ON THE USE OF DIC-3D TO DETERMINE THE PERMEABILITY TENSOR AND COMPACTION LAW OF FABRIC BY VARTM

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Keywords: VaRTM, digital image correlation, level Set, permeability,

Abstract

The present paper examines the VaRTM (vacuum infusion) manufacturing process from the viewpoint of the compaction phenomena. The panel thickness evolution during the infiltration was measured using a three dimensional digital image correlation technique in a set of detailed vacuum infusion experiments with corn syrup mixtures through an E-glass fabric preform. The displacement of the bag surface evolves during the infusion tests as a consequence of the stress transfer between the fiber bed and the resin infused at the atmospheric pressure. Both filling and post filling stages are analyzed in the experiments. The fluid flow is modeled using the Darcy's equation for porous materials in combination with a level set approach to track the evolution of the flow front through the preform. The parameters of the model, permeability, fiber bed compaction law and viscosity of the fluid are measured independently and used as input data for the model. The results of the model are compared in terms of thickness and pressure evolution through the fiber preform.

1. Introduction

VaRTM (vacuum assisted resin transfer moulding or vacuum infusion) is an open mould process with reduced tooling costs in comparison with the standard resin transfer moulding techniques RTM. The procedure is based on the use of the vacuum driving force to infiltrate resin through a vacuum bagged fiber preform. The fact that a mould face is replaced by a standard vacuum bag, make this process hard to control from the viewpoint of final thickness and, especially the void content of the composite part. During the last decade, special efforts were made to understand the physical mechanisms involving the infiltration such as the compaction and curing phenomena and the way to couple them into efficient constitutive equations for accurate and predictive simulations. This combined approach in which simulation is coupled to detailed experiments is mandatory for an efficient optimization of the final performance of the composite material.

The compaction phenomena occurring during infusion process is a consequence of stress interaction between the infused resin and the fiber bed preform. At the beginning of the process, the fiber preform is vacuum bagged and the stress transferred direct to the fiber bed. When the resin

Input data		
ϕ	0.48	Porosity of plain woven E-glass fiber [1]
W	[0.49-0.51]	Areal density of plain woven E-glass fiber $[kg/m^2]$
ρ_f	2540	Density of glass fiber $[kg/m^3]$
μ	0.45	Fluid Viscosity at 20°C $[Pa \cdot s]$

Table 1. Materials properties

is infused at the atmospheric pressure, a stress transfer between the fluid and the fiber bed is produced resulting in a spring back effect in the fiber preform with an increase of its thickness. The thickness increases monotonically until the saturation of the composite part is attained. A good understanding of the infusion compaction phenomena is mandatory for a good control of the final panel thickness. In this work, we have carried out a coupled experimental-numerical approach in order to study this compaction phenomena in a E-glass fabric preform. From the experimental viewpoint, infusion tests were carried out in a highly controlled environment and the compaction displacements were obtained through digital image correlation during the filling and post-filling phase. A set of two cameras were used to acquire images of the bagged surface of the infusion experiment at specific times and using them to determine the compaction displacement evolution of the fiber preform. A model was developed to address the fluid flow in a porous media by integrating the Darcy's differential by the finite difference technique in combination with the level set approach. This later method allowed to track the fluid interface during the filling stage of the infusion. All the physical properties used in the model, permeability, viscosity, fiber bed compaction, are determined from independent tests. The results obtained were compared with the compaction displacement recorded by digital image correlation.

2. Material and experimental techniques

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

A blend of corn syrup with water at a concentration of $70\% - 30\%$ was used as infusion fluid in the experiments. The corn syrup blends were first degassed for 20 minutes using a vacuum container immediately before the experiments took place. The viscosity of the fluid was measured with a rotational viscosimeter Fungilab with L2 type spindle at 30rpm at the lab temperature. No shear strain rate effects were taken into account and the fluid, therefore, is considered to behave as a Newtonian type. The viscosity of the corn syrup mixtures is reported in Table (1) for 20°C room temperature. Other fabric properties, porosity, areal weight and fiber density, are also reported in the same table.

