MANUFACTURING SIMULATION AS PART OF THE DIGITAL PROTOTYPE

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Abstract

The research project **A**ctive **R**esearch **E**nvironment for the **N**ext generation of **A**utomobile (ARENA2036) is a long term project funded by the Federal Ministry of Education and Research Germany. Within this project four sub-projects are located. DigitPro, one of those sub-projects, deals with the development of a **Digit**al **Pro**toype. A closed simulation process chain is built which not only covers different simulation disciplines such as crushing or process analysis, but also various software solutions and material models. The main goal is to use the digital prototype to decrease the weight if an automotive structure by 10% and the development time by 50%.
In this project one of the focused manufacturing processes for composite structures is the braiding technology followed by an infusion process. A complete numerical prediction is necessary for the braiding as well as for the infiltration process to decrease the development time and to increase the mechanical performance of braided structures. Within this work an overview of the newest developments in braiding and infiltration simulation and especially in the transfer of the necessary data from one process to the next is given.
An overview on the succeeding project "Digital Fingerprint" will be given as the results of the project DigitPro will be used there.

1 Introduction

With respect to economic and ecological issues structures for technical applications have to be lighter, multifunctional but still cheap. These controversial requirements can only be achieved by the combination of different areas like the optimization of the manufacturing processes, the use of innovative materials - such as fiber reinforced plastics (FRP) and its suitable application - and highly automated, intelligent production processes. Especially the last request is one of the tasks within Industry 4.0, where different production steps are intelligently connected among each other and with the components itself.
By the use of fiber reinforced materials the amount of different variations increases as a very high number of possible combinations exists. This high complexity leads to an increasing demand on virtual prediction methods – such as the **Digital Prototype**. The aim of this kind of a virtual process chain is the numerical illustration and prediction of the complete production chain. This should lead on the one hand to an optimized manufacturing process where the specific material behavior is considered and on the other hand to optimized properties of the final structure.
The necessity of a virtual prediction of the structural behavior of FRP parts is based on the fact that it consists of the fiber and resin properties and that the fiber architecture strongly influences the properties of the final structure. The forming of textiles is limited due to forming effects. Using simulation techniques the final fiber architecture and thus the final properties can be known bevor the real manufacturing starts. By virtually changing the boundary conditions of the manufacturing process the fiber architecture can be optimized and thereby the lightweight potential can be maxed. As the forming effects might lead to a non-optimal fiber distribution the deviations are known thanks to the simulation and can be taken into account. Both ways lead to a reduction of the material usage and save weight and costs.
Using the virtual optimization the process boundary conditions can be adapted in a way that on the one hand, as described above, the ideal fiber architecture can be achieved, and on the other hand, the process itself can be designed cheaper, projectable, faster and even realizable. Provided that good

simulation models are existing, an optimization of the real manufacturing process regarding cost, time and performance is possible.
Within the research campus ARENA2036 the project DigitPro handles the **Digital Prototype** for the automotive industry. Therefore different manufacturing processes are considered and are virtually described. As manufacturing processes the so called open reed weaving (ORW) and the draping of such ORW-textiles is focused as well as the braiding technology and the following resin infusion.
To achieve a closed virtual process chain a new data container using the HDF5 file format is defined [1, 2]. All input and output data of each simulation step is stored in that data container, which for this reason serves as storage but also as documentation of the corresponding virtual process chain. In this Digital Prototype – or **Digital Fingerprint** - all data of the real manufacturing, the testing or the quality management can be stored next to the simulation data. Thanks to a strict organization the whole history of each structure can be scanned, even in the final assembly, using „*near field communication*“ or „*barcode*“-systems (cf. Figure1). This digital fingerprint is the direct connection to the Industry 4.0. A log file is deposited in which all following processes in every variation is listed. The data itself is stored in a cloud-based neutral HDF5 format.

