SIMULATION OF MOLD FILLING IN RESIN TRANSFER MOLDING CONSIDERING THE LOCAL FIBER ARCHITECTURE AFTER THE PREFORMING PROCESS

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ABSTRACT

Resin transfer molding (RTM) is an industrial process to produce structural composite parts. During manufacturing, a dry fiber preform is draped into a cavity and is compacted by a hydraulic press. Afterwards, the cavity is injected with a matrix material (e.g. epoxy resin) until the whole part cures and can be demolded. To be suitable for mass production, the process has to be more time-efficient and better designed. With an optimized injection strategy, it is possible to reduce the cycle time significantly and avoid potential air traps in the part. Numerical simulation tools provide efficient solutions to find the best injection strategy. However for a realistic modelling it is necessary to take into account the local fiber orientations and fiber volume fractions resulting from the preforming process. For woven fabrics, this is already state of the art. For unidirectional fabrics, like in this work, no robust method exists, which is able to determine the local fiber architecture from draping simulation. Therefore mesoscale-modelling for draping simulation is used in combination with experimental methods like ultrasonic incineration to consider the local fiber architecture in this work. To transfer these data to the mold filling simulation model a special interface is developed. In this work these methods are applied to the mold filling simulation of a complex formed composite part. To demonstrate the influence by considering the local fiber architecture, a reference model is created additionally, where the fiber architecture is defined globally, without considering the draping process. Finally both models are compared against each other.

1 INTRODUCTION

Because of their low density combined with good mechanical properties, fiber reinforced structures are increasingly used in industrial applications. For small series productions, it is already possible to observe the economic boundary, but for mass production, for example in the automotive industry, the economic production of composite parts is still a big challenge. Reasons for that are high material and production costs coupled with a low degree of automation, compared to metallic parts. There are already several production methods for structural composites in the industry. Due to its high automation possibilities, resin transfer molding (RTM) offers huge potential for large batch production of high performance composite structures. As initial process step a dry fiber preform is draped into a mold cavity and is compacted by a hydraulic press. Afterwards, a matrix material (e.g. epoxy resin) is injected until the preform is completely impregnated. After curing the consolidated composite part and can be de-molded. To be suitable for mass production the manufacturing process has to be more time-efficient and properly designed. An important step to achieve this target is to optimize the molding process. Simulation tools support this development by replacing time-consuming and cost-intensive real test method [1-3]. Therefore it is necessary to ensure the validity of the simulation. An important precondition for a sufficient simulation is an integrated modelling of the entire RTM process chain, where all significant process parameters and process results are transferred between the single simulation steps [4-6]. For woven fabrics the interface between draping simulation and molding simulation is already established. Bickerton [7-9] uses for this purpose a kinematic draping model in combination with simple curvature models and Louis [10] extends this by using homogeneous FE

models [11] for the draping simulation. The local fiber volume fraction can be calculated for woven fabrics by the use of local shear angle (angle between weft and warp-direction) with the following formula, as discussed in [12-13]:

$$\varphi_a = \frac{\varphi}{\cos \alpha} \tag{1}$$

For non-crimp-fabrics like unidirectional fabrics (UD) this calculation of fiber volume fraction cannot be used. Furthermore the simulation of the draping process requires considerably higher efforts because with the absence of woven nodes a higher degree of freedom arises. This result in a different forming behaviour compared to woven fabrics, which cannot be predicted as precisely by homogenised material models [14]. Therefore mesoscopic models for draping simulation are implemented in the last years to solve that issue [15-16]. The focus of this work is the transfer of local fiber architecture from such a mesoscopic drape simulation to the mold filling simulation. For this purpose a special interface, using Computer Aided Engineering (CAE) methods, is necessary. The CAE interface is supported by experimental methods like ultrasonic incineration, which help to determine the local fiber volume fraction. Subsequent these methods are used for the mold filling simulation of a complex formed composite part.