The infusion set-up was monitored with three pressure transducers (Omega PX61V0-100AV) equally distributed over the length of the infusion strip at 25, 50 and 75% of the length. The transducers were inserted in the mould through specific cylindrical cavities machined on it,

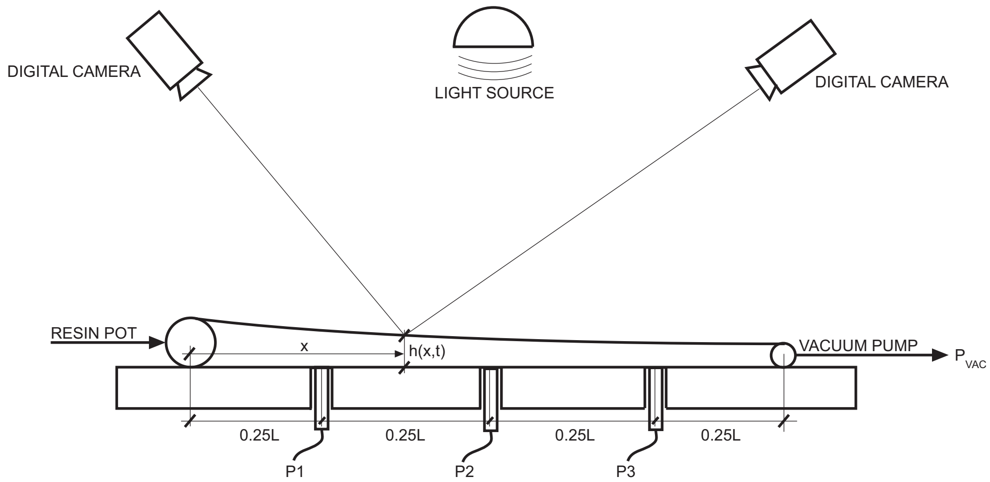


Figure 1. Sketch of the experimental infusion set-up and the digital image correlation system.

Figure (1) . The vacuum pressure was controlled by a screw-driven pressure valve regulator (TESCOM DV) while a pressure transducer (HBM P8AP) was used to monitor the current vacuum pump pressure applied in each of the experiments.

Displacements due to fabric compaction during the experiments in the vacuum bag side were obtained by means of the digital image correlation technique, DIC3D (from Correlated Solutions Inc.)[1]. To this end, the vacuum side of the experiment was first sprayed with white paint followed by the dispersion of fine black dots to create the speckle required for the displacement correlation. Two digital cameras were placed close to the experiments as appears in Figure (1). High resolution images were acquired by means of two digital cameras at a rate of an image per 6 seconds. The digital image correlation is performed over an specific area of interest (AOI) with the dimensions of 20x210mm. The individual particle position is track by the system over the area of interest (AOI) in the test and this information is used to obtain the three dimensional displacement field in the vacuum side due to the compaction was used in the analysis.

The fundamentals of the technique are simple: the displacement field is computed by tracking the distribution of grey intensity levels on the bag surface of the infusion set-up by using images acquired at different stages of the process. The position of an arbitrary pixel i of the image in the initial stage, after vacuum is being applied to the bag, can be expressed in terms of its own coordinates $\mathbf{x}_i$ in a given reference configuration. This pixel moves to a new position which is given by its coordinates $\mathbf{X}_i$ in the deformed configuration. Obviously both coordinates are related by the displacement vector field as $\mathbf{u}_i = \mathbf{X}_i - \mathbf{x}_i$. The correlation procedure tries to globally minimize, within the AOI, the gray intensity level differences around a specific set of pixels known as the subset. The minimization algorithm is not applied over the whole pixel set of each image but on a reduced set equally spaced at given distance called step. After the minimization problem is solved, the final displacements of the vacuum bag are obtained and analyzed. The digital image correlation was applied in this case by using 29 and 7 pixels for the subset and step sizes which meet the requirements needed for the analysis.

3. Model

The model used for the compaction phenomena during the infusion experiment is based on the resolution of the fluid flow through porous media based on the Darcy's equations. In that case, the average fluid velocity through the fiber preform is proportional to the pressure gradient being the proportionality factor related with the fabric permeability tensor **K** and the fluid viscosity μ

$$\mathbf{v} = -\frac{\mathbf{K}}{\mu}\nabla p \tag{1}$$

Additionally, the mass conservation equation should be invoked at this point taking into account the effect of fiber bed deformability contribution (contrary to the standard RTM injection where thickness is imposed by the closed mould) as

$$\nabla \mathbf{v} = -\dot{\varepsilon} \tag{2}$$

which can be related finally, with the local volume fraction of reinforcement, $V_f(p)$ during the compaction phenomena as Eq. (3). The volume fraction of reinforcement, or porosity, is pressure dependent so the final thickness of the composite preform will depend on the pressure transferred from the resin to the fiber preform. Additionally, the permeability tensor is also dependent on the volume fraction of the reinforcement attained at each time so the final partial differential equation for the pressure field is highly non-linear.

$$\nabla(\frac{\mathbf{K}}{\mu} \cdot \nabla p) = -\frac{\partial v_f/\partial p}{v_f}\frac{\partial p}{\partial t} \tag{3}$$

In this equation, the Terzaghi effective theory is used which establish the stress transfer mechanism between the solid and fluid phase during the filling stage. The resolution of the partial derivative equation requires the knowledge of the physical parameters involved in the infusion process, namely, fiber compressibility $V_f(p)$ and permeability $\mathbf{K}(p)$ and fluid viscosity μ.

