prepreg is therefore degraded. The observation of the part showed a resin rich region between the vacuum bag and the prepreg;
- the thickness remains constant to its nominal value in the flanges.

The measured thicknesses are translated in a fibre volume fraction V_f used to compute the properties applied in the numerical simulation. A thickness variation of -10% is measured in the outward facing angle A1 which lead to a fibre volume fraction of 61% (the nominal V_f of the prepreg is 55%). In the oinner facing angle, the measured thickness variation is +20%, which leads to a fibre volume fraction of 46%. The measured spring-in of both experimental parts are presented in Table 1. The comparison

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between two experimental measurements, with and without a resin rich region in angle A2, showed the effect on the resin rich region with an increase of the spring-in angle. On A1, the spring-in remains constant, no change has been brought in the manufacturing.

Table 1. Measured spring-in of the manufactured parts.

	Spring-in angle on A1	Spring-in angle on A2
Z-part, nominal	1.72±0.1°	1.58±0.1°
Z-part, resin rich region	1.66±0.1°	2.24±0.1°

These experimental observations are reproduced numerically using different strategies, detailed in section 2. The comparison between experimental measurements and numerical predictions is given on Fig. 2:

- "Simulation 1 – nominal *Vf*" is the reference case, the nominal fibre volume fraction of 55% is used to compute the properties of the prepreg applied to all elements. The thickness of each ply is kept constant at the nominal value of 0.205mm;
- "Simulation 2 – properties modification in both angles": the properties of the prepreg with the nominal fibre volume fraction of 55% is applied to all elements except those in the curvature radii: the measurement of the thickness variation is converted in a variation of the *Vf* which allowed to compute the properties of those elements. V_f of 61% and 46% is considered for angles A1 and A2, respectively. The thickness of each ply is kept constant at the nominal value of 0.205mm in the entire part;
- "Simulation 3 – homogeneous thickness modification in both angles": the material properties are the same as in Simulation 2, but the thickness is modified in the curvature radii. The measured thickness variation is applied to all plies: the thickness variation is -10% and +20% for angles A1 and A2, respectively, which leads to a new thickness per ply of 0.18 mm on A1 and 0.24 mm on A2. An illustration of the modelling of a reduced thickness in A1 is presented on Figure 3a.
- "Simulation 4 – reduced thickness in A1 and resin bleed in A2": the only difference with Simulation 3 concerns the angle A2: the nominal thickness is applied but a layer of resin is added locally inside the radius to match the measured thickness. The resin ply is 0.4mm thick to reach the 2.4mm measured in that curvature radius. An illustration of the modelling is presented on Figure 3b.

The comparison between the nominal cases, both experimental (blue bars) and numerical (orange bars) showed a good agreement for the two angles A1 (outward facing angle) and A2 (inner facing angle), the prediction remains within the incertitude of the experiment (see the error bar). It can be noticed that for angle A1 the measured fibre volume fraction V_f is higher than the nominal value, due to the vacuum bag which pinches the prepreg as explained previously. Therefore, a difference of V_f is present, locally on A1, between the experiment and the simulation.

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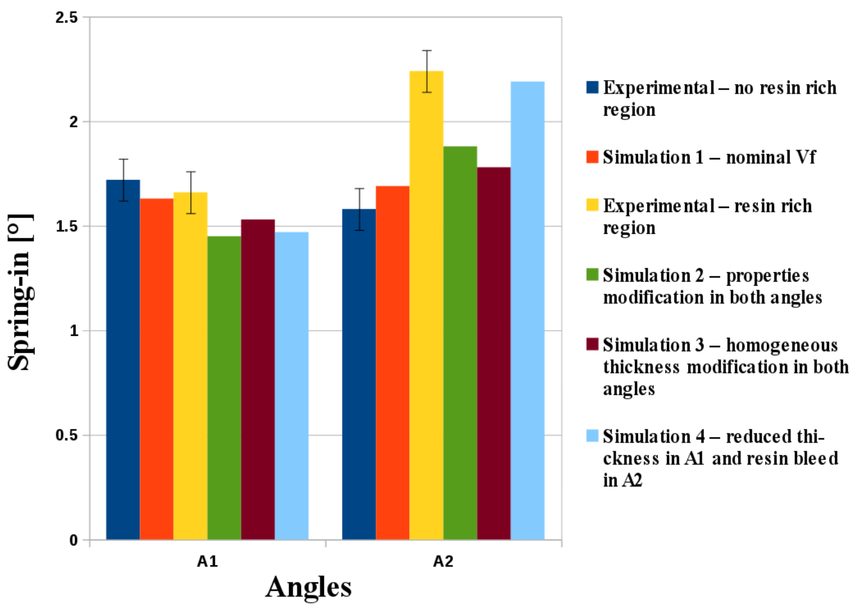

