A SIMPLIFIED NUMERICAL APPROACH TO SIMULATE RESIN TRANSFER MOLDING WITH A DISPERSION MEDIUM

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ABSTRACT: Resin Transfer Molding with a Dispersion Medium (DM-RTM) is a liquid composite molding manufacturing technique well suited for high fiber volume aeronautical parts. DM-RTM, also known sometimes as Liquid Resin Injection (LRI), consists of incorporating a highly permeable dispersion medium into the laminated preform to accelerate fiber impregnation. This cost-effective molding technology is contemplated for use in the manufacturing of large size aeronautical parts of complex shape because of its ability to quickly fill-up the mold, and hence reduce total cycle time. The high difference in planar permeability between the dispersion medium and the fibrous preform (of almost three orders of magnitude) induces a through-thickness flow that cannot be neglected event for thin parts. The resulting three-dimensional filling of the mold cavity can no longer be assumed to take place following a two-dimensional uniform flow front through the thickness of the part. To improve the performance of such a process, more scientific knowledge of three-dimensional impregnation phenomena is required. This work concerns the analysis of through-thickness flows coupled with standard planar filling simulations. Numerical simulation is a useful design tool in the virtual prototyping of the molds required to produce complex composite parts by resin injection. Computer analyses aim to model, predict and control the events that occur during the fabrication of composite parts by liquid composite molding. In this work, a pseudo three-dimensional numerical analysis is presented to simulate mold filling in presence of a dispersion medium. The numerical approach is validated with experimental results that demonstrate the capability of the proposed "*simplified*" solution. A test case was carried out on a composite part to highlight the advantages of the numerical simulation. Finally, DM-RTM filling is applied to a complex aeronautical part.

KEYWORDS: DM-RTM, integrated approach, aeronautics, composite

INTRODUCTION

Over the last few years, thermoset composites have played a key role in the development of new commercial aircrafts because of their high specific properties, corrosion resistance and low fatigue. Recently, a wide variety of new manufacturing processes has appeared as an alternative to high cost pre-impregnated fabrics and autoclave cured composites. Liquid Composite Molding (LCM) techniques such as Resin Transfer Molding (RTM) and Vacuum Assisted Resin Infusion (VARI) have become increasingly popular for structural parts. These techniques based on resin injection through fibrous reinforcements allow a significant reduction of manufacturing costs through usage of complex 3D braided fabrics and multifunctional integration. Resin Transfer Molding with a Dispersion Medium (DM-RTM) is a liquid composite molding manufacturing technique well suited for high fiber volume aeronautical parts. DM-RTM, also known as Liquid Resin Injection (LRI), consists of incorporating a highly permeable dispersion medium into the laminated preform to accelerate fiber impregnation. This cost-effective molding technique begins to be used for the manufacturing of aeronautical parts of complex shape, because of its ability to quickly fill up the mold and reduce total cycle time. The ability to numerically predict the different manufacturing stages is well recognized as playing a key role in the industrialization of such processes. Numerical simulation tools able to predict the isothermal and non-isothermal injection stages of RTM [1-3], compression RTM [4], VARI [5], articulated RTM [6] and various similar processes have been developed over the last 10 years. Efforts have also been made to simulate SCRIMP-like processes [7-8] were a high permeable media is used to assist in resin infusion under vacuum conditions. In this work, unidirectional flow experiments have been conducted to study the DM-RTM process. A one dimensional model has been developed to characterize the coupled permeability of the fabric and the dispersion medium. Finally, a finite element model has been coded to solve the complex 3D impregnation phenomena and apply it to a real aeronautical part.

GOVERNING EQUATIONS

The impregnation of a porous preform by a liquid resin can be modeled as a transient Darcy's flow [1]. Darcy's law enables estimating the average superficial fluid velocity **v** from the pressure gradient ∇P via the following relationship:

