MODELLING OF GEOMETRICAL INSTABILITIES IN ASYMMETRIC COMPOSITES PLATES REINFORCED WITH 3D INTERLOCK FABRICS

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Keywords: Fiber-reinforced Composites, Process Modelling, Liquid Composites Molding

ABSTRACT

The present work focuses on the development of a fully integrated simulation code to compute the residual stresses evolution during the RTM (Resin Transfer Molding) manufacturing of composite plates reinforced with 3D interlock fabrics. First, a numerical simulation of the resin flow is computed under non-isothermal conditions at constant flow rate injection. Then, the degree of cure and temperature gradients developed during the injection stage are computed and integrated as initial boundary conditions of a staggered thermo-chemical-mechanical calculation. Advanced material models have been implemented into subroutines on a commercial FE package, Abaqus, to take into account the cure kinetics and the evolution of thermo-mechanical properties with temperature, degree of cure and time. A standard CHILE thermo-mechanical material model has been implemented and compared to a more compliant viscoelastic material modeling. To compare the results obtained with both models, the residual stresses and resulting deformation during manufacturing of asymmetric plates have been simulated and compared to experimental data. Six asymmetric [0/90] plates made of 3D interlock woven fibers were manufactured by RTM and characterized after demolding, reheating and cooling. The comparison between experimental data and numerical calculations brings a new insight of the internal stresses developed in composite materials made of 3D woven fibers.

1. INTRODUCTION

Polymer matrix composites have been increasingly used in aerospace applications over the last 60 years. This trend is partially due to their high specific mechanical, corrosion and fatigue resistance properties, when compared with those of traditional metals. However, their use in structural components has been limited due to their low delamination resistance (for laminated composites) and post manufacturing geometrical instability. Three-dimensional woven architectures are composed of superimposed weft town linked in plane and out-of-plane by warp tows. The presence of tows through the thickness improve the damage and delamination resistance while reducing the fabrication cost for thick parts when compared to two-dimensional (2D) laminates [1-3].

Geometrical instabilities are essentially triggered by the residual stresses built-up during manufacturing. Resin's chemical shrinkage, difference in the coefficients of thermal expansion (CTE) between the fibers and the matrix, and the interaction with the tool are known to be the main mechanisms responsible for the residual stresses generation [4-6]. Over the years the geometrical instability triggered by the residual stresses have been studied in UD and woven fabrics, both experimentally and numerically [7-10]. Several authors have used viscoelastic models to describe more accurately the evolution of the stresses during the curing, thus taking into account the time dependence and stress relaxation [11-13]. The residual stresses developed in composites reinforced

with three dimensional woven fabric at the micro-scale level have also been studied [14, 15]. In these studies, the reinforcement's architecture interaction with the resin were analyzed during the resin polymerization. Limited or practical no scientific studies, have been presented about the geometrical instabilities due to residual stresses in 3D interlock woven fabrics.

This work aims at evaluating the manufacturing residual stresses in 3D composites through a coupled experimental-numerical approach. Six asymmetric composite plates reinforced with 3D carbon fabric, were manufactured by Resin Transfer Molding (RTM). The temperature and the linear displacement of the plate were monitored during cool-down after molding. A fully integrated finite element model has been developed to compute the warpage generated in asymmetric plates during its manufacturing. A multi-scale homogenization method was used to calculate the composite viscoelastic properties used for mechanical calculation. Finally, a comparison between the total warpage obtained in the experimental analysis and in the numerical simulations is presented.

2. FINITE ELEMENT ANALYSIS

A staggered approach has been used to simulate the residual stresses during the manufacturing of asymmetric plates by RTM. PAM-RTM software was used to simulate the resin flow into the mold (flow module) and to deliver the degree of cure and temperature at the end of the mold filling. These results are then transferred to Abaqus in which thermo-chemical and thermo-mechanical modules are successively computed as shown in Figure 1. A MATLAB code was developed to transfer PAM-RTM data as initial boundary conditions into Abaqus. In the present work it has been assumed that the mechanical state does not influence the thermo-chemical calculation.