2 EQUATIONS AND MATERIAL PARAMETERS

Mold filling during RTM manufacturing is an unsaturated flow through porous media and can be approximated by Darcy's law [17]:

$$\vec{v} = -\left(\frac{\vec{\vec{K}}}{\mu}\right)\nabla(\vec{p}) \tag{2}$$

where v is the mass averaged velocity [*m/s*] and p is the pressure field [*Pa*] in the cavity. Important material parameters are the viscosity, μ [*Pas*], of the matrix material and the permeability, K [m^2], of the fibers. The permeability is anisotropic and is defined by a second order tensor. In the principal coordinate system, there are three significant parameters: K_1, K_2 and K_3. The direction with the highest permeability is K_1. K_2 is the direction with the lowest permeability. For unidirectional fabrics K_1 is parallel to fiber direction and K_2 is perpendicular to the fibers. The permeability in thickness direction, K_3, can usually be neglected due to the small thicknesses of composite parts [18]. Until now, there is no standard procedure to determine the permeability experimentally [19, 20]. This leads to some uncertainty in dimensioning and simulation. In this study, a permeability measurement setup is used, which is able to determine the permeability directly during RTM manufacturing [21]. This guarantees a process-oriented approximation of the permeability. In Magagnato [21] the results of the permeability measurements for a unidirectional fabric (producer: SAERTEX GmbH & Co. KG, fiber: Toray T620), which is used in this work, are presented. The permeability of this textile strongly depends on fiber orientation and fiber volume fraction.

The viscosity of a reactive matrix material, used in RTM manufacturing, is a function of temperature and curing degree. In this study, a non-reactive test fluid called Mesamoll is used to blend out the effect of strongly changing viscosity.

3 CAE CHAIN FOR RTM PARTS

The main process steps in RTM manufacturing consists of cutting and draping of textile materials to a dry fiber preform, the exact placement of the preform in a heated cavity, the injection of a matrix material (thermoset or thermoplastic) and the de-molding of the cured composite part. In a CAE chain each step is modelled using its own simulation software package. The simulation steps are linked with each other by information flows, which are presented by green arrows in Figure 1 and which comprise the transfer of important fiber data. If simulation results suggest a change of the structural design (e.g. due to insufficient feasibility or due to bad structural performance, see red arrows), the process chain starts again. [4, 5]

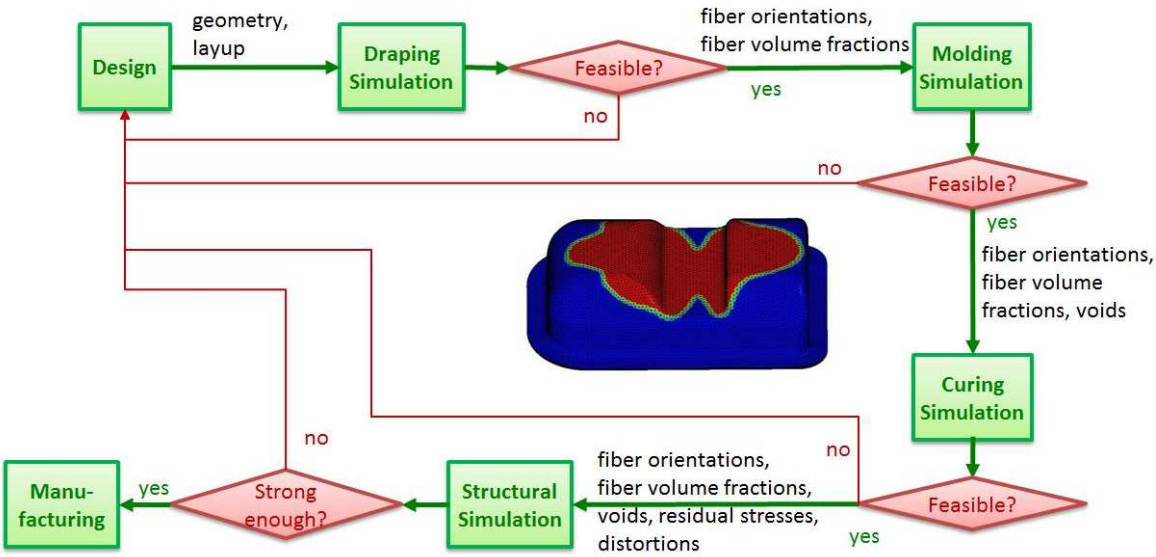

Figure 1: CAE chain for Resin Transfer Molding [4-5]

For the exchange of data between the different simulation software packages a universal data format (vtk) is appointed. Different command line scripts ensure the type conversion from the specific data formats of the different FE software package to the vtk format. In [5] all command line scripts, which have been implemented to build up the CAE chain, are listed. In this work, the focus is on molding simulation. Therefore, the transformation scripts for LS-DYNA and PAM-RTM have been applied.

