DIGITPRO – VALIDATING THE LINK BETWEEN BRAIDING SIMULATION, INFILTRATION AND MECHANICAL TESTING

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Abstract

In this study, the development of a digital prototype on the example of a braided structure is presented. The different fields of engineering which have been considered are braiding simulation and virtual infiltration as well as mechanical testing. The main goal of the digital prototype is to connect the various input and output files of the software tools, to establish a user-friendly readability via a neutral, binary HDF5 file format as well as decreasing the cycle time during product design. On the basis of the example geometry a braiding mandrel concept was developed. A subsequent braiding simulation provided the fibre placement, the fibre orientations and the braiding path, which was transferred to a KUKA robot via a CAM interface for the actual manufacturing process. The braided structures were analysed with an 3D measuring system (GOM ATOS Triple Scan). The results were used for the virtual infiltration and validated with experimental vacuum infusion tests, section cut specimens, ashing specimens and tensile coupon specimens.

1. Introduction

The subproject DigitPro (holistic digital prototype for lightweight design in large-scale production) is one part of the science campus ARENA2036 funded by the Federal Ministry of Education and Research Germany (Forschungscampus ARENA2036). It is one of the stragetic, major science campuses in Germany and is the only one which started directly into the main section of research. ARENA2036 is an acronym for Active Research Environment for the Next generation of Automobile and the amendment 2036 will be the 150th anniversary of the automobile. DigitPro deals with the manufacturing process chain and tries to improve the connections between the different simulation tools. At this juncture it will decrease the weight of an automotive structure by 10 % and the development time by 50 %. It faces new material models, process simulations, virtual testing and new CAM interfaces to control manufacturing machines.

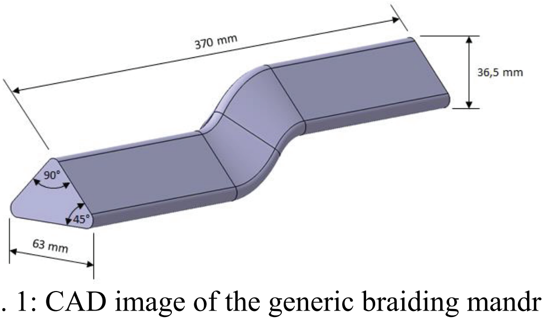

Fig. 1: CAD image of the generic braiding mandrel

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The chosen geometry for simulation and validation was a triangular, cross-sectional, s-curved mandrel with round edges (cf. Fig. 1). The geometry was chosen to show effects like fibre angle deviations, curvature of braiding yarns, detachments and thickness variations.

2. Development of procedure

This chapter shows the method and tools used for the simulation of the braiding process, the permeability measurement and the virtual infiltration.

2.1 Braiding simulation

In literature, usually analytical or kinematic methods are applied to calculate the textile structure which forms on the mandrel during the braiding process [1]. Here, the more sophisticated and detailed explicit numerical finite element method (FEM) is used. It includes friction as well as dynamic effects and therefore has the potential to model any type of desired and undesired effects during the braiding process for any mandrel geometry. For implementation, PAM-CRASH V14 by ESI Group is used, where the braiding machine is modelled by 64 “braiding yarns” moving on sinusoid paths and 32 stationary “standing yarns” (cf. Fig. 2). Spring elements create a constant yarn tension, and the mandrel is moved through the braiding ring in the centre of the braiding machine. With the right relation between axial speed of the mandrel and rotational speed of the braiding yarns, a braiding angle of $\beta = \pm 45°$ is achieved.

