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# A 2.5D Model of the Resin Infusion Process, Experiments and Simulation

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## ABSTRACT

Resin Infusion (RI) is one of the Liquid Composite Moulding processes, and is increasingly being used to manufacture high performance composite structures. Application of a flexible bag as one part of the mould results in laminate thicknesses varying significantly during filling, and in the period after filling, during which final laminate quality is reached. A 2.5D RI simulation has been developed, and is compared to detailed experiments for three moderately complex preform shapes. Evolution of resin pressure is predicted with good accuracy, and laminate thicknesses changes are moderately underestimated. SimLCM is demonstrated to be superior to a constant thickness Resin Transfer Moulding simulation, and is currently being extended to model the post-filling period.

## KEYWORDS

Resin Infusion; VARTM; Liquid Composite Moulding; simulation

## 1. INTRODUCTION

Resin Infusion (RI) is part of the Liquid Composite Moulding (LCM) process family. The term LCM describes the closed mould processes in which a liquid polymeric resin is impregnated through a fibrous reinforcement. Commonly applied LCM processes include Resin Transfer Moulding (RTM), Compression RTM (CRTM), RTMLight and Resin Infusion.

During manufacture with an LCM process, the operator typically has little control over the advancement of the flow, and successful process development by trial and error requires experience and can be long and expensive. Reduction of development costs requires a good understanding of the process physics, and can benefit from development of an accurate simulation tool. Significant effort has been placed into establishment of RTM and CRTM simulations that accurately predict fill time, flow front advancement and dry spot formation [1-

4]. These two processes, through the use of rigid mould tools, allow for accurate control of the laminate thickness and therefore of the fibre volume fraction. A simulation tool therefore only requires an acceptable reinforcement permeability model to provide flow data.

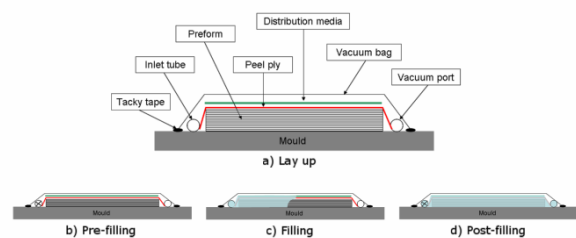


Figure 1: Steps of the RI Process

As opposed to RTM and CRTM, RI uses a single sided mould, the reinforcement being contained within a cavity formed and sealed by a vacuum bag. As the vacuum bag employed during the process provides minimal flexural rigidity, local compaction of the fibrous reinforcement is governed by the pressure difference between the inside of the cavity and the external atmospheric pressure. Local laminate thickness will vary in relation to the resin pressure inside the cavity, as will the reinforcement permeability which is governed by the local reinforcement architecture [5-7]. Not only is the resin flow affected by these changes in laminate properties, but it is also necessary to understand and simulate these variations in order to be able to predict and control the final part quality.

If infusion is to be used in the aeronautics industry as a replacement for autoclave prepreg process, simulation tools will have to not only predict the flow during the filling stage but also the evolution of the laminate throughout the filling and post-filling up to the curing of the resin. This paper presents experimental and numerical results, from a program aimed at developing SimLCM, a generic LCM process simulation.

## 2. EXPERIMENTAL OBSERVATIONS

### Setup

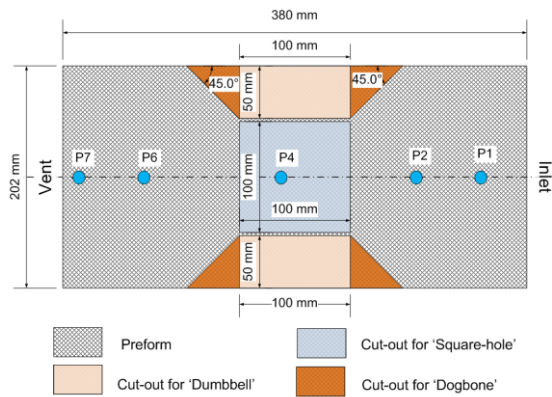
The RI monitoring setup used for the experiments presented here was described in [6-8]. As well as recording inlet and vent pressure, fluid pressure was recorded at five points along the laminate (35, 90, 200, 310, and 365 mm from the inlet, P1, P2, P4, P6, and P7 respectively). Laminate thickness was measured across the whole surface using a stereophotogrammetry system [6,8].

