Integrated In-Plane Infiltration Simulations in the Design of Liquid Composite Processing

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SUMMARY: This study adopts the two-phase flow approach in the infiltration of a porous fibrous preform, considering a varying degree of fluid saturation across the preform. The infiltration simulations have been integrated with the numerical results of forming simulations based on the solid mechanics, finite element approach. The local fiber orientation and local fiber fraction predicted from the forming simulations are used in a permeability model to predict the in-plane distribution of permeability components across the shaped preform. The predictions of FLOWPOR, an in-house developed two-phase flow algorithm for both orthogonal and non-orthogonal structured grids, are successfully compared with experimental data of the flow progress in in-plane radial diverging flow, in-plane radial converging flow and flow in a hemispherical hat preform geometry.

KEYWORDS: infiltration, flow, simulations, permeability, liquid processing, composites.

INTRODUCTION

Composites manufacturing via the liquid processing route is a multi-stage process involving at least two totally different types of materials, the fiber reinforcement and the liquid curing resin. Hence, the computer modeling of such processes comprises the integration of simulations using numerical algorithms from multidisciplinary areas, covering both solid and fluid mechanics.

The first stage includes the computer simulation of the forming of fiber reinforcement, following a solid mechanics approach in this study. The required input data comprise the mechanical properties of the fiber reinforcement. Results of the forming simulation include the distribution of fiber orientation and fiber volume fraction which are going to affect both the permeability distribution of the fiber preform and the mechanical properties of the composite product. The current study utilizes the results of forming simulations using the finite element solid mechanics approach, where the fabric is considered as a solid deforming sheet with measured mechanical properties and friction properties between the fabric and the mold [1].

A major element of an integrated process analysis is the modeling and prediction of the permeability variation across the preform due to the deformation occurring during forming. In woven and other bidirectional fabrics, shear is the main mode of fabric deformation when the fabric is formed over a double curvature mold geometry.

The present study has used the most advanced model so far of predicting permeability as a function of shear angle in in-plane shear, being developed by Heardman et al [2]. The model needs as input data only the permeability of the unsheared fabric.
Once, the permeability distribution is predicted, analysis of the filling stage is carried out using Darcy's law. RTM-dedicated software packages include LIMS, developed by the University of Delaware [3], and RTMFLOT, developed by Ecole Polytechnique de Montreal [4]. Both these algorithms are based on the finite element numerical technique in solving for the pressure field, and the mass conservation equation for calculating the advancement of flow front.

However, flow simulation of the filling stage might not be well established yet in cases with large regions of partially saturated porous medium during the filling operation. This has been the reason for discrepancy in some permeability measurements reported in the literature. One of the explanations has been linked with the difference between the fronts of the flow in the meso-channels between the fiber yarns and the micro-flow between fibers inside individual fiber yarns, which can be of course translated into the existence of a partially saturated zone during filling. Antonelli and Farina [5] carried out computer simulations of basic mold geometries using the ABAQUS finite element software package which considers two-phase flow through the porous medium, a liquid and a gas phase. In this method, the flow advancement is illustrated from the contour plots of the degree of saturation and it is possible to identify a partially saturated region by the flow front during filling. Unfortunately, no comparisons with experimental data were published in that study [5].

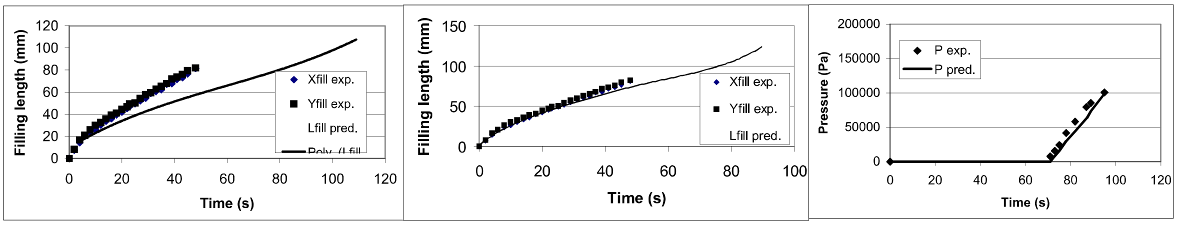
The present study includes modeling of flow through a porous medium of inhomogeneous permeability following the two-phase flow approach. A computer algorithm, FLOWPOR, has been developed for flow across both orthogonal and non-orthogonal structured grids and it has been validated by comparing predictions with experimental data of flow progress. The case-studies used in the computer simulations include radial outwards flow across a flat fibrous preform, reverse converging flow across a flat fibrous preform, and infiltration of a hemispherical hat preform with fluid injected at the center of the hat.