$$\mathbf{v}_r = -\frac{[\mathbf{K}]}{\phi\,\mu}\nabla P \tag{1}$$

where $[\mathbf{K}]$ is the permeability tensor of the porous medium, μ the resin viscosity and ϕ denotes the porosity of the porous medium. In the case of the DM-RTM process, a highly permeable dispersion medium is added above the fibrous preform to facilitate resin impregnation of the laminate (see Fig. 1). Important differences between the permeability of the dispersion media and the laminate (more than 1,000 times) induce a complex 3-dimensional resin flow. Due to the higher permeability of the dispersion medium (DM), resin initially flows through it forcing a though-thickness impregnation of the low permeability laminate. As depicted in Fig. 2 for a representative unit cell, the in-plane and through-thickness flows can be divided into three main flows: (A) the in-plane flow in the DM, (B) the in-plane flow through the laminate and (C) the through-thickness flow from the DM into the laminate. These resin flows can be estimated by applying Darcy's law with a pressure gradient ΔP_X^{DM} in the DM, ΔP_X^{fibers} through the laminate and ΔP_Z between them. Dividing the unit cell in the upper layer for the DM and in the lower layer for the laminate, equation (1) can be rewritten for each section in the following form:

$$Q^{DM} = -\frac{[\mathbf{K}_{DM}]}{\phi_{DM}\ \mu\ A}\nabla P_{DM} - Q_t \qquad (2)$$

$$Q^{fibers} = -\frac{\lfloor \mathbf{K}_{fibers} \rfloor}{\phi_{fibers}\ \mu\ A}\nabla P_{fibers} + Q_t \qquad (3)$$

where Q^{DM} is the flow rate through the dispersion medium, Q^{fibers} the flow rate in the laminate, A the in-plane area of the unit cell and Q_t the flow rate between the dispersion medium and the laminate. Two finite elements (FE) approaches are proposed to iteratively evaluate the complex resin flow in the DM-RTM process. In both cases, the DM is considered independent of the laminate. As shown in Fig. 3, a two-dimensional FE mesh is used to describe the DM and calculate the in-plane resin flow through equation (2). The in-plane flow in the laminate can be evaluated with equation (3) on a 2D FE mesh in the case of thin laminates (i.e., for shell-like composites) and on a 3D FE mesh for thick composites. In the first case, for thin laminates, the through-thickness flow Q_t can be estimated by applying Darcy’s law between the DM and the laminate. As depicted in Fig 4 (a) for two face-to-face finite elements representing respectively the DM and the laminate, averaged node pressures can be used to evaluate the through-thickness flow in the following way:

$$Q_t = \frac{\mathbf{K}^T_{fibers}}{\phi_{fibers}\ \mu\ A}(P^{DM}_{cg} - P^{fibers}_{cg}) \qquad (4)$$

where $\mathbf{K}^T_{fibers}$ is the transverse through-thickness permeability of the thin laminate, P^{DM}_{cg} the averaged pressure at the center of the finite element representing the dispersion medium, and P^{fibers}_{cg} the averaged pressure in the finite element representing the laminate. In the case of thick laminates modeled by a 3D FE mesh (see Fig 4 (b)), the pressure at the interface between the DM and the laminate is set for the nodes on top of the 3D mesh. Darcy’s law (equation (1)) is then solved for the thick laminate, and the tree-dimensional flow calculated. The transverse flow Q_t can then be evaluated as the normal flow through the face of the upper element. Fig. 5 shows the proposed flow chart to solve the filling problem in DM-RTM for thin and thick laminates respectively.

NUMERICAL AND EXPERIMENTAL VALIDATION

To validate the accuracy of the proposed numerical solution, a 2D through-thickness finite element geometry was created. The accurate 2D FE solution was used as reference to evaluate the degree of prediction of the proposed simplified solution. Fig. 6 shows a comparison between the 2D FE solution and the simplified approach for a rectangular plate of 40 cm length, a fibrous preform of 2 mm thick (50% fiber volume content) and a dispersion medium of 0,5 mm thick (80% porous media). A Newtonian fluid with a viscosity of 0,1 Pa.s was injected under a constant injection pressure of 1e6 Pa. A good agreement between both solutions can be observed. The proposed simplified approach models the 2D Darcy's flow through the thickness of the laminate.

An experimental validation for materials used for aeronautical composite parts was also conducted in CRC to validate the proposed model. Experimental injections were carried out for different injection conditions. Carbon fabric rectangular plates of 70 x 9 cm and 4 mm thick (70% fiber volume content) were layered above a dispersion medium of 0,5 mm thick (90% porous). A liquid resin with a viscosity of 0,02 Pa.s was then injected at constant injection flow rate. The resin flow front evolution in the dispersion medium and the fibers was recorded using fiber optic sensors. As depicted in Fig. 7, the experimental flow front positions in the DM and through the laminate were compared to the numerical predictions using the simplified approach. It was observed that when in-plane flow in the laminate region is not considered (i.e., zero in-plane permeability of the fibers $\mathbf{K}^{X}_{fibers}$), then the numerical solution diverges from experiments as can be seen at the beginning and at the end of resin injection (see arrows in Fig. 7). Hence it can be inferred that the in-plane flow through the laminate plays a key role at the beginning of the impregnation as well as at the end of mold filling. From this experimental validation one may conclude that the proposed simplified approach accurately predicts the resin flow in the dispersion medium and through the laminate for thin composite parts manufactured by DM-RTM.

