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PERMEABILITY AND COMPACTION MODELS FOR NON CRIMPED FABRICS TO PERFORM 3D FILLING SIMULATIONS OF VACUUM ASSISTED RESIN INFUSION

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SUMMARY: The vacuum assisted resin infusion process is a popular production technique for large composites structures: fibre reinforcement is placed on a rigid tool, then covered with a resin distribution medium and sealed by a flexible vacuum bag. During the infusion the fibre volume content varies due to the flexible nature of the vacuum bag and so the deformation of the modelled geometry. Flow simulation is a helpful tool for the process design, where in the permeability is an important parameter which is highly depending on the fibre volume content. In this paper, the process is modelled in 3D. The models for the permeability as well as the dry and wet compaction were derived from experimental data using polynomials and extended power laws, respectively. The deformation of the geometry is calculated by an Arbitrary-Lagrangian-Eulerian (ALE) method. The distribution medium is modelled as a 2D-surface layer to reduce the number of elements in the FE mesh. The influence of physical phenomena in dependence on the injection strategy is discussed.

KEYWORDS: Permeability, compaction, modelling, NCF, flow simulation, VARI, ALE

INTRODUCTION

Fibre reinforced composite structures are important in lightweight design. Taking into account the development of high volume production, the automation of the processes is of increasing importance. For understanding those processes properly, the knowledge of dependencies appearing in the process is desirable.

Vacuum Assisted Resin Infusion (VARI) is a production technique for fibre reinforced parts [1]: fibre reinforcement is placed on a rigid tool, then covered with a resin distribution medium or High Permeable Layer (HPL) and sealed by a flexible vacuum bag. By applying vacuum, the setup is compressed and the resin is infused into the fibre reinforcement. The HPL has a very high permeability, so the resin is distributed over a large surface of the part, filling it in thickness direction.

The challenge for the process designer is to create parts without remaining dry spots and voids. Therefore in the process design the positions of injection ports and vents are very important, especially regarding the fact that textile structure causes anisotropic flow behaviour during the impregnation. Flow simulation therefore has become a valuable tool for the design of the flow process. It has been used for the control of several parameters influencing the quality of the part.

In several papers [2, 3] it is stated that the flow front velocity has an influence on the generation of voids. This is caused by so called dual scale effects which are present during the impregnation. In [4, 5] methods are proposed to include this effect in the flow simulation. [6] found a relationship of the confluent angle of the flow front and the final void content.

The scope of the paper is to perform flow simulation for VARI processes in 3D as it gives the opportunity of virtually investigating the effects of possible decisions regarding the process. In resin infusion processes under flexible tooling the flow problem is coupled to the deformation of the fibre reinforcement as far as the permeability of the reinforcement depends on the fibre volume fraction, which can be expressed as a function of the compaction pressure.

The results of the measurements were used in the flow simulation. A methodology to implement the compaction behaviour is proposed. The high permeable layers were included by 2D-surface elements [7]. Based on the results of [8], regarding the compaction of HPL a methodology to measure HPL-permeabilities [9] was further developed and the results of the measurements were modelled and used in the simulation.

Modelling the VARI Process

The VARI process can be modelled on macroscopic scale by the theory of porous media. The continuity equation is given by [10]:

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla\left(\rho v\right) = 0\,, \tag{1}$$

where ρ is the fluid density, v the Darcy velocity and ϕ the porosity. A constitutive equation for the flow is Darcy's Law. In its simplest form, it is defined by

$$v = -\frac{K}{\mu}\nabla p\,, \tag{2}$$

with the pressure p, the fluid viscosity μ and the permeability tensor K. Assuming that the fluid is incompressible, by defining $S \in [0,1]$ as fluid saturation of the porous structure, it becomes the Richard's equation [11]:

$$\frac{\partial (S\phi)}{\partial t} = \nabla \left(\frac{K}{\mu} \nabla p \right). \tag{3}$$

For a calculation of Eqn. (3) the use of feasible boundary conditions and constitutive equations for the porosity ϕ and the saturation S is required.

