Simulation of the impregnation stage of the RTM process

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Introduction

Motivation: Resin Transfer Moulding (RTM) is a method of producing composite structures by binding the fiber preform within a resin. Composite structures manufactured by the RTM process can be of complex geometry, that are at the same time lightweight and capable of withstanding high stresses. RTM can be divided into four separate phases (Fig. 1): preform preparation and mould closure, resin injection, curing and finally removing the part. The part has to be void free and all fibers need to be wetted by the resin. Therefore knowledge of the resin flow during the injection stage of the RTM process is crucial.

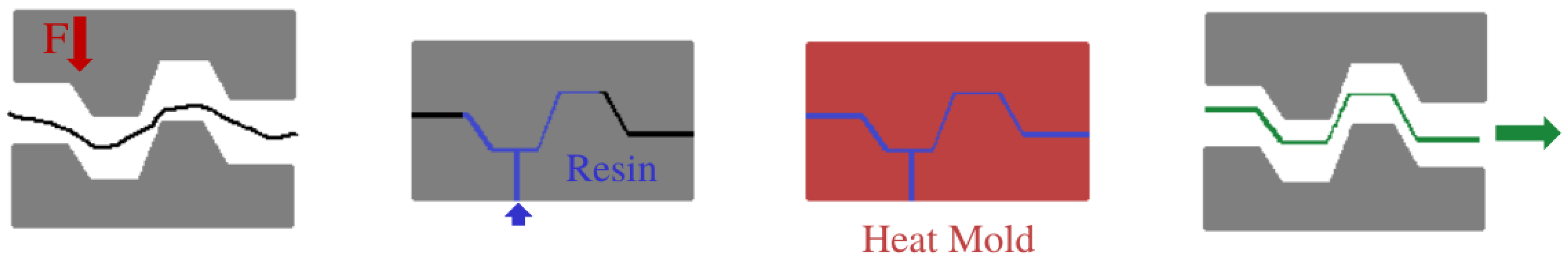

Figure 1 : Four separate phases of the RTM process.

Objectives: Development of a CFD Model to describe the injection stage of the RTM process

- Simulation of resin flow in technical components
  - Prediction of filling time
  - Avoidance of non-wetted ares
- Enhance understanding of key influencing quantity: permeability
- Calibrate and validate the model

Multiscales

A fiber layup consists of layers of textiles, which may have different material properties. The textile permeability is in general anisotropic and coupled to the fiber volume ratio (FVR). When placing the fiber stack into the mold, the textile layers get distorted and deformed resulting in different local fiber orientations and volume ratios, which may vary from nearly zero (e.g. at corners) to approximately 60 %.

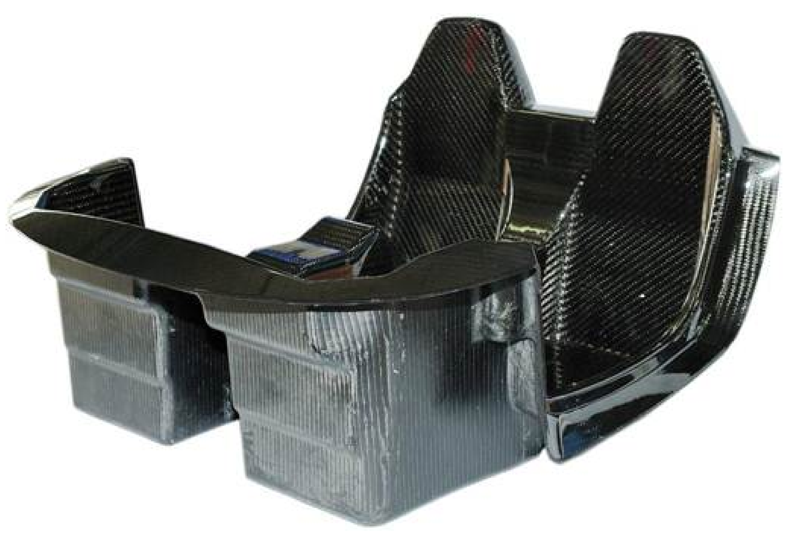

Figure 2 : Macroscale: Driver cabin completly made of carbon by SK Carbon Roding.

For a three-dimensional simulation of the impregnation stage of the RTM process a macroscopic description of fiber materials by porous media [1][2] of corresponding properties is needed. Individual rovings or even filaments can not be considered in this context.
Macroscale (length-scale = [m])
Needed: permeability of fiber stack

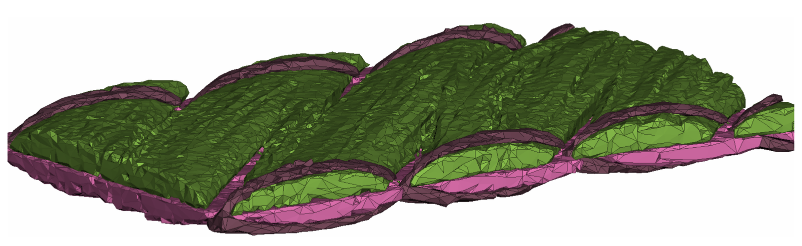

Figure 3 : Mesoscale: CT-Scan of bixal carbon HPT-610 fabric specimen by ITV Denkendorf.

