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Experimental comparison of a macroscopic draping simulation for dry non-crimp fabric preforming on a complex geometry by means of optical measurement

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Abstract

Scope of the presented work is a detailed comparison of a macroscopic draping model with real fibre architecture on a complex non-crimp-fabric preform using a new robot-based optical measurement system. By means of a preliminary analytical process design approach, a preforming test centre is set up to manufacture dry non-crimp-fabric preforms. A variable blank holder setup is used to investigate the effect of different process parameters on the fibre architecture. The real fibre architecture of those preforms is captured by the optical measurement system, which generates a three-dimensional model containing information about the fibre orientation along the entire surface of the preform. The measured and calculated fiber orientations are then compared with the simulation results in a three-dimensional overlay file. The results show that the analytical approach is able to predict local hot spots with high shear angles on the preform. Macroscopic simulations show a higher sensitivity towards changes in blank holder pressure than reality and limit the approach to precisely predict fibre architecture parameters on complex geometries.

Keywords

Composites, preforming, non-crimp fabric, draping, virtual modelling, simulation, fibre architecture, optical measurement, image processing

Introduction

Fibre-reinforced plastics (FRPs) provide a high potential for the design of lightweight components taking advantage of the anisotropy along component load paths and integrating functional elements during the manufacturing process. To meet the high demands of quality, safety and cost-efficiency, a broader use of FRP in automotive series still requires, among others, a reduction of development time and costs. Driven by those requirements, throughout the last few decades, sophisticated FRP materials and technologies have been developed with high innovation speed.

Likewise, the component and process complexity and material variety has largely increased, leaving major challenges for process design, quality assurance and simulation methods. Thus, the reliability of design and simulation tools for FRP manufacturing processes

has been focused in many research projects throughout the last decade.^{1–6} Despite the various studies already performed on model validation, optical measurements of fibre orientations along the entire surface of complex three-dimensional (3D) geometries used for the validation of draping simulation results could rarely be performed so far. Optical systems have been presented for the determination of local fibre orientation

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and defect detection.^{7–9} However, the previously available systems only allow for capturing and evaluating single images without relating them to the part. Therefore, a new robotically guided optical measurement system has been developed, which enables capturing single images and connecting them with reference to the part geometry. The evaluated fibre architecture is then represented as a 3D surface map of fibre orientations along the complete part surface of complex-shaped preforms. This surface map is further used in the presented work to compare real fibre architecture with draping simulation results.

Among the various FRP technologies, three basic forming processes can be identified when studying the available literature.^{2,10,11} These are stamp forming, membrane forming and local, incremental forming with a robot end effector. For the presented work, the process of stamp forming is investigated and schematically shown in Figure 1 in comparison to other approaches.

Although the membrane approach generally leads to less local defects, it is more critical in terms of wrinkles, as retaining the material along the contour of the fabric throughout the draping process is very complex. Without the possibility of applying defined tensions on the fibres, it is likely to generate wrinkles and other undesirable effects during the material forming step.

To overcome this critical issue, the stamping approach uses rigid forming elements. Stamping processes are very common and have a high potential for automation, which can be seen when studying patents which show variable and segmented stamp setups with low-friction surfaces,^{12,13} flexible compaction devices filled with fluids¹⁴ or a bulk material¹⁵ to map the shape of complex geometries.

When using stamping approaches, choosing optimized retaining and pre-tensioning systems is the key towards higher control for automated preforming systems. By changing the blank holder force distribution, the preforming results can be influenced, as shown before, e.g. by Leutz et al.¹⁶ and Nezami et al.¹⁷ Blank holders are the most used retaining system;^{10,18–20} however, the control of single plies of a stack is very complicated due to the complex interply-friction.¹⁷ Pre-tensioning systems offer a higher controllability during automated processing, but lead to mechanically complex systems. Passive systems, consisting of weight application or spring tensioning, or active systems, consisting for example of servo-drives, can lead to a very accurate application of loads and therefore to a precise control of the material flow.

