TARGET-ORIENTED PREFORM PRODUCTION OF GEOMETRICALLY COMPLEX COMPONENTS CONSIDERING MEASURED AND SIMULATED DRAPE BEHAVIOUR

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Keywords: Tailored fibre placement, Carbon fibre, Drape simulation

ABSTRACT

Tailored fibre placement (TFP) technology can produce load-adapted carbon fibre fabrics and at the same time reduce textile offcut scrap significantly, thanks to its close to net shape design. This aligns with industry's goal to cutting down on material waste in production and thus decreases CO_2 emissions. In this paper biaxial plies produced by TFP are used for draping on a multi-curved C-shaped preform tool. Drape behaviour is experimentally investigated by a picture frame test for shearing, a tool-textile friction test as well as a cantilever test for bending rigidity. A finite elements drape simulation is performed to macroscopically display fibre orientations after draping. A method based on 3D measurements by laser triangulation is applied to analyse actual fibre orientation. Lastly, simulated and measured fibre orientations are compared to determine deviations between experimentation and simulation. The results show to which extent the measured fibre orientations are in accordance with the simulated orientations. Deviations from the simulated model are highlighted and explained by waving happening during the draping in the simulated preform. Moreover, the deviations increase towards the edge of the surface what can be explained by slight differences between the real draping process and the simulated draping. Finally further measurements for improvement are suggested.

1 INTRODUCTION

In the production of complex large components for the aerospace industry, in addition to economic criteria, there is an increasing demand for consideration of ecological criteria. The key element for implementing such an approach is to further develop the application of resin transfer moulding (RTM) technology with the possibilities of digitization as well as consideration of innovative preforming and tooling technologies. The preforming process and the choice of textile semi-finished products have a relevant cost share of the production and influence on the mechanical performance of the component. With the pronounced anisotropy of carbon fibre reinforced plastics (CFRP), it is necessary to optimally adapt the orientation of the reinforcing fibres to the component load. To verify that the TFP preform allows a satisfying drape result, the drape process can be imitated in an experimental setup, where the resulting drape results are evaluated. To save the resources for unnecessary experimental setups, it is preferable to apply simulation method that predict these results in advance. It is desired to achieve a model setup with high predictive goodness. To do this, the use of a material model implemented in the simulation software LS-Dyna is examined.

With TFP technology, it is possible to apply yarns to almost any two-dimensional web. On modified embroidery machines, reinforcing fibres are fixed to an embroidery base by a sewing thread system. The modified embroidery head guides the rovings underneath the needle using oscillating movements and places it on the base material, securing the roving in place with stitches. To get the placement paths, firstly the preforms need to be available as a CAD model. This model is then converted into a stitching file which is read by the embroidery machine. In this way, a preform for a multi-axis loadable component can be produced successively, with almost no post-processing needed [1].

2 PREFORM DEVELOPMENT FOR A COMPLEX COMPONENT

For our investigations, the fibre paths were designed using the EPCwin 6.2 software from ZSK. For the contour data file, which corresponds to the outline of the preform, the surface of the CAD model of the 3D-printed tool was virtually unwound. The centreline of the top web of the mould served as the starting edge for aligning of the 0° ply. To align the 90° layers, the contour data file was split virtually into six parts, so that the roving path could be adjusted gradually within each part to match up one short side edge to the another one. The numerical control (NC) code generated with this for the TFP system contains the local fibre orientations, roving spacing and stitch lengths. For this test series, a roving orientation of 0° and 90° was selected. For the roving a carbon fibre 12 k HTS45 E23 from Teijin and for the polyester sewing thread Serafil 200/2 53*2 dtex from Amann & Söhne were used. A Thermogaze® TG7 fabric made of regenerated viscose produced by s-textrade was used as the embroidery base, which was later removed from the preform. Figure 1 shows the JGW 0200-550 TFP system from ZSK with which the preforms were produced.

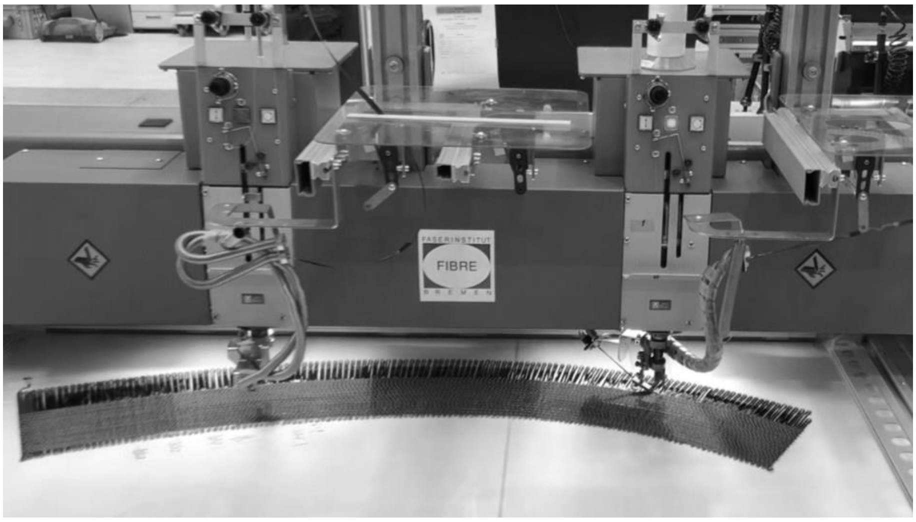

Figure 1: JGW 0200-550 TFP system for the preform-production.