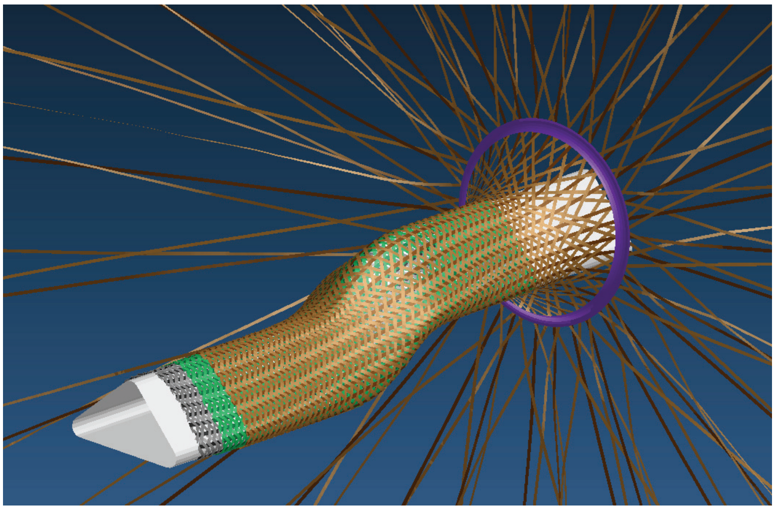

Fig. 2: Three layer braiding simulation (shell approach)

The yarns (12k carbon fibre) are modelled using shell elements with a width equivalent to the empirically determined maximum width attainable during the manufacturing process (disregarding compaction). The thickness is modelled by the contact distance. The material model used is MAT140, which was developed for the draping of dry textiles.

2.2 Infiltration

In this research, permeability determinations of a real semi-3D-structural part in a VARI-process (vacuum assisted resin infusion) and planar permeability tests in a closed-mold test bench will be shown.

2.2.1 Permeability determination

Permeability determinations at the IFB test bench were conducted with 2 bar infiltration pressure, a fibre volume content of 49.2 % (FVC), 2 layers of triaxial 45° braid (Toho Tenax STS40 24k) and an

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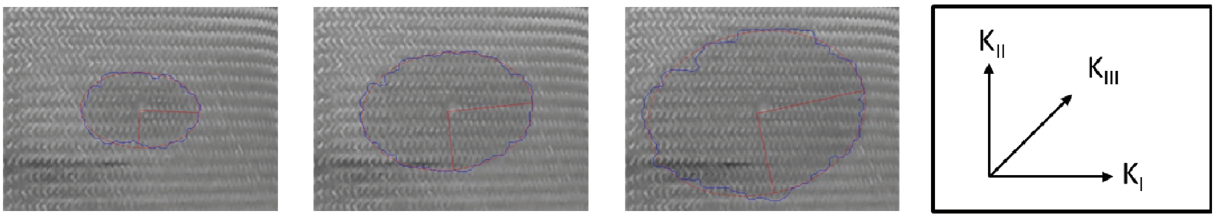
areal density of 886 g/m^2. The injection fluid used, was Glycerol 85 % with a dynamic viscosity of 90 mPas (at 23.5° C) and a density of 1226 kg/m^3. The result shows a uniform flow front (cf. Fig. 3). The resulting effective permeability values for virtual infiltration are K_I = 7.672e-11 m^2 in standing roving direction (0°) and K_{III} = 3.968e-011 m^2 in braiding roving direction (±45°).



16 s 20 s 28 s

Fig. 3: 2D flow front development in permeability test bench after 16 s, 20 s and 28 s

2.2.2 Vacuum assisted resin infusion

For infiltrating the generic geometry the vacuum assisted resin infusion process (VARI) was used. For better monitoring of the flow front, during experiment, the use of flow promoter, perforated membrane and peel ply was neglected (cf. Fig. 4). A infiltration pressure of 0.88 bar and the matrix system Baxxores® ER 5400/Baxxodur® EC 5440 from BASF with a dynamic viscosity of 323.1 mPas at (21° C) was used. The average permeability in flow front direction for the first measuring area was determined to K_I = 1.24e-11 m^2.