Typical boundary conditions for the VARI-process are known pressure or volume rate at the inlet and the outlet and homogeneous Neumann conditions for other boundaries, meaning that the volume rate normal to the wall of the mould is zero.

During infusion in VARI-processes the geometry of the laminate cannot be considered constant: air is drawn due to the applied vacuum that results in a compacted setup. The pressure of the infused resin reapportions the equilibrium of forces under the flexible bag in the impregnated area releasing a part of the deformation. In the whole process the magnitudes depending on transversal geometry may change [12, 13].

In the application of soil mechanics usually Eqn. (3) is rewritten to take into account the change of saturation, which is a function of the pressure [14, 10]:

$$C(p)\frac{\partial p}{\partial t} = \nabla \left(\frac{K}{\mu} \nabla p \right) \tag{4}$$

where $C(p)$ is the moisture capacity. Van Genuchten [15] and Corey Brooks [16] developed well known models for the flow in soil mechanics. [14] developed a third order time integration scheme for Eqn. (4).

In this work, a simplified van Genuchten model has been used to simulate the fluid flow, only taking into account the moisture capacity $C(p)$. The change of permeability in dependence of porosity and therefore the compaction has been modelled separately based on own measurements.

Modelling of Compaction and Permeability

The scope of the experiments was to find models for

- the fibre volume content $F_v = 1 - \phi$ in dependence of the compaction pressure $p_c = p_{atm} - p_f$, where p_{atm} is the atmospheric pressure and p_f the pressure in the fluid,
- the three eigenvalues in dependence of F_v corresponding to the three eigenvectors of the 3×3 permeability tensor K.

The material used was a glass fibre ±45° biaxial non crimped fabric with an area weight of 450 g/m^2. The permeability was determined by flow experiments using a constant pressure injection.

As textile exhibits isotropic in plane flow behaviour, for determining the in plane permeability the measurement in only one direction had to be performed in detail: the fibres were wetted using a line injection. The fluid used for the impregnation was an epoxy-resin with 290 $mPas$ at room temperature. Comparisons with vegetable oil of 70 $mPas$ showed deviations of less than 10%. The permeability in thickness direction was measured in saturated conditions using the vegetable oil.

The permeability K was determined varying F_v. In Fig. 1, the results of the permeability measurements are shown. By using models of Gebart [17] and Carman-Kozeny [18] the behaviour could not be predicted accurately as the derivation of K in dependence of fibre volume fraction is too low. Also using simple exponential or power laws did not lead to satisfying results. Therefore the permeability was modelled by using a polynomial of order 2 using interpolation of 3 points. For the in plane permeability this approach could be validated by interpolating the curve with the base points. The control points were used to verify the curve.

