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EXPERIMENTAL AND NUMERICAL ANALYSIS OF THE DIMENTIONAL STABILITY OF AN RTM CARBON EPOXY AEROSPACE STRUCTURE

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SUMMARY: The prediction of process-induced dimensional variability and residual stresses occurring during the manufacturing of composite structures is critical to produce parts where tight tolerances are required. Therefore, the development of material constitutive models and processing properties, and the validation of these models, are two essential steps in order to accurately simulate the behavior of the materials involved. In this paper, the glass transition temperature and the modulus development of a one-part epoxy resin are first presented. The material constitutive models were implemented in a three-dimensional finite element software based on the ABAQUS/COMPRO platform to analyze the RTM processing of a representative aerospace component. Both heat transfer analysis and stress analysis were conducted. Contact interactions were implemented in the stress analysis to simulate the tool-part interaction. The results predicted the composite debonding caused by the resin volumetric chemical shrinkage. At the end of the cure cycle, the mandrel was found in compression and the external mould stress free. A compressive stress gradient was developed through the thickness of the composite structure.

KEYWORDS: material characterization, process modeling, tool-part interaction

INTRODUCTION

Nowadays, in the industry, most of the knowledge in composite manufacturing is based on rules of thumb and experience. However for new and complex parts, such a process can take several iterations and leads to time consumption and cost increases. Therefore, a comprehensive understanding of the different phenomena involved in composite processing is crucial. Materials characterization and constitutive models development are key elements to optimize and predict final composite structure properties. Dimensional stability and residual stresses are one of the major issues for applications where tight tolerances are required. Over the last decade, several researchers investigated experimentally and numerically the factors leading to composite part distortions [1-8]. The most cited factors were thermal strain, volumetric chemical shrinkage and tool-part interaction. In this work, the dimensional stability of a representative aerospace component manufactured by RTM was investigated. The thermal stability, the cure kinetic, and the rheological and shrinkage behaviour of a one-part epoxy resin were characterized and modelled [9]. In this study, the glass transition temperature and the resin elastic modulus were measured using a rheometer in torsion. The developed material property models were then implemented in a 3D finite element model based on ABAQUS/COMPRO platform. Both heat transfer analysis and stress analysis were conducted where the tool-part interaction was investigated using finite element contact algorithms.

MATERIAL CHARACTERIZATION

Glass Transition Temperature

The rectangular solid sample torsion mode of the TA Instruments AR-2000 rheometer was used to test solid resin samples pre-cured to an initial degree of cure α_I past the gel point. Dynamic tests were performed at 5ºC/min to 180ºC followed by a short isotherm in an oscillatory mode at 0.1% strain and 1Hz. The glass transition temperature, T_g, was determined by observing the peak of the tan δ curve as experimental indicator. The evolution of the T_g with the degree of cure was modelled with the Di Benedetto equation [10]:

$$\frac{T_g - T_{g0}}{T_{g\infty} - T_{g0}} = \frac{\lambda\alpha}{1-(1-\lambda)\alpha} \tag{1}$$

where T_g is the glass transition temperature, T_{g0} and $T_{g\infty}$ are constants denoting the glass transition temperatures of uncured and fully cured resin respectively, α is the degree of cure and λ is a constant used as a fitting parameter valued between 0 and 1 [10].

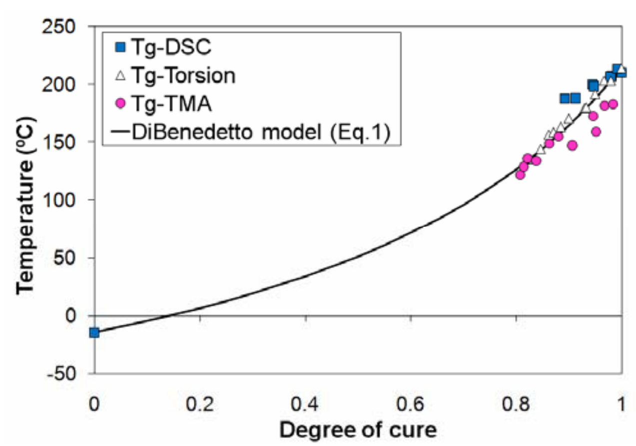


Fig. 1 Comparison of glass transition temperature measured with different methods.