Figure 2. Comparison between experimental measurements and numerical predictions.

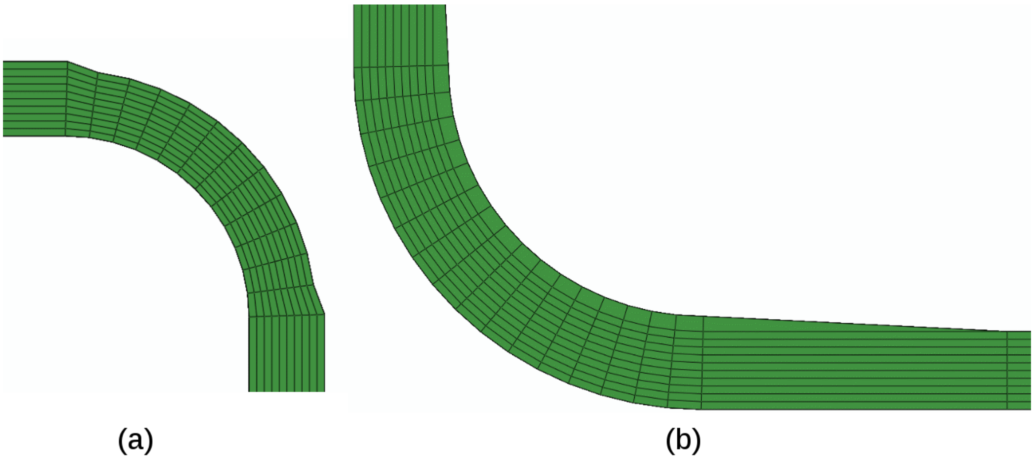

Figure 3. Modelling of (a) the fibre rich region by a reduction of the ply thickness and (b) a resin rich region with an extra neat resin ply in the inner facing angle.

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The same part (same geometry and stacking sequence) has been manufactured with the introduction of a resin rich region on angle A2 (yellow bar). The numerical simulations referenced 2 to 4 have been set up to model possible configurations representative of experimental observations. Simulations referenced 2 and 3 tend to take the predictions away from the measurements for A1 while getting slightly closer to the experimental value for A2. Modelling the thickness variations brings a slight improvement of the spring-in prediction on angle A1 while the predictions for A2 are degraded. Computing new properties, based on the measured V_f, does not seem to be sufficient to match the experimental. An additional level of refinement has to be added: the resin bleed observed on angle A2 is modelled with “Simulation 4”. Even if the prediction for angle A1 are still far from the experimental measurement, as no improvement has been brought compared to the previous simulation, a good agreement can be observed on angle A2. Modelling the resin thickness inside the curvature radius has an important influence on the spring-in due to the contraction of the resin which intensifies the spring-in effect. Modelling the repartition of the resin in the thickness direction seems the right approach to generate numerical predictions in agreement with the experimental measurement.

4. Conclusions

Modelling the variations of the fibre volume fraction in the curvature radii of parts is necessary as this parameter has an important impact on the results, both experimental and numerical. Even if the variations measured in this work are exaggerated for the purpose of the present study, it still remains a challenge in the industry. Variations of 5 to 10% compared to the nominal thickness is commonly observed.

Computing corrected properties based on the thickness measurements are not sufficient to match the experimental measurements. Results have shown the importance of a fine modelling of the resin location in the thickness of the part. Observations using micro-CT of parts out of the manufacturing process would give an idea of the repeatability and the details to be put into the numerical model to be able to predict with sufficient accuracy the cure-induced spring-in. The distribution of the resin in the thickness direction should be finely observed experimentally and reproduced numerically to have numerical predictions close to the experimental measurements.

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