3.1. Numerical strategy

The general governing equation for the pressure field $p(\mathbf{x}, t)$ is given in Eq. 3. It is valid only for those cases where the fluid fills completely the solution domain and can be used only for those cases related with post-filling operations. However, when dealing with the fluid phase, where the fluid flow progress and the flow front evolves, a numerical strategy should be set-up previously. Several possibilities to simulate filling stages are present in the literature, flow tracking, control volume, which are usually implemented in well known numerical finite element packages as LIMS or PAM-RTM. In this work, a new scenario based on the level set method is implemented for infusion problems.

In the level set method [2], the flow front is defined with a function $\mathbf{x}(\mathrm{t})$ than can be understood as the zero level curve of a higher order function defined as $\phi\,(\mathbf{x}(\mathrm{t}), \mathrm{t}) = 0$. Therefore, tracking the fluid interface is to find the zero level of the evolving function ϕ during the propagation. Taking the differential of the former expression and using the chain rule, the initial value problem for the level set function can be obtained as

$$\frac{\partial \phi}{\partial t} + \frac{\partial \phi}{\partial \mathbf{x}} \frac{\partial \mathbf{x}}{\partial t} = \frac{\partial \phi}{\partial t} + F|\nabla \phi| = 0 \tag{4}$$

where F is the velocity normal to the fluid front (tangential velocity do not produce fluid interface expansion). The Darcy's differential equations presented in Eq. 3 can be modified now by the level set function to indicate whether the region is filled by the fluid or not as

$$H(\phi) \cdot \nabla(\frac{\mathbf{K}}{\mu} \nabla p) = -\frac{\partial v_f / \partial p}{v_f} \frac{\partial p}{\partial t} \tag{5}$$

where $H(\phi)$ is a step shape function depending on the level set value through the domain. Typically, this function is smooth out in a narrow transition region of the fluid front in order to avoid numerical problems during the integration. In this work, the step function was taken as

$$H(\phi) = \frac{1}{1 + e^{-\alpha \phi}} \tag{6}$$

where $\alpha >> 1$ is the parameter controlling the step function. Therefore, in those regions filled by the fluid where $\phi < 0$ the step function acquires the value of the unity being zero in the unfilled regions where $\phi > 0$.

The coupled system of the Darcy's pressure equation and the level set update are solved within a 2D domain corresponding to the laminate rectangle shape LxB using the finite differences method. The spatial domain is discretized using a uniform grid with uniform increments of Δx and Δz while the time increment Δt is adjusted to a small value to satisfy the stable time increment given in the Courant condition. The spatial derivatives of the Darcy's equation are approximated with a central differences scheme and the time derivative with a standard Euler approximation. However, according to Sethian [2], a combined forward-backward algorithm should be used to track the strong gradient of the function ϕ at the flow front position due to the hyperbolic nature of the evolution differential equation.

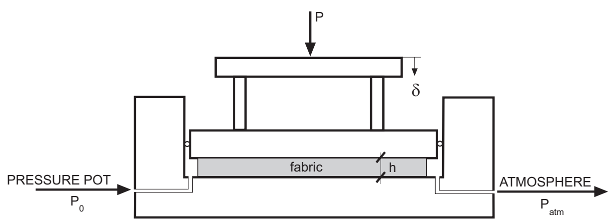
Initial and boundary conditions are imposed to the 2D rectangle domain. Initial conditions are the standard vacuum pressure at $t = 0$ for all the points of the grid. The boundary conditions at the four edges of the laminate reads as follows: first, the pressure is set to zero (vacuum pressure) at the outlet at $x = L$ while the inlet pressure at $x = 0$ is raised up using a exponential function $p(x = 0, z, t) = p_0(1 - e^{-At})$ (being A is a small number). Second, slip free conditions are set to the longitudinal edges and, therefore, the spatial derivative along the z direction are set to zero. This set of initial and boundary conditions produce unidimensional flow through the x direction according to the experimental set-up. The level set function is initialized with the distance function to the inlet port. Therefore, $\phi(x, z, 0) = x$ and this condition evolves with the level set governing equation through out the entire analysis. The flow front then, can be track at those points where the level set function is zero as $\phi(x, z, t) = 0$ during the filling phase of the problem. After the flow front reach the outlet position at $x = L$ the partial differential equation corresponds to the fully saturated case in Equation Eq. (3).