4 MOLD FILLING OF A CONVEX-CONCAVE COMPONENT

For the demonstration of the CAE chain, a convex-concave (CC) component is designed, representing the challenges in complexly shaped automotive parts, such as double curved corners and 90° direction changes. To compensate local material accumulations by the preforming process, the designers used different local thicknesses (from 2.7 mm to 6 mm) in the component, see figure 2.

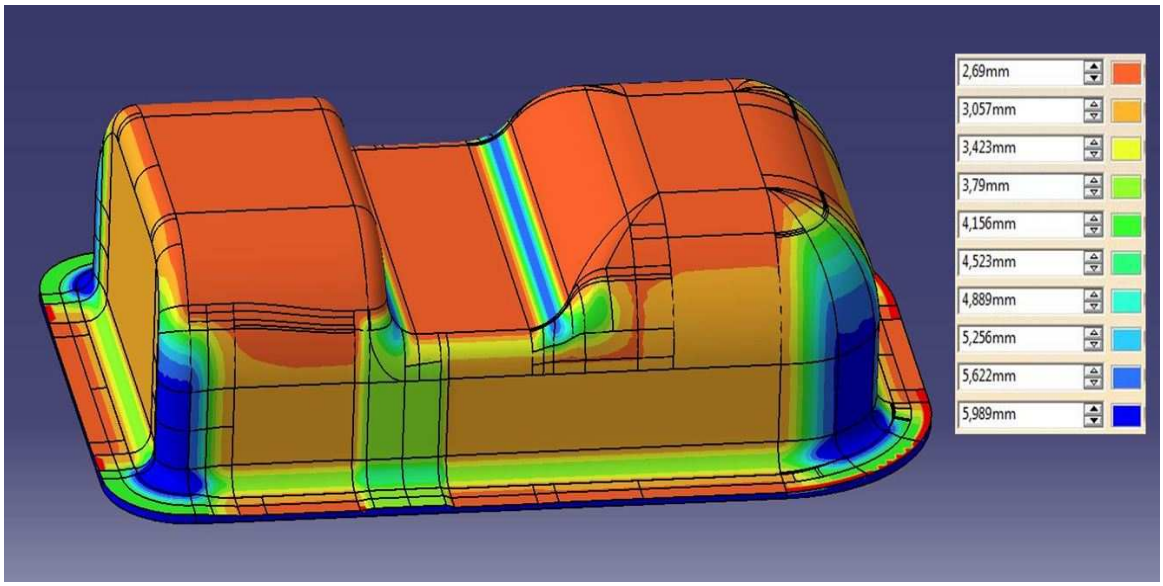

Figure 2: CAD-model of the convex-concave (CC) component with different local thicknesses

4.1 Setup of the simulation model

In figure 3 a finite element (FE) mesh for the CC component is shown. The injection is done with a pressure of 5 bars through a divided channel, see blue points in figure 3. The vents are implemented through four exhaust points in the outer corners (see green points in figure 3) of the CC component. The injection and venting strategy was determined by a simplified simulation model.

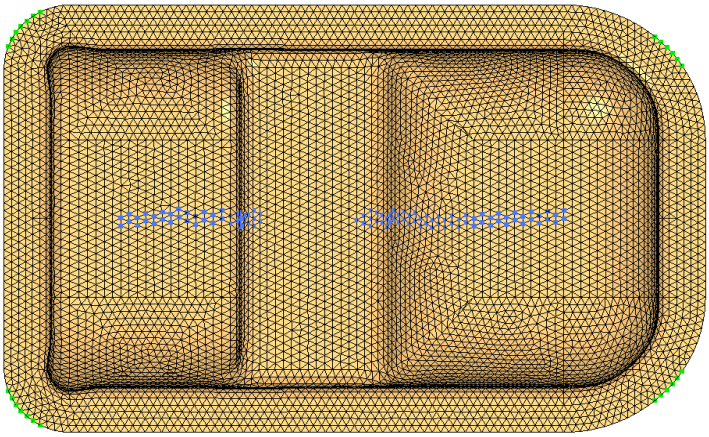

Figure 3: FE mesh with injection (blue) and vent strategy (green)

4.2 Import of local fiber orientation and fiber volume fraction

As illustrated in Magagnato [21], the orientations of the fibers and the fiber volume fraction have a big influence on the permeability of the used unidirectional fabric. Thus, for molding simulation, it is recommended to estimate these local fiber data from draping simulation. The draping simulation of the CC component was performed at ITV Denkendorf using a 2,5D- mesoscale approach in LS-DYNA. Figure 4 shows a virtually draped layer (unidirectional, 0°) of the CC preform. The fiber rovings are modeled with finite shell elements. In each element a vector for the local fiber orientation is deposited, see figure 4 (zoomed area). The draping simulation consists of eight of those meshes, each representing a single layer.

