ANALYSIS OF FIBER PREFORMING FOR IMPROVED MANUFACTURING OF CURVED PARTS BY FLEXIBLE INJECTION

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1 General Introduction

Advanced composites made of continuous fibers and thermosetting resin possess a widely recognized potential for structural applications. However, such materials may be hard to manufacture with consistent quality when a complex geometry is considered. Manufacturing defects such as resin rich zones or thickness gradients have indeed been observed in strongly curved parts made by autoclave [1, 2] or Resin Transfer Molding (RTM) [3, 4].

A new manufacturing technique called Flexible Injection is currently being developed at École Polytechnique de Montréal to allow faster and more reliable processing of high performance parts [5]. Preliminary work with curved geometry showed that manufacturing faults may appear at the corners of curved components made with this process [6]. The goal of the present paper is to understand the mechanisms that lead to such defects and propose corrective solutions by analyzing the deformation of the fiber bed during processing.

2 Manufacturing Experiments

2.1 Flexible Injection setup

The test part is a rectangular panel possessing two 90º corners (i.e., a stair-shaped component). Fig.1 shows the mold configuration at the beginning of the processing cycle. A flexible membrane is used to separate the overall chamber into a part cavity containing the fibrous preform and a compaction cavity (above the membrane). It can be noted that the two curved regions of the part are different in nature. As represented in Fig. 1, the top corner is associated with a convex mold (membrane on the the outside of the curve) and the lower corner corresponds to a concave tool (membrane on the inner side). This manufacturing setup was used to fabricate a series of parts following the procedure described below:

- A controlled quantity of resin was first injected in the part cavity.
- A pressurized fluid (called compaction fluid) was then injected in the compaction cavity to push the membrane and complete the impregnation of the fibers.
- The part was cured under constant pressure of the fluid.
- After completion of the cure, the fluid was removed from the cavity and the part was demolded.

All the experiments were carried out at room temperature with a constant injection pressure (p_i = 200 kPa) and a constant compaction pressure (p_c = 600 kPa).

2.2 Materials

The parts were fabricated with vinyl ester resin Derakane 411-350 and E glass quasi-unidirectional fabric Saertex Saeruni. Prior to processing, the fibers were preformed by spraying a small quantity of resin on the fabric plies to act as a thermosetting binder. The stacking was then compacted under a constant preforming pressure p_p between two rigid plates reproducing the stair shape of the part. The radii of curvature of the preforming tool were controlled by applying self-hardening modeling clay with a radius gauge in the corner of the plates. After cure of the binder, this preforming procedure allowed obtaining semi-rigid preforms that can be handled easily. A typical stair-shaped preform is shown in Fig. 2. All the preforms prepared during the study consisted of 5 plies of fabric oriented in the 0º direction of the part.

3 Analysis of Fiber Bed Deformation

With Flexible Injection, the shape of the product results from a consolidation stage of the impregnated preform. For the particular case of strongly curved geometry, the deformation of the fiber bed must be analyzed throughout the entire production cycle to understand how the final geometry develops.

3.1 Corner preforming

During the first stage of the production cycle, the fabric plies are forced to adopt a curved geometry between two rigid preforming plates. This configuration is similar to the mold closing stage found in RTM. For tightly bent shapes, it has been observed that fibers tended to be more compacted at the corner of the tool [3, 4]. This corner thinning behavior illustrated in Fig. 3 can be quantified by the following ratio:

$$r_h = \frac{h_c}{h} \qquad (1)$$

where h is the thickness of the flat section and h_c is the thickness at the center of the curve.

The corner thinning phenomenon was studied by mounting a simple apparatus on a MTS testing machine to reproduce the corner preforming conditions. The experiments were repeated for two inner preforming radii r_p (1.25 mm and 6.5 mm) and thicknesses ranging from 3 to 5 mm. In every case, the outer preforming radius R_p was sufficiently small to not come into contact with the fibers. The obtained results are reported in Fig. 4. As can be seen, the thickness ratio increases when the preforming thickness decreases and when the inner radius increases. By influencing the placement of the fibers in the corner, the preforming conditions are then likely to affect the geometry of the resulting preform and, in turn, the quality of the final part in the curved areas.