### Plan of Experiments

To provide challenging validation cases for SimLCM, three different 2D shapes were infused. All shapes were based on a 380x202 mm rectangular preform. The ‘Square-hole’ shape has a 100x100 mm square removed at centre, the ‘Dumbbell’ has 100x50 mm cutouts on each side halfway along the length, and the ‘dogbone’ is a repeat of the ‘dumbbell’ but with the cutout tapered to 45°. Schematics and dimensions of the preform shapes are depicted in Figure 2.

The ‘dumbbell’ and ‘square-hole’ are identical regards simulation. Completing both experiments allows for pressure data to be taken along two paths, without adding more pressure transducers to the mould. The ‘dogbone’ addresses the effect of a tapered transition.

All experiments were performed with the inlet at atmospheric pressure, and the vent at 4.7 mbar. The preform consisted of 10 layers of a 450 g/m<sup>2</sup> Chopped Strand Mat (CSM) that was characterised for compaction and permeability [9,10]. The test fluid was a mineral oil, Mobil DTE Heavy, with a viscosity of 0.2 Pa.s at 20°C.

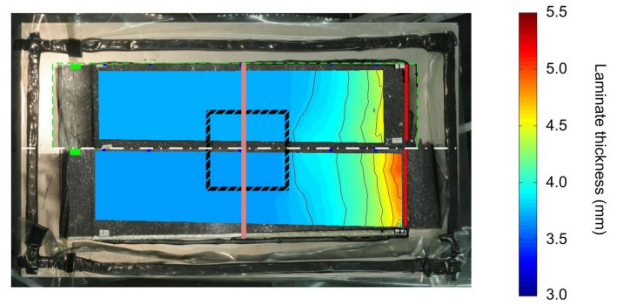


**Figure 2:** Schematic description of the preform shapes.

### Observations

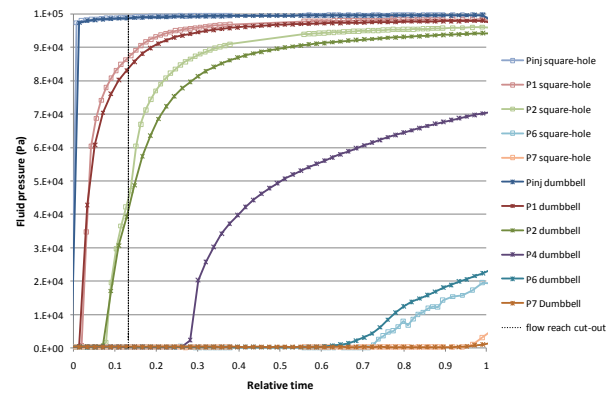
When comparing the ‘square-hole’ and ‘dumbbell’ at the same relative fill time, it is observed that the thickness distribution (Figure 3) and flow front shape and position are very similar. In Figure 3, the thickness map of the ‘dumbbell’ experiment (top) was overlaid on the processed image of the ‘square-hole’ experiment (bottom), lining up the cut-out of the dumbbell with the top half of the square hole. It is therefore possible to

assume pressures measured along the centerline of the ‘square-hole’ infusion are equivalent to those along the outside edge of the ‘dumbbell’ infusion, and vice-versa.



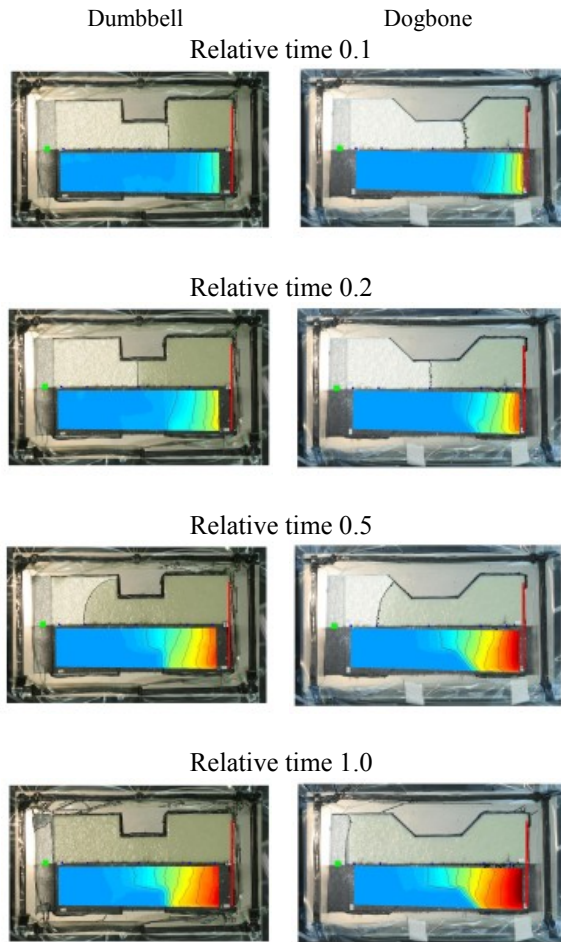
**Figure 3:** Comparison of the thickness distribution in the ‘dumbbell’ (top) and ‘square-hole’ (bottom) when the flow front (in pink) reaches 200 mm from the inlet.