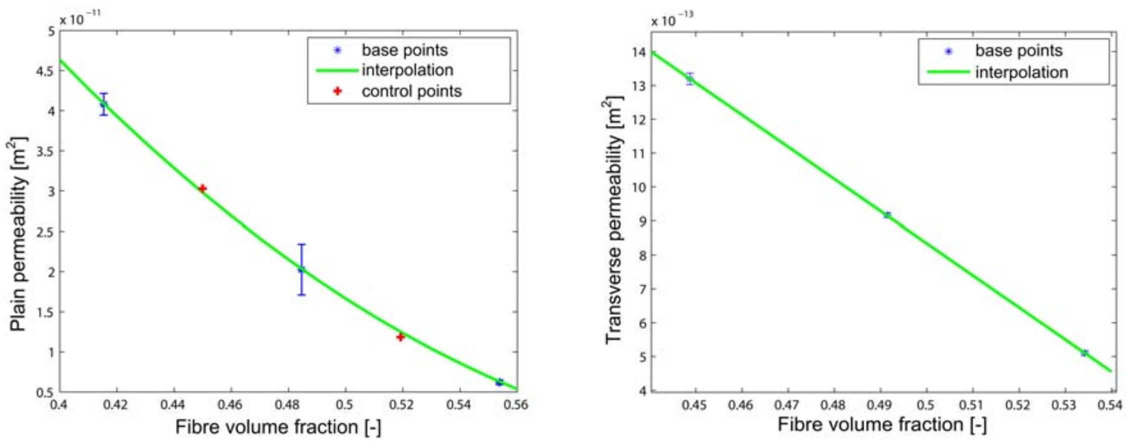

Fig. 1 Data from permeability measurements for in plane and through thickness direction.

The most commonly used expression to model the compaction behaviour is the power law used by [19]. Van Wyk [20] derived the power equation for a 3D network of randomly oriented fibres. The physical model assumed that the fibres behave like bending beams that transmitted loads through contact points and the compaction pressure increased with the cube of the fibre volume content. Gutowski [21] and co-workers proposed different versions of a compaction model for aligned and ondulated fibres, where fibres are initially curved and straighten under pressure. In [22], Batch and co-workers measured compaction pressures of different kind of reinforcements. They fitted their experimental data to a model where the fibre is modelled as a bulking arc doing contact by two single points at the beginning of the compaction, increasing the contact region gradually as the compaction pressure increases. Fibre volume content was related linearly with compaction pressure at the beginning of the compaction but presented a nonlinear relation for higher values of pressure.

The compaction experiments were carried out in a universal testing machine. Square specimens of carbon fibre non-crimp fabrics (H1NC and S2NC) disposed alternatively in triaxial and quadraxial arrangement and a biaxial NCF glass fibre reinforcement (referenced before in this article) were stacked in samples of different thicknesses and compacted in dry and saturated state. A 50 x 50 mm steel square plate under the samples concentrated the pressure in a well defined area. A compression strain was applied at constant velocity (0.5 mm/min) and the force required to reach each level of compaction was recorded. With the recorded forces, the applied transversal pressure was calculated and represented versus the fibre volume content. The initial fibre volume content, at zero stress, was chosen arbitrarily at the lowest level of pressure accurately measurable (approx. 1 N).

The wet samples were saturated with a commercial resin. The samples have been compacted in the range of the compaction pressures applied in resin infusion processes. As far as in industrial conditions no repeated loadings are expected, freshly cut samples were used in each measurement, not considering history effects. Experimental curves for dry and wet compaction for non-crimped fabric samples of different thicknesses were obtained. Fig. 2.a presents a reduction of the fibre volume obtained by increasing of the layers stacked in the sample. This shows a good agreement with previous studies [19] where for the same level of compaction pressure, a higher fibre volume ratio was found reducing the number of layers. The experimentally obtained values of fibre volume content are higher for saturated fibres than for dry fibres for significant values of pressure, as represented in the Fig. 2.b, showing that the lubrication of fibre to fibre contacts causes an increase in the material deformation. The experimental measurements have been statistically treated and fitted to a model of the form of Eqn. 5:

$$\begin{aligned} V_f &= V_{f0} && \text{for all } P < P_{in}, \\ V_f &= a \cdot P^b + c && \text{for all } P_{in} \leq P \end{aligned} \qquad (5)$$