Solid lines shown in Fig. 4 were obtained with a simplified 2D finite element model developed with ANSYS. The initial geometry and the boundary conditions used for the simulations are shown in Fig. 5. The preforming tool was modeled as a very rigid isotropic material. The mechanical response of the fiber bed was modeled with a transversely isotropic constitutive law implemented in a usermat subroutine. The transverse behavior of the fibers was represented by the following nonlinear compaction model:

$$\sigma_T = E_0(\varepsilon_T - \varepsilon^*) - A_0(\varepsilon^* - \varepsilon_T)^{B_o} - \sigma^* \qquad (2)$$

where σ_T and ε_T are the through-thickness stress and true strain; E_0, A_0 and B_0 are fitting parameters obtained from planar compaction tests. ε^* and σ^* are used to take into account the difference between the local initial thickness h^* and the natural thickness of the fabric h_0. These parameters were calculated with the following equations:

$$\varepsilon^* = \ln\left(\frac{h_0}{h^*}\right) \qquad (3)$$

$$\sigma^* = E_0(-\varepsilon^*) - A_0(\varepsilon^*)^{B_o} \qquad (4)$$

Finally, linear relationships were used to describe the longitudinal and shear behavior of the fiber bed:

$$\sigma_L = E_L \times \varepsilon_L \qquad (5)$$

$$\sigma_{LT} = G_{LT} \times \varepsilon_{LT} \qquad (6)$$

All the model parameters are listed in Table 1. As can be seen in Fig. 4, the simulation results are in good agreement with the experimental observations. In the next section, the model is extended to the entire production cycle of Flexible Injection.

3.2 Overall production cycle

The simulation of fiber bed deformation was carried out for the 4 different stages of the production cycle presented in Fig. 6. Firstly, the preforming step was simulated as described in the previous section. At the end of this stage, the constitutive law of the fibrous preform was modified to replicate the effect of binder cure on the preform mechanical properties. The shear modulus was thus increased from 0.08 MPa to 5.1 MPa to reproduce the limitation of interply sliding. Moreover, the impact of binder cure on the compaction behavior was accounted for by replacing the through-thickness constitutive equation (2) by the following expression:

$$\sigma_T = E_2(\varepsilon_T - \varepsilon_2) - A_2(\varepsilon_2 - \varepsilon_T)^{B_2} - \sigma^* \qquad (7)$$

where E_2, A_2 and B_2 are fitting parameters obtained from planar compaction tests of preformed samples and ε_2 satisfies the following relation:

$$\sigma_1 = E_2(\varepsilon_1 - \varepsilon_2) - A_2(\varepsilon_2 - \varepsilon_1)^{B_2} - \sigma^* \qquad (8)$$

where σ_1 and ε_1 are the through-thickness stress and strain at the end of the preforming stage.

After changing the preform properties, the preforming tools were removed from the model and the preform was let free to recover from the preforming state. As seen in Fig. 6b, the simulation shows a modification of the preform angle during this elastic springback. This prediction is in agreement with the actual shape of the preform (see Fig. 2), at least from a qualitative point of view. When the preform is laid in the manufacturing setup, it is forced to conform to the stair shape of the bottom mold (refer to Fig.1). As shown in Fig. 6c, this step was simulated by applying a small draping force on the extremities of the preform to bring it into contact with the processing tool. Finally, a uniform processing pressure was applied on the preform to reproduce the processing stage (see Fig. 6d). It must be noted that the pressure is directly applied on the fibers and that membrane deformation and resin flow are not considered in the model.

4 Influence of Processing Conditions on the Quality of the Manufactured Parts

Manufacturing experiments and numerical simulations were used to investigate the influence of processing conditions on the quality of the composite component in the curved regions. Three parameters were studied:

- fiber volume fraction V_f;
- inner preforming radius r_p;
- preforming pressure p_p.