As macroscopic draping simulations provide the possibility to model complex and variable processes

Figure 1. Overview of basic forming processes and its major derivations.

including blank holders as described above, there has been a growing interest during the last years in validating commercial and research simulation approaches for different dry and pre-impregnated textile sheet forming processes.^{21–26}

The software used in this study is PAM-FORM V2013.5, which uses a continuum mechanics approach within a finite element (FE) code for calculating the forming of fibre-reinforced sheets. In order to model stack forming of textile layers, the basic macroscopic mechanisms the simulation has to take into account are the fibre-parallel strain, which means the structural strain of the ply due to mainly straightening of fibre undulations, the intra-ply shearing and the inter-ply shearing.¹⁹ The textile layers are represented by the nonlinear elastic, orthotropic material model Mat140. The material model bases on assumptions presented by Johnson et al.,²⁷ representing the textile sheet as a superposition of an elastic fibre phase and a viscous matrix phase.

The capabilities and limitations of macroscopic draping simulation tools for simulating the specific draping behaviour of textile sheet materials were numerously investigated for woven fabrics, but not yet enough for the diverse class of stitched non-crimp-fabric (NCF). These show complex and diverse mesoscopic phenomena as shown by Dumont et al.,²⁸ which influence the draping behaviour on the macroscopic level but have to be neglected in the simulation. Moreover, the use of blank holders to manipulate the draping result to, for example, avoid wrinkles requires detailed knowledge of textile forming processes and is a challenge to be modelled within an explicit numerical simulation.

Therefore, scope of the numerical study is to assess the capability of the simulation to numerically predict the forming behaviour and fibre angles of an NCF with a complex shape and process.

Material

Among the large variety of textile sheet materials for FRP production, this work focuses on the specific forming behaviour of dry, stitched biaxial NCF like those used in resin-transfer-moulding (RTM) processes. NCF shows a complex forming behaviour that is challenging to handle both in the manufacturing process and in the draping simulation.

The material used for the experimental investigations presented in this paper is a biaxial carbon fibre NCF with tricot stitching and an areal weight of 410 g/m² (Figure 2). The NCF consists of carbon fibres of type Toray T70050 C and PES stitching yarns with 76 dtex. NCFs show a complex forming behaviour due to their textile architecture, which is not only characterized by the yarn count, density and lay-up but additionally by the properties of the stitching.

For fixation of the preform after draping, the thermoplastic binder veil Spunfab PA1541 with 6 g/m² areal weight was applied between two 0/90 layers, which were stacked symmetrically to the middle plane of the preform. After forming, the preform was heated up to the melting temperature of the binder material (about 100°C) before releasing the preform from the mould. The spring-back effect is small (<5 mm, when comparing the distance of the corners of the draped structure prior and after demoulding).

Methods

Preforming tool

This work aims at performing further draping studies on a complex geometry with a variable blank holder concept in order to assess the possibilities of influencing the draping behaviour in the real forming process. The preforms are manufactured and subsequently analysed as shown in Figure 3.

Figure 2. Front and back sides of investigated NCF.

Figure 3. Conducted process steps and methods.

Figure 4. Process test rig for process and process parameter investigation.

To investigate the possibilities of influencing a draping process with variable blank holder and pre-tensioning systems, a robust testing environment was developed, which is depicted in Figure 4.

The process test rig consists of three sub systems: the actuating system, the retaining/pre-tensioning system and a thermal activation system as well as two surrounding cooperating robots. These robots can be used for handling of materials, quality assurance equipment or for the steering of new local, incremental end effectors.

The actuator system consists of up to seven servo drives (maximum loading of about 2.5 kN), with a highly accurate path and force control and another eight pneumatic drives (maximum loading of about 1.5 kN). These actuators can be positioned using an adaptive tube frame, where each XY position and all important tilt angles can be adjusted. Different pre-tensioning systems can be applied. The thermal activation system is another key to fast and reproducible processes. Up to 14 heating activators, 20 thermal sensors and a water-based thermal heating and cooling system can be combined individually towards an adapted thermal activation system. The combination of all variable

process parameters is done by specifically developed control software which enables a quick and fast programming and control of processes.

For the experimental preforming studies, a forming system which can be used with global or local blank holders was designed, including heating capabilities of up to 4 kW of heating power for thermal activation of a thermoplastic binder fixing the preforms. The tool geometry and design is shown in Figure 5. All surfaces that are in contact with the material are treated with an anodic oxidation in order to harden its surface. The control of the blank holders 1, 3, 8 and 9 is done by a servo drive. All other blank holders were loaded using pneumatic actuation.

