INVESTIGATION AND SIMULATION OF FORMING BEHAVIOUR OF PREFORMS MADE BY DIRECT FIBRE PLACEMENT

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Abstract
This paper describes a method to predict the forming capability and behaviour of preforms made by direct fibre placement. At the beginning, the most relevant material properties for forming simulation, using the finite element tool AniForm, are identified. Experimental methods to model the material are declared. In addition to standard tests like bias-extension and cantilever test, pull through tests are done on a novel test bench to evaluate the tool-ply and also ply-ply friction. The resulting simulation material model is calibrated with experimental forming tests on the generic double dome geometry. Mainly due to the thermoplastic binder, temperature has a significant influence on the forming results. The main issues observed in the forming tests are gaps within a ply due to the missing knit threads connecting the fibre layers. As a result the characteristics of the forming tests match with the simulation results. By using the macroscopic forming simulation method, defects can be identified sufficiently accurate and the results can also be used for subsequent processes, for instance the fibre orientations for structural analysis.

1. Introduction

Reducing waste and increasing the productivity are main goals in serial production of fibre reinforced composites. Compositence direct fibre placement technologies are designed to meet these demands by fast near net shape deposition of multiple tows simultaneously. For productivity reasons, fibres are placed on a simplified layup geometry with respect to the intended part shape. By a subsequent forming step the preform is given its final component geometry. Process simulation methods are necessary to evaluate the forming results in an early state of the composite part development. Forming simulations with finite element software tools may influence design changes, the stacking sequence or forming conditions to optimize composite structures. A good prediction of the behaviour of unidirectional layers is important to detect defects or imperfections and derive mechanical properties of the preform.

Deformation mechanisms and exact material properties under various conditions have to be known. Compared to fabrics the unidirectional layers are only interconnected by thermoplastic binder. Fibre movement during forming is not limited by knit threads or interleaving fibres. Once activated or under heat and forming conditions, the binder alters the friction behaviour between the fibres in comparison to a purely dry material.

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2. Deformation mechanisms and test setups

The basis of all computer aided simulations is a realistic material model. The material must be well understood and experimental methods are necessary to measure material properties. With respect to moulding, the following deformation mechanisms can be noticed: in-plane shear, bending, delamination, tooling slippage and ply slippage [1]. Different test setups are available in the literature to measure these properties individually to avoid a combination of different deformation mechanisms [1, 2].

The forming results are largely determined by the friction behaviour of the material [3]. To measure the frictional properties a novel pull out/pull through test bench has been developed at Compositence. Temperature, contact pressure, speed and fibre orientations can be adjusted individually in order to test a wide range of forming conditions (Fig. 1).

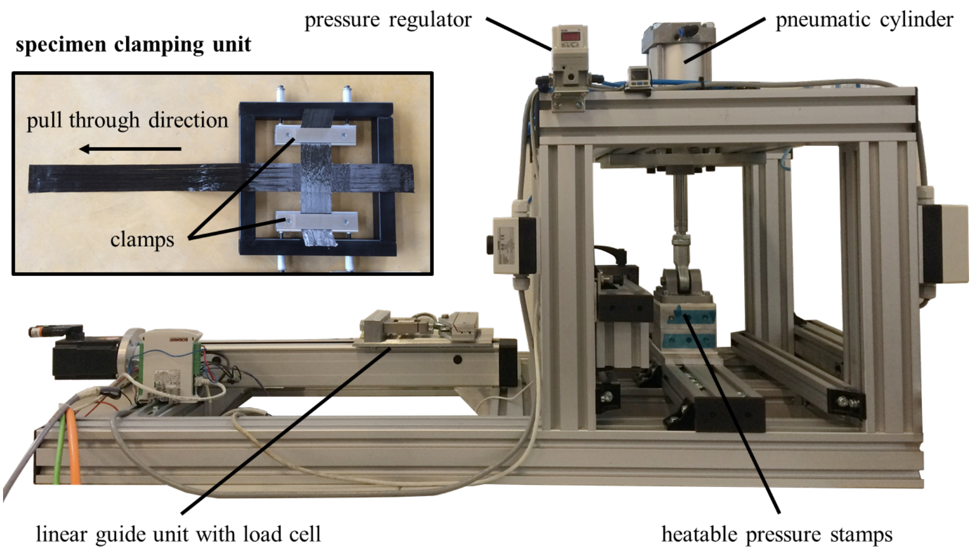


Figure 1. friction test bench to measure tool-ply and ply-ply friction

The picture frame and the bias-extension test are common methods for characterising shear behaviour of fabrics [4]. Preliminary tests show, that the UD layers produced by a placement process have a different shear behaviour compared to fabrics. The bias-extension test shows that the ±45° specimen breaks apart after small deformations. Instead of intra-ply shear deformation, the resistance force drops to nearly zero and the plies slip from each other. Thus, the shear behaviour is mainly influenced by the interface in-between the plies [3].

