ON THE MULTI-SCALE MODELLING OF THE MANUFACTURING OF A THICK WALLED COMPOSITE PANEL- THEORETICAL AND EXPERIMENTAL STUDY

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Abstract

The present paper is focused on the improvement of modelling techniques for the MVI process. The work is subdivided into three parts dealing with a shot description of the process, with a new approach for the consistent multi-scale modelling of the resin flow and with a practical validation test case respectively. The major achievements of the theoretical part are the introduction of a unified application of the theory of mixtures as well as the volume average for the determination of effective material properties of porous media on one hand and the formulation of an interface layer to model the flow properties at the transition between two adjacent layers on the other hand. It has been shown that this approach provides accurate results and more flexibility for the modelling of technical laminates.

1. Introduction

A survey of the recent reports on the field of development and improvement of manufacturing processes for composite shows clearly significant efforts related to modelling techniques as well as process knowledge [1,12 et al.]. Despite evident advancements many key questions remain unsolved, such as questions related to the critical geometric ratios for infusion and injection, or the requirements of a consistent and progressive approach for the handling of global effects having severe consequences at the microscopic scale and vice-versa. Considering the overcome of large CFRP-Part with complex shaped geometry or simply taking the ongoing integration level that require more and more accurate and reliable process design (i.e. flow behaviour at discontinuities, detection of porosities) into account, it is obvious that additional efforts are necessary in order to reach the required maturity level of the modelling of CFRP-manufacturing processes.

Several works dealing with the numerical prediction of the permeability tensor have been published and, due to the complexity of the problem one can expect further developments in the future. The majority of the papers are focused on fabrics and UD material whereas Non Crimp Fabrics (NCF) mostly occurs in relation with compaction and draping behaviour. The basic idea of the numerical prediction of the permeability consist in the computation of the pressure and velocity field on a given domain, that generally is expected to represent a basic pattern of the reinforcement of interest. These main assumptions together with the practical definition of the permeability build the weak point of the most papers. The permeability is assumed to be a constant material property and therefore a strong dependence of the results from the geometry is given. The application of the theoretical values to serial processes delivers poor results due to the fact that both the assumed and the effective cross section are not matching each other.

It must be emphasized that the assumption of a single phase and fully saturated flow also leads to less accurate results. Within the present paper a model with variable saturation has been adopted. By introducing the so-called compressibility variable, the possibility is given to model several kind of materials, including multiphase continua with non-linearity, such as performed by Ehlers [2].

Based on the works done by Ladeveze [3], a new approach was developed to enable a consistent modelling of the flow front evolution through different scales. The developed solution offers more flexibility for the modelling of discontinuities and enable a better up scaling of the effective properties. The new mathematical formulation of the multi-scale flow problem is compatible with the homogenization theory for layered media developed by Hornung und Allaire [4,13].

2. The MVI Modified Vacuum Infusion Process

The Modified Vacuum Infusion process (MVI) is part of the group of liquid composite moulding processes (LCM) and is used as a main application in the aircraft industry for large structures. In analogy to these processes of this group the "dry" reinforcement fibres is laid up in an open mould and afterward the auxiliary material (like vacuum foil or distribution media) will be placed on the fibres, which is responsible for the resin distribution. Unlike the RTM (Resin Transfer Moulding) process the resin flows only with the help of the differential pressure in the part, which results from the ambient pressure and the vacuum inside. Figure 1 among other things this gives a limit of the speed of the infusion.