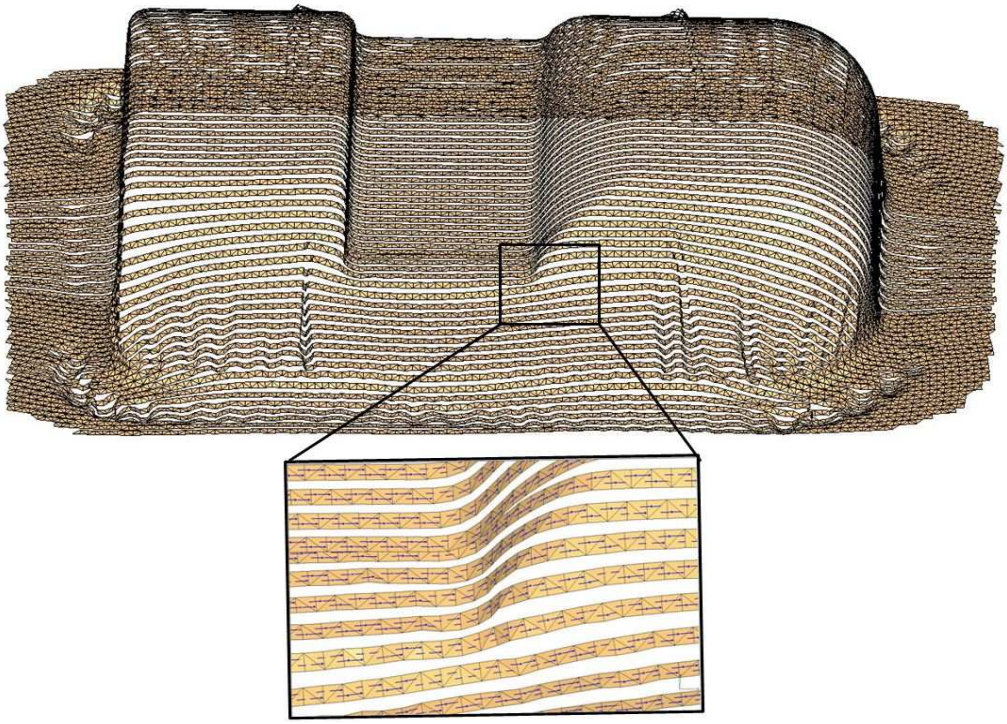

Figure 4: Results of the draping simulation for the top layer of the 0° layup
[Draping simulation: ITV Denkendorf]

To transfer the local fiber orientations from a draping mesh to a molding simulation mesh the mapping software MpCCI MapLib from Fraunhofer SCAI [22] is used. The molding mesh is a three-dimensional volume mesh, which is composed of eight elements in thickness direction. Each element ply is mapped from the corresponding layer of the draping simulation. After mapping and format conversion, the mesh with the updated fiber orientations can be imported into PAM-RTM. Figure 5 shows an augmented part of the mesh of the CC component, where on the right hand side the fiber orientations are imported from the draping simulation ("CAE model"). To demonstrate the improvements obtained by using the CAE chain, a reference model is created, where the global fiber orientation of each layer is projected in each element on the component's surface, see Figure 5 on the left side. This is an easy approach to model the fiber orientation, if no draping simulation is available. As indicated in figure 5, there are differences between the two models in the approximation of the local fiber orientation, especially in the curved areas. The CAE method models the transition of the fiber alignment in a smoother manner than the reference model.