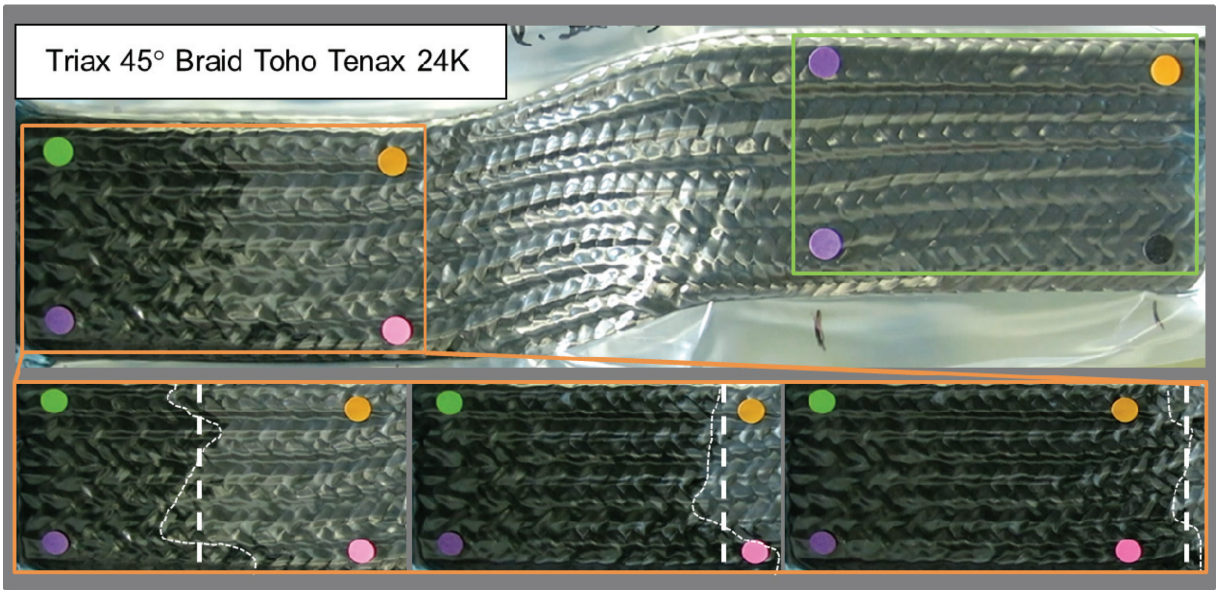


Fig. 4: Flow front development of generic geometry in VARI process (1st area of measurement)

The VARI infiltration showed a inhomogeneous flow front at the beginning and a more homogenous at the end of the filling process. This arised through the use of triaxial braid as preform textile, the use of flexible membrane as tooling and the variation in covering ratio and fibre orientations induced by the braiding machine.

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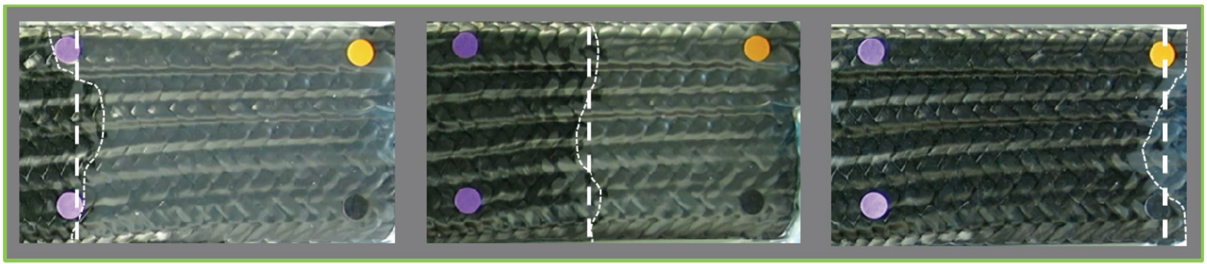

Fig. 5: Flow front development of generic geometry in VARI process (2nd area of measurement)

The flow front seems to be faster at the standing yarns which were orientated in the 0° direction and have a lower crimp value compared to the braiding yarns. The slower impregnation flow front at the end of filling process reduced this impact but didn't eliminate it (cf. Fig. 5). A further effect which could be observed was the distinctive dual scale flow. The channels between the yarns were filled faster than the yarns by itself, which can produce micro-pores inside the yarn.

3. Application to practical case

In DigitPro, a pratical application was chose to demonstrate the capabilities of the methods descriped in chapter 2: a part in the floor module of an automobile responsible for its structural stiffness. This now metallic part will be made using Toho Tenax STS40 24k carbon fibre yarns and an epoxy matrix system of type Baxxores ER 5400/Baxxodur EC 5440. A slightly larger mandrel was designed to adapt the generic geometry to the wider yarns, see Fig. 6. It was manufactured using additive manufacturing with PA-6 as deposit material.