Cantilever tests (DIN 53362) are often used to determine bending stiffness of textiles. The influence of bending stiffness can be noticed by undulations and wrinkles during forming. Due to the presence of thermoplastic binder in the stacked material, the bending behaviour is highly dependent on the temperature. Therefore the bending characterisation has to be performed under a defined draping temperature. The cantilever test is not suitable for this material at the defined temperature because of the weak bond of the fibres. Therefore a new bending test is developed.

3. Material characterisation

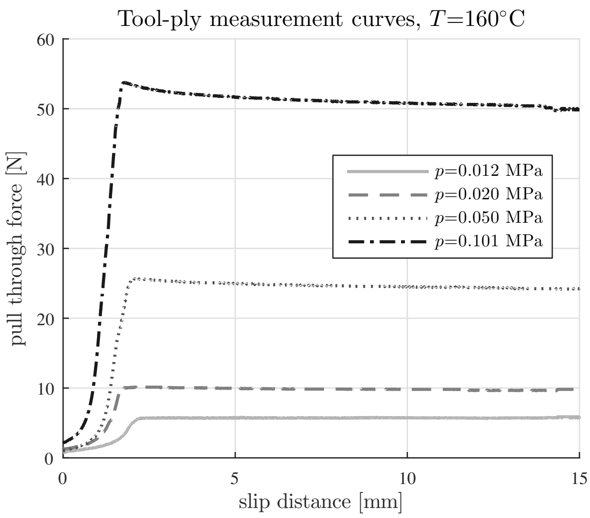
The material characterisation is done with a 24K carbon fibre, which is spread to the placement configuration width of 12 mm. Between each layer a thermoplastic binder is applied with an areal weight of 10 g/m². Experiments are done with temperatures above the melting point of the binder. Therefore, temperatures between 120 °C and 160 °C are considered.

3.1. Tool-ply friction

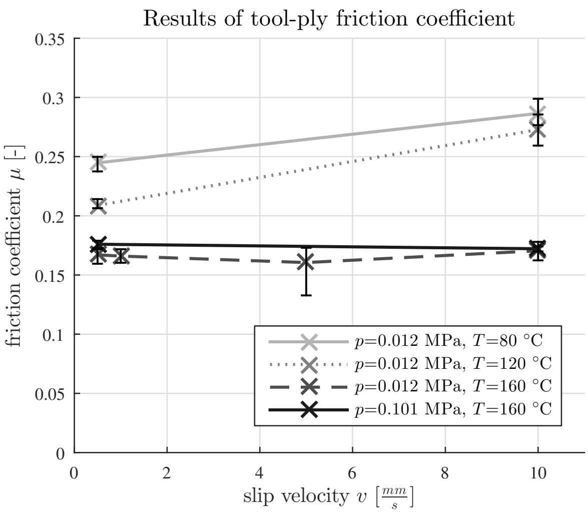
The highest tool-ply friction forces are expected between mould and blankholder. Blankholders are necessary to control fibre slippage while forming. To measure tool-ply friction one single tow is pulled through two heated guides. These guides also have a width of 12 mm to avoid a widening of the tow. Balancing weights are used to apply different contact pressures. In the regular placement process there is no binder applied on the outside of the preform. Therefore, the friction between the fibre and the tooling can be measured without any influence of the binder.

