Numerical modelling of thermoplastic resin behaviour for thermoforming of laminates composed of non-crimp fabrics

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Abstract. Although composite materials have been used for many years in aeronautic and defense industries, the interest in the automotive industry has grown only recently. However, since they are expensive, aeronautic materials cannot be directly used for automotive and new woven fiber composites are being developed such as Non-Crimp Fabrics (NCF) with thermoplastic resin. Woven fiber composite material properties depend on many parameters such as non-linearity of tensile stiffness in yarn direction, shearing effect between fibers, temperature and strain rate dependency. Numerical simulation becomes a helpful tool which can be used to estimate the risk of defects after forming. A reliable characterization of resin behavior with respect to the process temperature and speed will allow users to optimize the process and reduce development cycles.

In this study, we investigate a method to model a NCF thermoplastic composite taking into account both thermal and strain rate dependency using the non-linear finite element solver RADIOSS®. A new multi-layer property is used to model the NCF resin and fabric components. Fibers are modeled with a hyper-elastic anisotropic fabric material model available in RADIOSS, and the resin is modelled as an elastoplastic thermal and strain-rate dependent material. The laminate behavior is characterized using data from Bias tests in two different directions and validated process simulation. A numerical study is used to show the influence of process temperature and speed on the final shape and presence of defects. The first section in your paper

1. Introduction

Nowadays, several types of continuous fiber reinforcement for advanced composite materials are available in the market like woven, non-crimp and braided fabrics. Textile industries are improving their weaving and stitching methods in order to decrease cost and improve performances. One of the most important barrier to the composite usage is the manufacturing process. It is slower and more expensive than processes associated with more traditional materials like metals increasing the final product cost.

Some automated manufacturing methods have been developed in order to make composite parts competitive. One of these methods is thermo-forming which benefits from all the know-how acquired from metal press forming also known as hot stamping [1]. Traditionally, process design has been done by trial and error which increases cost and the product development time. A large number of parameters such as temperature, tool speed, fabric structure, resin behavior etc. can further increase the level of complexity. Under such situation, finite element analysis (FEA) seems to be a powerful tool to design
and optimize process parameters through simulation. In the case of composite thermo-forming, material modelling is one of the most important aspects for the accuracy of simulation. Few material models that have been developed for Uni-directional (UD) [2] and woven [3-5, 6] composite fibers but much less for NCF. Two main approaches exist in literature. The first one consists of modelling NCF as two orthogonal fiber systems using two laminas [7]. The other one combines viscoelastic shells and 1D elements to represent the whole fiber, resin and stitch assembly.

In this paper, a pragmatic approach will be presented using a combination of fabric material laws already available in RADIOSS [8] and two different behaviors associated with resin, elastoplastic (law73) or viscoelastic (user law) both with thermal dependency. The material behavior with these two approaches will be identified using bias tests and applied to a thermo-forming simulation of an industrial part.

2. NCF Material Model

The non-crimp fabric to be simulated is composed of two UD (Carbon) plies and one two polymer (PA6) veils as shown in figures 1 and 2.

![Figure 1. NCF material.](image1)

![Figure 2. Scheme of one ply.](image2)

Veils will melt during the process and impregnate both UD plies. This assembly will be reduced to three components that will be modelled as plies (upper UD, polymer, bottom UD) in one laminate. A multilayer shell element available in RADIOSS allows the usage of different material laws inside the same laminate. A composite fabric material law is assigned to the UD plies (0.1mm) and law 73 or user material to the veil-resin ply (0.1mm).

2.1. Fiber Model

The fiber material is assumed to be hyper-elastic anisotropic. Tensile stiffness in two independent yarn directions can be defined as linear or non-linear, and softening property can be added. Material non-linearity behavior is handled using stretch coefficient in each yarn direction. This coefficient models the initial fiber stretching before stress occurs in a physical forming process as shown in Fig. 3. The shear is defined as a function of the angle between warp and weft fiber directions as shown in Fig. 4.
Figure 3. Yarn directions behavior

Figure 4. Shear behavior

With this material law, users can set the initial angle between both directions and by doing so, simulate non-orthogonal fabrics. In our case, stitch direction is assumed as direction 1 and UD fiber as direction 2. In that case, we’ll find an angle of 45° between stitch and UD for the upper ply and -45° for bottom one. The warp and weft directions are coupled in tension and uncoupled in compression as shown in bending generates global stresses only in compression. Each fiber is described as a nonlinear beam and the two warp and weft fibers are connected with a contacting spring. A bending factor of 0.001 is defined to ease the Young’s Modulus when the weave is in compression. This bending factor also defines the curvature of the stress-strain curve for a non-linear stiffness model. Fiber behaviour can be also modelled by stress-strain curves.