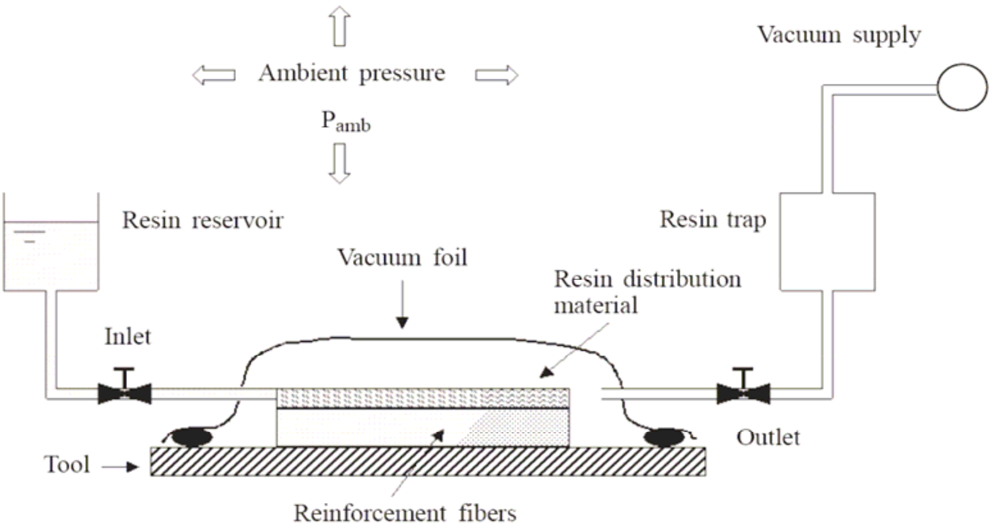


Figure 1: Set-up of the Modified Vacuum Infusion process

The main function of the auxiliary material is on the one hand to enable the discharge into the vacuum bagging as well as the targeted distribution in the part and on the other hand to apply a vacuum into the vacuum bagging, so that the air can be removed from the part and simultaneously the needed differential pressure can be generated.

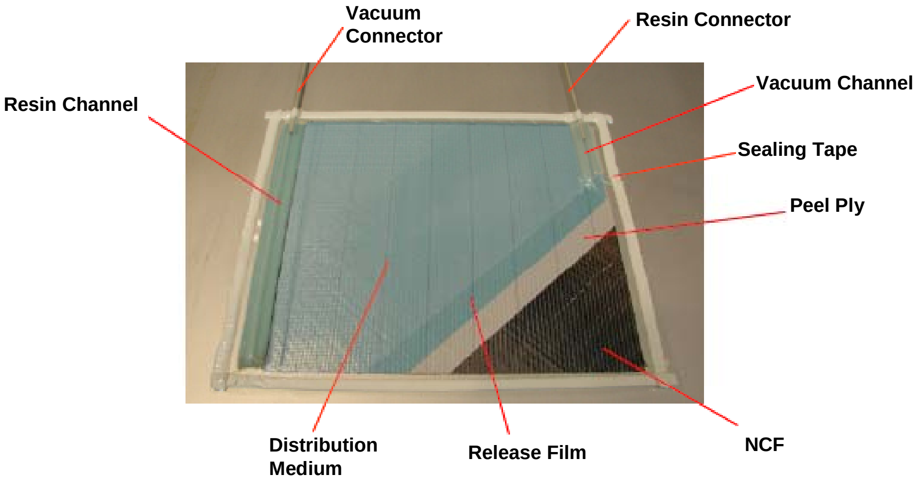


Figure 2: vacuum setup principle

Therefore, different materials are involved in the vacuum setup (Figure 2). The auxiliary materials, which are highlighted for this process, are the distribution medium and the resin runners. The resin channels are used to transport large amounts of resin in the vacuum setup to the favoured areas. The distribution medium has the task to distribute the resin homogeneously on the part. It should be noted that in complex parts with local thickness variations a different amount of resin has to be distributed to single areas. Therefore a special arrangement of the distribution medium is important due to the slower distribution speed of the resin in the thickness direction of the part compared to the distribution speed in the area particularly for complex and thick parts.
Especially with very thick-walled parts different factors are involved in the interpretation of the resin front. Here, for example, the comparatively slow resin flow through the thickness direction in combination with the pot life of the resin has to be considered. The total time of filling depends on the chosen infusion strategy for the part. Also a maximum flow path of the resin into the laminate exists, both in the plane and in the thickness direction. In case of the filling in the thickness direction it is also important that the laminate can be infiltrated without porosity especially by parts with different thicknesses.

2. Fundamentals

2.1 On the modelling approaches for porous media

The work presented in this paper is based on the theory of porous media in the sense of [2] that is by combining the theory of mixtures with the concept of volume fraction. The major advantage of the theory of mixtures leads to the fact that no measure or effort is made to incorporate the microscopic information of the structure at the macroscopic level. Therefore it is assumed that every quantity is already a local average. This aspect has been used to develop the concept of interface between two adjacent layers as presented in next section.

Concerning the concept of volume fraction, the present work is based on the assumption that all the j-components building the porous medium are not miscible and describe interacting continua (a solid skeleton and a fluid) without any vacant space. The saturation condition reads:

$$\sum_{k=1}^{j} \varphi^k = 1 \qquad (1)$$

where φ^k denotes the local ratio of the volume fraction of the constituent k.