3.2. Material parameters

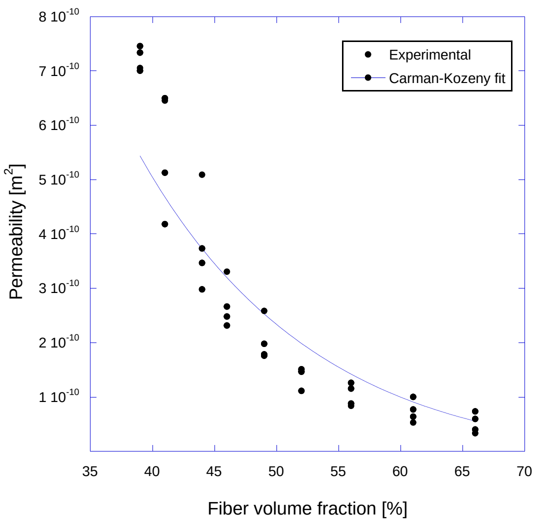
The permeabilty dependence on the fiber volume fraction is usually taken into account by means of the Carman-Kozeny model [3] as

$$K_i = k_{i0} \frac{(1 - V_f)^3}{{V_f}^2} \tag{7}$$

where k_{i0} is an empirical constant which will depend on the fiber bed architecture. It should be noted also that the permeability is orientation dependent and different permeability constants are required for the in-plane and out-of-plane flows through the fiber preform. However, in this work, the fluid flow is mainly unidimensional and only in-plane flow is studied. An sketch of the experimental set-up used in the measurements is plot in Figure (2)a). The permeability was measured for the E-glass fabric using a closed mold with one face machined on PMMA to allow visual inspection of the flow progress during the infiltration avoiding wall race-tracking. Inlet pressure is imposed in a series of pressure steps (between 0.25, 0.5, 0.75 and 1.0 bars) while the outlet is maintained at atmospheric pressure measuring the mass rate obtained for the given imposed pressure gradient. The mould is coupled to an electromechanical testing frame which allow a detailed control of the fiber volume fraction (gap thickness of the closed mold) during the tests. The experiments were used to obtain the in-plane permeability factor for different preform volume fraction which was fitted to the Carman-Kozeny law Eq. (7). The $k_{i0} = 4.43 \cdot 10^{-10}$ factor for the $[0]_8$ lay-up configuration was obtained by least square fitting of the experimental results.



(a)



(b)

Figure 2. a) Sketch of the experimental test for in-plane permeability measurements, b) Permeability factor for different fabric thickness (volume fraction).

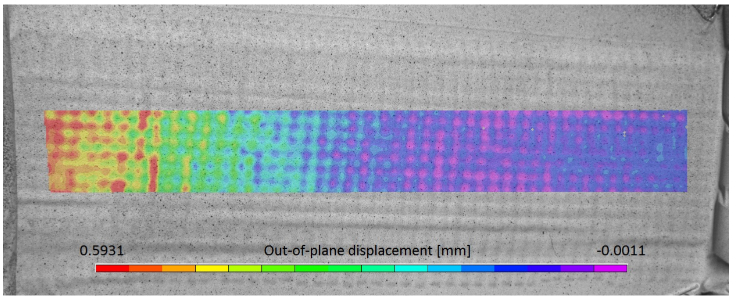
The compaction of the fiber preforms is determined by means of digital image correlation. These set of experiments are standard vacuum bag experiments in which the displacements of the vacuum bag are obtained with the digital image correlation analysis used previously. Tests were carried out by loading and un-loading the preform with the vacuum pressure gage and taking images of the bagged surface after several seconds of stabilization without external applied pressure gradient. Experiments were carried out using dry and wet preforms in order to characterize the material during the filling and post-filling states of the infusion, [4]. When testing dry fiber preform, some hysteresis effects due to the porosity and the yarn nesting are present. The experimental results were used to fit a power law by the least square method to the fiber volume fraction for a given applied vacuum pressure, [5]

$$V_f = a \cdot (\sigma_{zz})^b \tag{8}$$

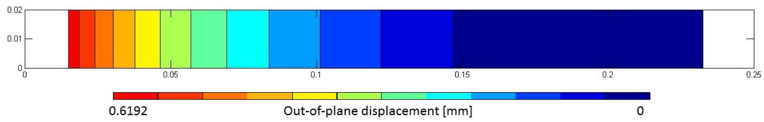
where $b = 0.064$ is the stiffening index, and resulting and $a = 0.2861$ is the fiber volume fraction for 1 Atm. These values were obtained for the $[0]_8$ lay-up configuration.