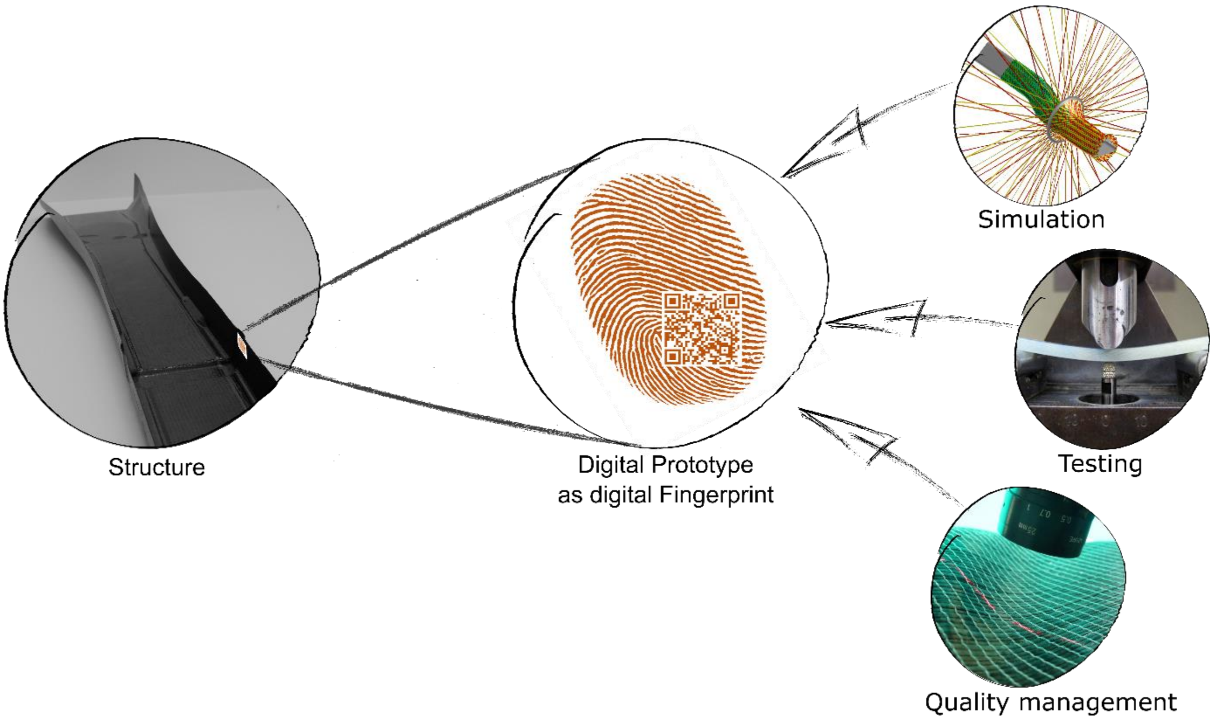

Fig.1: The Digital Prototype as Digital Fingerprint

Using different software-tools for the different simulation steps an input deck is created by a parser taking the necessary data out of the data container to the simulation tool and storing it back in the data container after the simulation. The results of a forming simulation such as the braiding process simulation for instance can be transferred directly to the resin injection simulation and those results again to the structure simulation. The defined data container is designed in a way new processes can be added to the Digital Prototype very easily.

2 Braiding Simulation

As said before, one of the key manufacturing processes in the Digital Prototype is the braiding process, which is ideal for tube-like structures. Braids feature complex fibre architecture, which can be quite well determined for simple, straight geometries with a constant, circular cross-section. The thickness of a braiding layer, gapping effects as well as fibre undulations can either be analytically calculated or empirically predicted [4]. The mentioned parameters are exclusively dependent on the braiding machine setup, the number of braiding bobbins, fibre tension, linear yarn density and the desired braiding angle. Also, the movement of the mandrel through the braiding machine has a strong impact on the final structure behaviour.

A finite element based simulation approach for the braiding process is used to predict the complex final fibre architecture which can then be used for the following numerical simulation steps. Due to the mentioned effects, the resulting fibre architecture can differ largely from the expected one.
In order to predict these differences, physical effects have to be included in numerical models, e.g. friction and occurring dynamic effects. This is the reason why an explicit, numerical finite element simulation (PAM-CRASH V14, ESI Group) is used in the project DigitPro. On the one hand it is, due to the high level of detail, computationally expensive. On the other hand, it has the potential to model any kind of desired and undesired effects. The goal is to reduce the development costs, as less preliminary experimental tests and real manufactured prototypes are needed.
A braiding simulation of a generic geometry is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The yarns are represented by linear 2D shell elements [2]. The kinematic of the real braiding machine is copied, and the mechanical properties of the dry carbon fibre yarns are modelled using a specially adapted material formulation, where the bending stiffness is not coupled to the tensile stiffness. This is very important as dry textiles always have different in-plane and out-of-plane behaviours which has to be considered for getting suitable prediction.