The preforms were produced with an oversize so that discontinuities such as start and end points as well as turning loops could be cut out after the fibre laydown, without decreasing the size of the final contour. The rovings were placed at a distance of 3 mm using a wide zig-zag stitch. In the lower 90°-layer, the rovings were only fixed by stitches at the turning loops. Using the so-called fast deposit function, the rovings were deposited in the later part area without stitches and only sewn in place via the second 0° layer. The embroidery base was removed after fibre placement, so that the deformation properties depend only on the TFP layers. To remove the embroidery base, the preform was thermally treated in the oven at 120 °C for 1.5 hours. The pyrolysis of the embroidery base subsequently allowed it to be removed mechanically. For the preform draping on the mould, it was cut to match the component contour and was provided with two incisions on the outer radius. This is aimed at preventing preform compression due to excess material and are seen in Figure 2 in addition with 90°-layer and 0°-layer fibre directions.

After trimming, the preform was placed onto a pick-up station and thereon aligned along its 0° centreline. The pick-up station was 3D-printed, what made it possible to include the actual torsion of the tool. A rigid handling system, which is equipped with vacuum grippers and positioning pins, was constructed. With the pins fitting both into pick-up station as well as preform tool, the handling system could be positioned precisely. Using this system, the preform was picked up exactly at the centreline and placed onto the centreline of the tool surface. The mould surface was previously provided with an adhesive fixation on the component edge to hold the preform in shape after draping. After being placed down, the preform was draped evenly by hand starting from the top centre surface towards the two side ends over the entire length of the inner and outer tooling sides and pressed firmly against the adhesive fixture.

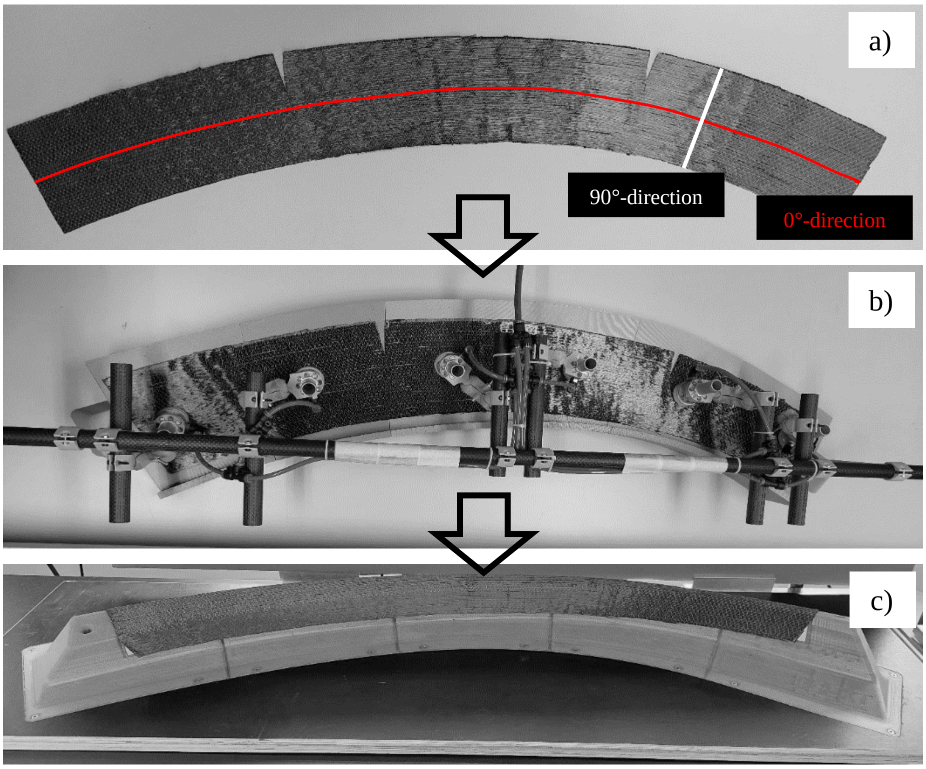

Figure 2: a) Trimmed preform after removal of base material with 0° and 90°fibre direction indicated, b) Preform placed on double-twisted 3D-printed pick-up station with handling system positioned and c) Preform placed on tooling and draped to final contour.

3 PREFORM CHARACTERIZATION OF MACROSCOPIC FORMING BEHAVIOUR

The main mode of deformation for textiles like woven and non-crimp fabrics is the in-plane shear. Despite of the low in-plane shear stiffness of fibrous materials compared to polymer composites, its presence is crucial for the apparition of wrinkles. [2] Therefore the shear behaviour has to be considered in a macroscopic drape simulation.

A widely used procedure to determine the shear behaviour of textiles is, besides the also well-known bias extension test, the so-called picture frame test method. Within the activities described in this paper the picture frame test is used to characterize the preform's shear properties, whereby a direct and pure shear deformation is applied to the textile sample. The picture frame used for the characterisation has a side length of 222 mm and a clamping jaw width of 87 mm, cf. Figure 3. The textile sample in shape of a cruciform with arm length equal to the jaw width is clamped in place. The fibres are prevented from slipping by leather inserts between textile and clamps which are replaced by new ones after each test. The clamped fibres pass through a comb whose needles allow rotation of the yarn. No pretension has been applied to the textile.