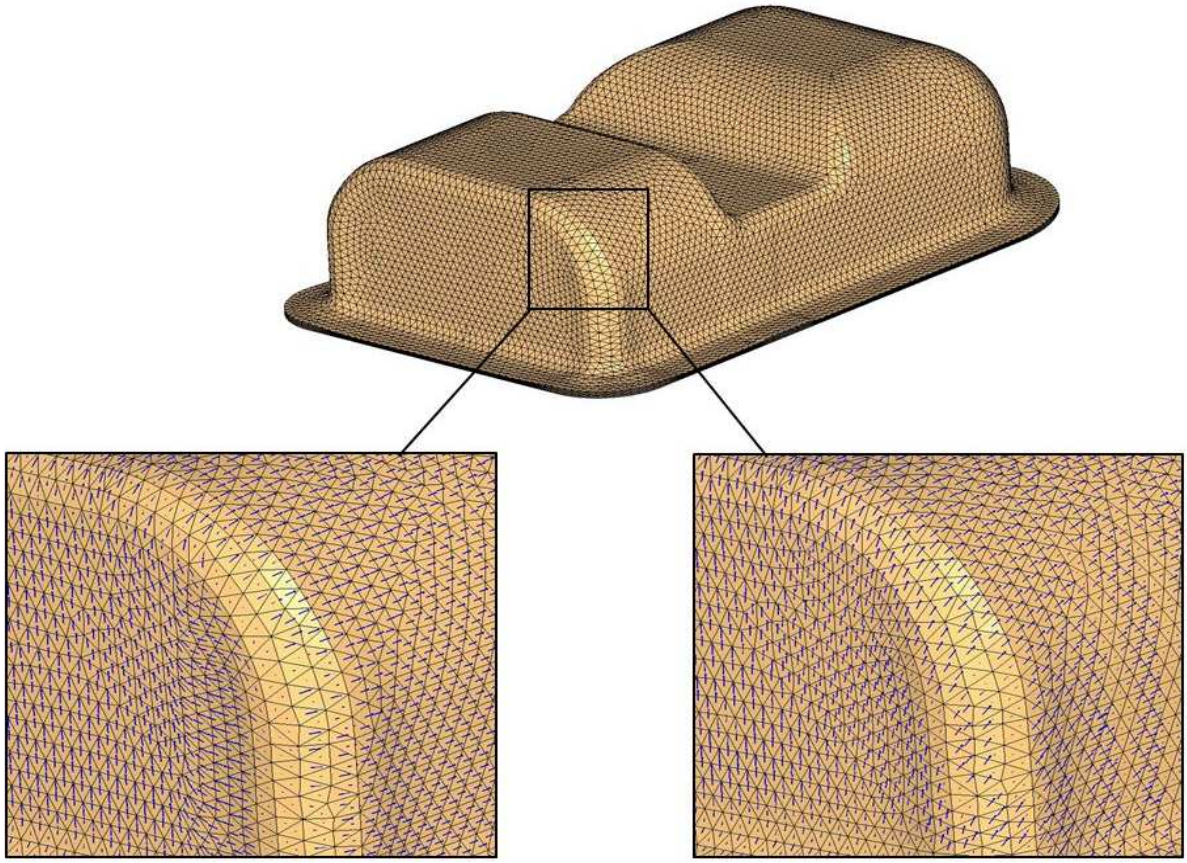

Figure 5: Comparison between the two fiber orientation models: reference model (left) and CAE model (right), the small dashes show the fiber direction (0° layup) in each element

To model local changes in fiber volume fraction, local thicknesses in the cavity (cf. figure 2) and local material accumulations, which result from preforming, have to be considered. Until now, there is no valid method for unidirectional fabrics to determine the local fiber volume fraction directly from draping simulation. Additionally draping simulation is not yet capable to reliably predict both the distance between fiber bundles and the ply thickness. Therefore, in this work, the local fiber volume fractions are determined experimentally via ultrasonic incineration. More detailed information on this method is described in Magagnato [23].To consider the local fiber volume fractions in the molding simulation, the draping-model is subdivided into different zones to which the respective values of the experimental determination are assigned. For the reference model, a constant fiber volume fraction is assumed, which is calculated considering the known preform weight, the fiber and matrix density and the cavity volume.

4.3 Molding simulation results and discussion

For the molding simulation, the material and process parameters, as discussed in chapter 2 and 4.1, are entered into both simulation models. Furthermore the injection and ventilation strategy is implemented (cf. figure 3). As described in chapter 4.2, two different models are implemented: a CAE model with considering the local fiber architecture and a reference model, where the fiber architecture is defined globally. In figure 6 the flow front for the reference model is confronted with the CAE model at different time steps (25 seconds, 50 seconds and 100 seconds). For both models the flow spreads out quickly in fiber direction (0° layup). Perpendicular to fiber direction the flow spreads out slowly. The comparison of both models shows a significant influence by considering the local fiber architecture. The CAE model captures local inhomogeneities in the preform and generally the flow front is growing faster compared to the reference model.