Optimization of preforming setup and test overview

For the variable blank holder trials, the blank holder force distribution was optimized using an analytical approach. This geodesic approach applies the idea of a main deformation mechanism based on relative movement between neighbouring fibres (see Figure 6). Thereby, no significant shear angle change occurs, in contrast to the standard shear approach. For the

Figure 5. Overview of the test setup.

Figure 6. Basic deformation mechanisms during shear.

analysis, an equally split pattern is projected onto the geometry. The resulting local lengths are then compared in order to investigate the relative movement needed between two neighbouring fibres (Figure 7). For simple structures, the result is similar but not the same when compared to the fishnet algorithm. A detailed description of the approach can be found in Härtel.²⁹

The analytical approach was developed especially for unidirectional textile material, but also provides a reasonable insight in the geometric constraints for biaxial textiles. By using this approach, one can quickly assess the effect of different starting points – i.e. the area of local fixation of the material at the beginning of the draping process – on the overall relative movement of fibres needed to form the geometry. Less relative movement generally implies a better forming result. In Figure 7 the local relative fibre movement needed to form the geometry is visualized. For the given geometry, the result of the analysis shows that there are three major geometrically critical areas regarding relative fibre movement. There is a convex and a concave

corner in the upper right region of the geometry and there is the steep wall towards the lower flange. Other regions of the geometry are less critical in terms of draping errors like wrinkles.

For the presented geometry it was thus found that it is advisable to fix the textile in the upper right corner at the crossing of the red and blue line visualized in Figure 7. The results led to a setup which applies high forces on blank holders 2, 4 and 7 in order to keep the textile fixed at this position and aligned.

In Figure 8, the global relative movement is depicted, which equates the sum of the local relative movements between neighbouring fibres calculated in the previous step (see again Figure 7). The maximum needed relative movement is around 15 mm/Roving. When analysing these results, the interaction of the three mentioned constraints in Figure 7 becomes obvious and a special region of interest (ROI) evolves, which is marked in Figure 8. In this region, major deformations inducing high shear angles and wrinkles are expected.

Table 1 lists the trials conducted in this work with the according layup and blank holder forces. Test setup 1 and 2 consisted of a die, two sequential stamps and a global blank holder. The differences of the two trials are the fibre orientation and the retaining forces due to the blank holder (50% higher in trial 2). Based on the findings previously described, trial 3 uses a variable setup with separate blank holders working in sequence. Each blank holder (see Figure 5 for numbering) applies its dedicated force level calculated by the analysis described above.

Optical measurements

A major challenge for the precise validation of draping simulations based on experimental results is the measurement of actual fibre angles on a complex shape.

Figure 7. Local regions of relative fibre movement as a result of a geodesic analysis.

Figure 8. Sum of relative fibre movement and resulting ROI at the lower flange of the geometry.

Table 1. Overview of the conducted tests and its setups with corresponding blank holder pressure levels.

Trial	Layup	Global BH N/mm ²	BH1 N/mm ²	BH2 N/mm ²	BH3 N/mm ²	BH4 N/mm ²	BH5 N/mm ²	BH6 N/mm ²	BH7 N/mm ²	BH8 N/mm ²	BH9 N/mm ²
1	[90/0/0/90]	0.015	–	–	–	–	–	–	–	–	–
2	[0/90/90/0]	0.023	–	–	–	–	–	–	–	–	–
3	[0/90/90/0]	–	0.032	0.2	0.053	0.1	0.0072		0.1	0.055	0.06

Recently, a robot-controlled preform analysis system has been developed, which is able to provide optical measurement data of complex 3D carbon fibre textiles. The optical system takes advantage of texture analysis algorithms which are applied to extract fibre orientation and other critical properties from image data. Here, a statistical approach is used which measures the peak of an edge direction histogram as presented by Miene et al.⁸ In order to evaluate the fibre orientation over the whole 3D surface, a suitable quantity of

single pictures is captured perpendicular to the surface to avoid distortion effects (Figure 9). Therefore, a CCD camera sensor with a diffuse light source is therefore guided by an industrial robot (KUKA Quantec 120). The required sensor positions with respect to the part are previously calculated by a CAD algorithm based on the local curvature of the part geometry. By combining the robot position data with image analysis results, a virtual 3D map of local fibre orientations is generated. These results can further be

Figure 9. Robot-controlled image capturing on an NCF preform.