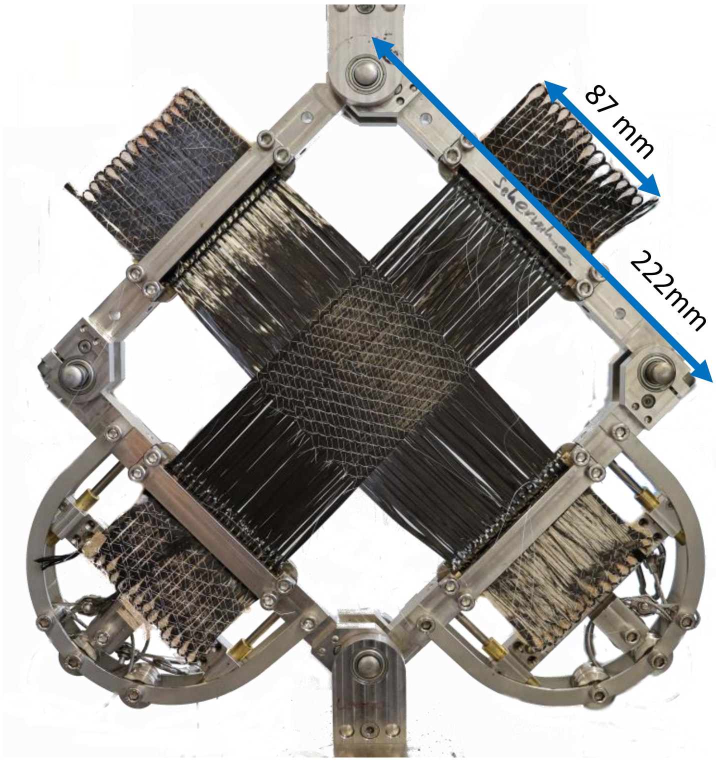

Figure 3: Picture frame with mounted textile.

A universal testing machine was used to record the force and displacement during the picture frame test. The load cell has a capacity of 1 kN and an accuracy of 0.1%. Figure 4 shows a sheared textile during testing. After each run, dummy runs were performed without the textile clamped to determine the influence of the shear frame mechanics on the force measurements. The force values from the shear force characterisation were then adjusted for the effects of the shear frame. Due to the variability in the data, which is in part induced by the manual handling of the textile, the experiment has been repeated seven times. From these adjusted data, the curves for shear angle vs. normalized force were determined, as described e.g., in [3,4]. The curves for the individual experiments are depicted in Figure 5. Based on the observed shear curves a smooth spline has been fitted, which is depicted as thick red line.

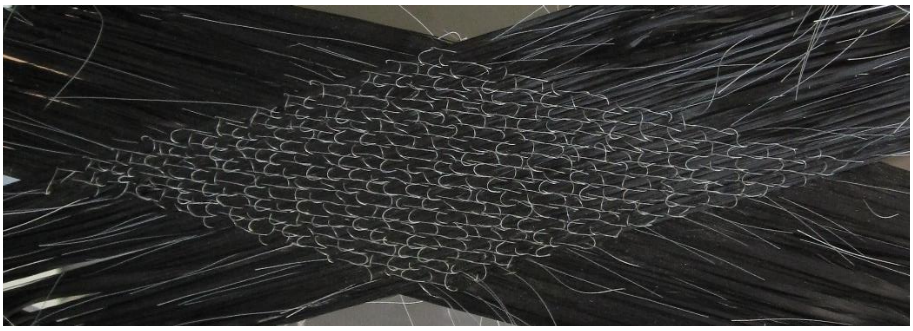

Figure 4: Sheared textile sample during the picture frame test.

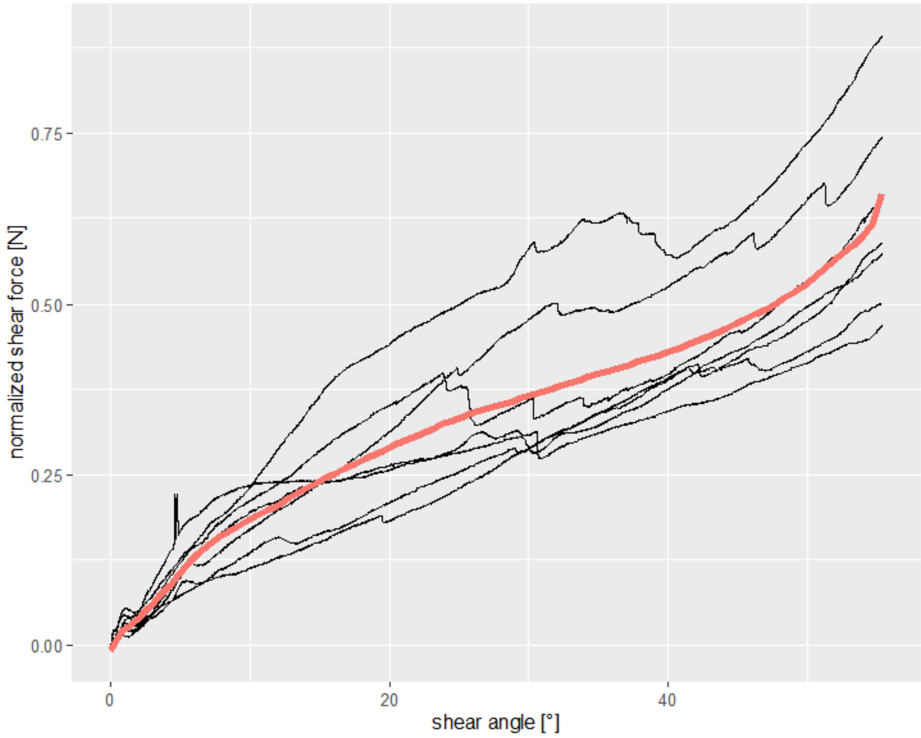

Figure 5: Smoothed normalized shear curve and individual shear curves for seven experiments.