Fig. 1 compares the predicted and measured glass transition temperatures with the degree of cure. This model with the following constant values, T_{g0} = -14.23ºC, $T_{g\infty}$ = 213.75ºC and λ = 0.396, accurately predicts the evolution of the glass transition temperature, with a R^2 value of 0.999.

Glass transition temperatures obtained by two other methods, MDSC and TMA, are also compared to the predicted temperatures. The Di Benedetto equation captures the trend of the T_g obtained with different methods well.

Elastic Modulus

The rectangular solid sample torsion mode of the TA Instruments AR-2000 rheometer was also used to measure the elastic modulus development of solid resin samples by following the change of the shear moduli, *G'* and *G"* with the temperature. Samples were manufactured with a known degree of cure α_1, past the gel point, and were tested at isothermal temperature in order to investigate the temperature-cure dependence of the elastic modulus. Assuming that the resin is isotropic and the Poisson's ration remains constant with the temperature and the degree of cure [11, 12], the shear modulus can then be related to the tensile modulus with the following equation:

$$E = 2G(1+\nu) \tag{2}$$

where E is the elastic modulus, G is the shear modulus and ν is the Poisson's ratio.

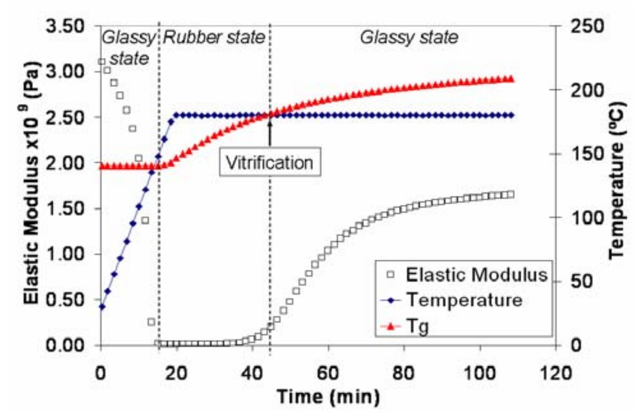


Fig. 2 Evolution of the elastic modulus with temperature and time.

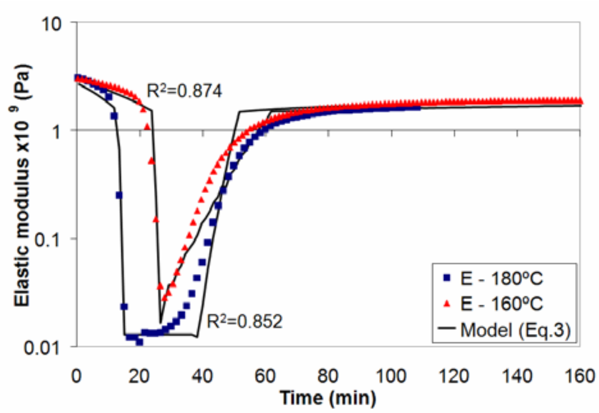
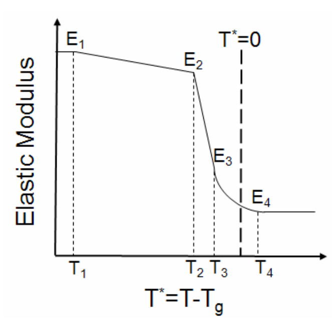


Fig. 3 Comparison of the experimental and predicted elastic modulus data in time.