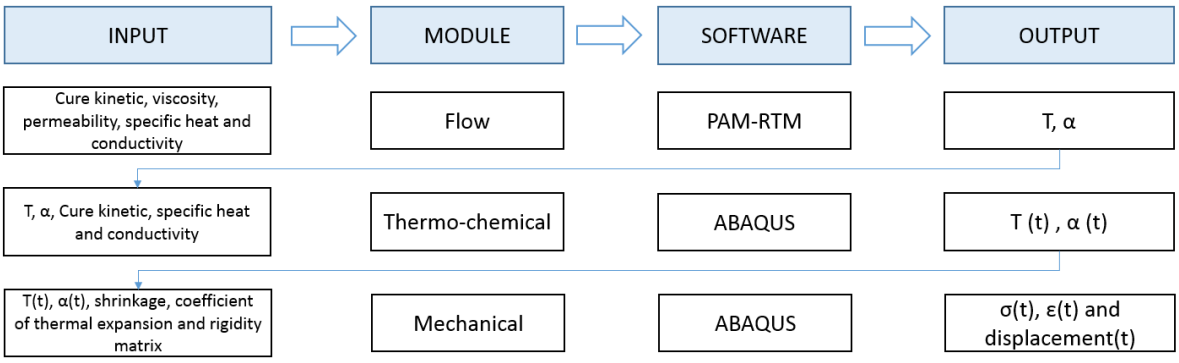

Figure 1. Staggered strategy used to compute the residual stresses evolution during the RTM manufacturing

2.1. Thermo-chemical module

The thermo-chemical model computes the temperature and degree of cure distribution throughout the plate during the manufacturing. Heat transfer and cure kinetics models are combined based on the energy conservation law and reads [16-18] :

$$\rho_c \zeta_{pc} \frac{dT}{dt} = \frac{d}{dx_i}\left(\gamma_{ij}\frac{dT}{dx_j}\right) + \dot{Q}_r \text{ (no sum on c index)} \quad (1)$$

where ρ_c, ζ_{pc} and γ_{ij} are the composite's density, specific heat at a constant pressure and thermal conductivity tensor, respectively. Q_r represents the internal heat generation, in this case, the resin's chemical reaction is the only source of internal heat generation and is calculated as:

$$\dot{Q}_r = \rho_r (1 - V_f) H_r \frac{d\alpha}{dt} \quad (2)$$

where ρ_r is the resin's density, V_f is the fabric volume fraction, H_r is the total reaction enthalpy and $d\alpha/dt$ is the chemical reaction rate. The chemical reaction rate can be expressed as [19] :

$$\frac{d\alpha}{dt} = \left(A_1 \exp\left(-\frac{E_1}{RT} \right) + A_2 \exp\left(-\frac{E_2}{RT} \right) \alpha^m \right) (1-\alpha)^n \tag{3}$$

where A_1, A_2, E_1 and E_2 are the rate constants and activation energies respectively, m and n are the orders of the chemical reaction.

A HETVAL user-program has been written in Abaqus to compute the internal heat generation and degree of cure evolution during curing after filling.

2.2. Thermo-mechanical module

Thermo-mechanical modeling was used to compute the stresses and strains taking into account both mechanical and thermal loads. Incremental models were developed to implement the viscoelastic constitutive model from Equation (1).

The thermal and chemical strains are computed through the UEXPAN sub-routine as:

$$\varepsilon^T = CTE(T,\alpha)\Delta T \tag{4}$$

$$\varepsilon^c = \begin{cases} 0 & \alpha < \alpha_{gel} \\ \beta\Delta\alpha & \alpha \geq \alpha_{gel} \end{cases} \tag{5}$$

where CTE is the instantaneous coefficient of thermal expansion and depends on the temperature, T, and degree of cure, α. And where α_{gel} is the resin's gel point and β is the coefficient of chemical shrinkage which is linearly dependent with the degree of cure [20].