For finite elements (FE) simulation on a macroscopic level, furthermore the characterization of bending and friction behaviour is crucial. The characterization of the frictional behaviour between preform and mould is performed by applying a homogeneous contact pressure to the interface to be characterized. A relative displacement is generated between the contact pairs and the force required for the displacement is measured. This 'sliding carriage' method is standardized in DIN EN 14882:2005-11 and ASTM D1894-01. The static and dynamic friction coefficients for the friction between an ULTEM sample attached to the sled (cf. Figure 6 and Figure 7) and an underlying textile sample have been determined according to the DIN norm, respectively, as $\mu_s = 0.626$ and $\mu_d = 0.663$. Surprisingly the dynamic friction coefficient determined in the experiment has been higher than the static friction coefficient. This can be explained by the high amount of sewing thread on the surface of the textile sample. At the beginning of the experiment the sewing thread in the samples is quite loose, and therefore sliding occurs between the sewing thread and the ULTEM sample as well as between the sewing thread and the underlying carbon fibres. After the initial movement of the sled, the initially loose sewing thread is under tension. The friction force between yarns and ULTEM sample increases slightly, because of the movement of the sled and the fixation through the stitches.

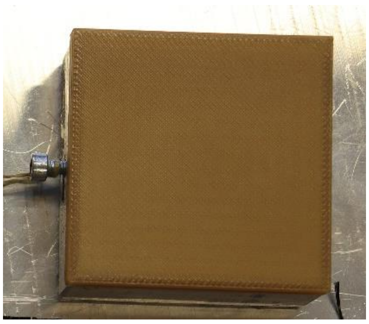

Figure 6: ULTEM sample attached to the sled.

Figure 7: Sliding carriage experiment.

The characterization of the bending behaviour of the preforms was carried out by means of the 'single cantilever' method standardized in DIN53362. Thereby a textile strip is pushed over an edge until the overhanging part of the sample touches an inclined plane next to the edge, what can be seen in Figure 8. The final overhang length of the textile strip is then measured. The mean overhang length based on five samples was 13.4 cm.

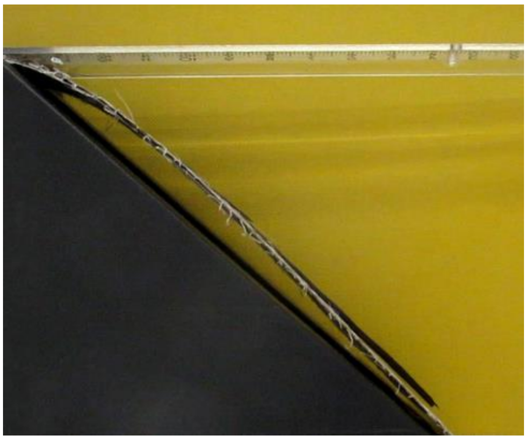

Figure 8: Simple cantilever test.

4 MACROSCOPIC FINITE ELEMENTS SIMULATION OF THE DRAPE BEHAVIOUR

A finite elements drape simulation is performed using the software package LS-Dyna. For the textile the material model 'MAT_249-REINFORCED_THERMOPLASTIC' is applied, which is an appropriate model for thermoplastic prepregs and dry fabrics [5]. It can be used to model not only woven but also unidirectional layers and non-crimped fabrics (NCF). It is generally the recommended model for NCF by the software's provider. The textile mesh, depicted in Figure 9, has 24462 elements with 24928 nodes and its geometry resembles the actual preform. As a simplification the mesh has been divided into 24 subsections along the curvature of the midcurve. Within these subsections the fibre directions are homogenized. Another consequence of this discretization is the slightly edgy shape of the contour of the mesh.

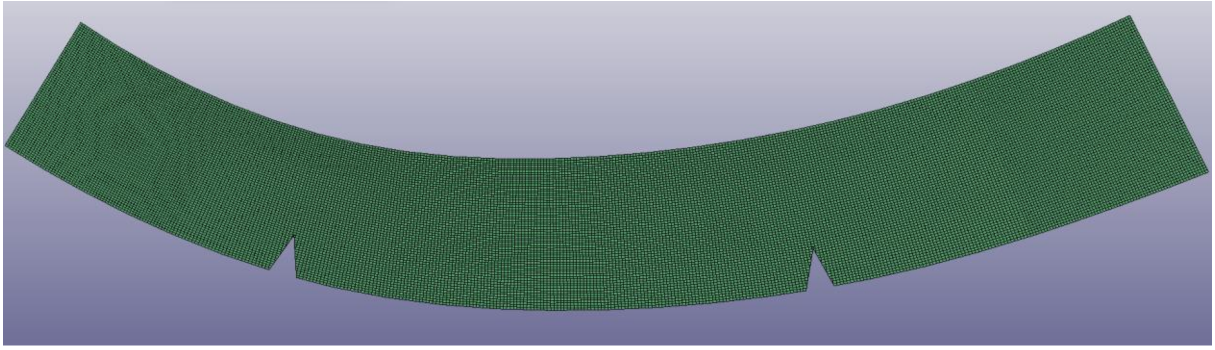

Figure 9: Mesh of the textile geometry.