CASE STUDY

A test case was carried out for a real aeronautical part to demonstrate the capabilities of this new numerical approach. The composite part consists of a fuselage panel, auto-stiffened panel of 3,5 x 3 meters, with a ratio between length and thickness higher than 1000. A preliminary study showed the difficulties to reproduce the different resin flows for this kind of process with standard numerical solutions (i.e., using shell elements with averaged permeabilities or 3D elements). Fig. 8 displays a preliminary result for a shell mesh with an average permeability (i.e., thickness weighted permeability). It was experimentally observed that the filling prediction with averaged permeability did not represent the DM-RTM process. As illustrated in Fig. 9, important differences were obtained between the averaged permeability solution and the proposed simplified approach (i.e., differences in filling times and different shapes of the flow front). As depicted in Fig. 10, the proposed solution allows a fast analysis of the evolution of the resin front in the DM and through the laminate.

CONCLUDING REMARKS

In this work, a methodology is proposed to compute three-dimensional flows in the Resin Transfer Molding with a Dispersion Medium (DM-RTM). Two numerical solutions were proposed based on finite element analysis. The first one considers the case of thin laminates (i.e., shell-like composites), while the second one is focused on thick laminates. The complex 3-dimensional resin flow evolution is solved by a simplified approach consisting of calculating the in-plane flow in the DM followed by the transverse through-thickness flow, so that finally the in-plane flow through the laminate can be numerically estimated. Numerical and experimental validations demonstrate that the in-plane flow through the laminate plays a key role at the beginning and at the end of resin injection. A good agreement between measured and predicted flow fronts in the DM as well as through the laminate was observed for the experimental validation presented. Finally, a test case was studied for an aeronautical composite part to highlight the advantages of the proposed numerical formulation. This simplified approach can accurately predict the evolution of the resin flow in the dispersion media and through the laminate for thin composite parts manufactured by DM-RTM.

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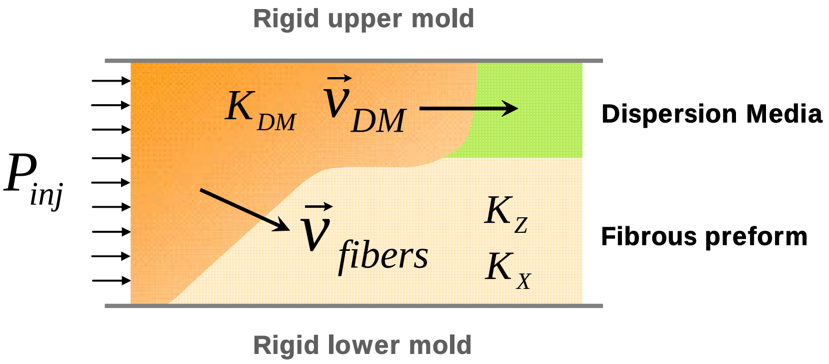

Figure 1. DM-RTM manufacturing process: a highly permeable dispersion medium is added above the fibrous preform to facilitate resin impregnation.