4. Results

The numerical model is validated comparing the results obtained from the infusion experiments in terms of pressure sensor evolution and compaction displacement obtained with the digital image correlation procedure (Fig 3). Figure 4 a) shows the numerical and experimental panel thickness evolution for the filling and post-filling stages for different positions through out the length of the panel (11%, 16%, 32%, 50%, 70%, 90% of the total length, respectively). The pressure evolution obtained from the sensors at 25%, 50%, 75% and 100% of the length of the panel (4 b)). All the curves in Figure 4 a) show increasing thickness of the fabric preform (spring back effect) during the filling stage due to the stress transfer between the resin and the E-glass fabric, Figure 3b). The pressure exhibit a monotonic increase until the flow front reaches the outlet which is followed by a pressure stabilization. At this point, the inlet is closed and the post-filling starts showing a decrease of the panel thickness due the re-compaction of the fiber fabric. The results are in good agreement with the experimental in both variables.



(a)



(b)

Figure 3. Contour plot of panel thickness deformation by digital image correlation Figure a) and from numerical model Figure b). Inlet set on the left and outlet on the right. Color scale from min. value (pink-blue color) to max. value (red color)

5. Conclusions

A set of detailed experiments were developed to understand the compaction phenomena occurring during the infusion of a viscous fluid through a fiber preform. The digital image correlation

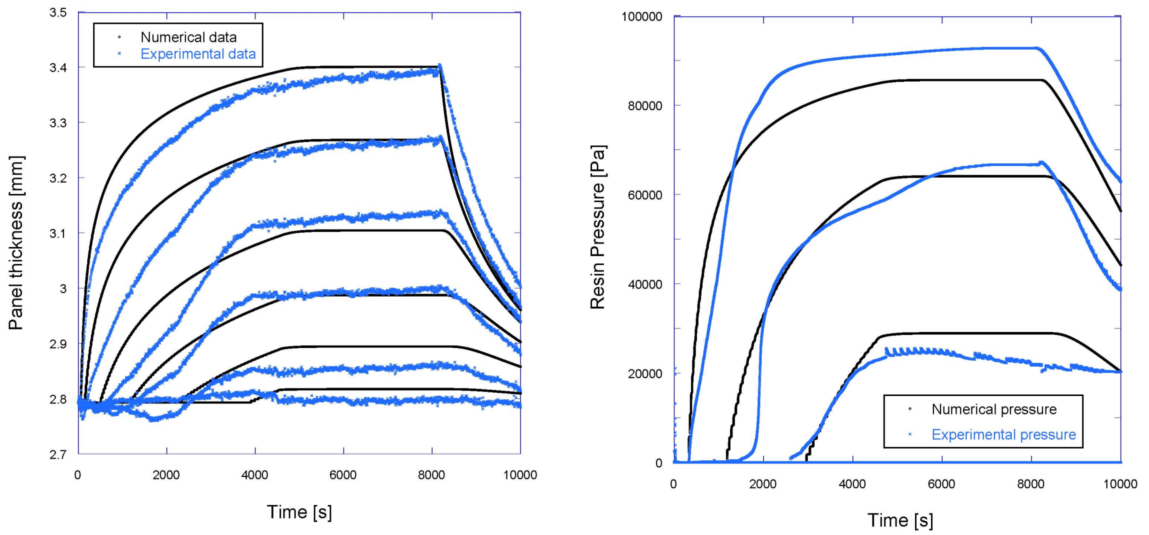


Figure 4. Experimental (blue colour) and numerical (black colour) thickness evolution (a) and pressure evolution (b) of test 8 layers

system was used to account for the deformations induced by the stress transfer between the fiber preform and the infused fluid. A model was developed in this case to understand the effect of fiber compaction during the infusion. The model is based on the resolution of the Darcy's equation for the fluid flow in porous materials and also takes into account the deformability of the E-glass preform caused by the compaction stress. During the filling stage, it was necessary to set-up the model in such a way that is possible to study the evolution of the flow front. The model was based on the level set approach which was coupled to the previous Darcy's equation for a partial saturated fiber preform. All the parameters of the model, permeability, viscosity, compaction of the fabric preform, were measured independently and used as inputs of the model. The results were compared with the experiments showing good correlation in terms of fabric deformation and pressure sensor evolution.

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