2.2. Resin Model

As mentioned under introduction, we’ll try two different approaches to model the resin. We need to take into account the resin influence on the global composite stiffness during the stamping process and be able to capture the strain rate and temperature influence on the deformation pattern. First approach is already available in RADIOSS (law 73) and consist of an elastoplastic material model based on orthotropic Hill plasticity with thermal and strain-rate dependency. For our purpose, we consider resin as isotropic and only thermal dependency will be introduced (by curves) as shown in figure 5. Yield stress is chosen to be very small to trigger plasticity early.

Second approach has been implemented using the User-material framework in Radioss. In this case, we model the resin behavior as viscoelastic adding a simplified thermal dependency. A general Maxwell element model is implemented [9] with ten viscous contributions. Following the works of Guzman et al [10], we introduce a linear dependency with respect to the temperature:

$$\gamma_i(T) = \alpha_i T + \beta_i$$

and only two Maxwell elements are used. The resultant behavior of this material law is shown in the following figure:
3. Validation of Material Models

Tests are conducted in an oven and repeated at various temperatures up to 275°C, just under the PA6 melt temperature. Two directions are tested with stitch running horizontally and vertically. Mechanical response is measured at 250°C and then thermal dependency is at 200°C, 150°C and 100°C. Results for elastoplastic and viscoelastic materials are shown in the following figures.
The viscoelastic model is compared only for temperatures that are close to melt point, the reason being this law is aimed to simulate only the thermal stamping process and we assume the temperature will not vary much during the process. To capture correctly the change of material behavior beyond these temperatures, it is necessary to introduce a thermal dependency in the elastic modulus in addition to the viscous part. That would represent the crystallization of the resin.

4. Thermo-forming model

The thermo-forming model shows a channel-like geometry where the challenge is to achieve a wrinkle-free part. The laminate is composed of 7 NCF plies with an initial temperature of 300°C. Tools (die and punch) are set up at constant temperature (270°C). Two types of contact are modeled, one between the tool surface and composite plies and the other between the plies. Both contacts allow heat exchange between the parts in contact. In the case of ply to ply contact, a generalized viscous friction law is used, following the equation below:

\[
\mu = Fric + C_1 \cdot p + C_2 \cdot V + C_3 \cdot p \cdot V + C_4 \cdot p^2 + C_5 \cdot V^2
\] (2)

Radiation and convection are also activated during the thermo-forming simulation even though the stamping process is too fast to allow a significant heat exchange through these phenomena. All thermal parameters are accelerated 5 times to decrease the simulation time.

Plies are meshed with elements of 2 mm formulated with reduced integration and physical stabilization schemes [11]. All the plies are put in tension by 8 clips modeled by rigid bodies and beam spring elements. Die movement is controlled by imposed velocity in order to get a final gap between tools equal to part thickness.

![Figure 12. Thermo-forming finite element model.](image)

5. Results

Test results are shown in figures 13 and 14. Fiber buckling is observed in the part (red circle in Figure 13). Some fiber sliding is observed on the right side of the part which cannot be predicted with the current approach. Other interesting detail about the ply bending stiffness is the final deformation pattern and the size of wrinkles outside the melted zone (Figure 14).
Figure 15 and 16 show the UD ply direction for both elastoplastic and viscoelastic approaches. Globally, both results are quite close to each other and show a direction change in the same zone where fiber buckling is observed.
Figures 15 and 16 show the UD ply direction for both elastoplastic and viscoelastic approaches. Globally, both results are very close to each other and point out a direction change in the same zone where fiber buckling is observed. One way to estimate the risk of fiber buckling is to look at strains in UD direction (Figure 17 and Figure 18). Both models show a strong compression in the same region as buckling is observed. However, the viscoelastic law seems to predict a higher value of compression and so a higher value of fiber buckling. Thinning for up and bottom plies can be observed in figures 19 and 20. This value is computed from the resin layer strains. Trends are quite similar with a higher estimation of thinning value for the viscoelastic model. Thickness augmentation due to compression seems really close for both cases.

6. Conclusions

A fully thermo-mechanical simulation of NCF composite press forming has been presented in this study. Two different approaches have been developed to simulate the influence of polymer resin on the composite plies deformation during the process. The first approach is based on an elastoplastic material law with thermal and strain rate dependency already available in the industrial code RADIOSS. The second approach is based on a viscoelastic material law with thermal dependency in the viscous
contribution in order to reproduce the polymer resin behavior for temperatures close to the melt point. This material law has been implemented in an user-material law for RADIOSS. Validation of material models is presented using bias tests data from different temperatures showing the capability of elastoplastic approach to go from melt temperature to smaller ones. Both approaches are applied to an industrial process and compared with experimental observations. Elastoplastic and viscoelastic approaches provide a good estimation of fiber directions and highly compressed zones leading to fiber buckling in the real sample.

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