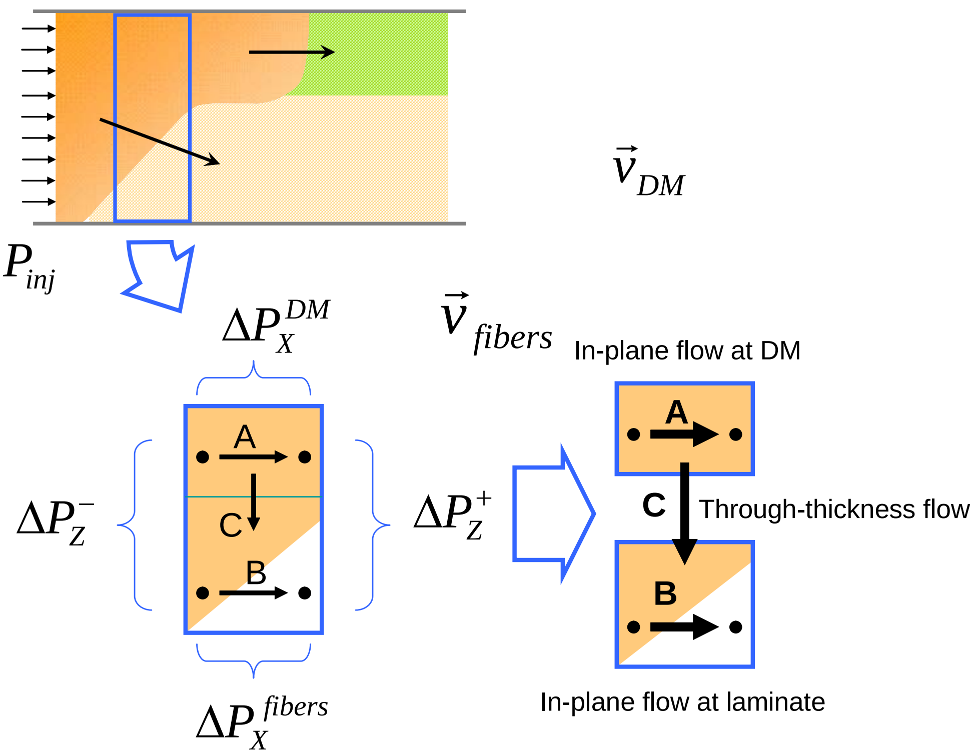

Figure 2. Pressure and resin flow distribution during DM-RTM mold filling.

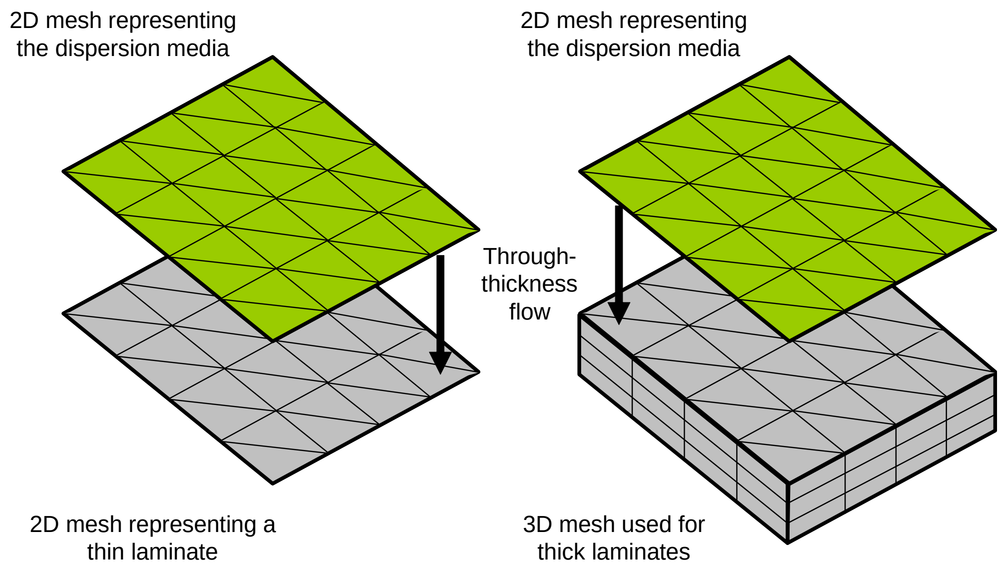

Figure 3. Two proposed geometrical representations: a 2D FE mesh is used to describe thin laminates (i.e., for shell-like composites) and a 3D FE mesh is used in the case of thick composites. In both cases a 2-dimensional FE mesh is used to describe the DM.