The balance equation for the mixture exhibits the same generic shape of the classical mechanics of single-phase media:

$$\frac{d}{dt}\int_{\Omega}\psi dv = \int_{\partial\Omega} n\cdot\Gamma d(\partial\Omega) + \int_{\Omega}\sigma_p dV \tag{2}$$

φ represents any transportable scalar or tensor valued variable, Γ is the flux through the boundary of the domain of interest and σ_p denotes the volumetric changes of φ (source term or body forces) in the domain considered.
Using the material time derivative,

$$\frac{du}{dt} = \frac{\partial u}{\partial t} + \dot{u}\nabla u \tag{3}$$

setting the appropriate values for the variables and combining the momentum and mass balance lead to the generalized equation of Darcy without gravitational effects:

$$S\frac{\partial p}{\partial t} + \nabla\cdot\left[\frac{-K}{\eta}\nabla p\right] = 0 \tag{4}$$

where S represents a given saturation function, K , η, ∇p and Q represents the permeability tensor, the dynamics viscosity of the fluid, the pressure gradient and a source term respectively.
The saturation term was defined as a function of the volume fraction of the fluid, the solid skeleton and fluid compressibility. According to (1) the saturation for non-miscible and fully saturated porous media simply results to

$$S = x_s(1-\varphi) + x_f\varphi \tag{5}$$

The successful application of (5) to the simulation of the resin flow during the manufacturing of CFRP-part depends on many factors such as the applied boundary condition or the choice of the material properties.
For practical application, the most published works on the numerical permeability prediction are only related to small sized and simply shaped geometries and therefore exhibit a lack of rules and method for their sizing to large or complex shaped structures, such as they occurs in many applications. Furthermore there are no approaches for the estimation of the effective permeability of a given stacking sequence made by the combination of well-established materials. The following section deals with an up-scaling approach that is intended to support the accurate modelling of flow behaviour of technical laminates.

2.2 Homogenization approach

2.2.1 A dual homogenization approach

A major difficulty of the efficient modelling of the flow front evolution during the impregnation of fibre reinforcements remains the determination of the effective material properties. The Equation of Darcy, rewritten for a pressure analysis introduces a material parameter to quantify the loss of pressure through friction over the total internal area of the fibres, the so-called permeability. Practical investigations denote the dependency of this coefficient from many parameters, both material as well as process dependent. This property is one major reason why actual efforts to build a permeability database often deliver unsatisfactory results.
The strategy proposed in the following sentences doesn’t consist in creating a new theory, but to consider the permeability as a multi-scale variable. We assume that the permeability within a single ply mainly depends on the “texture” of the ply (material type, size of the bundle, connectivity and tortuosity inherent to the manufacturing of the fibre reinforcement). At this level (micro scale) the permeability tensor is assumed to satisfy the basic requirement of a material parameter, i.e. the indifference of frame. This value is therefore constant and can be used to

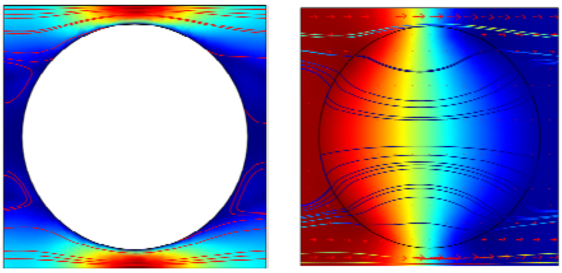
define a material database. The representative elementary volume (REV) equals a unit cell and the properties of the ply are obtained by a pure volume average.

The second step of the homogenization deals with the stacking sequence, where the effective properties are computed according to the homogenization of a layered media [4]. At this level (meso-scale), an interface has been introduced to model the flow behaviour at the transition between two adjacent layers with different angles in analogy to [3]. The REV builds here correspond to the stacking sequence and the final properties are obtained from expansions series.

2.2.2 Effective properties of a single ply

The start point of the investigation is the definition of an adequate geometry for the REV. In the most publication the case of transverse flow is modelled by assuming a quadratic cell. Within the works, some modifications have been made with regards to the cell geometry: the basic cross section for the material considered has been revised and different combination of flow regimes have been analyzed and compared with [5].