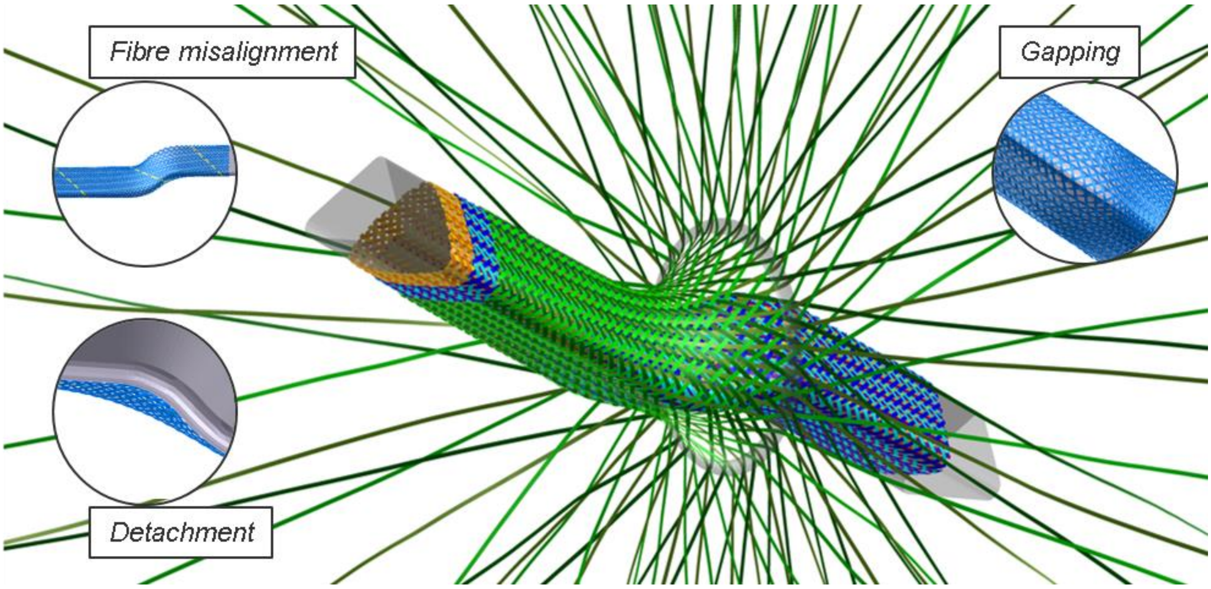

Fig.2: Simulation of the braiding process of a generic geometry.

It can be seen in the figure that the effects mentioned above can be modelled. There are variations in fibre angles as well as some gapping and bridings effects. All of them are influencing directly the mechanical behaviour of the final structure.
An optical measurement system, co-developed by IFB and FIBRE [2; 5], can be used to determine the fibre angle of the real manufactured component (cf. **Fehler! Verweisquelle konnte nicht gefunden werden.**) based on a grey scale analysis [6]. The gained information gives a good validation of the simulation compared to finished part. Micrographs of the braided composite part show the inside of the fibre architecture, making a validation of the fibre undulations possible. This is necessary to improve the simulation approach and to fit several unknown parameters in the numerical model. An approach which is fitted to a simple geometry can then be used for predicting more complex structures which will decrease the amount of real tests and safes a lot of money.
Although modelling the yarns with shell elements is a big simplification, a quantitative comparison is possible. Any detachments of the braid can be detected and measured using a 3D scanning system (ATOS by GOM), see **Fehler! Verweisquelle konnte nicht gefunden werden.**. All these types of quality assessment can be saved to the digital fingerprint of the part, so that a continuous quality monitoring is possible.