The following sections present two selected examples illustrating the importance of the preforming conditions.

4.1 Preforming geometry

Fig. 7 shows cross-sectional images of the concave corner of parts manufactured with a fiber volume fraction of 60% and two different inner preforming radii r_p. With r_p = 4 mm, a large resin rich zone is observed on the outer side of the corner. This defect comes from an open gap existing between the preform and the processing tool and is predicted by the numerical simulation. Moreover, parametric studies indicate that decreasing the inner radius to 1 mm helps eliminating this defect. As seen in Fig.7, this conclusion is well supported by the experimental observations.

4.2 Preforming pressure

Apart from resin rich zones, curved sections of the part may also exhibit thickness variations. For example, Fig. 8 shows a corner thinning behavior in the convex curved region of a part manufactured with a fiber volume fraction of 53%. Both numerical simulations and experimental observations indicate that this default can be significantly diminished by reducing the preforming pressure from 100 kPa to 30 kPa.

5 Conclusion

Flexible Injection is a new Liquid Composite Molding technique that can potentially offer shorter cycle times and lower void content than traditional RTM. However, the flexibility of the tooling can be a problem when strongly curved shapes need to be produced. This paper investigated this specific behavior by analyzing the deformation of the fiber bed during the entire production cycle. The methodology was based on a combination of numerical simulations and manufacturing experiments. It is shown that the preforming parameters have a direct impact on the layup quality in the curved regions. Overall, the study suggests that thorough knowledge of the fibers mechanical behavior is necessary to select appropriate preforming conditions and produce defect free parts over a wide range of fiber volume fractions.

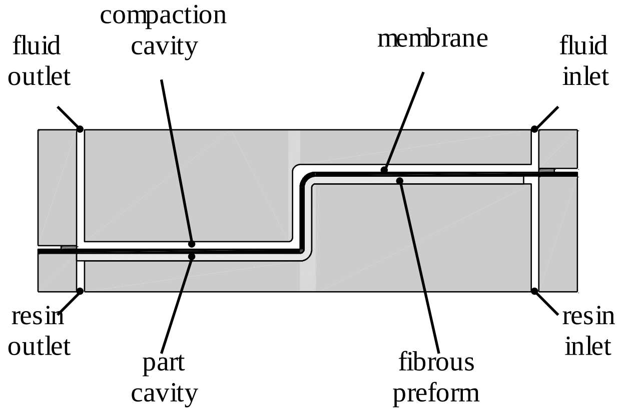

Fig.1. Schematic representation of the manufacturing mold.

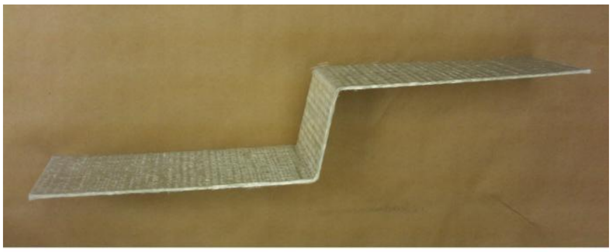

Fig.2. Semi-rigid fibrous preform.

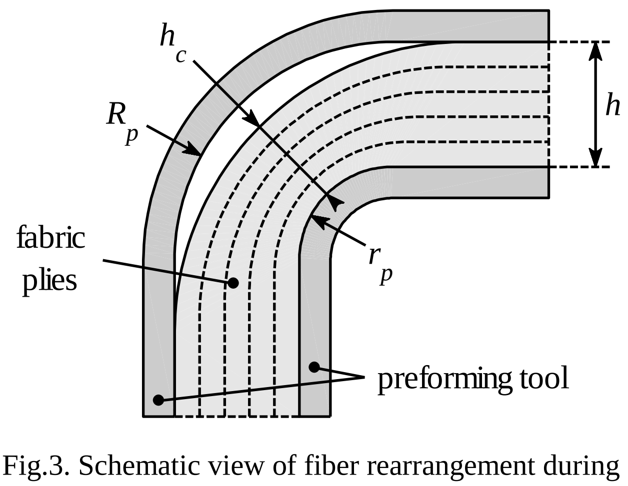

Fig.3. Schematic view of fiber rearrangement during corner preforming.