Figure 10. Model setup in PAM-FORM.

mapped to an arbitrary FE mesh for direct comparison with simulation results. For the presented work, the DEX Process provided within the Visual Environment software from ESI Group has been used for the mapping of fibre orientation vectors on the mesh, which is provided by the draping simulation. This novel approach is applied to evaluate the experimental draping tests and to allow for precise 3D fibre architecture validation on complex geometries with different textile materials, such as NCFs, wovens or braids, as shown by Böhler et al.³⁰

The robot-controlled image-capturing provides high-resolution photos, which are additionally analysed with the image analysis program Fiji³¹ on the mesoscopic scale. Here, in addition to the automatic image analysis of the fibre angle, shear angles are measured manually for a few areas which show high shear deformation. Determining the shear angle also requires the orientation of the lower fibre direction of the biaxial NCF, which can be identified in many cases on a high-resolution image, especially if the yarn density is not too high. Furthermore, gaps occur during shear deformation between the yarns frequently, as those

are specific to mesomechanic behaviour of many biaxial NCF, and thus expose the lower fibre direction. Moreover, fibre angles of the two layers in a biaxial NCF correspond well with the points where the stitching yarn is piercing through the textile layers. In an earlier study this was observed on a hemisphere specimen, which only consisted of one biaxial NCF layer.²⁷ Particularly in areas of high shear, where mesoscopic mechanisms like yarn buckling occur for NCF materials, the analysis of the stitching points facilitates the measurement of shear angles. With the information on the angle between both fibre directions, the shear angle can be calculated as difference to 90° for an initially orthogonal NCF.

Modelling

The variable blank holder concept described above uses blank holders positioned closely around the cavity and is divided into nine segments which can be moved separately. The respective simulation model with punch, die, blank holder and two textile layers is shown in Figure 10.

Figure 11. Test setup for free cantilever test, shear stiffness, textile thickness (left) and measured shear curve of the biaxial NCF (right).

No material viscosity was used in the model, as dry materials were investigated here. The two fibre directions in PAM-FORM represented by one shell layer. In case of the tested NCF this means that the asymmetry of the two-layered, bidirectional NCF has to be neglected. Belytschko-Tsai (BT) shell elements with five integration points over the thickness were used for the deformable textile layers. Compared to Hughes-Tezduyar (HT) shell elements, which are also available within this code, BT shells have a larger error in the calculated shear angle, but require much shorter computing time.

The material model requires material data input for in-plane shear stiffness as well as tensile and bending stiffness along fibre directions. For this study, picture frame tests were performed to measure curves for shear stress over shear angle as already presented in Mallach and Kharchi.³² Those were adapted to the specific input for shear stiffness in PAM-FORM. The bending stiffness tests (see Figure 11, left upper test set up) were performed with a stripe of 400 mm × 40 mm. A single-ply stripe was lifted from a horizontal plate by means of a round metal bar of 10-mm diameter until hanging free of any contact with the plate. Due to the long specimen lengths no clamping was necessary, as the stripe is stabilized by its own weight. The simulation model consisted only of the ply stripe loaded with gravity, bending over the modelled round bar. The stripe was not lifted from a plate in the model to cancel out that numerical sliding interface and hence, possible unknown numerical effects. The stiffness was then calibrated by modifying the bending stiffness of the fabric in the simulation model until a good accordance with the testing results was achieved. The tensile stiffness was measured in tensile tests on textile stripes based on DIN 13934-1 and transferred to the model as true stress over true strain. Isotropic friction coefficients have to be defined between the layers and between layers and

tools and were set to 0.3 and 0.15, respectively, based on experimental tests and experiences from earlier studies. The layer thickness is modelled as curves dependent on shear angle, measured on sheared and fixed picture frame specimen. Exemplarily, the test setup for the cantilever test, the picture frame test and the thickness measurements are shown in Figure 11 together with the mean shear curve of the biaxial NCF used in this study.

In a previous study, the software was analysed concerning the simulation sensitivity towards material and numerical parameters, which indicated that the simulation overestimates shear angles in many areas with sensitivity to changes in tensional and bending stiffness.³² This phenomenon is rather of numerical than physical nature and underscores the importance of a proper calibration of the simulation input values. However, it was shown that with a large data basis and simulation knowledge, the numerical results of the shown model exhibits a very good global forming behaviour. Thus, this calibrated model was picked up for this study to perform variations in blank holder concepts with two layers of biaxial NCF.