Fig. 6: Fibre orientation of dry manufactured geometry

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3.1 Validation results: fibre orientation

Like shown in [2] and [3], an optical measurement system developed at the IFB together with FIBRE Bremen is used. It consists of an object lens, a CCD-sensor and an illumination device. The pictures are then analysed and the fiber directions are separated by using an algorithm based on a grey-scale analysis [4]. The fibre orientations are then mapped onto a finite element mesh and is then compared to the results out of the braiding simulation (cf. Fig. 7).

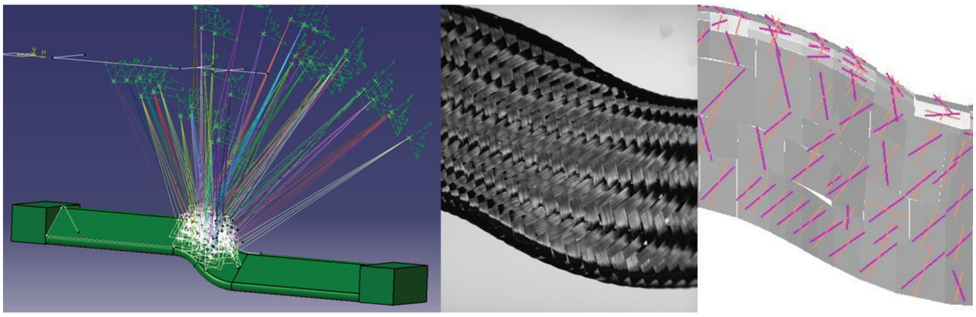

Fig. 7: Robot path planing for 3D measurement of fibre orientation

There is an averaged deviation of ±1.4° braiding simulation and automated optical measurement. This shows that the simulation can be used for prediction of the braided fiber orientation for the generic structure.

3.2 Validation results: yarn architecture

With the use of micro-graphs, the internal textile structure of the braid is analysed and compared to the results of the braiding simulation. In the simulation, the compacting induced by VARI process is not considered. However, a qualitative comparison is possible. Due to the method used, where shell elements represent the yarns, only the "major axis" of the ellipsoid yarn shape is modelled.

Fig. 8 shows that the architecture of the real braid is similar to the simulation result. The standing yarn (0°) of the third layer can be seen, while the others lie in a different section plane. The braiding yarns (±45°) take an inclined position in the same direction. They overlap with neighbouring braiding yarns within their respective layer but also partly with yarns of other layers. A difference in the width can be seen, which is due to the simulation approach. The standing yarn is less undulated in the real structure, which can be caused by compaction during infiltration or by a higher yarn tension.

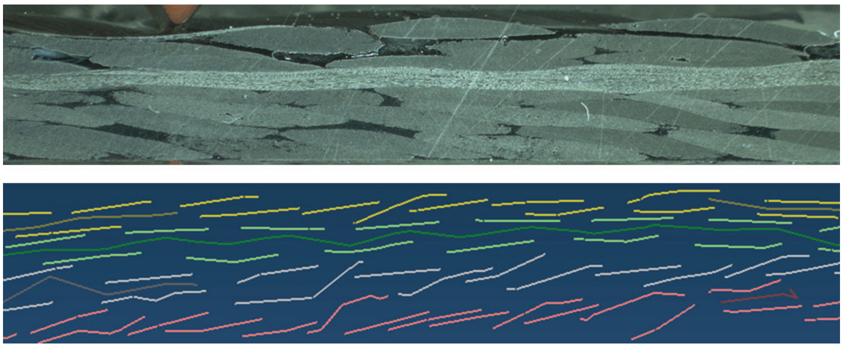

Fig. 8: Cut-sections of 4 layers triaxial braid (top: real structure; bottom: simulation)

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3.3 Validation results: infiltration process

Validation of infiltration process in the test bench showed good agreement of simulated and experimental flow front propagation of less than 2 % in median (cf. Fig. 9).