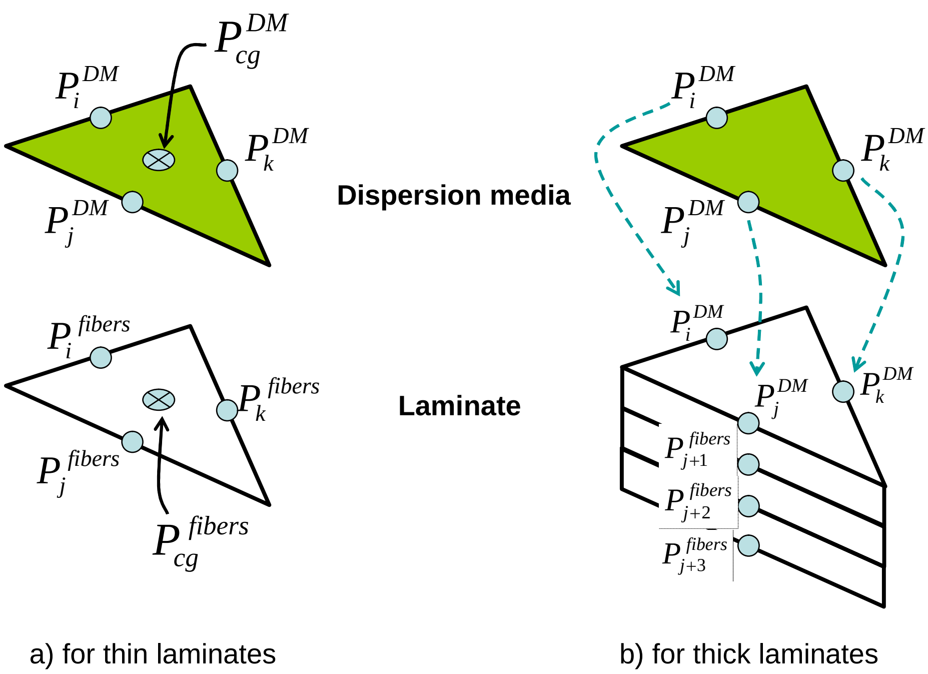

Figure 4. Pressure distributions for the two proposed numerical solutions.

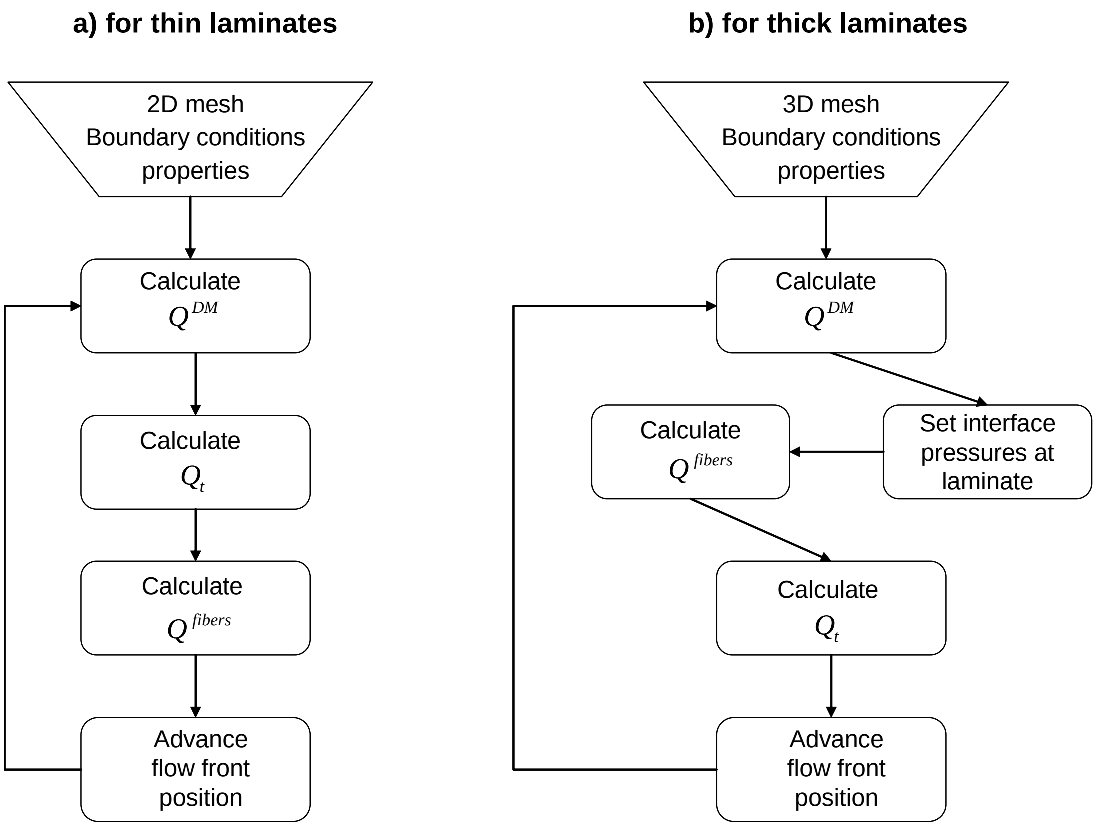

Figure 5. Flow chart of the finite element solver used to simulate DM-RTM mold filling for thin and thick laminates respectively.