The mesh of the forming tool is shown in Figure 10. The rough forming, as the folding over of the preforms edge, is carried out by means of four tubes. Negative moulds are subsequently used to form the textile mesh into the final shape via the surfaces at the top and sides.

Two fibre families have been defined for the material. The first fibre family is the 0°-layer and the second fibre family the 90°-layer. The fibre directions are defined element-wise and match the local fibre directions of the TFP-preform. A discretization of the shear curve determined by the picture frame test described above has been used to define shear stress vs. shearing between the first and second fibre family in the model.

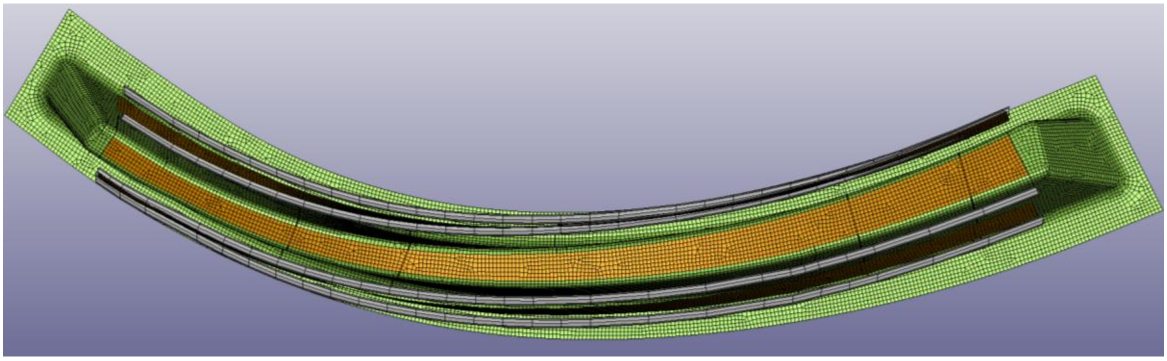

Figure 10: Mesh of the tool and forming surfaces.

The forming tool is modelled as a rigid body with material model '020-RIGID'. The contact between the rigid tool and the textile is defined as the contact called 'AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE'. The values for static and dynamic coefficient of friction are taken from the characterization in the sliding carriage described above. To resemble the bending behaviour of the cantilever test, a manual calibration of the model was performed via variation of the location of the integration points. For the model used in the simulation for this paper the integration rule was defined in 'INTEGRATION_SHELL' as shown in Table 1.

Coordinate of integration point	Weighting factor
-0.3	0.277778
0.0	0.444444
0.3	0.277778

Table 1: Position of the integration points for calibration of the bending rigidity.

From the simulation results the orientation of the fibres in the draped textile can be determined. In case of local wrinkling or unfavourable orientation of the fibres the geometry of the preform should be adapted, to achieve a better drapability. Compared to the experiment, in the simulation neither of the cut-outs is closed, cf. Figure 11. Generally, it is therefore supposed that the two cuts are wider than necessary. In addition, as can be seen in Figure 12, areas of high shear occur on the inwards curved part of the spar.

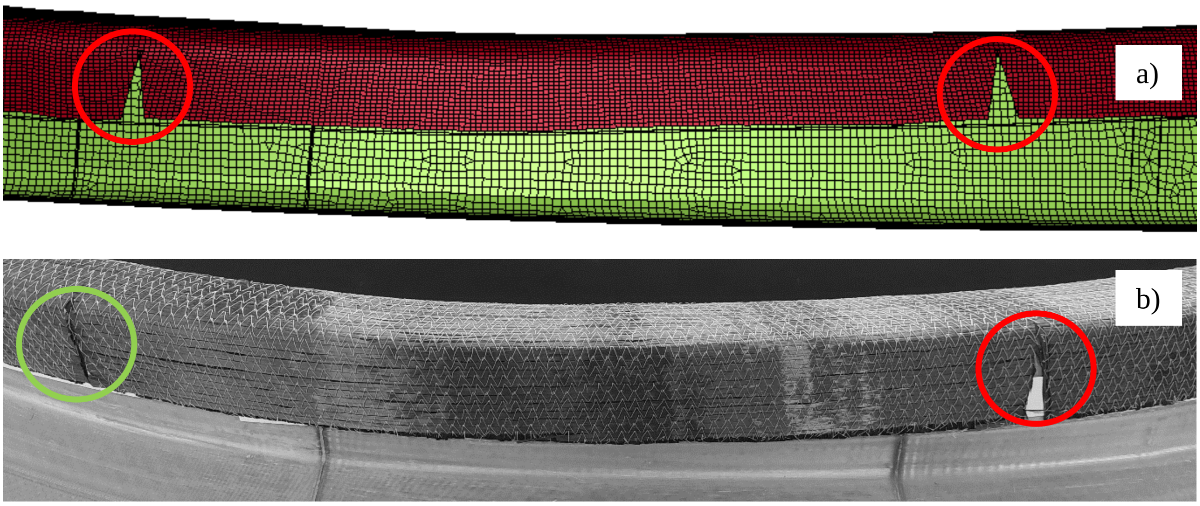

Figure 11: a) Cut-outs in the last step of the draping simulation show no closing and b) only left cut-out shows closing after experimental draping.