Comparison of simulation results with experimental preforming studies

Figure 12 shows the preforming process without blank holder on the left and the fixed preforming result manufactured with blank holder. During the whole investigation it could be shown that material and process boundary conditions have an enormous impact on the forming result.

The ROI identified by the geometrical analysis (Figure 8) as one of the most critical region regarding wrinkling could be verified on all manufactured preforms in that area. Exemplarily this is depicted in

Figure 12. Preforming process shown without blank holder (left) and fixed preform (right).

Figure 13. ROI on preforms of trials 1 and 2.

Figure 13 for trials 1 and 2. The figure shows the final preform result in the ROI and the mesomechanic effects that occur due to high shear angles and wrinkling, such as yarn buckling and yarn gaps. The ROI is later on referred as hot spot 2 as one of the two regions with highest shear angles on that preform.

Two simulation setups are shown in this chapter with boundary conditions according to trial no. 1, 2 and 3. Trials 1 and 2 were performed with a global blank holder and a contact pressure of 0.015 N/mm^2 and 0.023 N/mm^2 , respectively. Within the according simulation, which represents both trials 1 and 2 as the two NCF layers are represented by one shell layer, the blank holder pressure was set to 0.017 N/mm^2 . Test 3 and the according simulation was performed with the variable blank holder setup and contact pressure values described before. The simulation model for trials 1 and 2 as well as the simulation model for trial 3 are shown in Figure 14. Two hot spots are marked which show the highest shear angles in both simulation models. Hot spot 2 matches the ROI identified by the analytical approach.

The change in blank holder pressure leads to distinct differences in the global forming result and shear angle distribution. For the marked hot spot 1, a shift of the highest shear angle position can be observed. However, the shear angle magnitude does not significantly change. For hot spot 2, there is a change in shear angle distribution and magnitude, with angles up to 50° for the variable blank holder setup in contrast to 40° for the global blank holder setup.

Compared to the experimental NCF forming processes, the calculated shear angle maxima of both models shown in Figure 14 are too high, as there are rarely shear angles higher than 30° on the preform, as visualized in Figure 15. It can be seen that there are shear angle differences in the experimental results of tests 1 and 2, which have different orientations of the upper fibre direction. However, shear angles larger than 30° occur only as a very small local phenomenon on the real preform.

The main reason for those deviations may be found in the specific mechanisms NCFs perform at high shear angle. They show not only pure shear deformation but

Figure 14. Final draping simulation result according to trials 1 and 2 (left) and trial 3 (right) with marked hot spots 1 and 2 (=ROI). Pressure values of the blank holders are given in N/mm^2 .

Figure 15. Shear angles on experimental performs of trials 1 and 2 at the hot spots (left) and the according simulation result (right).

additional mechanisms like fibre sliding as reaction to shear stresses. As the two fibre directions in one NCF can slide relatively to each other, macroscopic wrinkles can cause mesoscopic yarn buckling that occurs in only one of the two stitched layers, depending on the local stress state. Figure 16 shows this phenomenon exemplary for the marked region. While in one fibre direction (Figure 16, right), yarn buckling occurs on the mesoscopic scale, no yarn buckling appears for the second fibre direction (left) in the upper layer in the same region. It can be concluded that NCF yarns have certain degrees of freedom during deformation of a real textile, which is potentially influencing the fibre direction on the preform surface. There is no

possibility to account for those specific mechanisms in the simulation, as the material model uses a continuum mechanics approach and the two fibre directions are modelled within one shell layer. It is obvious that in a continuous shell element with pure fibre rotation, the lateral compression perpendicular to the yarn direction has to be significant for high shear angles, whereas for the presented NCF the yarns have certain degrees of freedom and even for high shear angles no lateral compression between the yarns occurs.

Qualitatively, these mesomechanic specifics of NCF are commonly understood, but the presented methods have, moreover, the scope to quantify the resulting discrepancy between simulation and NCF forming. For that purpose, both the captured and the calculated fibre directions were projected on the same FE mesh as described in chapter Optical measurements. The simulation results were mapped with the ESI macro DEX process. Subsequently, the difference of both fibre orientation vectors was calculated and is visualized in Figure 17 for trials 1, 2 and 3.