For the properties of the single ply, the classical of RVE can be chosen according to the strong periodicity of the computation domain. The unit cell constructed here is based on pure geometrical consideration of the material. For each single layer an approximated cross section of the fibre selected, leading to a different basic geometry of the model compared with the most publications [5,6,7]. Two flows regimes were assumed, the pure Navier-Stokes, the combination of Navier-Stokes and Brinkmann. Typical pressure and velocity distribution obtained are illustrated in picture below.



a) b)

Figure 3: typical pressure and velocity field (dimensionless, fibre volume fraction 60%) for a square unit cell: pure Navier-Stokes equation (a) vs. combination of Navier-Stokes and Brinkmann (b)

Let us consider now the steady state version of the flow problem through porous media describes by the elliptic equation (6) well know as the divergence of the Darcy equation:

$$\nabla \cdot \left(\frac{K}{\eta} \nabla p \right) = 0 \quad (6)$$

Introducing the linearity condition $\tilde{p} = x\tilde{\mathbf{e}}$ for any arbitrary boundary in the local canonical basis (e_1, e_2, e_3) it is obvious that $p = \tilde{p}a$ und $u = \tilde{u}a$, where u, the Darcy's velocity, is defined as:

$$u = -\frac{K}{\eta} \nabla p \quad (7)$$

$\tilde{\mathbf{e}}$ represents a set of unit vector, that will be assumed to be orthogonal. Applying the basic principle of the RVE, the volume averaged flux reads:

$$\langle u \rangle = \frac{1}{V} \int_{\Omega} -\frac{K}{\eta} \nabla \tilde{p} a \, dV \quad (8)$$

From which the effective permeability can be derived as:

$$\tilde{\mathbf{K}}_{eff} = \frac{1}{V}\int_{\Omega} -\frac{\mathbf{K}}{\eta}\nabla\tilde{p}a\, dV \qquad (9)$$

2.2.3 Effective properties of a stacking sequence

Let us consider the generalized DARCY equation for a given porous domain denoted by Ω :

$$\begin{cases} S\dfrac{\partial p}{\partial t} + \nabla\cdot\left(\dfrac{K}{\eta}\nabla p\right) = Q & \text{in}\,\Omega \\ \dfrac{\partial p}{\partial n} + p_0 = \gamma & \text{on}\,\partial\Omega \end{cases} \qquad (10)$$

For further simplicity we assume a steady state analysis, a Dirichlet boundary condition and set the source term equals to zero. The homogenization problem derived from (6) reads

$$\begin{cases} \nabla\cdot\left(\hat{K}^{\varepsilon}\nabla p^{\varepsilon}\right) = Q \\ p = p_0 \end{cases} \qquad (11)$$

By setting $y = \dfrac{x}{\varepsilon}$, $p^{\varepsilon}(x) = p^0(x,y) + \varepsilon p^1(x,y) + \varepsilon^2 p^2(x,y) + \cdots$ and by applying the derivation rule $\nabla = \nabla_x + \dfrac{1}{\varepsilon}\nabla$ to (7) one obtains

$$\begin{aligned} &\varepsilon^{-2}\nabla_y\cdot\left(\hat{K}(\tfrac{x}{\varepsilon})\nabla_y p^0(x,\tfrac{x}{\varepsilon})\right) + \varepsilon^{-1}\left(\nabla_y\cdot\left(\hat{K}\nabla_y p^1(x,\tfrac{x}{\varepsilon})\right) + \nabla_y\cdot\left(\hat{K}\nabla_x p^0(x,\tfrac{x}{\varepsilon})\right) + K\nabla_x\cdot\nabla_y p(x,\tfrac{x}{\varepsilon})\right) \\ &+ \varepsilon^0\left(\nabla_y\cdot\left(K\nabla_y p^2(x,) + K\nabla_x p^1(x,)\right) + K\nabla_x\cdot\nabla_y p^1(x,\tfrac{x}{\varepsilon}) + K\nabla_x\nabla_x p(x,\tfrac{x}{\varepsilon})\right) = Q(x) \end{aligned} \qquad (12)$$

After identifying the coefficients, the general shape of the homogenized problem becomes:

$$\begin{cases} \nabla\cdot\left(\hat{K}\nabla p\right) = f \\ p = p_0 \end{cases} \qquad (13)$$

where the differential operator $\nabla\cdot\left(\hat{\mathbf{K}}\nabla\mathbf{P}\right)$ represents the homogenization of the operator family $\nabla\cdot\left(\hat{\mathbf{K}}^{\varepsilon}\nabla\mathbf{p}^{\varepsilon}\right)$