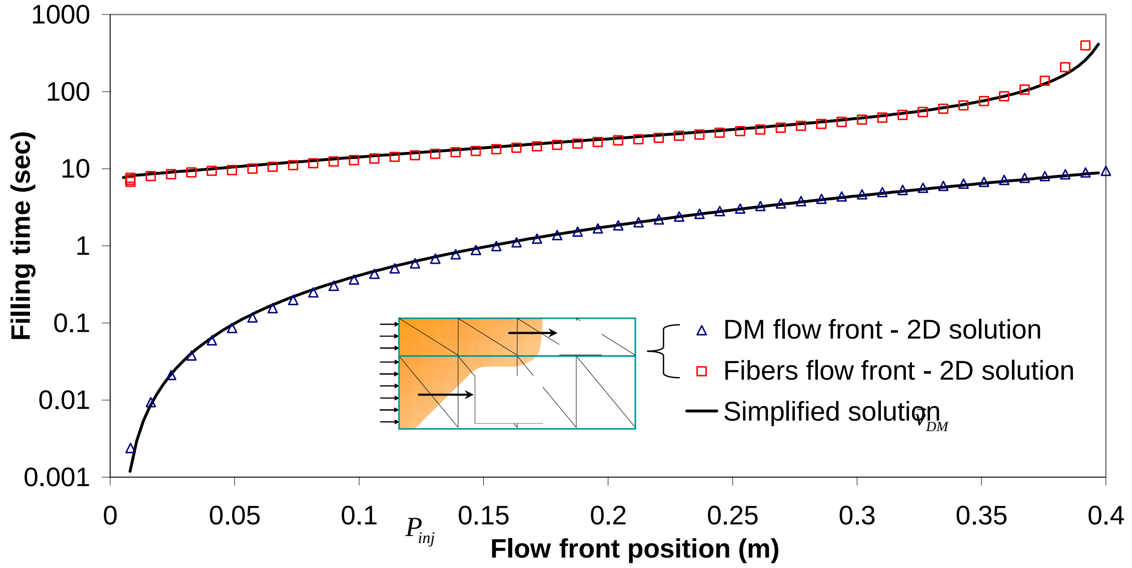

Figure 6. Comparison of the proposed simplified DM-RTM solution with a 2D through-thickness FE solution.

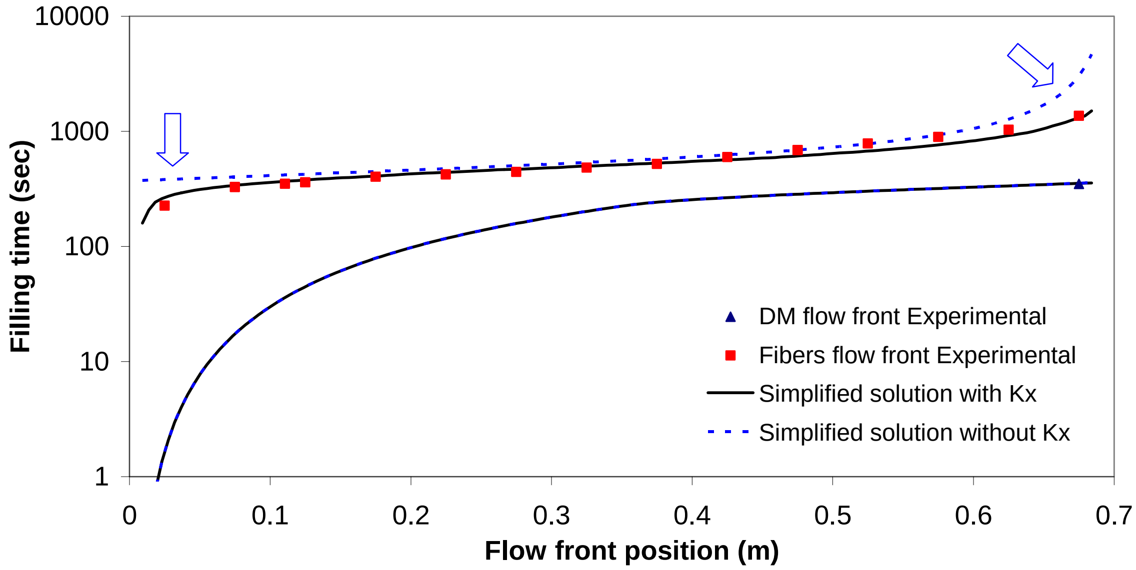

Figure 7. Experimental validation of the proposed simplified approach to simulate DM-RTM mold filling.