Figure 4 presents fluid pressure traces measured during the ‘dumbbell’ and ‘square-hole’ experiments. When the flow front reaches the cut-out, there is an increase in the rate of pressure increase at P2 and also in a lesser amplitude at P1. The increase of pressure is more significant in the area in line with the cutout (‘square-hole’) than in the area where there is continuity of the reinforcement along the length (‘dumbbell’). This pressure gradient across the width indicates that there is a small transverse flow; the fluid does not stagnate in the corners.



**Figure 4:** Comparison of the fluid pressure along the laminate during filling stage of the ‘dumbbell’ and ‘square-hole’ experiments.

Figure 5 presents side by side measured laminate thickness distributions as well as flow front progression at four key instances during filling for the ‘dumbbell’ and ‘dogbone’ shapes. The thickness scale on this figure is the same as in Figure 3. On each image, the position of the inlet is indicated by a red line, the transducers are marked with a blue dot, and the vent is represented by a green square. Additional discussion is provided on these scenarios in the following section in the context of the simulation results.



**Figure 5:** Evolution of flow front and laminate thickness during filling of the ‘dumbbell’ and ‘dogbone’ experiments.

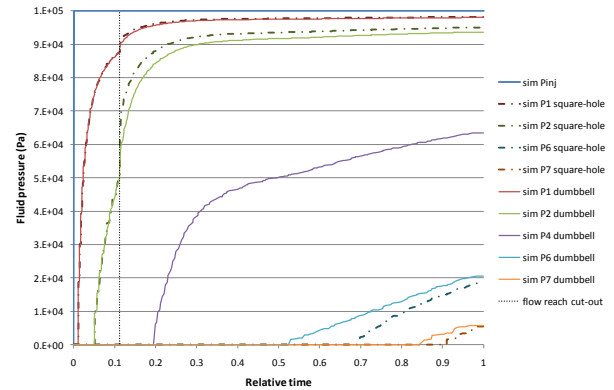
### 3. DEVELOPMENT OF THE SIMULATION

SimLCM is being developed for simulation of LCM processes using bags and semi-rigid tooling. Laminate thickness evolution is coupled strongly with mould deflections, and predictions will be made through both filling and post-filling, addressing what final laminate composition and thickness will settle to, and the time required. Comparisons are made here to the filling phase for moderately complex geometries. Empirical permeability and compaction models for the CSM have been described previously [6,9].

#### Results

Figure 6 presents in a similar fashion to Figure 4 the predicted evolution of fluid pressure at the same positions as the pressure transducers for the ‘dumbbell’ and ‘square-hole’ experiments. It is notable that the rise of pressure as the flow front reaches the cutout is more pronounced than in the experiments, particularly at P1. This might be due to the use of an elastic compaction model for the reinforcement; viscoelastic compaction behaviour would have a dampening effect, slowing the rate of pressure increase at P1 and P2. The final pressure