The determined permeability should take into account the mesostructure of the fiber material, i.e. the orientation, the sewing thread, the cross-sectional shape and the way of weaving of the rovings.
Mesoscale (length-scale = [mm])
Needed: permeability of roving

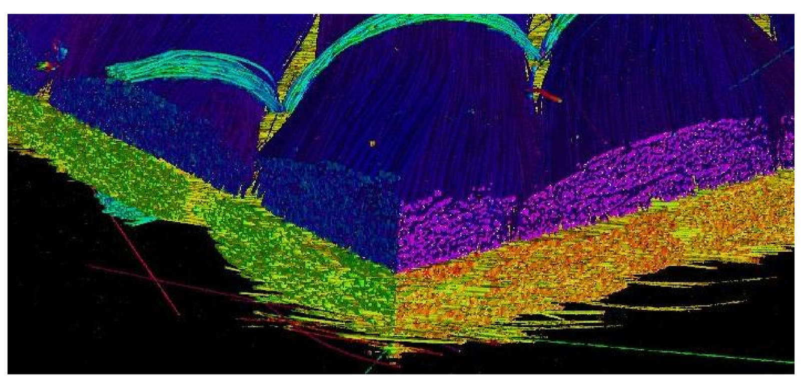

Figure 4 : Microscale: CT-Scan by ITV Denkendorf showing filaments of a carbon fabric.

A known expression for calculating the permeability of uni-directional (UD) fibers [3] is used inside the rovings and sewing threads, which are composed by aligned filaments (microstructure).
Microscale (Length-scale = [μm])

Due to the regularity of the textile, the permeability is predicted by employing an unit-cell impregnation model. Using known local parameters like shear angle, compression and orientation of the rovings, the permeability of the fiber material can be provided as an input parameter for the macroscopic sink term (Darcy's law Eq. (3)). In order to keep the runtime of a simulation of the impregnation stage of a composite structure small, the permeability tensors are stored at a database.

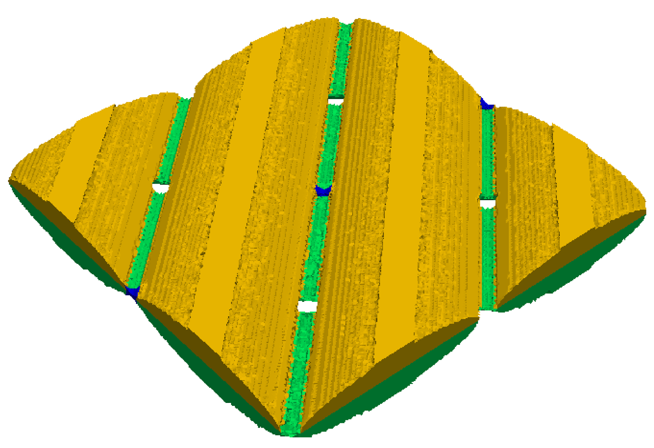

Figure 5 : Unit-cell model of the bixal carbon fabric HPT-610.

Mathematical Modeling

At the microstructure level the flow of one phase is described by the Navier-Stokes equations. Since knowledge of the resin flow at macroscale is needed, to avoid voids and to guarantee that the resin is well distributed, the set of equations is homogenized [4]. The resistance to the flow through the fiber material, which are modeled as a porous media [1][2], is given by Darcy's law (Eq. (3)). The one-fluid formulation of homogenized, isothermal, incompressible, variable-density Navier-Stokes equations

$$\nabla \cdot (\rho\phi\mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial \rho\phi\mathbf{u}}{\partial t} + \nabla \cdot (\rho\phi\mathbf{u} \otimes \mathbf{u}) + \phi\nabla p - \nabla \cdot (\phi\mu\mathbf{u}) - \nabla(\phi\mathbf{u}) \cdot \nabla(\mu) - \mathbf{S} = 0 \tag{2}$$

describe the dynamics of multiphase flows where ϕ is the porosity, which can be defined as $\phi = \frac{V}{V_t}$ (or $\phi = 1 - \text{FVR}$) , where V_t is the total volume and V is the volume of the voids. Darcy's law

$$\phi\mathbf{u} = \frac{-\boldsymbol{\kappa}}{\mu}\nabla p \tag{3}$$

denotes the flow through a porous media. In equation (2) Darcy's law is written as the sink term $\mathbf{S} = -\phi\mu\boldsymbol{\kappa}^{-1}\mathbf{u}$, since the equation implies a pressure drop. The permeability $\boldsymbol{\kappa}$ of the fabric specimen has huge impact on the resin flow and is predicted by an unit-cell model (Fig. 5). The phase interface is captured by a Volume-of-Fluid method. A scalar volume fraction field α is tracked by the transport equation

$$\frac{\partial \phi\alpha}{\partial t} + \phi\mathbf{u} \cdot \nabla\alpha = 0. \tag{4}$$

