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A level set approach for the analysis of flow and compaction during resin infusion in composite materials

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ABSTRACT

Fluid flow and fabric compaction during vacuum assisted resin infusion (VARI) of composite materials was simulated using a level set-based approach. Fluid infusion through the fiber preform was modeled using Darcy's equations for the fluid flow through a porous media. The stress partition between the fluid and the fiber bed was included by means of Terzaghi's effective stress theory. Tracking the fluid front during infusion was introduced by means of the level set method. The resulting partial differential equations for the fluid infusion and the evolution of flow front were discretized and solved approximately using the finite differences method with a uniform grid discretization of the spatial domain. The model results were validated against uniaxial VARI experiments through an $[0]_8$ E-glass plain woven preform. The physical parameters of the model were also independently measured. The model results (in terms of the fabric thickness, pressure and fluid front evolution during filling) were in good agreement with the numerical simulations, showing the potential of the level set method to simulate resin infusion.

1. Introduction

VARI (vacuum assisted resin infusion) is an open mould process that uses vacuum as driving force to infiltrate resin through bagged fiber preform. One mould face is replaced by a vacuum bag, leading to reduced tooling costs but increasing the complexity of the infiltration process from the viewpoint of the control of final thickness and porosity. Research activities in recent years were focussed in understanding the physical mechanisms of infiltration including fluid flow, compaction and curing to overcome these limitations. The final goal was to develop simulation tools that can predict accurately the VARI process (see, for instance, Correia et al. [3], Šimáček et al. [14,13], Michaud and Mortensen [9], Trochu et al. [17], Joubaud et al. [7], Modi et al. [10]).

The infiltration and the associated thickness changes during infusion are a consequence of the stress partition between the infused resin and the fiber preform. Before infusion, the atmospheric pressure is transmitted to the mould through the fiber bed skeleton. Part of the load carried by the fibers is transferred to the infused resin, leading to a spring-back of the fiber preform with the corresponding increase in thickness, which continues until the fluid front reaches the outlet gate and the steady-state regime is attained. However, the changes in the compaction of the fiber bed during infiltration modify the permeability and the infiltration velocity. As a result, the pressure gradient in the liquid along the infiltration direction is not constant and depends on a complex interaction among permeability, fiber compaction and the stress partition between the fluid resin and the fiber bed. The relevant strategies for the analysis of resin infusion were reviewed by Correia et al. [3] and apply simultaneously Terzaghi's effective stress theory to model the stress partition and Darcy's and continuity equations to simulate the fluid flow. The fabric compressibility introduces additional difficulties with respect to the constant thickness case (standard resin transfer moulding using two rigid moulds) which are taken into account by formulating the continuity equation in the deformed control volume of the material.

This analysis strategy gives rise to a non-linear partial differential equation for the pressure field which can be solved with the appropriate boundary and initial conditions at the inlet and outlet resin gates. The pressure field is controlled by the permeability and compressibility of the fiber bed which varies with the fiber volume fraction according to the local stress partition. However, the solution of the infusion problem has to take into account that the infiltration front evolves during the filling stage from the inlet to the outlet gate until the total saturation of the fiber preform. Therefore, the partial differential equation for the pressure field,

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valid only for the fully saturated media, should be solved with a moving boundary condition, namely the flow front, during filling. Several strategies have been developed to track the flow front position in injection/infusion problems, including the explicit updating of the flow front based on Darcy's average fluid velocity or the control volume algorithm developed by Bruschke and Advani [1]. Within this context, the level set method [11,12] has emerged as an efficient tool to solve moving boundaries problems in multiphysics and was successfully applied to study crystal growth and solidification [2] and fluid flow [16], among various problems. The method is based on the development of an evolving level set function controlled by a Hamilton–Jacobi differential equation matching its zero level with the evolving flow front. The level set equation is used to separate two media (i.e. dry and wet regions during infusion/injection) with different properties, which are taken into account into the conservation equations of fluid flow.

The level set approach is used in this investigation to study fluid flow and fabric compaction during resin infusion of composite materials. The model was developed for multidimensional flow although the experimental validation was carried out for unidimensional in-plane flow through a porous fiber preform (standard VARI process without distribution media) for simplicity. To this end, infusion tests were carried out and the out-of-plane displacements of the vacuum bag during the filling and post-filling stages were measured by digital image correlation while the fluid pressure at different locations was provided by pressure transducers. All the physical properties of the fluid and the fiber bed (permeability, viscosity as well as the relationship between the fiber bed compaction pressure and the fiber volume fraction under dry and wet conditions) were determined from independent tests. The experimental set-up as well as the results of the infusion experiments are presented in Section 2, followed by the tests to measure the fabric permeability and fiber bed compaction. The level-set model to simulate the infiltration process is detailed in Section 3, while Section 4 presents the comparison of the experimental data with the model predictions in terms of the vacuum bag compaction displacements and resin pressure evolution. The potential of the level set approach to simulate resin infusion in composite materials is clearly demonstrated.