This could not be confirmed in the experiment and exposes one possible reason for the missing closing of the one cut-out.

Furthermore, the draped textile mesh does not follow the desired contour in the highlighted area (cf. Figure 12). High shear deviations in the fibre directions are observed and a maximum shear angle of 38° is reached.

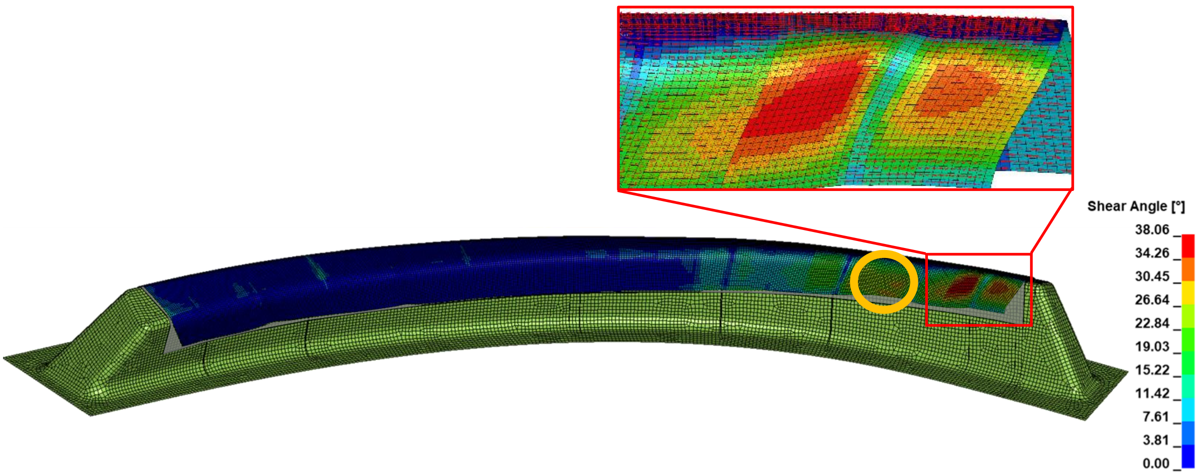

Figure 12: Areas of medium and high shear (circled and zoomed area including fibre directions, respectively) and material shortage (grey shaded areas).

The simulation hints at difficulties which are likely to appear in the draping process. However, it has to be considered that the final draping mechanism is not the exactly the same as in the simulation and therefore deviations in the experiments have to be expected. With the results of the subsequent experimental measurements, it will be possible to evaluate the quality of this first simulation and to further calibrate the model.

5 EXPERIMENTAL EVALUATION AND ASSESSMENT OF THE PREFORM DRAPE BEHAVIOUR BY MEANS OF A 3D MEASUREMENT SYSTEM

A 3D measurement system based on laser triangulation was developed for process control and to evaluate the drapeability of the TFP preforms. We use the laser triangulation sensor KEYENCE LJ-X8200 which provides a height profile together with intensity information. By an industrial robot, the laser triangulation sensor is moved in multiple straight lines across the 3D preform in order to scan the topography of the surface. This results in a height profile (Figure 13) and a grayscale image (Figure 14). In case of the curved spar investigated here the entire measurement consists of three views – one from top and one from each side. For the results presented here we restrict to the top view.

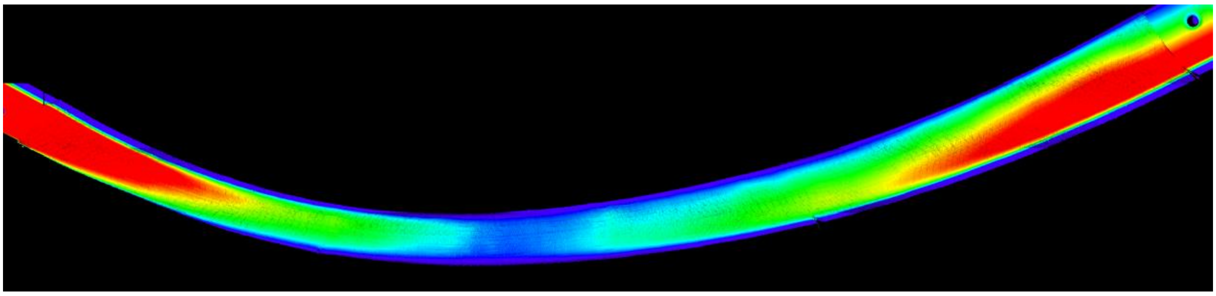

Figure 13: False colour visualization of height profile data of top view.