For the assessment of the macroscopic flow behaviour a concept of interface between two adjacent plies with different orientation has been introduced. The interface follows the idea of an extended boundary condition. The principle consists into applying the weak formulation of the DARCY equation additionally to the flux at the selected boundary. This has been done with the commercial software COMSOL Multiphysics®, which offers the possibility to handle partial differential equations as well as weak formulations within the same model. The generalized boundary condition, an extension of the Neumann Boundary condition, is therefore equals the normal flux for continuity reasons and reads:

$$-\mathbf{n}\cdot\left(-\frac{\mathbf{K}}{\eta}\nabla\mathbf{p}\right) = -S_{\xi}^{\text{int}}\frac{\partial p}{\partial t} - \nabla_{\xi}\cdot\left(\frac{-\mathbf{K}_{\xi}^{\text{int}}}{\eta}\nabla_{\xi}\mathbf{p}\right) \qquad (14)$$

This approach offers the possibility to predict the effective values of the permeability tensor for stacking sequences made from different materials, as well as to model discontinuities inside the laminate. Further advantages of the interface concept are the accurate prediction of the pressure field, the modelling of high permeability layer and the reduction of the computation effort.

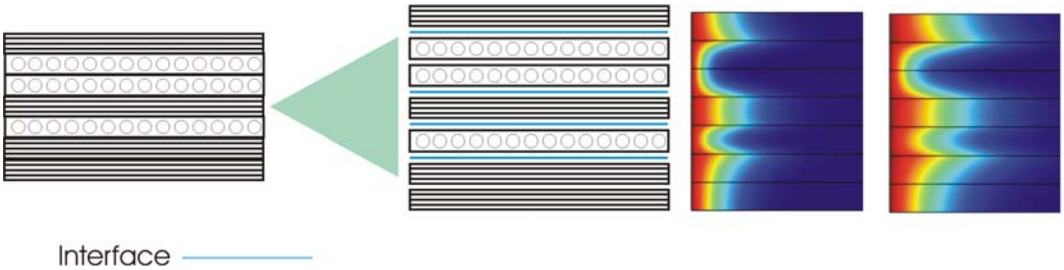


Figure 4: concept of the interface. Only adjacent layers with different orientation are separated by the interface (left). The influence of the interface upon the pressure and distribution is depicted on the right side.

2.3 On the applied boundary conditions.

The periodicity of the velocity field and the homogeneity of the pressure field were supposed to be satisfied at the external cell boundaries. For the interior boundaries, the continuity equation was imposed at all the boundaries to ensure coupled flow laws. For the external boundaries two cases were applied. For the first one, the classical symmetry conditions have been selected, that is with respect to mass and force balance:

$$\begin{cases} \mathbf{n}\cdot\mathbf{u} = 0 \\ \mathbf{t}\cdot\boldsymbol{\sigma}_c\mathbf{n} = 0 \end{cases} \tag{15}$$

For the vertical boundaries of the RVE, the periodicity of the velocity field was assumed and the Cauchy stress tensor σ_c was reduced to the viscous part:

$$\begin{cases} \mathbf{u}(u,v,w) = \mathbf{u}^{per}(u^{per},v^{per},w^{per}) \\ \frac{1}{2}\boldsymbol{\tau}\mathbf{n} = \eta\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\mathbf{n} = 0 \end{cases} \tag{16}$$

The Boundary conditions discussed above are easily extended to a 3D model for volumetric approach.