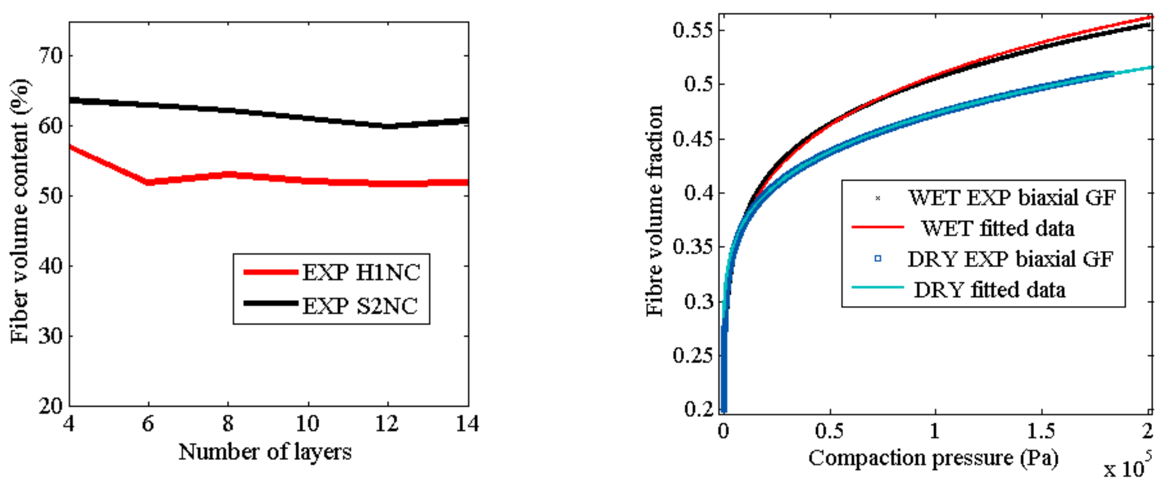

Fig. 2a Variation of fibre content with the number of stacked layers (left). Fig. 2b Experimental and fitted curves for dry and wet compaction of GF-biaxial (right).

Eqn. 5 can be considered as an extended version of the model of Robitaille [19], but introduces a value of initial fibre V_{f0} content for levels of zero or near zero compaction pressure P_{in}, that represents the fibre volume fraction when no compression load is applied. This condition is necessary to get a reliable implementation of the models in the simulation of resin infusion.

Including the Models into the Simulation of the VARI Process

The simulation of the VARI process is based on Eqn. (4), an equation which is typically used in the simulation of transport phenomena like heat transfer and diffusion processes. The factor $C(p)$ has to be modelled for the simulation. In [23] a simplified van Genuchten model is numerically investigated for the application in RTM-processes showing good results in accuracy related to CPU-time and to analytical solutions available for Darcy's law.

The flow simulations were performed using the heat transfer application of "COMSOL / a commercial finite element program". The change of geometry was calculated by coupling the thermal field with the mechanical application. A deformed mesh application was used to take the geometry change into account as it has an influence on the final pressure distribution. This application uses ALE – methods for calculating the variables on the deformed mesh. With this approach the possibility of modelling the VARI process in 3D is given.

A typical result of the flow simulation is shown in Fig. 3: A rectangular plate is impregnated by an injection from the left upper point. The high permeable layer distributes the resin over the top surface impregnating the reinforcement in thickness direction. The colours show the fibre volume content. As in wet conditions the setup is more compacted. Close to the flow front is the highest fibre volume content, leading to the maximum thickness difference dz .

Discussion of Physical Phenomena and Experimental Validation

For the simulation of VARI-processes the following phenomena had been investigated:

- reinforcement deformation under vacuum,
- permeability change due to compaction.

In these virtual experiments there was no high permeable layer present. The simulations were performed using constant pressure boundary conditions for a line injection (L) and a point injection (P). The modelled part had a natural thickness of 16 mm. The simulations were preformed using the modelled parameters for permeability and compaction and using the ALE-formulation resulted in a decrease 2.2% (L) and 3.4 % (P) of the filling time respect to the conventional approach. This deviation can be considered relatively small. As the usage of the ALE-formulation is increasing the degrees of freedom by a factor of 3 and the CPU-time by a factor of at least 10 the convenience of it has to be discussed for particular cases.

The simulations taking both effects into account were compared to RTM-simulations. In [13] it is proposed that there is an apparent overall permeability describing the process for a line injection, but also that this apparent permeability is not necessarily applicable to 3D flows. This affirmation was confirmed by the investigations: an apparent permeability could be found for L and P. If the apparent porosity was set to an equal value, the permeabilities were also equal, but as the apparent porosity cannot be the same due to the different pressure distributions, the ratio was quantified to L/P = 1.06.