Fig. 2 shows the evolution of the elastic modulus during the cure. First, a decrease in the elastic modulus is observed as soon as the sample reaches the glass transition region ($T > T_g$). Then the elastic modulus remains low and starts to increase at the vitrification ($T < T_g$) to finally reach its maximum value. Thus the glass transition temperature is an important factor in the evolution of the elastic modulus. A model expressed as a function of $T^* = T - Tg$ was developed to describe its evolution [13]. T^* represents the difference between the instantaneous cure temperature T and the instantaneous glass transition temperature Tg. The elastic modulus model can be expressed as:



$$E(T^*) = \begin{pmatrix} 0 \\ E_1 \\ E_2 + (E_1 - E_2)\dfrac{T^* - T_2}{T_1 - T_2} \\ E_3 + (E_2 - E_3)\dfrac{T^* - T_3}{T_2 - T_3} \\ A\exp(-K.T^*) \\ E_4 \end{pmatrix} \quad for \begin{pmatrix} \alpha < \alpha_{gel} \\ T^* < T_1 \\ T_1 \le T^* < T_2 \\ T_2 \le T^* < T_3 \\ T_3 \le T^* < T_4 \\ T_4 \le T^* \end{pmatrix} \tag{3}$$

Table 1 presents the values of the fitting parameters which give the best agreement with the experimental data.

Table 1. Parameters values of the elastic modulus model

Parameters	Value	Parameters	Value	Parameters	Value
α_{gel}	0.7	T_1	-150 ºC	E_1	$3.20\ 10^9$ Pa
A	$9.0\ 10^7$ Pa	T_2	-7 ºC	E_2	$1.50\ 10^9$ Pa
K	0.4 ºC	T_3	-15.18 ºC	E_3	$1.11\ 10^9$ Pa
		T_4	-5 ºC	E_4	$1.30\ 10^7$ Pa

Fig. 3 compares the experimental and predicted data obtained at 160ºC and 180ºC. Overall, the model captures both the onset of the modulus decrease due to the glass transition and the vitrification at different curing temperatures, with R^2 values above 0.85.

DIMENSIONAL STABILITY MODELLING

The epoxy resin material property models (cure kinetics, viscosity, chemical shrinkage, glass transition temperature, elastic modulus) were implemented in a 3D finite element model based on ABAQUS/COMPRO platform. The COMPRO subroutine uses the material models to compute the change in material properties during the cure. First, a heat transfer analysis was conducted to predict the evolution of the degree of cure of the composite structure. Then, a stress analysis was performed to evaluate the residual stresses and the tool-part interaction using contact constraints.

Geometry

Manufacturing of structural hollow parts involving a mandrel is common in aerospace, such as airfoil geometry or helicopter tail boom. Hence, in this study, a hollow cylinder manufactured with an internal mandrel and an external mould was used as a simplified representative of an aerospace component as shown in Fig. 4.

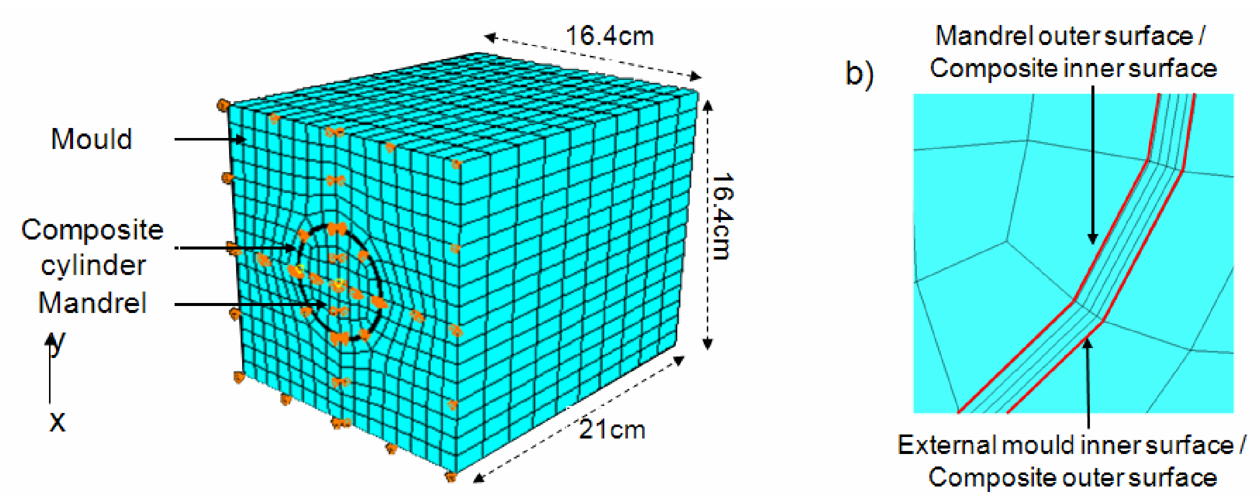


Fig. 4 a) Finite element geometry of the composite cylinder in the mould and symmetric boundary conditions – b) Details of the composite cylinder through thickness mesh.