NUMERICAL SIMULATIONS AND RESULTS

The two-dimensional in-plane flow through a rectangular plate with central fluid injection was considered in Case-study I. The Newtonian infiltrating fluid was silicone oil of a viscosity of 104 mPa s which was injected under a constant injection pressure of 0.21 MPa. A rectilinear numerical grid of 25x25 nodes was considered in the computer simulations and the predictions from both ABAQUS and FLOWPOR compared well with the experimental data. It must be noted that the value of permeability inputted in the simulations has been derived from the experimental data of Case-study I.

Case-study II comprises the infiltration of an almost square-shaped fibrous preform plate of in-plane dimensions 248x246 mm, where the infiltrating fluid was injected at the preform perimeter under a constant pressure of 0.1 MPa while the mold was under vacuum of –0.1 MPa (so the injection pressure difference was 0.2 MPa).

The filling process consists of a radial converging flow. The value of permeability inputted in the simulations using either ABAQUS or FLOWPOR has been derived from the experimental data of radial diverging flow of Case-study I. Figure 1(a) presents the advancement of flow front at the mid-lines of symmetry (Lfill = 0.5(Xfill + Yfill)) as a function of time, as predicted by ABAQUS, which lies behind the experimental data. On the other hand, the predictions of FLOWPOR in Figure 1(b) agree very well with the experimental data. We believe that the main reason for this is that FLOWPOR predicts a larger unsaturated area behind the flow front in converging radial flow than ABAQUS which must be also true experimentally. Hence, the converging radial flow may be essentially faster than the diverging radial flow due to the fact that as the flow accelerates during filling in the converging flow, the micro-infiltration of fiber yarns takes longer to complete resulting in a larger unsaturated area during filling. Figure 1(c) presents a very good correlation of the pressures predicted by FLOWPOR with the corresponding experimental data from a pressure transducer located on the x mid-line, 25 mm from the center of the mold (radius of transducer port = 2 mm).



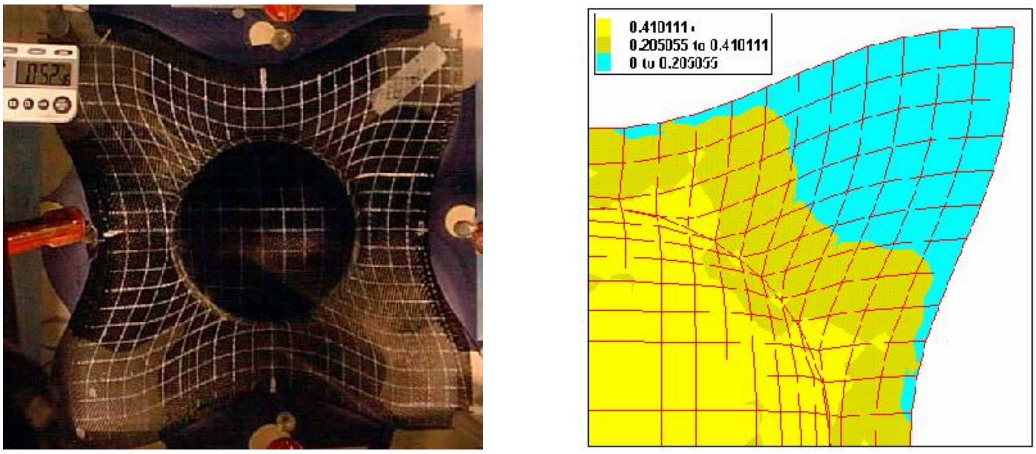
(a) (b) (c)

Fig.1. Case-study II: converging flow: predictions by (a) ABAQUS (b) and (c) FLOWPOR.

Case-study III involved RTM flow in a hemispherical hat preform with central injection. Initially, a constant homogeneous porous preform thickness of 4 mm was considered which would result in $V_f = 0.55$ in a unsheared fibrous preform (eg. at the dome of the hemispherical hat geometry). The forming simulations predicted a maximum shear angle of 45^{o} at the edge of the dome on the diagonal of the fabric which yields $V_f = 0.78$ at that location. This is certainly higher than the expected packing fiber volume fraction for woven fabrics ($V_{f,max}$ = 0.62-0.65) and such a molding would not be possible to be manufactured using RTM in the hemispherical hat geometry of homogeneous thickness of 4 mm.