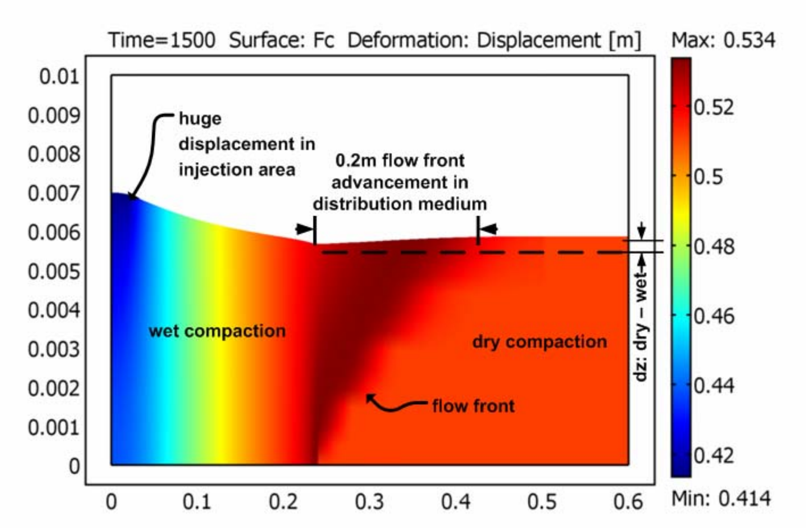

Fig. 3 Deformed geometry of a laminate with a natural thickness of 10 mm, the colours represent the local fibre volume content during the injection phase.

As in these investigations the flow can be described with one dimension, further investigations have to be performed with regard to a general behaviour. For testing the actual state the couplings have been used to compare the simulation with validation experiments. In the simulation the high permeable layer (HPL) was modelled using 2D-surface elements [7]. The permeability of the HPL in dependence of compaction pressure was measured by an indirect method [9], which was further developed with respect to VARI-simulations. For the VARI experiment 28 layers with the dimensions of $600 \times 400\ mm$ and a HPL with $400 \times 400\ mm$ were placed on a glass tool and impregnated with a line injection. With mirrors the flow front advancement in the HPL and at the bottom could be evaluated.

In Fig. 4 the results of the experiment and the simulation are compared. In general there is a good agreement of the simulation and the experiment. Especially in the beginning of the injection and when the flow front reached the end of the high permeable layer some deviations occur. This could be caused by improper description of the kinematic boundary conditions caused by help agents as films and injection channels. The investigation of these deviations will be part of the future work.

CONCLUSION

The aim of performing VARI-simulations could be reached. The used parameters could be measured with a high reproducibility. The comparison of simulation and experiment already showed a good agreement between each other. The future work will be aimed to special topics related to the mechanical system in the setup itself to characterize the interaction of the different materials used in the process.

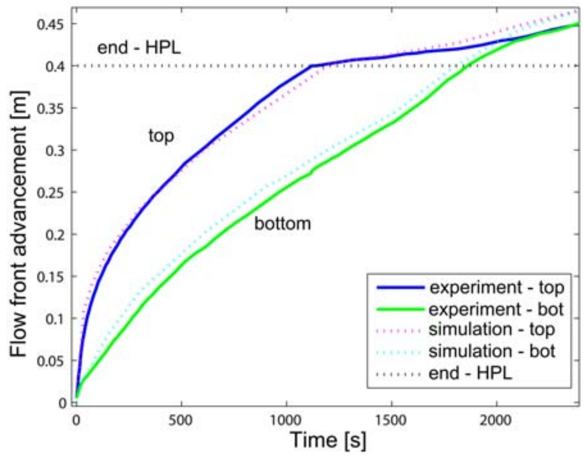

Fig. 4 Comparison of experiment and simulation.

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