Measuring curves at 160 °C with different contact pressures are shown in Fig. 2 (a). The friction or pull through force is almost constant after the rise at the beginning of the test. Mean values are calculated from the steady state level. Tool-ply friction can be described by the coulomb friction, where the friction coefficient μ is calculated by the measured force to overcome friction $F_{\text{pull through}}$ divided by the normal force $F_{\text{normal load}}$ (Eq. 1). Friction occurs at the top and at the bottom of the specimens, therefore a factor 1/2 is considered. The calculated friction coefficients are shown in Fig. 2 (b). At 160 °C the coefficient is nearly independent from slip velocity v and contact pressure p. At lower temperatures the friction is generally higher and shows also dependence of velocity.

$$\mu(T, v) = \frac{F_{\text{pull through}}}{2 \cdot F_{\text{normal load}}} \tag{1}$$



(a) Pull through forces with different surface pressures at 160 °C



(b) Dependency of tool-ply friction coefficient

Figure 2. Measurement curves and results of the tool-ply friction

3.2. Ply-ply friction

To investigate ply-ply friction, experiments are done with fibre placement specimens. These specimens have the shape of a cross, which is made out of three layers with six tows each. Additionally to previous variable conditions, different fibre angles are taken into account. The outer plies are in the same orientation and can be clamped in a frame. The middle ply is placed under 45° and 90°. The middle ply

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is clamped on the driven load cell and will be pulled through the outer plies (Fig. 1). Binder is applied on the connecting surface between the plies. To prevent slippage of the outer plies, those can be pre tensioned in the frame.

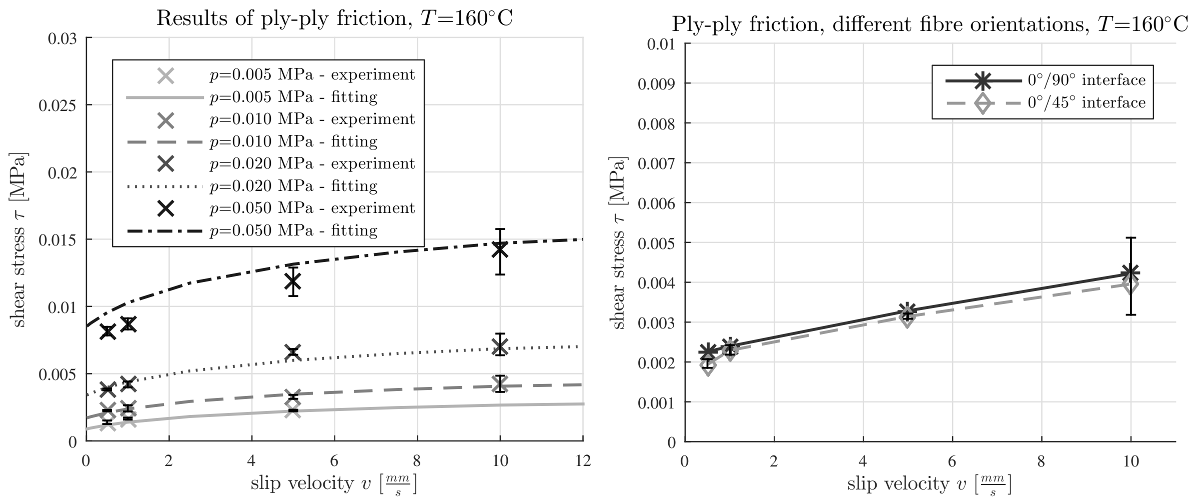
In the first experiments individual tows were pulled out of the specimen concisting of multiple parallel tows. The measured force reaches a high value, followed by sharp drop and decreasing course. It is assumed that the tow is getting thinner due to alignment of filaments. Contact pressure is no more homogeneously distributed. Results are irreproducible and requires alternative test procedures. Subsequently all further tests are performed with all fibres of the middle ply being pulled simultaneously. To keep contact pressure constant, pull through instead of pull out test are performed.

Fig. 3 (a) displays the results of the ply-ply friction tests. The shear stress τ_{friction} is calculated from the measured pull through force $F_{\text{pull through}}$ divided by the contact area A, see Eq. (2). A factor of 1/2 is necessary, because of the upper and lower contact surfaces. The results indicates that friction is dependant on normal pressure as well as on slip velocity. The shear stress increases with an increasing normal pressure and a higher slip velocity. This indicates a hydrodynamic type of friction, which results from the molten binder between the fibre layers.

$$\tau_{\text{friction}}(p, T, v) = \frac{F_{\text{pull through}}}{2 \cdot A} \tag{2}$$

The deviations within the test results increase with increasing slip velocity and increasing normal pressure. Possibly the reason for this deviation is the variance of the amount of the binder. The binder influences the viscous part of the friction, which increases with high slip velocities and normal pressures.