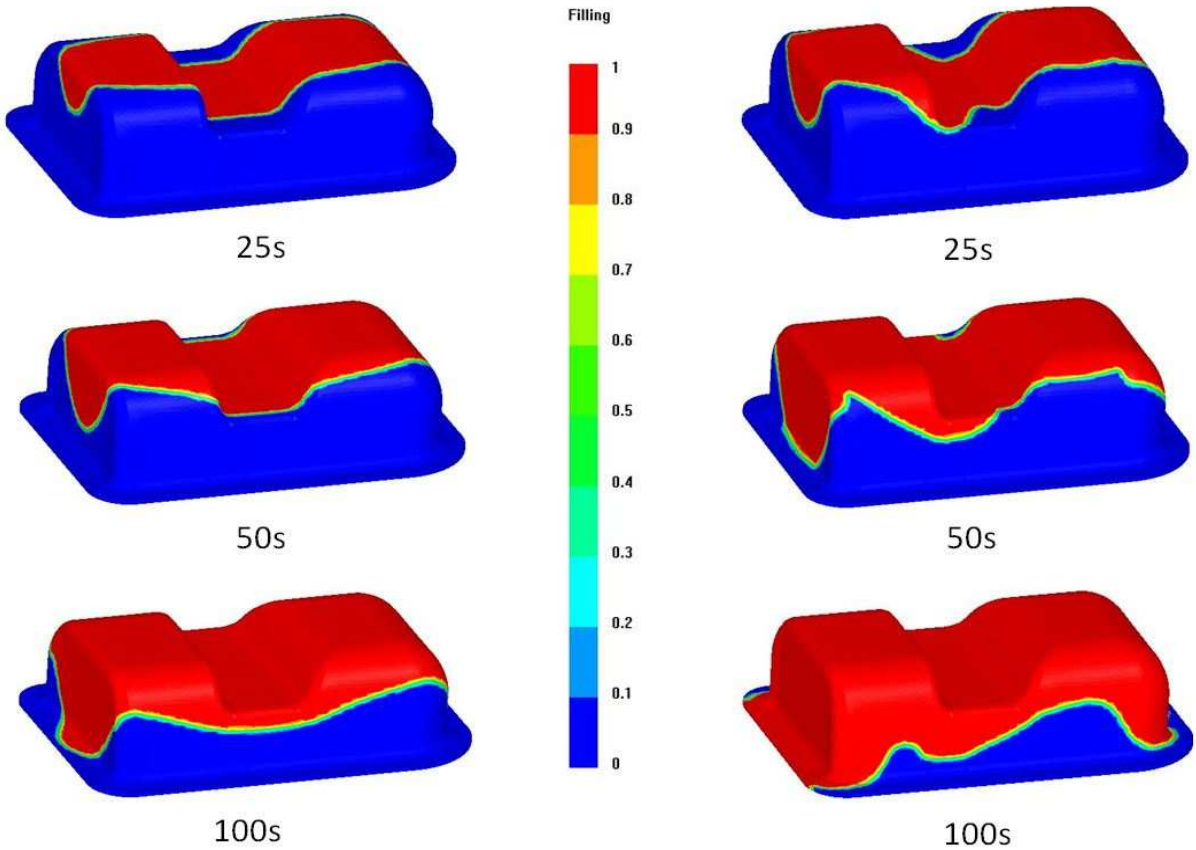

Figure 6: Comparison of the flow front between the two fiber orientation models:
Reference model with global fiber architecture (left) and “CAE model” with local fiber architecture (right)

5 CONCLUSIONS

In the present work, the RTM molding process for a complexly shaped composite component has been investigated numerically. Due to the preforming process, local inhomogeneities of fiber orientation and fiber volume fraction arise in the component. To consider these inhomogeneities in the FE model, a CAE-interface between draping simulation and molding simulation was used to provide the local fiber orientation. The local fiber volume fraction was determined experimentally via ultrasonic incineration. To demonstrate the influence of using these methods for the simulation, a reference model was created additionally, where the fiber architecture is defined globally, without considering the draping process.

By comparing both simulation models, a significant difference in the flow front progress is visible. The CAE model is able to capture the local inhomogeneities in the preform, which affects the flow front in a strong manner.

In future research, the local fiber volume fraction will be included directly from draping simulation to consider this information already in the preceding design and dimensioning process. Furthermore a detailed experimental validation of the simulation results with pressure sensors will follow in Magagnato [23].

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