The properties of the characterized RTM epoxy resin with an AS4 unidirectional carbon fibre were used. Aluminum properties were used for both the external mould and the mandrel. The lay-up used was $[0]_5$ in the longitudinal direction for a fibre volume fraction of 50% and a thickness of 2 mm. Three dimensional 8-nodes elements were used: DC3D8 for heat transfer analysis and C3D8 for stress analysis. The thickness of the composite structure was meshed with four elements. Half of the actual cylinder length was modelled and symmetric boundary conditions were applied.

Heat Transfer

A typical cure cycle for the RTM epoxy system was used: 120 minutes isotherm at 180ºC followed by a cool down to 25°C at 1ºC/min. At the beginning of the simulation, the preform was assumed completely saturated with resin. The mould was assumed adiabatic with an initial temperature of 180ºC. As in practice, the resin is injected at 80ºC in a mould preheated at 180ºC, the initial composite temperature was set at 175ºC to account for an initial temperature gradient in the composite. The initial degree of cure of the epoxy resin was set to 0.001.

Stress Analysis

The stress analysis used the results of the heat transfer simulation to compute the stress, strain and the nodal displacements. The analysis takes into account the evolution of the composite properties during the process. An incremental method, the cure hardening instantaneous linear elastic (CHILE) approach, was used to compute the composite elastic properties and the change in residual stresses during the cure cycle [14]. The contact interactions between the mould and the composite were defined as follows: "hard" contact relationships were applied to prevent the transfer of tensile stresses across the interface and minimize the surface interpenetration. The maximum value of the shear stress that can be carried by the interface before the surfaces begin to slide was set to 10^{-5} Pa with a coefficient of friction of 0.3, in order to model frictionless behaviour.

Results

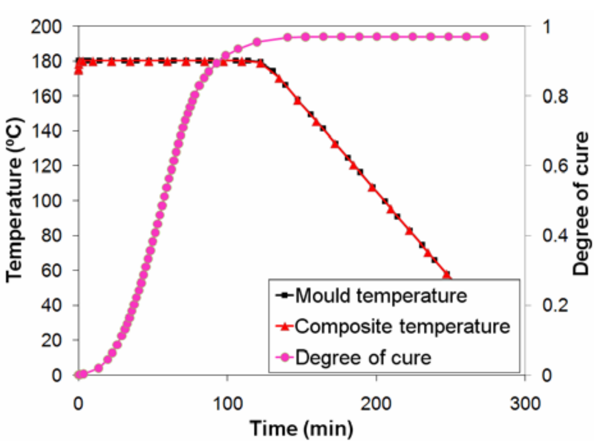


Fig. 5 Temperature and degree of cure evolution at the center of the composite.

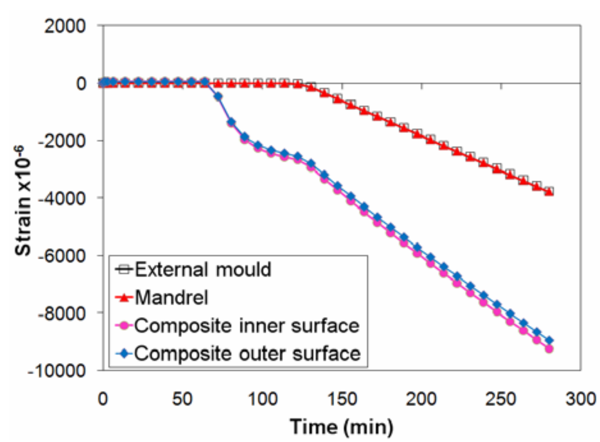


Fig. 6 Strain evolution at the interfaces.