Fig. 3 (b) shows the results for specimens with different fibre interfaces. The results do show no influence of the fibre orientation on ply-ply friction within $45-90°$ with respect to the pulling direction 0°.



(a) ply-ply friction with parameter fitting at 160 °C

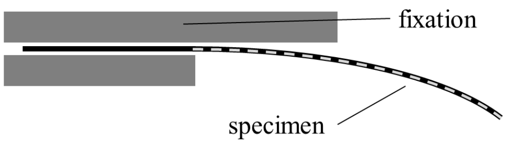
(b) ply-ply friction depending of fibre orientation

Figure 3. Ply-ply friction results at 160 °C

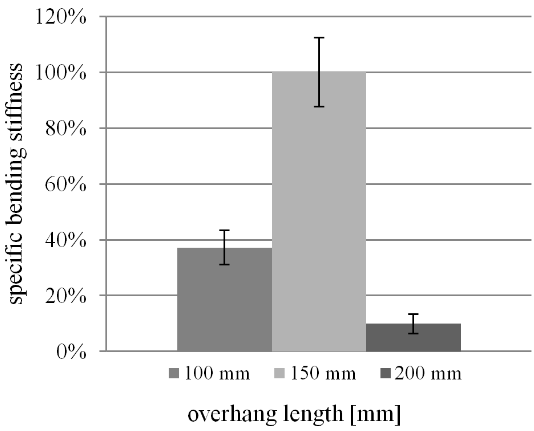
3.3. Bending characterisation

The characterisation of the bending stiffness is done by using a two layered unidirectional specimen with binder in-between. The fibre orientations are aligned to the specimen axis. The specimen together with the test setup is prepared at room temperature and then inserted in an oven at the defined temperature. By the rising specimen temperature, the binder slowly starts to melt and the bending stiffness decreases. Due to the slow movement, kinetic effects can be neglected. The curve, which is described by the specimen, is measured by an image evaluation program as shown in Fig. 4 (a). The bending stiffness is computed at a defined interval according to the Euler-Bernoulli beam theory and averaged. It is assumed that the behaviour of a unidirectional stack of two layers is similar to a single layer. This simplification is necessary, because a single layer of this material is not manageable.

In Fig. 4 (b) the averaged bending stiffness for three different overhang lengths are shown. It can be seen, that the bending stiffness is dependent to the overhang length. The comparatively low value for the overhang length of 200 mm can be explained by buckling. At this configuration the applied moment by the weight is too high for the material and buckling occurs close to the fixation point. This behaviour highly decreases the measured bending stiffness.



(a) schematic representation of the experimental procedure with image evaluation



(b) specfic bending stiffness depending from overhang length

Figure 4. Determination of bending stiffness due to image evaluation of the bending curve

4. Material modelling

Simulations are performed using the implicit finite element software AniForm. AniForm is a fully non-linear FE-code for simulations of large deformations with highly anisotropic materials. The deformations are calculated based on the in-plane, bending and interface material behaviour. These behaviours are described by different material submodels which can be combined in a mixed model in order to represent the macroscopic behaviour of the laminate.

The in-plane and bending deformations are described by an orthotropic material with high stiffness in fibre direction. As the tows do not have any connection in-between the UD layers, the assumed stiffness in transverse direction is set to a low value. Both models contain a Newtonian fluid model to add a slight viscosity in order to decrease simulation times.

The results of the experiments show a decreasing shear stress for both tool-ply and ply-ply friction for an increasing temperature. As AniForm does not offer a temperature dependent material behaviour, separate material models are necessary for different forming temperatures. The following example shows how the interface model is built for a forming temperature of 160 °C. As shown in Fig. 2 (b) the tool-ply interface at 160 °C can be described as a coulomb friction with a constant coefficient.