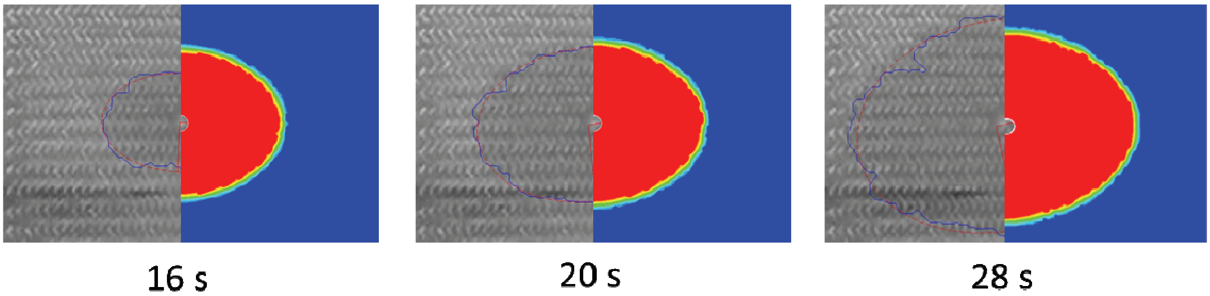

Fig. 9: Comparison of 2D flow front development in permeability test bench and simulation after 16 s, 20 s and 28 s

Simulations were conducted with the commercial finite element tool PAM-RTM™ V14 (ESI Group). The generic geometry was simulated with a one layer shell modell and a part thickness of 4 mm. The viscosity of the matrix system Baxxores® ER 5400/Baxxodur® EC 5440 changed linearly from 231.15 mPas to 350 mPas (after 84 minutes).

Comparison of the VARI-infiltration and the 3D simulation showed acceptable agreement (cf. Fig. 10). The possible explanation for the deviation are the folds of the flexible membrane at the edges of the geometry which act as runners. Other reasons could be the viscosity and the density of the used matrix system, which were taken from its data sheet. As it is known that viscosity influences the infiltration result enourmous, this could be a next step in research.

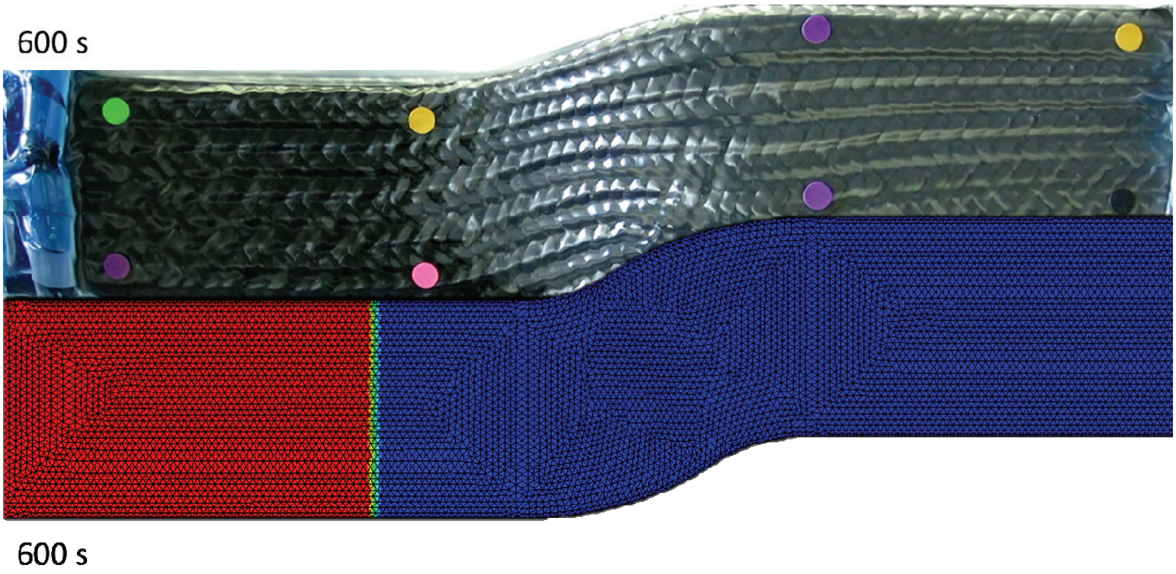

Fig. 10: Comparison of VARI-infiltration and simulated flow front propagation

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3.4 Testing of mechanical properties

Six tension specimens were cut from the generic part in order to obtain real, local properties. The goal is to compare them to results from standard tension tests manufactured using "undisturbed" material. The part geometry does not allow to extract full-size specimens according to Airbus Test Method AITM 1-0007. Therefore, shorter specimens with a free testing length of only 40 mm (instead of 180 mm) are manufactured. The width is 32 mm and with four layers of triaxial braid, the thickness is about 4 mm. Also, the tabs are shorter at a length of 30 mm. Due to the significant undulations in the material, the determination of an exact thickness is difficult (cf. Fig. 11, left).

