SIMULATION METHOD FOR THERMOFORMING OF APPLICATION-ORIENTED TEXTILE STRUCTURES AND MULTI-LAYERED REINFORCED ORGANOSHEET

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Abstract

The correct modeling procedure of a thermoforming process involving an endless fiber reinforced thermoplastic sheet material (organosheet) is still a challenge. An important factor in the customization of an organosheet is the configuration of the reinforcement. It is desirable to be able to analyze all the different structural reinforcement possibilities for a thermoforming process using a single simulation approach. There are several different disadvantages in the usage of a continuous material model, as is commonly used for metal forming simulation and other mainly isotropic materials. Theoretically, for every different textile structure a new material model has to be defined and there is no guarantee that the continuum mechanics based material model can describe the deformation behavior properly. In this work an alternative possibility will be shown by using a hybrid model consisting of shell and beam elements defined by standardized material model cards. The results of the thermoforming simulations can be used as the input state for a cooling simulation in order to analyze component distortion or in a structural analysis. The resulting fiber orientations can be mapped onto pure shell or solid elements and then used to create structural simulations at room temperature together with typical orthotropic composite material models.

1. Introduction

For the purposes of designing lightweight parts in the automobile and aerospace industry, endless fiber reinforced materials are used. The possibility to lay-up the yarns in the direction of the applied forces can provide great advantages in terms of material saving.

One method to realize a part with a defined fiber orientation is to directly lay-up unidirectional tapes onto a tool. However, this method requires complicated tooling and a time intensive lay-up process. Another method is to thermoform using a thermoplastic matrix preimpregnated blank sheet, or so-called organosheet, in a simple press forming process. In this approach, the designer can customize the structure of the blank sheet for the purposes of generating the correct fiber orientations following the thermoforming process. An important factor in the customization is the configuration of the reinforcement. Regular weave structures or non-crimp fabric (NCF) textile structures where the direction of the fibers in different layers can be varied can be used. In the NCF case, the appropriate stitching influences the degrees of freedom of the yarns and the overall drapability.

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From a modeling point of view, it is desirable to be able to analyze all the different structural reinforcement possibilities for a thermoforming process using a single and efficient simulation approach.
In the past Duhovic et al. [1] developed a forming simulation method to predict the resulting fiber orientation and the influence of stitches on a dry textile reinforced structure. This macro scale modeling method was based on the idea from Sidhu et al. [2] who combined shell and truss elements in a unit cell system. In this approach, truss elements represent the properties of the yarns or tows, while the shell elements represents a fictitious medium that takes into account the stiffness due to interyarn scissoring. This fictitious medium can also be used to represent the properties of a polymer resin when dealing with preimpregnated materials. In [3] Schommer et al. presented some improvements on this method to include the possibility to simulate a realistic fully non-isothermal forming process.
The results in these past works could only be used for standard weave materials or purely 0°/90° NCF structures. But many textile structures shows some special features like stitching, auxiliary yarns or even a 3D structure. With this in mind new developments in the hybrid shell/beam-element simulation method took place which will be presented in this work.

The goal of the forming simulation is the prediction of fiber orientation, distribution and drape induced defects in the part, for example yarn spreading, gaps, wrinkling, buckling or delamination.These results can be used as the input state for a cooling simulation to analyze component distortion or a structural analysis, for example, to evaluate the stiffness or crash performance of a part. Irrespective of the type of reinforcement structure, the beam element directions represent the resulting fiber orientation. For a structural simulation at room temperature, the direction can then be mapped onto pure shell or solid elements and used in a typical structural simulation together with common orthotropic composite material models.

2. Application oriented thermoforming simulation

2.1. Macro scale unit cell model for standard weave material

As mentioned in the Introduction, reference [3] describes a hybrid simulation method designed for the accurate modeling of the thermoforming manufacturing process of an organosheet by using the general FEM-Software LS-DYNA®. The macro scale model (Figure 1) is based on a unit cell that is represented by shell and beam elements which share specific common nodes.Here, the beam elements represent the bending stiffness of the composite material, which is mostly defined by the properties and the direction of the fabric. This is why the beam elements lie in the fiber direction and represent the actual yarns of the fabric. The material model choosed for the beam-elements is an elastic-plastic, temperature dependent model. The stiffness defined in the material is based on an experimental bending test as described elsewhere in more detail [3].

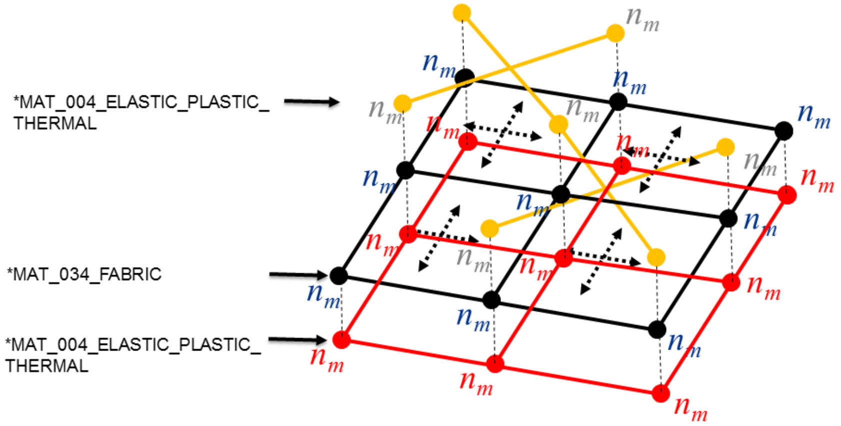

Figure 1. Finite element mesh unit cell used to represent the forming behavior of a thermoplastic organosheet material.