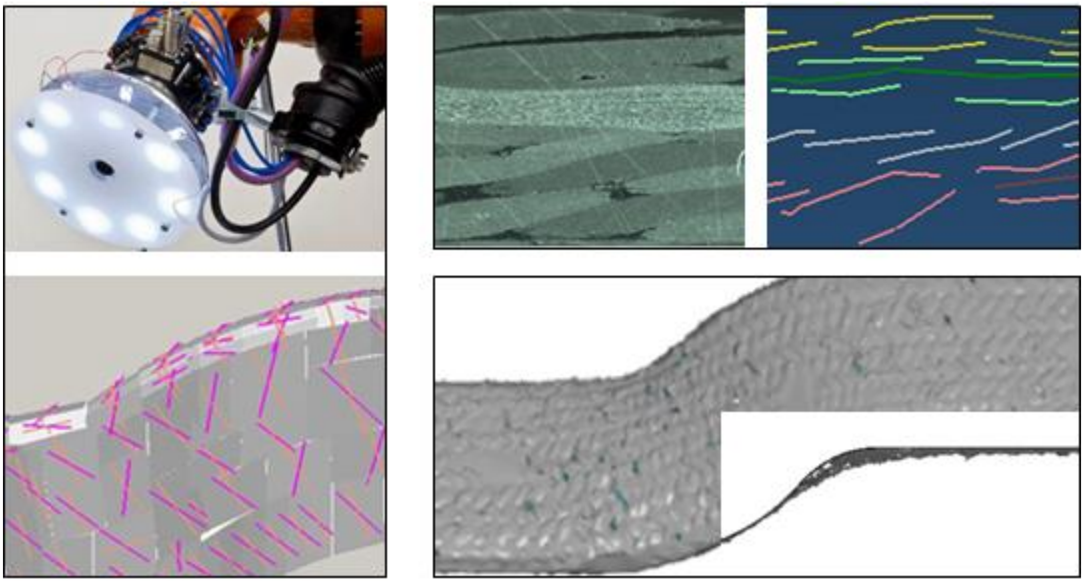

Fig.3: Recording of the fibre angle (left), real and virtual micrograph of the braid architecture (top right) and 3D scan of detachment effects (bottom right).

Relevant parameters for the braiding process are the fundamental processibility, the mandrel path, the choice of yarn tensions and the bobbin setup. These can be virtually determined in the braiding simulation and transferred to the real manufacturing, reducing the number of preliminary tests.
Furthermore, mechanical properties of the finished composite part can be calculated based on the result of the braiding simulation. Values like the local fibre angle, material thickness and pure resin pockets due to gapping all have an influence on the stiffness and strength of the final part. Corrections can be introduced early on in the development process. Once set-up, the digitally determined target architecture becomes the quality reference for the production of real parts in a next generation manufacturing line.
The combination of simulation with reality is ensured by using a CAM interface, which was developed at the IFB. The mandrel path or rather the robot path responsible for the guidance of the mandrel through the braiding machine is directly adopted from the simulation. A first iteration step of the path is gained by the geometry information. Using that in the finite element simulation the path is adopted with respect to the effects mentioned above. After some iterations the ideal mandrel path is determined which then is interpreted as robot path and transferred to the manufacturing step afterwards.

This way, a good prediction of the part properties and an ideal robot path are achieved. Another ambitious project is the development of an electronic bobbin which enables the change of yarn tension during the braiding process. As a result, more degrees of freedom for the manufacturing process are possible. This leads to better, lighter and cheaper parts.

3 Resin injection simulation

The resin injection simulation is an important part of the FRP process chain and uses the results of the braiding simulation.

If components are not properly infiltrated or just with poor quality, previously calculated material properties are not achieved. The most important parameter in LCM (liquid compression molding) processes is the permeability of a technical fabric to a fluid media. The determination of this parameter is difficult, but is essential for simulation. At the moment almost planar permeability values are used, as near-net-shape prediction in measuring benches or tools are only realizable with increased effort and for each new component. The transfer of the ideal, planar permeability values to near-net-shape draping or to near-net-shape braiding structures is not adequate. Different component thicknesses in the tool design and fiber angle variations prevent this as locally varying permeability is occurring (see Figure 4).

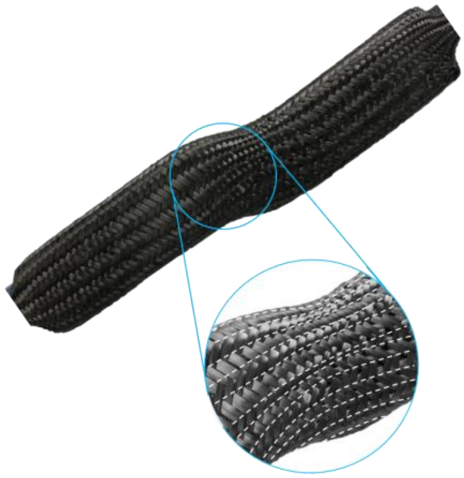

Fig.4: Variation of fibre angle in a triaxial braiding process

In the project DigitPro a new numerical approach of predicting permeability values is concerned. The textile layup of the target structure, based on the data of the braiding process simulation stored in the Digital Prototype, is modelled mesoscopically and a flow through the textile is generated using a CFD solver. Also the Dual-Scale-Effect can be simulated, around and through the individual yarns. This simulation can be realized within a few hours and to this state of development a good impression on the input parameters is given.