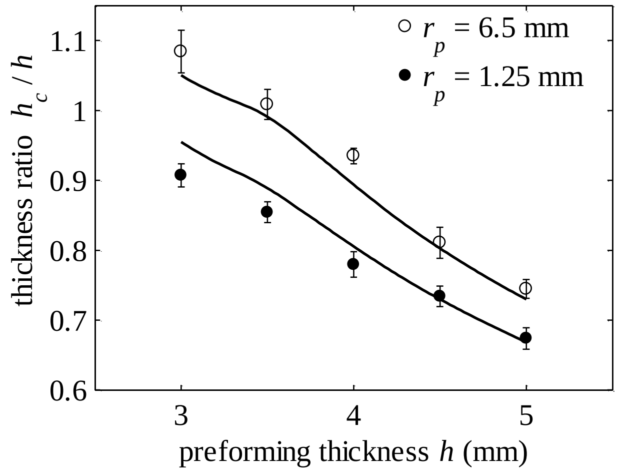

Fig.4. Variation of the fiber bed thickness at the corner of the preforming mold with inner radius r_p.

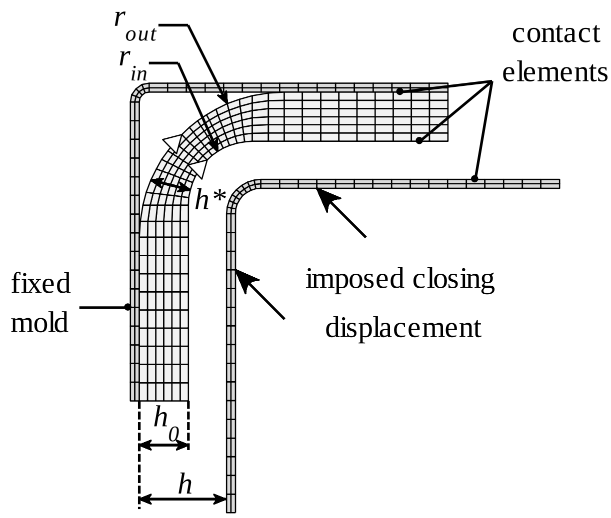

Fig.5. Finite element model used to replicate corner preforming.

Table 1. Summary of input parameters for the finite element model

Initial geometry (mm)				
h_0		r_{in}		r_{out}
5		6.5		14.6
Mechanical properties of pristine fabric				
E_0 (kPa)	A_0 (MPa)	B_0	E_L (GPa)	G_{LT} (MPa)
47	8	5.9	27	0.08
Mechanical properties of preformed fabric				
E_2 (kPa)	A_2 (MPa)	B_2	E_L (GPa)	G_{LT} (MPa)
55	44	5.8	27	5.1