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Ply-ply friction shows an hydrodynamic behaviour which is represented by a combination of penalty with coulomb friction and a penalty with polymer friction model. The shear stress of the penalty with coulomb friction model is described by Eq. 3, where μ represents the friction coefficient, E_p the penalty stiffness and δ the penetration depth. [5]

$$\tau_\text{coulomb} = \mu \cdot E_\text{p} \cdot \delta \tag{3}$$

The shear stress of the penalty with polymer friction model is described by: [5]

$$\tau_\text{polymer} = \tau_\text{p} + \tau_0 + a \cdot (p + p_0)^b \cdot \dot{\gamma} \cdot \eta_\text{c} \tag{4}$$

where τ_p represents the contribution to the penalty contact. τ_0, a, p_0 and b are fitting parameters and p denotes the normal pressure. The shear rate $\dot{\gamma}$ of the fluid film is related to its film thickness h and the slip velocity v: [5]

$$\dot{\gamma} = \frac{v}{h} \tag{5}$$

The viscosity of the fluid is described by a cross model, where η_0, C and n are fitting parameters and $\dot{\gamma}_\text{q}$ the equivalent shear rate.: [5]

$$\eta_\text{c} = \frac{\eta_0}{1 + (C \cdot \dot{\gamma}_\text{q})^{(1-n)}} \tag{6}$$

The fitted curves of the combined ply-ply interface model as well as the experiment results of the ply-ply friction can be found in Fig. 3 (b). The interface model also contains an adhesion model in order to represent the stickiness of the binder. Due to the absence of a characterisation test for adhesion, values for the adhesion model are based on an educated guess.

The interface model consists of two penalty contacts and therefore, the applied normal pressure is split equally between both friction models. The simulations are performed with twice the normal force on the blankholder and the friction coefficient of the tool-ply model is halved.

5. Comparison to experimental forming tests

The practical forming experiments are performed at the Institute of Aircraft Design (IFB) at the University of Stuttgart. Their main purpose is to validate the results of the simulations performed by Compositence. Another aim of these tests is to gain experience in working with this special kind of material and to obtain knowledge about its specific draping behaviour.

5.1. Draping device and test method

Fig. 5 gives an insight in how the draping experiments are performed. On the left-hand side the setup of the draping device is illustrated. The double dome benchmark geometry [6] has been chosen for its wide scientific appreciation. In connection with investigations of forming behaviour of textiles, it is especially interesting as it provides single as well as double curved areas. The negative mould of the double dome geometry is mounted on the draping platform. Pneumatic and electric actuators are attached to the top of the device to press the blankholder and the draping stamp to the mould.

A schematic top view of the experimental setup used for the forming experiments is shown on the right-hand side of Fig. 5. The pneumatic actuators apply a force to a blankholder plate in order to create retaining forces on the textile placed on the draping mould. By a rigid aluminium frame, this force is distributed constantly on the entire surface of the blankholder plate. The forming test sequence is always

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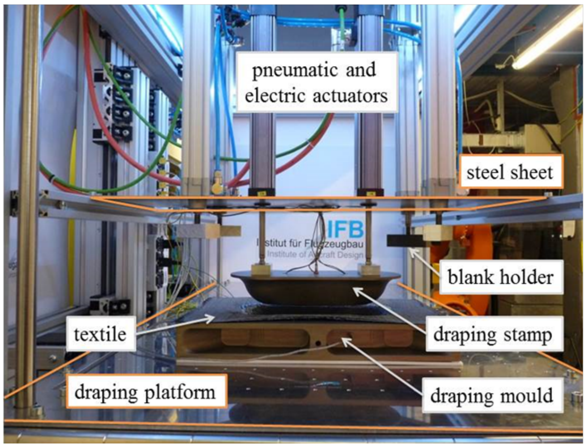

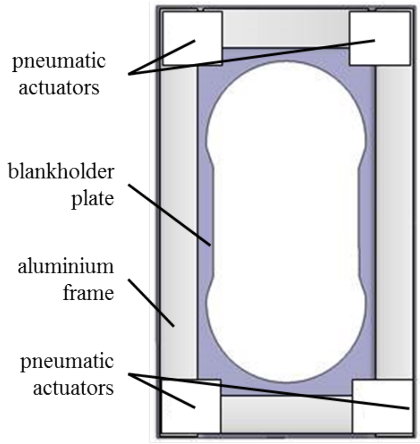

Figure 5. IFB draping device (left) and draping configuration (right).

performed as follows: Heating of the mould and stamping tool, inserting the preform, applying the blankholder forces, engaging the isothermal draping process. The tests are done with different conditions like temperature, preform layups and blankholder pressure.