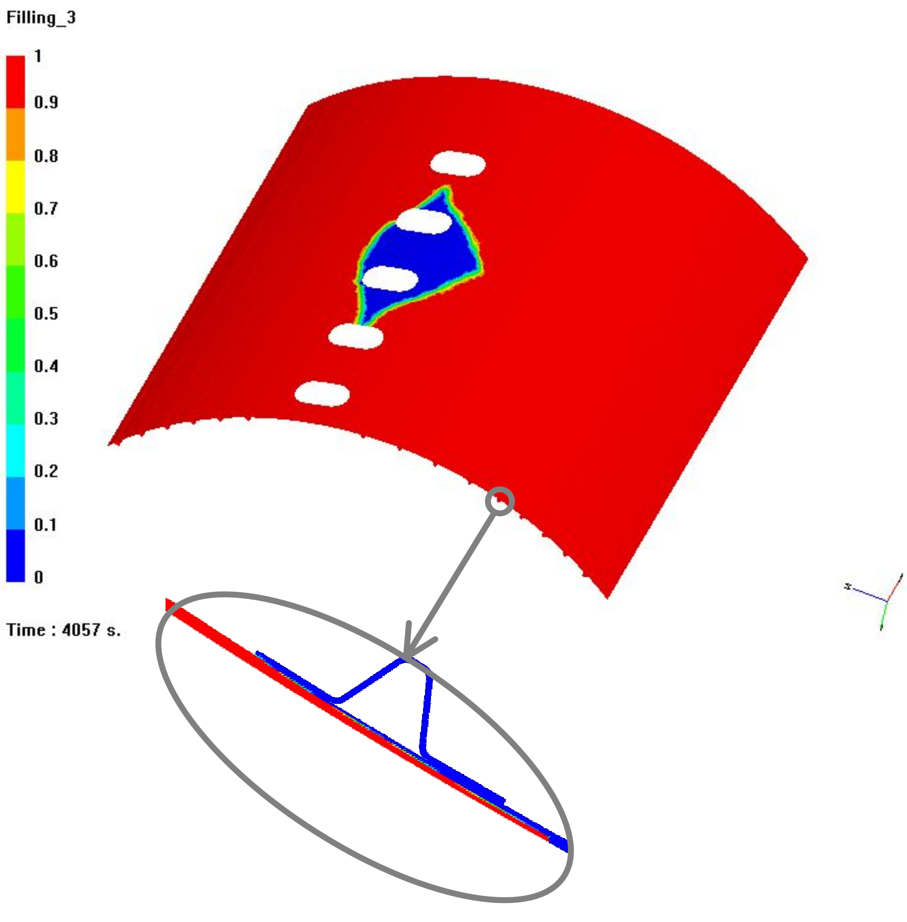

Figure 8. Filling results of the aeronautical composite part with the average permeability solution for a mesh of shell elements.