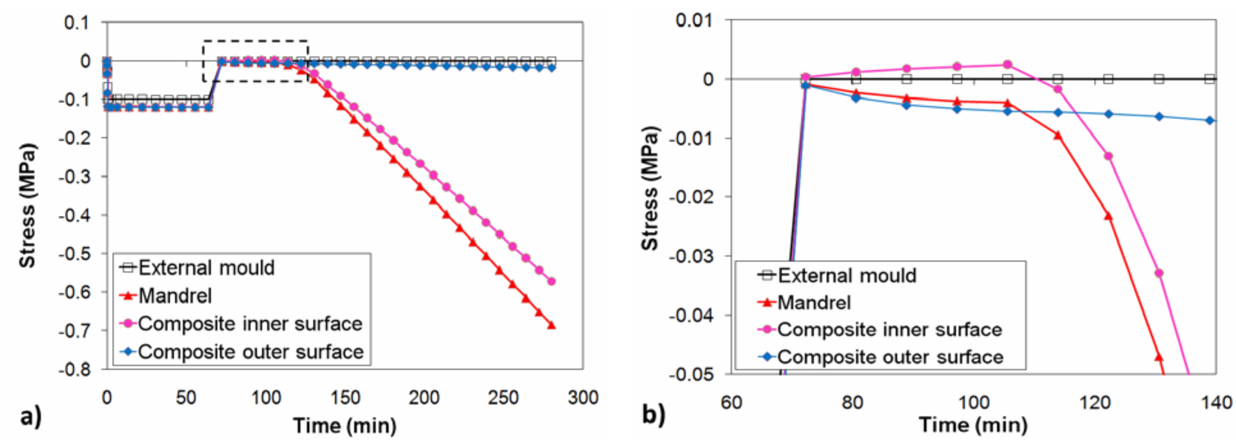


Fig. 7 Stress evolution at the interfaces: a) during the whole cure cycle; b) at the end of the isotherm.

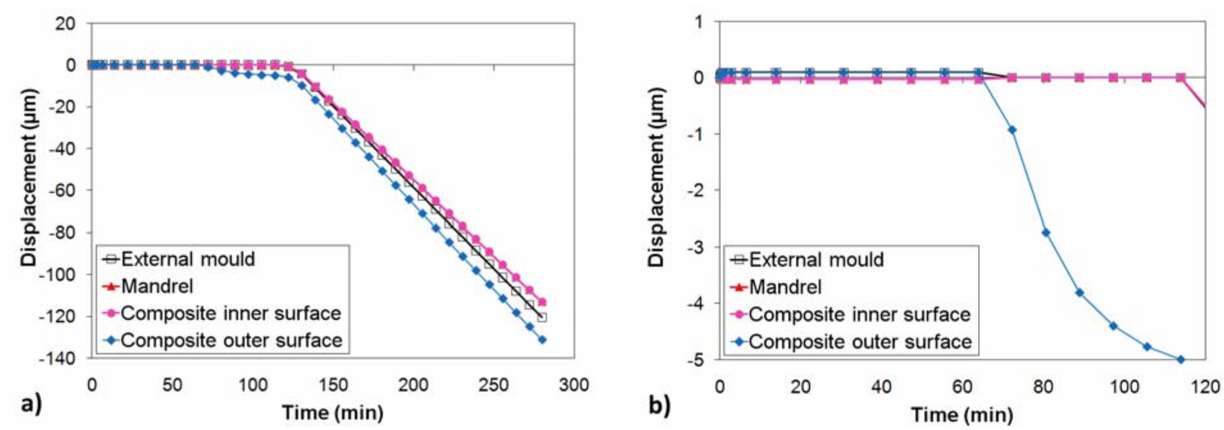


Fig. 8 Displacement evolution at the interfaces: a) during the whole cure cycle; b) during the isotherm.

Fig. 5 shows the evolution of the predicted temperature and the predicted degree of cure at the center of the composite during the cure cycle. A negligible cure exotherm was predicted (< 1ºC during the isotherm) and no thermal lag was observed between the composite part and the mould during cooling. Since the predicted temperatures were uniform over the entire part during the cure cycle, no degree of cure gradient were present. A maximum degree of cure of 0.97 was reached at the end of the curing process.