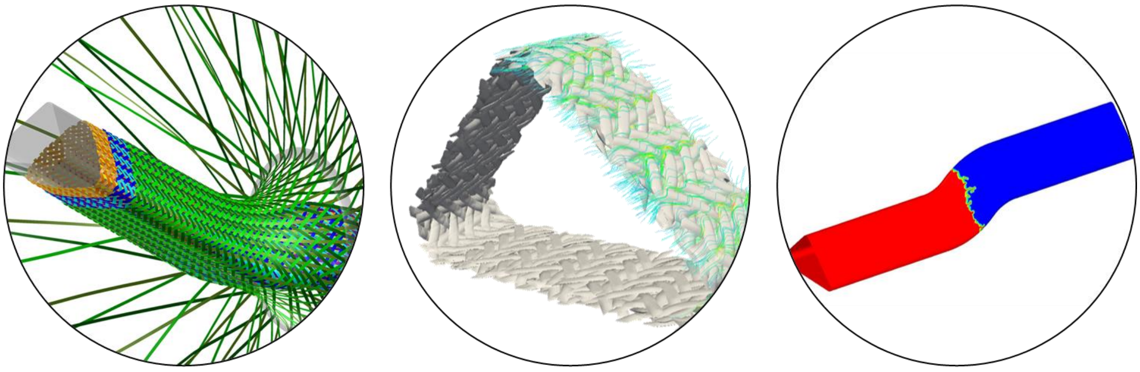

Fig.5: Transfer of fibre architecture to preform FEM filling simulation

The final near-net-shape, three-dimensional permeability tensor field (see Figure 5 and 6) allows the prediction of critical points in the component and can also be used for FEM filling simulation. Therefor a mapping algorithm such as Envyo [7] is used. Discrete determined permeabilities are mapped on a two dimensional macroscopic finite element net and a liquid compression molding simulation is performed. This helps defining inlets, outlets and injection pressures in the real manufacturing process [3].

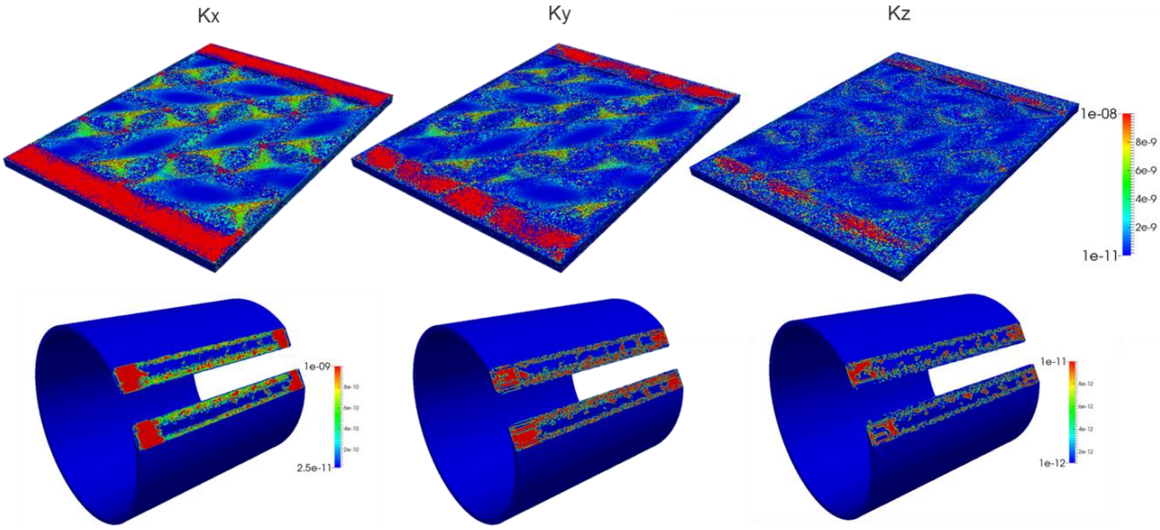

Fig.6: Permeability tensor field of a unit cell model and a near-net-shape cylindrical tube

The output parameters of virtual permeability prediction and FEM filling simulation are stored in the Digital Prototype and are used for the follow-up processes and quality management.
The validation of the resin injection simulation at the end of the process chain is made by VARI- and RTM-permeability measurements and is also stored in the Digital Prototype. Hence, the tracking of the development of the real component is completely possible.

4 Summary

The **Digital Prototype** as a kind of **Digital Fingerprint** gives the possibility to store the history of each structure and release it at any moment. Considering the manufacturing processes of braiding and injection a virtual environment in a HDF5-format for this Digital Fingerprint is built which can be extended by any other manufacturing process. It seems to be possible that specific manufacturing effects are acceptable as long as they are known and can be considered in the following processes. A strong interconnectedness of the different processes and the virtual prediction leads to individually and automatically defined boundary conditions. A possibility to decrease the waste of material and the costs of the structures seems to be the use of such **CAM-Interfaces** in the future.

5 Literature

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