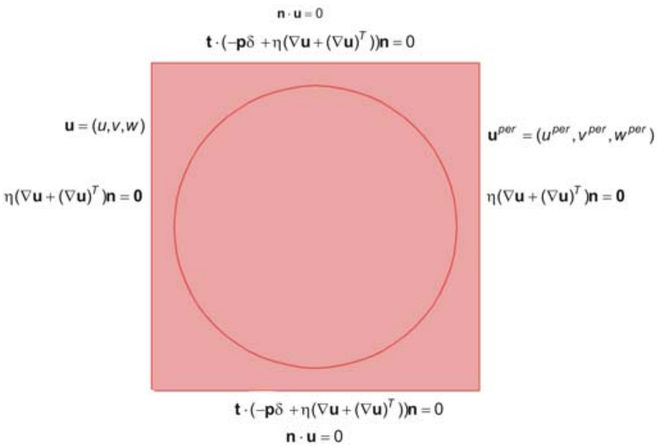


Figure 5: Applied boundary condition on a RVE

2.4 Modeling of the flow front.

The most common ways to compute the position of the flow front position and evolution are the flow analysis network (FAN) [8,9] and the control volume approach (CV) [10,11]. In the special case of mould filling, the pressure field is computed first and the mass balance is solved for the control volume or for the domain builds by selected finite volumes or elements. This process is then repeated until any point of the mould cavity reaches or excess the maximum degree of filling. Two major disadvantages of both methods remain the strong dependence on the domain approximation and the fact that the computed front is don't represent a real interface. The approach chosen for this work is the so-called level-set-method, which offers the possibility to compute the curvature of the flow front. The level set method is a flexible and well-established method for front tracking which several application fields and could be summarized as a diffusion-convection problem:

$$\frac{\partial\theta}{\partial t} + u \cdot \nabla\theta = \varepsilon_1 \nabla \cdot \left[-\theta(1-\theta)\frac{\nabla\theta}{|\nabla\theta|} + \varepsilon_2 \nabla\theta \right] \qquad (17)$$

θ is the level-set-function, $\varepsilon_1, \varepsilon_2$ are initialization parameters, n is the interface normal and Λ the interface curvature. The level-set-method was applied at different scale to follow the evolution of the flow front. Figure 6 shows the theoretical filling process of square packing.

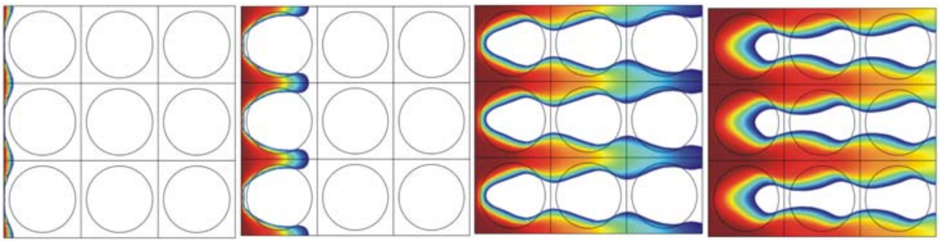


Figure 6: flow front evolution during the filling of a square packed reinforcement

For the computation of the interface fluid-vacuum a value of 0.5 for the level-set-function was fixed. For a detailed representation of the flow front shape, one can introduce the interface normal and the curvature as defined by equation (18) and (19).

$$n = \frac{\nabla\theta}{|\nabla\theta|} \qquad (18)$$

$$\Lambda = -\nabla \cdot n \qquad (19)$$

3 Numerical application

3.1 computation approach

Various analyses were carried out, starting from the single ply properties and concluding with the simulation of a thick laminate. The sizing approach for the determination of the laminate permeability was initiated by the modelling of the single ply properties as already discussed by several authors [14-16] and followed by the computation of resulting properties of the stacking sequence. At the single ply level we assume a modified geometry, which is closed to the cross section of the material used.

Within this work no special considerations were made for the implementation of the compaction behaviour. This property was assumed to be constant at begin of the infusion and defined as a material parameter. For partial saturated or miscible continua of the variable in (5) have to be extended on an appropriated way.