As evident from the figure, for all three cases there are broad regions where the difference between the measured and calculated fibre angle is larger than 15° . It can also be seen that for trials 1 and 2, which share the same simulation model but in real forming have a different fibre orientation of the upper layer, the regions of high deviations are different for the two fibre directions (Figure 17 left and middle). A comparison of simulations 1, 2 and 3 (Figure 17 middle and right) on the contrary indicates that for different blank

Figure 16. Macroscopic simulation and mesoscopic behaviour of a small area on the preform in trial 1 (right), trial 2 (left) and simulation.

Figure 17. Deviation of numerical from experimental fibre orientation of the upper layer, white arrows indicate the fibre direction for which the deviation was calculated.

Figure 18. Fiber orientation of the simulation model (dashed line) projected on experimental result tests 1 (left) and 2.

holder pressures but same fibre orientations, deviations between simulation and experiment occur in the same regions. Though, simulation model 3, which uses much higher local blank holder forces than simulations 1–2, shows even stronger fibre angle deviations. This indicates numerical effects leading to stronger fibre rotations in the elements when higher tensional strains

occur, which has no physical foundation. No further investigation of that hypothesis is performed in this study, but numerical sensitivities were observed throughout the simulations and have to be taken into account when dealing with such complex simulation systems. However, it can be assumed that one particular reason for those deviations is the continuum

mechanic representation of a material whose forming behaviour is characterized by mesoscopic mechanisms.

Figure 18 shows a detail of hot spot 1 of the preforms manufactured in trials 1 and 2 and the corresponding fibre orientations of the simulation as overlay (see again also Figure 17). There is a good correlation of the fibre directions for test 1. On the contrary, the high deviations for test 2 and the simulations 1–2 become obvious on the right hand side of Figure 18. The calculated fibre orientation in that direction follows a curved path with strong directional changes. Regarding NCF, this underscores one of the major limitations of macroscopic draping simulations. The strong rotations of the fibre directions depicted on the right hand side of Figure 18 are rotations of continuous shell elements which cannot perform any other major in-plane deformation. The real NCF on the other hand shows smoother changes in fibre direction. The large gaps between the yarns indicate that relative yarn sliding may be a significant mechanism as a reply to shear stresses and eventually leads to lower fibre rotation and shear angles.

Conclusions

The presented study shall be a contribution to the understanding of discrepancies between the results of macroscopic draping simulations and the specific, complex forming behaviour of NCF. On the one hand, the preforming studies presented here were reproducible concerning the global forming behaviour of the NCF. Local variations of the blank holder pressure only led to small changes in wrinkle appearance, but the hot spots of highest shear angles and potential wrinkling, which were predicted with good accuracy by the analytical approach, were always similar and thus constrained by the geometry to a high degree. On the contrary, the simulations presented in this study showed a numerical sensitivity towards changes in blank holder pressure, which is not realistic when compared to experimental results. The comparison of the fibre angle captured by the optical measurement system and the fibre angle calculated by the macroscopic simulation shows that especially in the hot spots where highest shear angles occur, the deviations are significant. The specific mesoscopic mechanism of NCF material, in particular relative yarn movement, potentially is a major reason for that. Moreover, numerical effects can further contribute to those deviations, as representing a thin anisotropic layer with high tensile but low shear and bending stiffness within an explicit simulation is challenging. Thus, macroscopic, continuum mechanics draping simulations should be understood more as a means of designing and understanding the preforming process, being capable of predicting areas of

higher shear angles, wrinkles and the overall forming behaviour, but with limits regarding the precise determination of fibre architecture. Even with further improvements in the macroscopic modelling of shearing and bending of textile NCF layers, certain deviations of calculated fibre angles have to be accepted due to the mesomechanic behaviour of NCF, which cannot be represented by a continuum mechanics approach. It is conceivable that in the long term mesomechanic simulation approaches will gain importance for the modelling of NCF, whereas in the near future, for example, an efficient coupling of mesomechanic and macromechanic models is more eligible according to the presented study.

Moreover, the importance of using optical measurement techniques for a precise evaluation of real and simulated fibre architectures becomes apparent, as the accurate determination of fibre architecture parameters is a key element towards the use of draping simulation results for part design, process optimization and structural dimensioning.

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