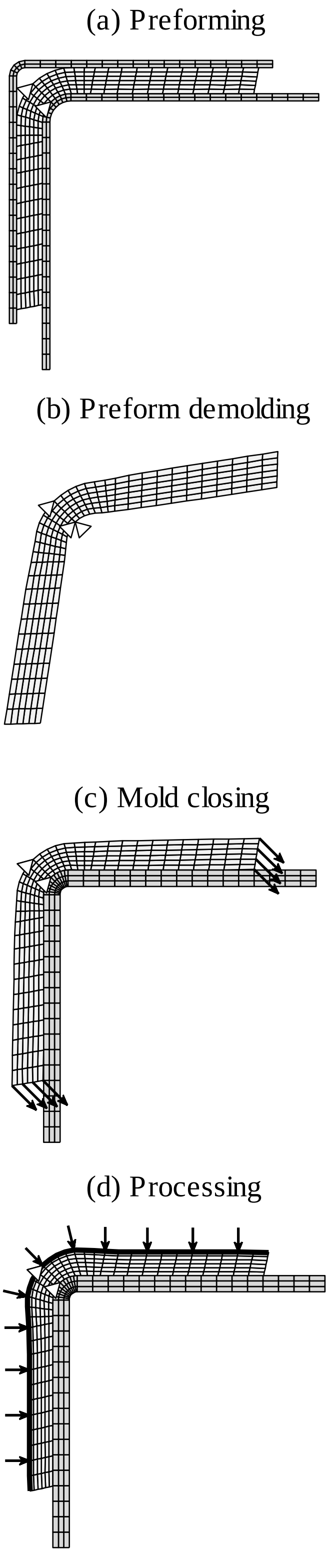

Fig.6. Simulation of fiber bed deformation in the convex corner during the complete production cycle.

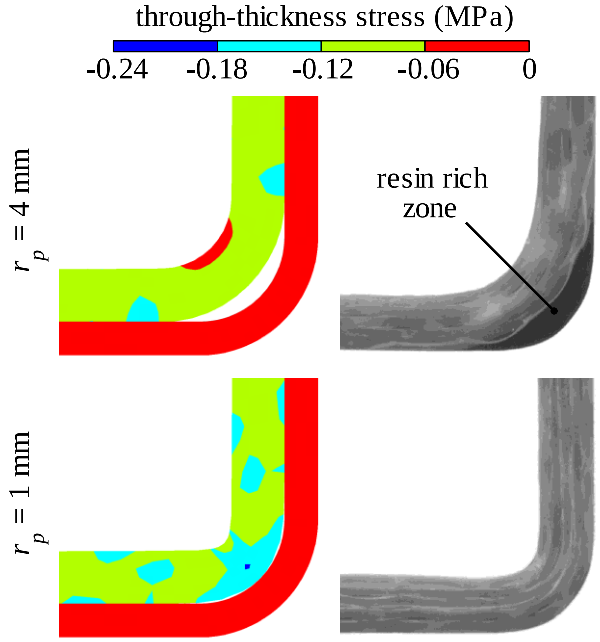

Fig.7. Influence of the inner preforming radius r_p on the quality on the concave corner (V_f = 60% and p_p = 100 kPa).

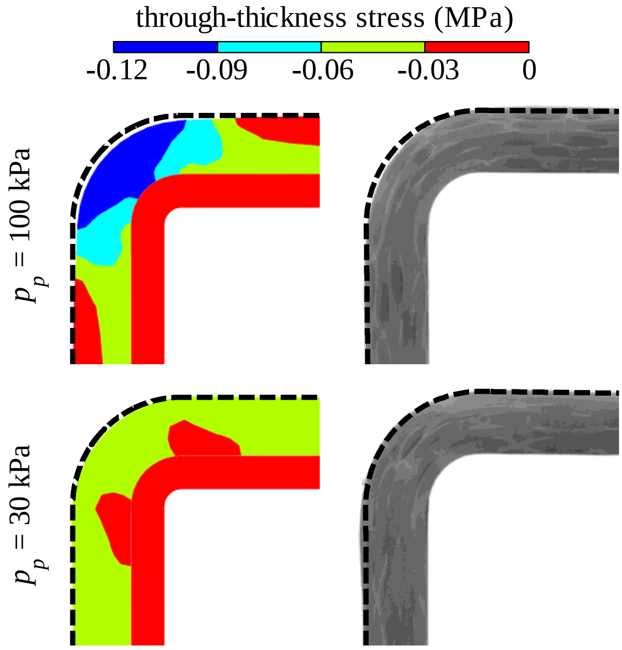

Fig.8. Influence of the preforming pressure p_p on the quality on the convex corner (V_f = 53% and r_p = 3 mm; dashed lines represent perfect thickness profiles).

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