Most thermoset matrices are known to exhibit a strong viscoelastic behavior at high temperature and/or low degree of cure. This work focuses on implementing a complex viscoelastic model developed in a parallel work [11], for calculating the residual stresses and compare these with the standard CHILE material model. The instantaneous stress, σ (t), can be described using the three-dimensional linearly viscoelastic constitutive theory as [21, 22] :

$$\sigma(t) = \int_0^t C(\mathrm{t}-\tau) : \frac{d\varepsilon}{d\tau} d\tau \tag{6}$$

where C is the stiffness matrix and can be written using Prony series as:

$$C(\mathrm{t}) = C_\infty + \sum_{k=1}^{N} C_k \, \mathrm{e}^{-\frac{t}{\omega_k}} \tag{7}$$

where C_∞ is the completely relaxed stiffness tensor, C_k are the orthotropic stiffness tensors associated with the relaxation times ω_k, and N is the Prony series number.
Courtois introduce the temperature and degree of cure dependence with the shift factor a_T as [11, 23] :

$$\mathrm{a}_T = \begin{cases} \exp\left(\frac{E_{a1}}{R} \left(\frac{1}{T} - \frac{T}{T_g(\alpha)} \right) \right) & T < T_g(\alpha) \\ \exp\left(\frac{E_{a2}}{R} \left(\frac{1}{T} - \frac{T}{T_g(\alpha)} \right) \right) & T > T_g(\alpha) \end{cases} \tag{8}$$

where E_{a1} and E_{a2} are the activation energy, being $E_{a1} < E_{a2}$, R is the universal gas constant and $T_g(\alpha)$ is the composite's glass transition temperature given by the DiBenedetto relationship as [24] :

$$\frac{T_g(\alpha) - \mathrm{T}_{g0}}{\mathrm{T}_{g\infty} - \mathrm{T}_{g0}} = \frac{\lambda\alpha}{1-(1-\lambda)\alpha} \tag{9}$$

where T_{g0} is the glass transition temperature of the uncured resin (α=0), $T_{g\infty}$ is the glass transition

temperature of the completely cured resin (α=1), λ is a material constant.

The viscoelastic material model was implemented using an incremental form in Abaqus through UMAT user material subroutine, in which the stress are computed at each increment as [11, 23]:

$$\Delta\sigma = C_0 \Delta\varepsilon^M - \sum_{k=1}^{N} C_k \Delta\varepsilon_k \tag{10}$$

where C_0 is the Jacobian matrix and for viscoelastic behavior is calculated as:

$$C_0 = \frac{\partial\Delta\sigma}{\partial\Delta\varepsilon} = C_\infty + \sum_{k=1}^{N} C_k \tag{11}$$

and where ε_k is the viscous strain increment associated at each Prony serie and is calculated as:

$$\Delta\varepsilon_k = \frac{\omega_k a_T}{\Delta t}\left(\frac{\Delta t}{\omega_k a_T} + \exp\left(-\frac{\Delta t}{\omega_k a_T}\right) - 1\right)\Delta\varepsilon^M + \left(1 - \exp\left(-\frac{\Delta t}{\omega_k a_T}\right)\right)\left(\varepsilon^M - \varepsilon_k\right) \tag{12}$$

2.3. Geometry and finite element mesh

A 420 x 120 x 6.7 mm thick composite plate was modelled in Abaqus. The plate was divided in two equidistant sections through the thickness to simulate the asymmetric lay-up.

The determination of a linear viscoelastic behavior modeling of 3D woven composites is based on a multiscale homogenization strategy. A two-step transition scale using a Laplace Carson transform is performed to determine the equivalent macroscopic behavior. First, depend on the properties of the elementary constituents, carbon fiber and polymer matrix, the viscoelastic behavior of the yarns is determined by homogenization at the micro-scale using the Chamis model. The result is then used at the meso-scale to obtain the macroscopic homogenized viscoelastic behavior of the composite. At this scale, a voxelized FE mesh obtained from Computed Tomography observations is used [25, 26].