5.2. Comparison between forming simulation and test

Fig. 6 compares the top layer of a forming simulation with the corresponding experimental test of a [0°/90°/0°] preform formed at 160 °C. The simulation plot shows the Green-Lagrange strain transverse to fibre direction, in order to indicate gaps or compression. The contraction of the boundary of all three layers in the preform correlates with the simulation results. A calibration of the material model was necessary to improve the behaviour within the preform boundary, therefore the friction coefficient for the tool-ply interface had to be reduced by 20 %, compared to the material characterisation.

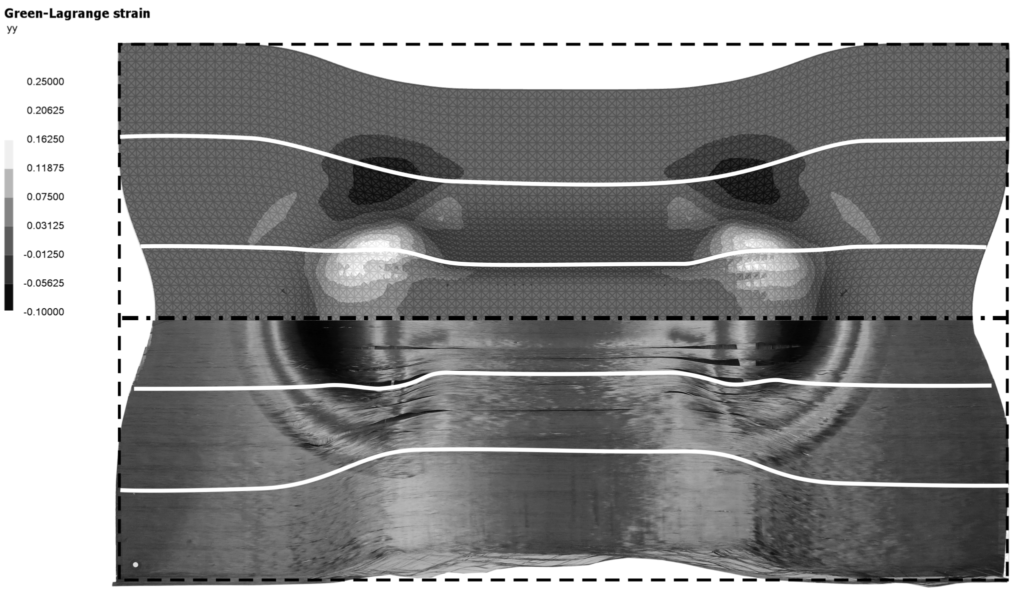

Figure 6. Comparison between simulation (upper half) and experimental forming test (lower half) of the top layer of a [0°/90°/0°] preform, formed at 160 °C

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Material slip as well as the marked fibre paths (white lines) are very similar between the simulation and the forming test. The formed preform shows gaps between the tows at the flank of the double curved surface. The post-processing shows a Green-Lagrange strain of 25 % transverse to fibre direction at the equal position (bright areas). The dark area at the top of the simulation result indicates a compression of tows of 10 %. In the same area compressed and wrinkled tows can be found at the test preform.

With higher number of plies, the simulation shows less and smaller transverse strains as well as compressions. Experimental forming tests of multi-layer preforms confirm the simulation results in the way, that there are almost no gaps at the critical points. With the reduction of the blankholder forces, gaps can be minimized, but to low forces leads to wrinkles. Furthermore the formability can be positively influenced by the use of a lower forming temperature. This implicates a new characterisation and modelling of the material especially for this temperature.

The laminate is discretised by 5 mm triangular shell elements. The AniForm shell elements are combined LTR3D and DKT Kirchhoff elements using the same nodes. Simulation times are between 1.5 h and 2.5 h using a Quad-Core Intel Xeon E5-2643 processor.

6. Conclusion

Compositence and the Institute of Aircraft Design investigate tools and methods to characterise the material behaviour of preforms, which are produced by a dry fibre placement process. Extensive tests under variation of forming conditions are done. Generated material models are compared and calibrated to generic forming experiments. The forming behaviour of the FE-simulation is realistic. Failure areas, especially gaps and compressions, can be recognized and predicted qualitatively well using a macroscopic method. The appearance of gaps between the unidirectional placed tows can be identified by high transverse strains within the simulation. Good and gapless results are generated by a combination of low temperatures, low blankholder forces and multi-layer preforms. Resulting defects and fibre orientations can be further used for structural analysis.

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