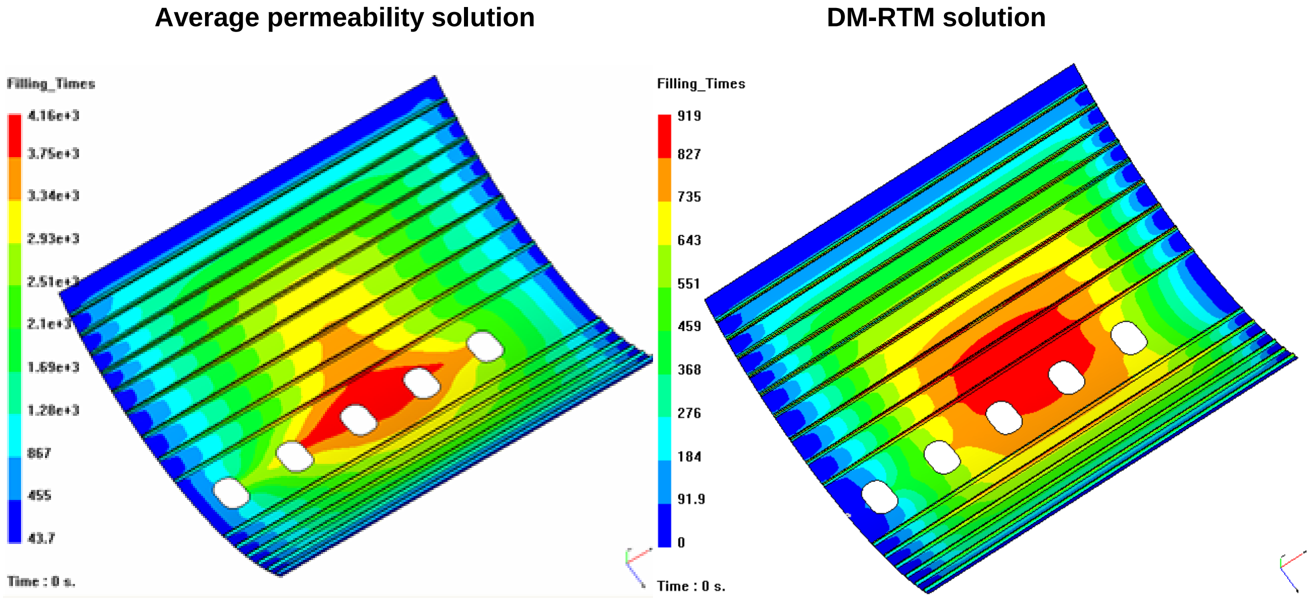

Figure 9. Comparison between the average solution and the proposed DM-RTM solution.

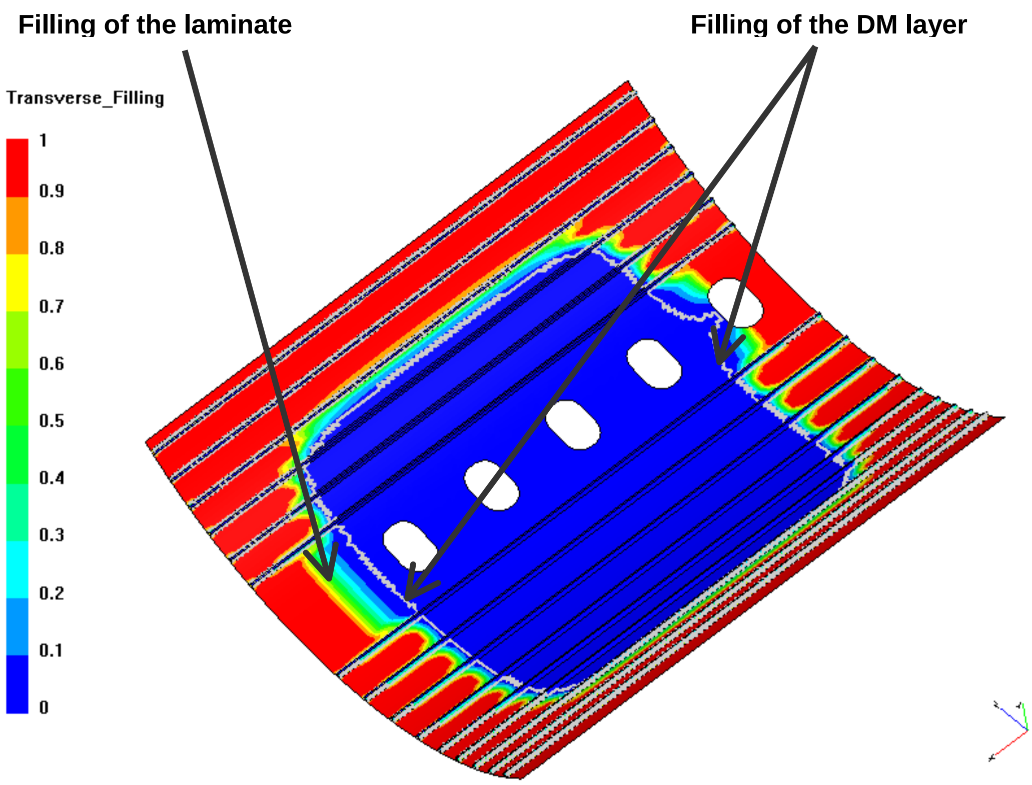

Figure 10. DM-RTM filling simulation of an aeronautical test part: in-plane filling of the DM layer and transverse flow through the laminate can be observed.