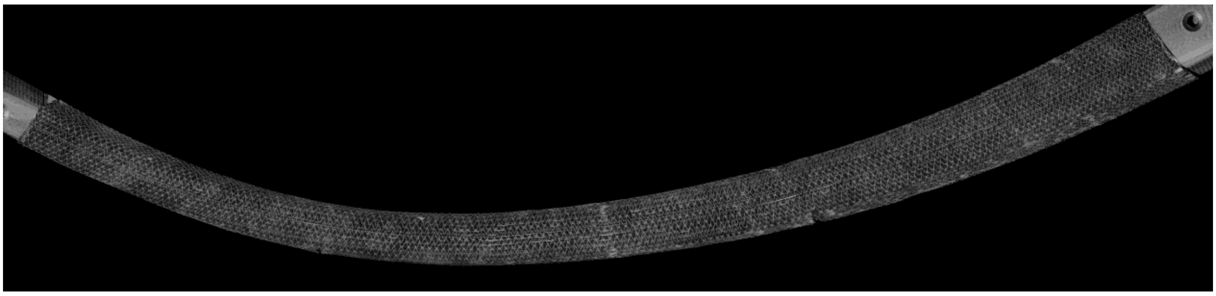

Figure 14: Corresponding intensity image.

Large-scale three-dimensional draping effects such as waves and wrinkles can be recognized directly on the 3D model of the preform or by analysing the difference of a measurement of the preforming tool without textile and with the draped textile on top. During this draping experiment no significant waves or wrinkles were created.

Gaps and out-of-plane undulations cause smaller local deviations in height. Gaps show up as local hollows and out-of-plane undulations show up as local elevations. In order to bring out the local three-dimensional texture of the surface, a highly smoothed version of the measured data is subtracted from the original data set. Using a false colour representation, areas below the local average appear cyan/blue and above local average appear yellow/red (Figure 15). This representation can be used to segment gaps, sewing thread and out-of-plane undulations.

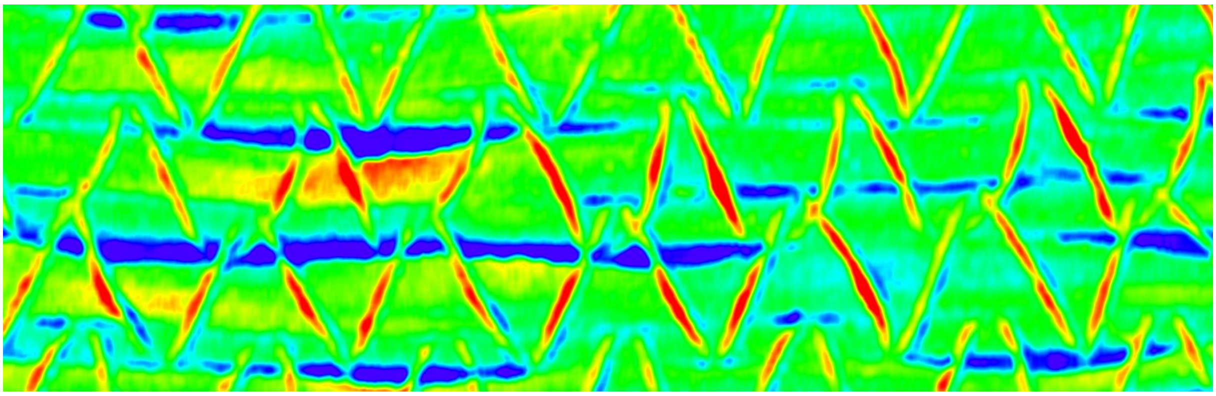

Figure 15: False colour representation of areas below (cyan/blue) and above (yellow/red) of local average height.

The image processing algorithm to measure the fibre orientation was originally developed for grayscale images [6]. It measures the gradient orientation and magnitude in each pixel of a greyscale image using an isotropic gradient filter based on the work of Scharr [7]. The calculated orientation information is then used to build up orientation histograms for local image regions. The fibre orientation itself is determined by analysing the orientation histogram. The gradient orientation can be derived just as well from a height difference as from a gray value difference. Therefore, after some pre-processing, it is possible to apply the algorithm directly to the height information.

The measuring system can be used both as a quality assurance instrument for evaluating and documenting the preform quality and for validating the results of the draping simulation by comparing the simulated and measured fibre orientations.

To compare simulated and measured fibre orientations both coordinate systems are aligned to each other so that origin, orientation of axis and data resolution line up. Then the mesh of the draped textile is projected onto the measured surface. Using a nearest neighbour algorithm for each element a measured fibre orientation is assigned and compared to the simulated orientation. The results for the top view measurement are shown in Figure 14 - Figure 16. The background image of the visualization shows the local height differences calculated from the difference between the original and the extremely smoothed height data with height values coded in grayscales. As mentioned above, the calculation of the measured fibre orientations was carried out on this type of data. The fibre orientation is visualised with vectors coloured in spectral colours corresponding to the measured angle. Horizontal orientation corresponds to 0°, orientations running counter clockwise.

The absolute angle difference between measurement and simulation (cf. Figure 17) is visualized by coloured dots changing from green over yellow to red with increasing angle deviation (Figure 18).

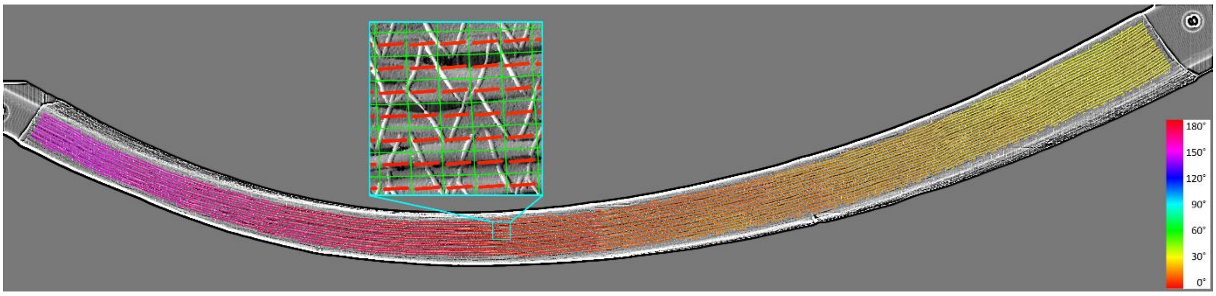

Figure 16: Measured fibre orientations.