The plate was composed by a total of 18768 elements, four elements were used for each layer through the composite thickness. Three dimensional 4-node solid elements compatible with PAM-RTM software were used. C3D4T and C3D4 elements were used for the heat and stress analysis, respectively.

For the thermo-chemical simulation, the temperature measured experimentally by the thermocouples placed between the tool and the laminate was imposed in the surface nodes, taking into account the thermal gradient through the thickness. Then, a surface film condition interaction was used to simulate the cooled-down by natural convection. For the thermo-mechanical model, the surface nodes were restrained during the manufacturing stage in which the plate was inside the mold. In the second stage of the simulation the plate boundary conditions were removed and the plate could deform freely with the temperature variation. The tool part interaction was neglected during this work.

3. EXPERIMENTAL METHODOLOGY

A 3D woven interlock reinforcement with carbon fibers from Hexcel Fabrics was considered herein. Each reinforcement ply was composed of four interlock layers, thus there were four stacked tows through the thickness direction. The reinforcement had an unbalanced warp/weft ratio. A commercial Diglycidyl Ether of Bisphenol F (DGEBF) one component epoxy resin was used as matrix.

Six longitudinal injections were carried out in a rectangular RTM steel tool with an internal cavity of 420 x 120 x 6.7 mm to manufacture carbon/epoxy laminates. Three micro-thermocouples were embedded into the reinforcement, at the bottom and top surfaces, and between the plies.

Prior to the injection the resin was preheated at 100°C to reduce its viscosity and degassed during 30 minutes. The resin was then injected into the heated tool with a constant flow rate of 20ml/min, followed by a compaction pressure to reduce the presence of porosity [19]. A two dwell cure cycle, one hour at the final glass transition temperature (*Tg*) followed by two hours at *Tg*+20°C, was used to ensure the completely polymerization of the resin. The plates were then cooled inside of the tool until the temperature measured at the center of the plate was below 100°C. Upon removal from the tool, the

plates were cooled down by natural convection to room temperature.

The geometrical distortion of the six plates were measured using a 3D digital image correlation system, from Correlates Solutions. The upper surfaces of the composite plates were painted in white with a stochastic black speckle pattern. Two high-resolution digital cameras, set to acquire images with 2448 x 2048 pixels, were placed above the plate. Two lamps were used to ensure a proper illumination of the plate during the plate's characterization. A photography of each plate was taken after the manufacturing at room temperature. The plates were heated free-standing in a convection oven at 140°C for 150 minutes. The plates were then removed from the oven and cooled down to room temperature by natural convection. The plates' longitudinal deflection was measured at room temperature after having submitted the plates to a free-standing post-cure.

4. RESULTS AND DISCUSSION

Figure 2 shows a comparison between the experimental measurements and the computed deflection at room temperature after the manufacturing of an asymmetric plate reinforced with 3D interlock fabric. The results presented in this section were normalized by the maximum deflection measured experimentally. The results obtained numerically presented a good agreement with the experimental measurements.

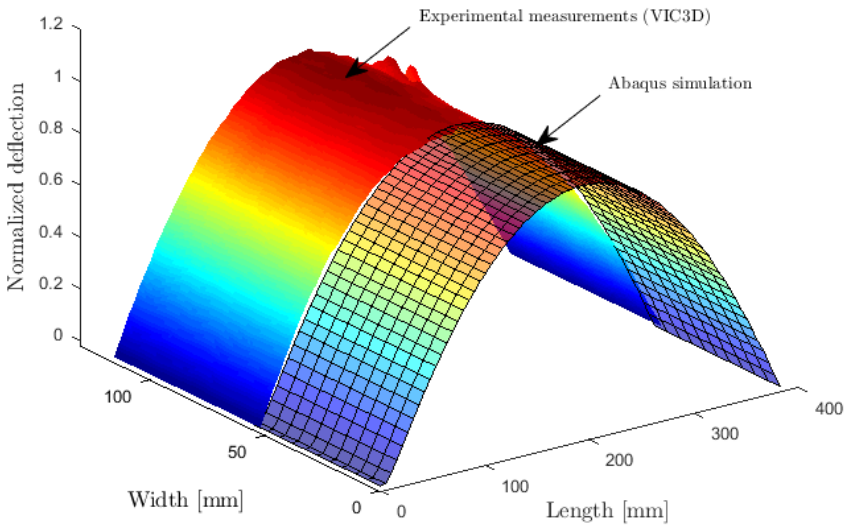

Figure 2. Comparison between the deformation measured experimentally and the computed deformation at room temperature of a thick asymmetric plate reinforced with 3D interlock fabric.