An RTM experiment was carried out allowing for a larger homogeneous thickness of 5 mm. In this, flow-channelling and leaking was observed in the flow across the flow dome due to inadequate compression locally in the dome, whereas the flow progressed in smooth manner on the flat surface of the hat geometry, through the fibrous porous medium and in a petal pattern. Regarding computer simulations of the flow in the hemispherical hat geometry, ABAQUS exhibited numerical instabilities and only FLOWPOR gave fully numerical converged solutions in all case-studies during the whole filling. Fig.2 presents the numerical predictions of FLOWPOR. Due to symmetry, only quarter of the hemispherical hat geometry was employed in the flow simulations. A smooth flow progress through the fibrous preform in the dome part was predicted by FLOWPOR, due to the fact that only Darcy's flow was included in the FLOWPOR and there was no model of Poisseuille flow in FLOWPOR to predict flow leaking.

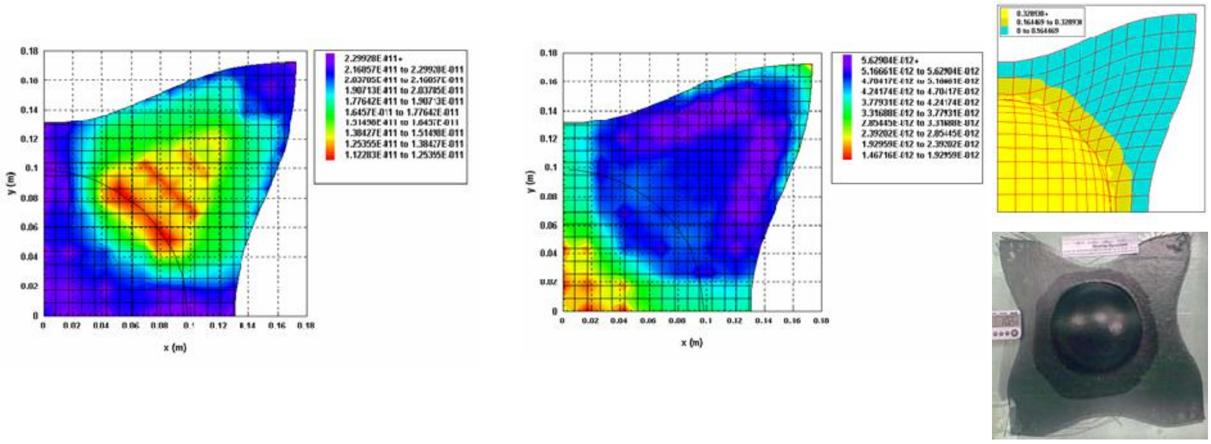
The flow patterns predicted on the flat rim display the petal pattern of the experimental results with the flow progressing faster at the mid-lines of the preform due to the higher permeability there, whereas the permeability is lower at the diagonal positions near the dome edge because of the higher shear angles there and the resulting higher local fiber volume fractions.



(a) (b)

Fig.2. Case-study III: Flow progress in RTM through a hemispherical hat preform:
(a) experiment; (b) FLOWPOR predictions.

Case-study IV involved RIFT flow through the hemispherical hat preform. The manufactured laminate had a thickness distribution, which together with the predicted interfiber angles from the forming simulations, yielded a predicted permeability distribution presented in Fig.3(a) and (b). The predicted local permeabilities were higher in RIFT than in RTM due to the lower V_f values in RIFT. In general, the agreement between the FLOWPOR predictions and the experimental results (Fig.3(c)) of the flow progress is very good in both the infiltration times and the corresponding flow advance, and the shape of the advancing flow front which is approximately circular.



(a) (b) (c)

Fig.3. Case-study IV: Flow progress in RIFT through a hemispherical hat preform:
(a) K_{xx} predictions; (b) K_{xy} predictions; (c)top: FLOWPOR predictions; (c)bottom:experiment.

CONCLUSIONS

The predictions of both ABAQUS and FLOWPOR agreed very well with the experimental data in the case of in-plane, radial diverging flow, a configuration often used in measurements of the in-plane permeability of fiber preforms. However, the case-study of in-plane converging flow highlighted the need of accurately predicting the unsaturated region behind the flow front: in this case, only the predictions of FLOWPOR, a two-phase flow code, agreed well with the experimental data of flow advancement and pressure.

The infiltration of a hemispherical hat preform with central injection proved an interesting and demanding case-study both experimentally and numerically. The infiltration simulations were integrated with the results from forming simulations based on the solid mechanics finite element approach, using ABAQUS Explicit. The RTM mold needed to be specially designed in terms of inhomogeneous preform thickness to accommodate the high fiber fraction, highly sheared preform regions. A permeability model was used successfully to predict the permeability distribution across the porous fibrous preform on the basis of the distribution of local fiber orientation predicted by the forming simulations. ABAQUS presented some numerical instabilities in the infiltration simulations for the hemispherical hat geometry whereas FLOWPOR yielded numerical convergence in all case-studies. The predictions of FLOWPOR were successfully validated with existing experimental data in the in-plane infiltration of a RIFT process in terms of infiltration times and shape of flow front.

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