Macroscale Simulation

The curved geometry "Sattel" is in total 20 cm $\times$ 20 cm $\times$ 5 cm large and the channel height varies between 0.8 mm and 2.1 mm. At top and bottom of the geometry the resin outlet was realised. The injection port is located in the middle of the geometry with radius 2 mm. The magnitude ot the pressure gradient between inlet and outlet amounts 1 kPA. As textile reinforcements we use a UD fabric. Through the curved shape of the "Sattel" geometry, the porosity, shear angle and fiber orientation varies significant. The required input data like porosity and fiber orientation are provided by an external drape simulation. Results can be seen in Fig. 6, where a comparison from a simulation (left) and an experiment [5] (right) is shown.

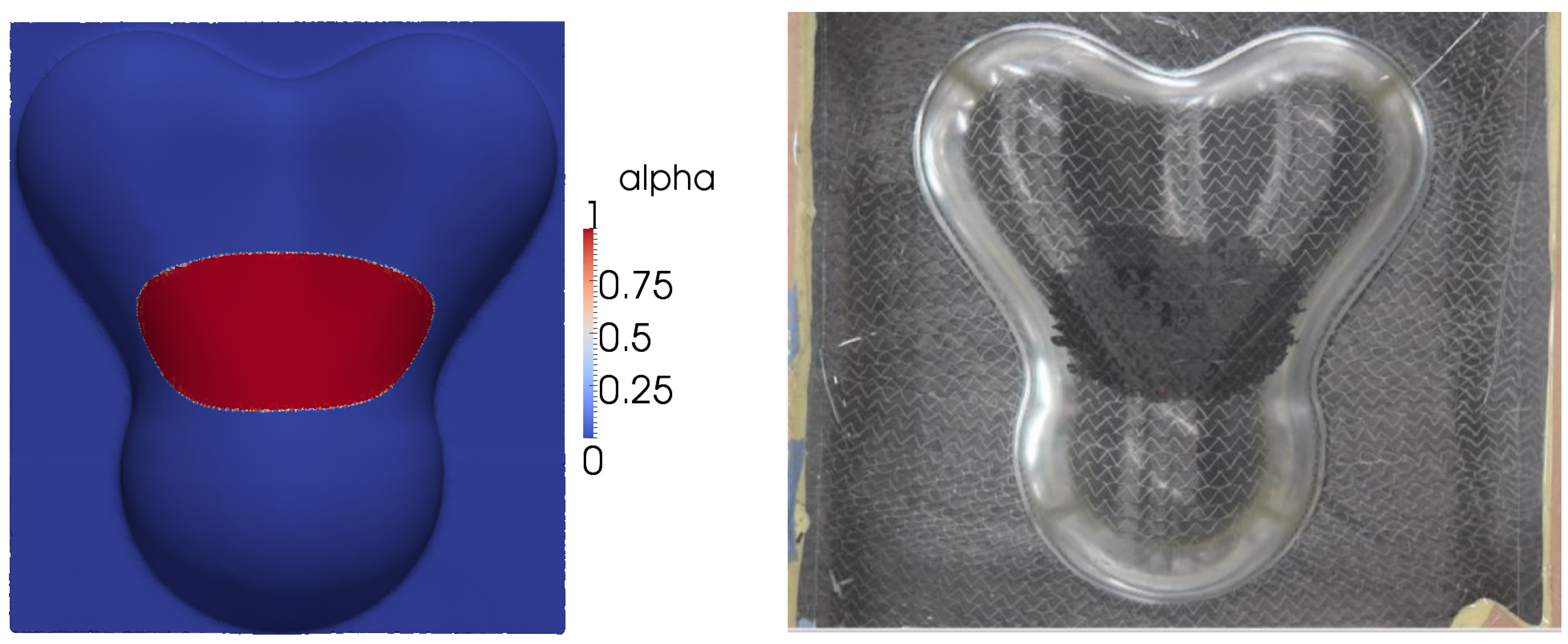

Figure 6 : Topview of the "Sattel" geometry. Simulation (left) and experiment (right) at $t = 20s$.

Acknowledgement

The authors wish to acknowledge the funding provided by the Federal Ministry for Economic Affairs and Energy.
ZIM-KF-project "Software based design of industrial mass production by RTM-process", Swim-RTM.

ZIM
Zentrales Innovationsprogramm Mittelstand

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