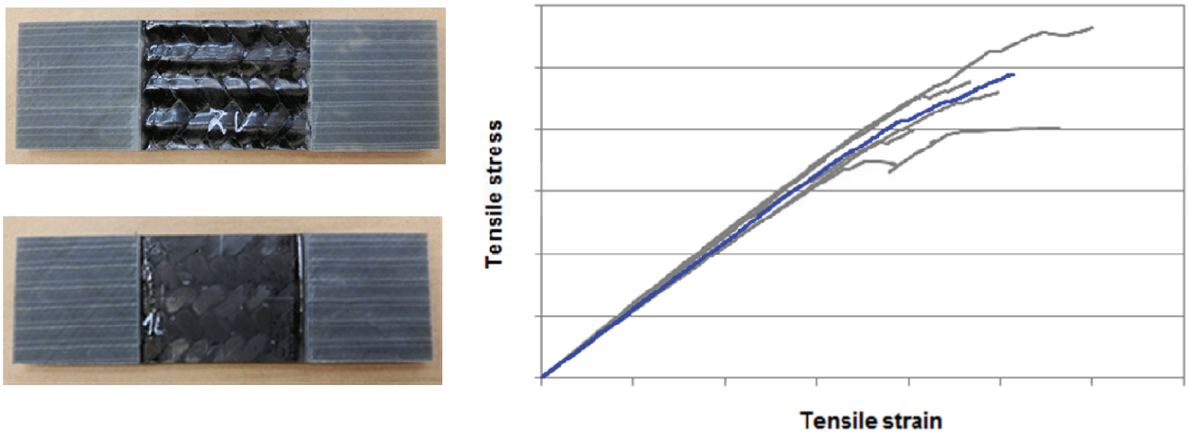

Fig. 11: Tensile coupon specimen and characteristics (blue curve is highlighted as a typical specimen)

This geometric limitation leads to two problems which are interlinked: the tabs have to be clamped with a large compressive force to avoid slipping during the tension test and the short specimen is subjected to significant clamping influences in its free testing length. The former leads to a higher level of induced multiaxial stresses in the material, leading to a distorted result. The latter leads to these extra stresses being closer to the middle of the specimen, where the strain measurement is done. These problems resulted in the specimens breaking erlier than expected (in comparison with standard specimens and data from similar materials). This is also expressed in the shape of the stress-strain-curves: some specimens have slipped in their grippings and in general there is a large scatter near the failure point. Therefore, only the stiffness can be realiably evaluated and lies at 33.1 GPa in average. The variation coefficient is small at 4.5 %, confirming the qualitative result from Fig. 11.

3. Conclusions

The successful linking between braiding simulation and infiltration simulation is a crucial part of the virtual process chain developed in DigitPro. This paper shows the method and also results for this connection. A generic geometry – which features important characteristics of a real automobile part – is designed and both braided and infiltrated. Also, several properties of the process, the braided structure and the final mechanical parameters are determined. If applicable, they are compared to simulation results for the purpose of validation.

The quantitative prediction of the fibre angles in the braid works well, with an average deviation of ±1.4 %. The comparison of the yarn architecture shows that in principle, the result in the simulation is similar and does offer a qualitative prediction. However, there are differences which are due to the following compaction which is not simulated here.

Permeability measurements of two-dimenional preforms in the permeability test bench showed good agreements with the simulated results. Permeability measurements of near-net-shape preforms at the geometry showed acceptable agreements with the simulated results. Nevertheless, the link between

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two-dimensional and near-net-shape permeability determination is limping and more efforts to this research have to be done.

The mechanical properties are determined “in-situ”, i.e. directly for the material of the generic part. Due to the limiting size, only the stiffness can be obtained. The Young’s modulus of the material only has a small variation and is in average 33.1 GPa, which now can be compared to values from standard tensile specimens.

This work is the basis for further development of the virtual process chain. Some good progress has been achieved since the beginning of the project, with the aim of verifying a reliably working, closed development loop for a braided composite part.

Acknowledgments

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