Fig. 6 and Fig. 7 show the evolution of the radial strain and the radial stress respectively, at the two part interfaces: external mould/composite outer surface and mandrel/composite inner surface. Fig. 8 presents the radial displacements of these interfaces during the cure. First, the composite expands as its temperature increases from 175ºC to 180ºC. The thermal expansion led to the development of compressive stresses in the tools as shown in Fig. 7a. Compressive stresses were built up in the composite as well as the external mould and the mandrel were preventing the composite expansion. Then, in Fig. 6, the strain decrease in the composite after 60 minutes corresponded to the shrinkage after gelation. The shrinkage led to the release of the compressive stresses in the composite and the tools. From Fig. 7b it can be noticed that small tensile stresses were built up in the inner surface of the composite as the mandrel was preventing the composite shrinkage. No stresses were created at the interface of the external mould. It can be observed in Fig. 8b that the displacement of the outer surface of the composite was not restrained by the external mould. As a result, debonding occurred between the outer surface of the composite and the external mould; explaining the absence of stresses at the interface.

Fig. 9 illustrates the stress distribution in the radial direction at the end of the cure cycle at 25ºC. At that stage, the external mould is stress free and the mandrel is in compression. A compressive stress gradient is also clearly observable in the composite thickness going from 60 kPa at the outer surface to 540 kPa at the inner surface. The thickness of the composite part decreased by 2 μm overall. In practice, internal tooling was difficult to extract from composite structures which validates the state of stresses obtained with the simulation.

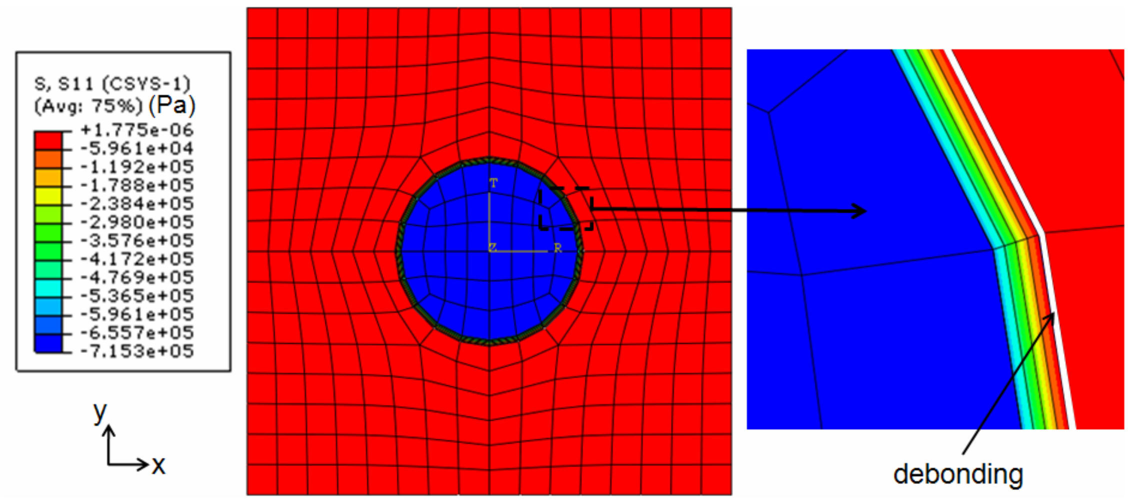


Fig. 9 Stress distribution in the radial direction at the end of the cure cycle at 25ºC (scale factor x20).

CONCLUSION

In this study, the glass transition temperature and the elastic modulus of a one part exoxy resin were characterized using a rheometer in torsion mode. The Di Benedetto equation captured well the trend of the glass transition temperature with the degree of cure. A model expressed as a function of $T^* = T - Tg$ was developed to describe the advancement of the instantaneous elastic modulus. The defined material models were then implemented in a 3D finite element software based on the ABAQUS/COMPRO platform to analyze the RTM processing of a representative aerospace component. Contact interactions were applied to simulate the tool-part interaction. The results predicted the development of compressive stress gradient through the thickness of the composite part and debonding between the mould and the composite due to the volumetric chemical shrinkage. The predicted strain/stress evolution should be then compared with measured data obtained from an actual part manufactured with an RTM instrumented tool to validate the material property models and the finite element approach.

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