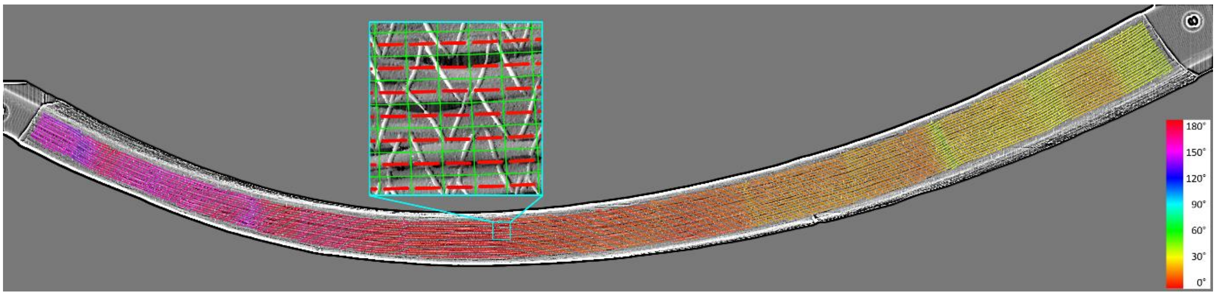

Figure 17: Simulated fibre orientations.

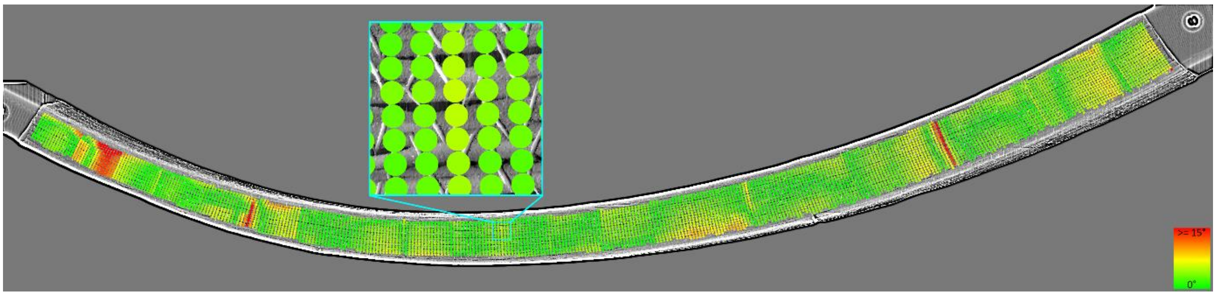

Figure 18: Absolute angle difference between measured and simulated fibre orientation visualized with coloured dots (darkest red corresponds to deviations of 15° and more).

6 CONCLUSIONS & FUTURE WORK

The presented approach enables preforms to be realized for optimal lightweight structural design with uninterrupted load-adapted fibre paths. This allows to exploit the lightweight potential of CFRP for applications with complex geometries. The material input required to manufacture the components can be reduced and, e.g., the energy consumption in the component utilization phase can be reduced. In addition, the preform laydown can be optimized by placing it over a window cut into the base material. For this, the part of the embroidery base that is identical to the contour file of the preform is removed before the roving is placed. Then the rovings are only fastened at the turning points during placement and placed over the window without stitches. The sewing of the layers after roving placement ensures the stabilization and manageability of the preform after trimming. When using bindered rovings, the preform can be formed in an automated production process and thermally fixed in the shape for further processing. A diaphragm system can be used for an automated draping and fixing process. The preform transfer can still be carried out using the shown handling system.

The model-based simulation presented here is a first trial after the characterization of the textiles' properties regarding shear, bending and friction. Overall, the simulated direction of fibres widely matches the directions measured in the experiment. However, the areas of high shear in the simulation model were not critical in the experiment, i.e., the simulation model is too pessimistic in this case. Further adjustments have to be made to the model to predict more realistic fibre directions and shear angles.

As the bending stiffness is not considered as a physical parameter in the applied material model, a satisfying calibration has to be achieved by variation of integration points and other parameters such as density and matrix specific properties. This has to be done in a next step. It is not unusual to specify weak matrix parameters even in the simulation of dry textiles; weak matrix properties have been applied for the simulation of dry fabrics using this material model e.g., in [8]. A first comparison with an alternative version of the simulation presented here suggests that a side effect of the high bending rigidity defined by the position of the integration points might be excessive shear in the draped textile mesh. A further calibration considering the insights gained from the experiment will most likely improve the prediction of the fibre directions. Another challenge for future improvements is to incorporate the measurements of the preforms fibre directions into the mesh, instead of the discretising the fibre directions within sections of the mesh.

ACKNOWLEDGEMENTS

We are grateful to the NBank of the Federal state of Niedersachsen for the financial support of the research project 'SMART & SUSTAINABLE RTM 4.0 - SAUBER4.0', in which this work is incorporated.

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