The temperature and degree of cure evolution during the manufacturing is presented in Figure 3. The computed stresses and displacement in the center of the plate are shown in Figure 3. A comparison between the stresses and displacement computed for a linear viscoelastic and an elastic model is presented. The manufacturing process can be divided in four sections, namely

a) **Resin curing**: A first phase where the matrix cures completely. During this stage, the temperature remains constant during the first 80 minutes (a.1) and then it increases in 20°C (a.2). The stresses generated during the first period are governed by the chemical shrinkage of the matrix. During the heating (a.2) the stresses are generated by a combination of chemical shrinkage and coefficient of thermal expansion mismatch. The viscoelastic model (black) present a stress relaxation over time, this phenomenon is more accentuated during the heating (a.2). This phenomenon is not observed in the elastic model (gray). During this stage the plate is constrained by the tool, and therefore the computed displacement is zero.

b) **Post-cure:** A second phase where the temperature and degree of cure remain constant. The

computed stresses and displacement remained constant during this period as well for both, elastic and viscoelastic models.

c) **Cool-down inside the mold:** During this section, the plate is cooled down inside the tool. The stresses generated are governed by the coefficient of thermal mismatch between the two plies of reinforcement.

d) Cool-down free standing: During the final phase, the plate is released from the tool and cooled-down by natural convection. Releasing the plate of the tool allow the reduction of the internal stresses and induced to a geometrical distortion. The final displacement obtained by the viscoelastic model is lower than for the elastic model. This can be explained by the residual stresses relaxation observed during the previous phases.