2. Experimental results

2.1. Infusion tests

Vacuum infusion was carried out through an eight ply E-glass plain woven fabric. Fabric strips of length $L = 250$ mm and width $B = 80$ mm were cut and placed on an PMMA tool surface previously coated with a release agent using a $[0^\circ]_8$ lay-up configuration. The fiber preform was covered with a standard vacuum bag (5 μm NBF-540-LFT) and the whole set was sealed with standard tacky tape (LTT-90B). Resin inlet and outlet were connected to the fluid pot and the vacuum pump, respectively, with a rigid tube of 12 mm in diameter.

A blend of corn syrup (70%) and water (30%) was used as infusion fluid. The blend was degassed immediately before the infiltration for 20 min using a vacuum container. The viscosity of the fluid was measured with a rotational viscosimeter Fungilab with L2 type spindle at 30 rpm at ambient temperature. No shear strain rate effects were taken into account and the fluid is assumed to exhibit a Newtonian behavior. The viscosity of the corn syrup blend at ambient temperature is reported in Table 1. Fabric properties (porosity, areal and fiber density) can also be found in this table.

The fluid pressure during infusion was monitored with three pressure transducers (Omega PX61V0-100AV) equally distributed over the length of the infusion strip at 25%, 50% and 75% of its length. The transducers were inserted in the mould through cylindrical cavities, Fig. 1. The outlet vacuum was controlled with a screw-driven valve regulator (TESCOM DV) while a pressure transducer (HBM P8AP) was used to monitor the current vacuum pressure, p_{vac}. The out-of-plane displacement field due to changes in the fabric compaction, $h(x,t)$ in Fig. 1, was continuously measured by means of the digital image correlation using the software VIC-3D [18]. To this end, a speckle pattern was created on the vacuum side of the bag by spraying white paint followed by the dispersion of fine black dots. Two high resolution digital cameras were placed as shown in Fig. 1 and 29 Mpixels images were acquired with both cameras at a rate of 10 images per minute. Digital image correlation was only performed within a specific area of interest (AOI) of length $L_{\mathrm{AOI}} = 0.21$ m and width $B_{\mathrm{AOI}} = 0.01$ m. The reference geometry was given by the vacuum bag surface after the application of some debulking cycles to minimize distortions due to the nesting of individual fabric yarns.

Table 1
Fluid viscosity and fiber preform properties.

Viscosity μ (Pa s)	2.35
Fabric porosity (%)	0.48
Areal density σ_f (kg/m^2)	0.49–0.51
Fiber density ρ_f (kg/m^3)	2540

The evolution of the vacuum bag thickness with time at different positions (located at 10%, 32%, 50%, 70% and 90% along the infusion line within the AOI) obtained by digital image correlation is shown Fig. 2. The initial thickness of the $[0^\circ]_8$ fabric after the application of the debulking cycles was ≈2.8 mm. A slight reduction of the local thickness was detected as soon as the fluid entered into the bag, which is usually attributed to fluid lubrication of the fiber bed at the flow front. Afterwards, the bag thickness increased continuously due to the stress transfer between the fiber bed and the infusion fluid. The external load induced by the atmospheric pressure, initially supported by the fiber bed skeleton, was progressively transferred to the fluid leading to a spring-back effect with the corresponding increase of the fabric thickness. The pressure build-up in the fluid was recorded by the transducers and is plotted in Fig. 3. The pressure increase is very fast as soon as the fluid reaches the corresponding position and rapidly attains an asymptotic value once the steady state regime is established and the whole fabric is filled by the fluid. Lubrication and spring-back effects during infiltration were also reported by other authors [19,4]. The inlet gate was closed at $t \approx 8000$ s, once the flow front reached the outlet gate, and the steady-state regime was attained. This leads to a progressive homogenization of the thickness within the infused area in the post filling stage, accompanied by a reduction in the fluid pressure as the load is transferred back to the fiber bed. The experiments were finished at $t \approx 10{,}000$ s.

The shape of the vacuum bag at different instants during the filling stage is shown in Fig. 4(a). The contour plot of the increment in the fabric thickness, $\Delta h(x,t)$, obtained by digital image correlation, is also plotted in Fig. 4(b) for the same infusion times. Both figures show that digital image correlation captures very accurately the progression of the fluid along the infusion length, which increases continuously until the fluid front reached the outlet gate and the fabric was completely saturated. Very interestingly, digital image correlation was able to capture the roughness of the plain woven fabric (tow width of ≈5 mm).

In fact, the information provided by digital image correlation allowed the determination of the flow front position even if the direct optical observation of the fabric was not possible due to the speckle pattern. According to the results showed in Fig. 2, the thickness of the fabric initially decreased due to the lubrication of the fiber-to-fiber contacts and then increased as a result of the