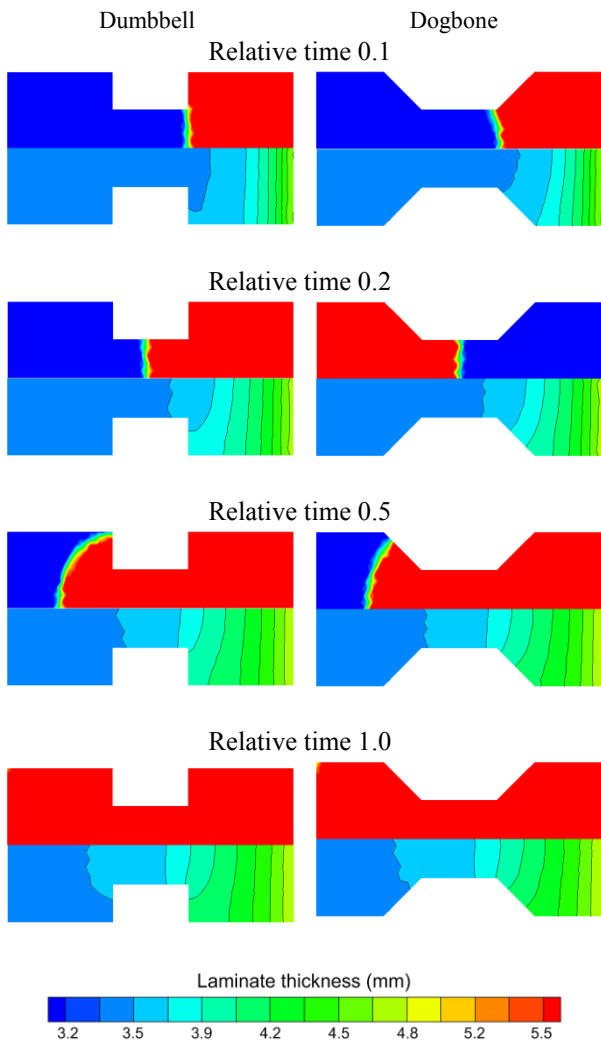
at P4 is slightly under-predicted while the pressures at P7 are over-predicted. However it was noted that the experimental pressures at P7 rose to the predicted level at the beginning of the post-filling. Despite those small differences, the simulation appears to provide good predictions of the evolution of fluid pressure.



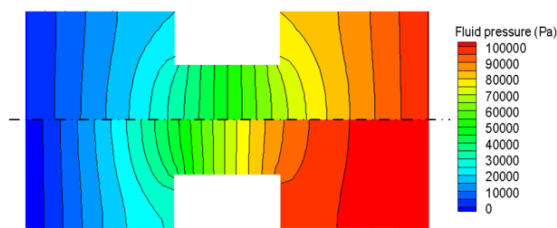
**Figure 6:** Comparison of the fluid pressure along the laminate during filling stage of the ‘dumbbell’ and ‘square-hole’ experiments.

Figure 7 presents flow front positions and laminate thickness distributions for simulation of the ‘dogbone’ and ‘dumbbell’ shapes, in a similar format as Figure 5. Comparing to Figure 5, it is observed that the flow front shape is predicted accurately, as is the shape of the thickness distributions. However, the magnitude of change of the laminate thickness appears underestimated to a modest extent.

From Figure 5 and 7 we observe that the flow front appears flatter in the ‘dogbone’ shape than in the ‘dumbbell’, particularly in the region beyond the cut-out. In this region there is a divergent flow from a narrow to a wider cross-section. The sharp transition of the ‘dumbbell’ shape may cause problems in manufacturing, as it is more likely to trap voids where the flow front hits the edge of the part. While an RTM simulation (assuming constant laminate thickness) can provide reasonable approximations of flow front progression, fill times will be better predicted by an RI simulation. In addition, fluid pressure and laminate thickness distributions at the onset, and through post-filling cannot be addressed. Figure 8 presents a comparison of the predicted pressure field at the end of filling, as predicted with an RI and an RTM simulation. As the RTM simulation does not take into account the change in laminate thickness and subsequent change in permeability, the pressure distribution is almost linear along the preform centreline. The RI simulation, taking into account laminate thickness variation and coupling of flow and thickness changes, predicts a significantly different pressure profile.



**Figure 7:** Simulation of the evolution of flow front and laminate thickness during the filling stage for the 'dogbone' and 'dumbbell' shapes.



**Figure 8:** Comparison of RTM (top) and RI (bottom) simulations of fluid pressure fields at completion of filling for the 'dumbbell'.

#### 4. CONCLUSION

This paper has presented recent development of the process simulation SimLCM to address resin infusion. Several complex 2D filling scenarios were presented, and compared to detailed experiments for validation. The simulation provides good predictions of flow progression and laminate thickness evolution, and provides a deeper analysis than that possible using a simple RTM

simulation. Ongoing work is focused on predictions through the post-filling stage of RI.

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