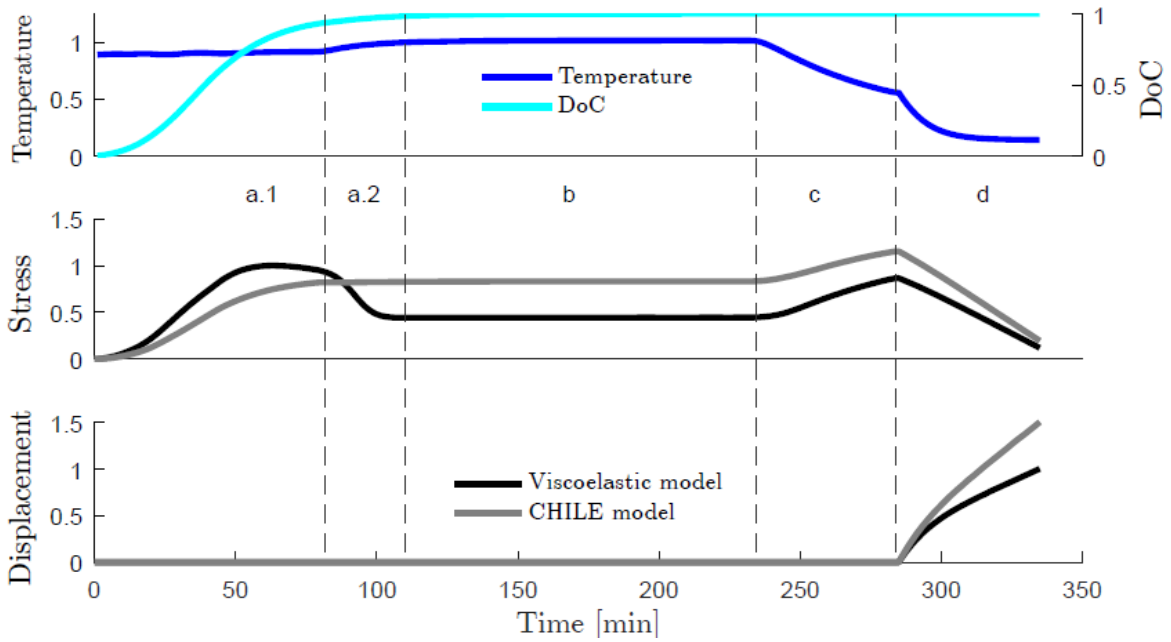

Figure 3. Temperature and degree of cure evolution during the manufacturing and the stress and displacement computed numerically with a viscoelastic and an elastic model for an asymmetric plate reinforced with 3D interlock fabric.

Finally, Figure 4 shows the effect of a free-standing post-cure in the plates' deflection at room temperature. An increment of 11% was measured experimentally after having submitted the plate for a 150 minutes isotherm at 140°C. The numerical simulations carried out with an elastic and a linear viscoelastic model suggest that the increment in the plates' deflection is caused by the viscoelastic behavior experienced by the resin matrix at high temperatures.

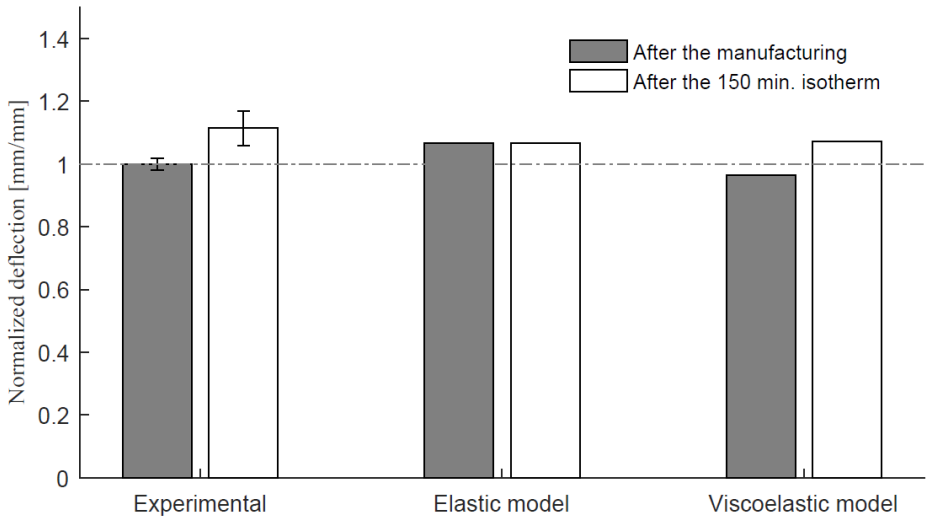

Figure 4. Maximal plate deflection at room temperature after the manufacturing (gray) and after the 150 minute isotherm.

5. CONCLUSION

In this study the geometrical distortion of asymmetric plates reinforced with 3D interlock fabric have been studied. A fully integrated simulation code has been developed to compute the geometrical instabilities developed during the manufacturing of composite plates. Three modules were used to simulate the injection stage and the thermo-chemical and thermo-mechanical phenomena. The predicted distortion of the plates show a good agreement with the experimental measurements. A comparison between a linear elastic and viscoelastic model have been presented. The results suggest that a viscoelastic model predicts more accurately the geometrical distortion evolution during the manufacturing and post-manufacturing processes.

The fully integrated simulation code proposed in this work allows to compute accurately the geometrical distortion triggered by the residual stresses generated during the RTM process.

ACKNOWLEDGMENT

The authors would like to acknowledge Safran Group and the Canada Research Chair program for the financial support and for providing the resin and reinforcements used in this work. The National Science and Engineering Research Council (NSERC) of Canada, the Fonds Québécois pour la Recherche sur la Nature et les Technologies (FQRNT), the Canada Foundation for Innovation (CFI) and of the Ministère de l'Éducation du Québec are gratefully acknowledge for their contribution with the infrastructure and expenses of the composite laboratory.

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