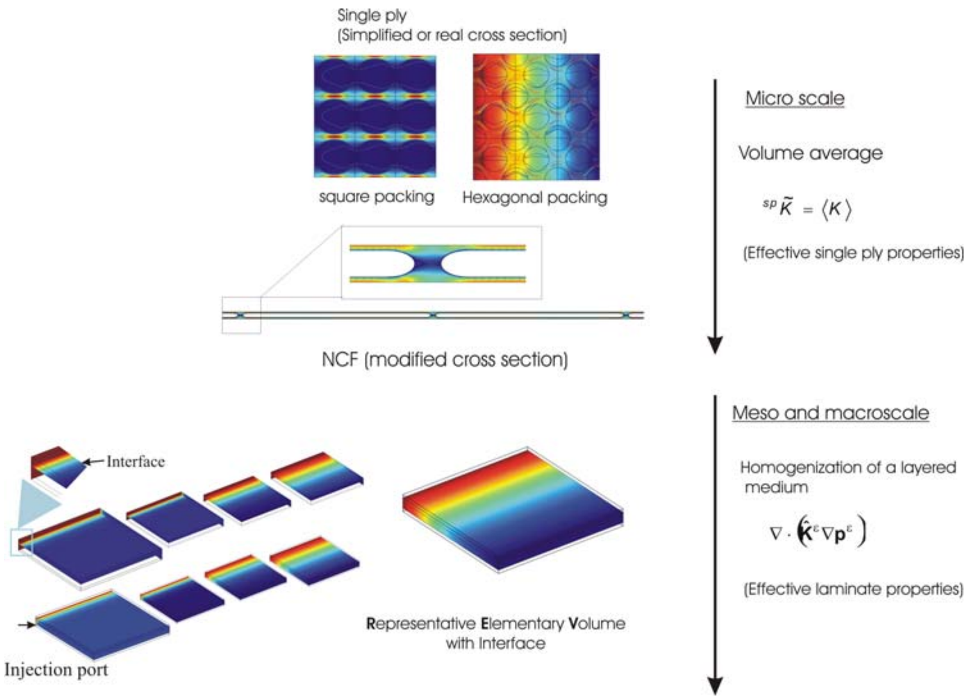


Figure 7. Proposed progressive approach for the numerical prediction of effective permeability of laminates

3.2 Infusion of a thick laminate

In the production of thick-walled parts (>10mm) the design of the infusion strategy is of particular importance, because here, in contrast to thin laminates, the slow infiltration speed in the direction of thickness becomes strongly noticeable. For the design of the best infusion strategy it is necessary to know the infiltration speed in the thickness direction and in the plane. Due to the different infiltration speeds a wedge-shaped flow front is formed in the laminate during the infusion, which especially in change of thicknesses in a part (e.g. intersection foam-monolith) can lead to loss of quality if this stays unconsidered. Three trials with triaxial and quadraxial non-crimped fabrics (NCF) and RT-curing resin (viscosity: about 150mPas) are made to show the behaviour of the resin in thick-walled parts. The dimensions of the parts are 900mm x 300mm x 50mm. A standard infusion strategy is chosen for the vacuum bagging and the distance between the resin channel and the vacuum channel is 900mm. The distribution medium is laid homogeneously at the top of the carbon fibres. The infusion is stopped at a filling level of about 25%, 30% and 80% of the part. Then the parts are cured. Through this approach the flow front becomes approximately visible and allows an evaluation of the trials. This enables a matching between the practice and the theoretical model.

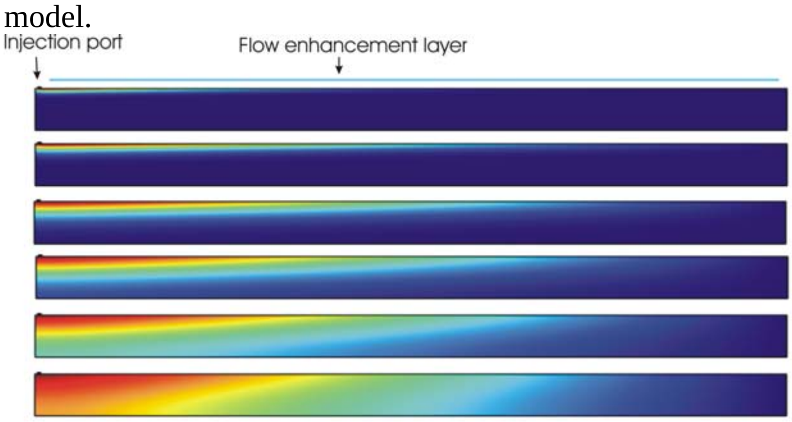


Figure 8: Pressure field and flow front evolution during the infusion of a thick laminate.

4 Conclusions and outlines

In fine, a method for the modelling of resin infiltration processes at different lengths of scale was developed and compared with validation trials. The introduced concept of interface can help to reduce the modelling and computational efforts for 3D models. Through a better approximation of flow phenomena at micro scale the opportunity for a realistic prediction of some manufacturing defects is given. The computation of the flow front with the level set offers the possibility to visualize the filling process within the whole computation domain including transition regions without loss of integrity. Further investigation dealing with the modelling of porosity fields as well as with the calibration of the interface are planned.

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