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In this model, a single layer of shell elements represents the resistance against shearing of the entire multi-layered composite. The direction of the shell elements is chosen so that tension/compression occurrs when the composite shows shearing. This technique avoids large warpage of the shell elements allowing higher shear angles to be simulated and helps keep the overall simulation time step constant. This also results in the fact that the shear stiffness of the composite is then represented by the tensile stiffness of the shell element. As material model for the shells, an elastic fabric model is used. A typical shear stress vs shear strain curve, as shown in Figure 2, is the input for the tensile behavior of the material model.

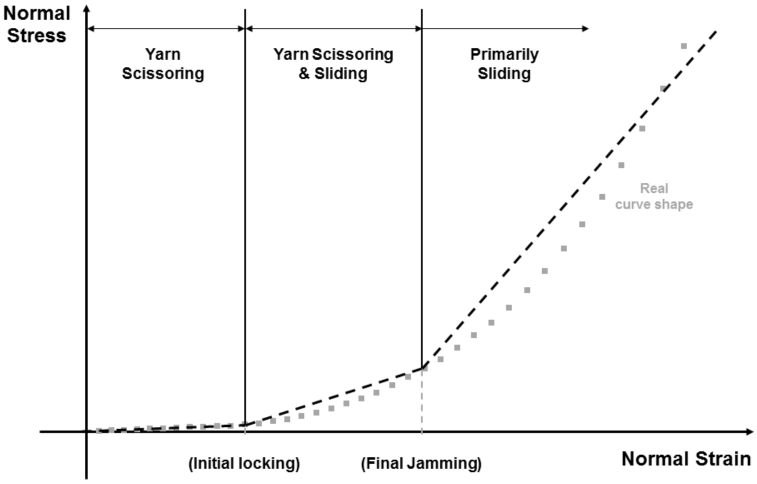

Figure 2. Tri-linear normal stress-strain relationship represented by shell elements**.** [2]

The second shell layer takes into account the non-isothermal effects in the composite material. Its temperature dependent stiffness serves as a scale factor for the overall stiffness.

This modeling method shows a very accurate prediction of the fiber orientation in forming processes for organosheets. But it has also its disadvantages.By using a second shell layer to take into account the isothermal effects, the necessary number of elements is doubled which increases the overall calculation time.
As the beam and shell elements are directly coupled by common nodes, the element sizes and directions are not independent from one another. In addition, the degrees of freedom in the movement of the beams are restricted.

2.2. Modification for customized textile systems

To eliminate the disadvantages in the previously described modeling method, some improvements were made. As an example, the improvements are shown here via the modeling of a “DRAPFIX Carbon Highly Drapable Non-Crimp Fabric” produced by “Gerster TechTex” [4].
The reinforcement lay-up has a NCF structure with carbon fiber yarns in 0° and 90° direction. The structure is stabilized by an PES auxiliary yarn. This configuration fixes the warp and weft yarns in the perpendicular direction in each layer but allows the movement in the fiber direction of each layer, as shown in Figure 3.
The modeling method shown before can not describe this movement pattern because of the fixed connection between the beam and shell elements.
In the improved version of the model, the setup of the beam and shell elements are completely disconnected. In a first step, an approximated repeating unit cell of the dry fabric is using beam elements (Figure 4a) left). The crossing beam elements (yarns) share no common nodes and are just connected by contact definitions. This allows the targeted definition of all desired degrees of freedom. As an example here, the pull out effect of single yarns can be seen in the real fabric (Figure 3) as well

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as the simulation (Figure 4b). This pull out effect can be controlled for example via the friction coefficient parameter in the contact definition card.

To realize a full multi-layered organosheet model it is necessary to control the shear behavior with a shell layer (Figure 4a) right). The shells share no common nodes with the beam elements. The interaction is also defined by using contact definitions. This allows a completely free dimension (size) and orientation flexibility to the shell elements with respect to the beam elements.

The only restriction for the orientation of the shell elements is that it is recommended to choose the element direction so that a shearing of the composite results in a tension of the elements for reasons already mentioned in Section 2.1.

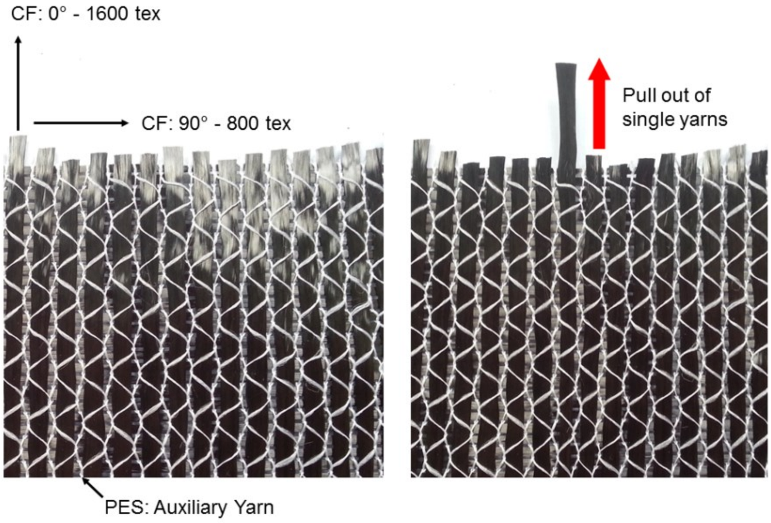

Figure 3. Description of “DRAPFIX Carbon Highly Drapable Non-Crimp Fabric” by “Gerster TechTex” [4]

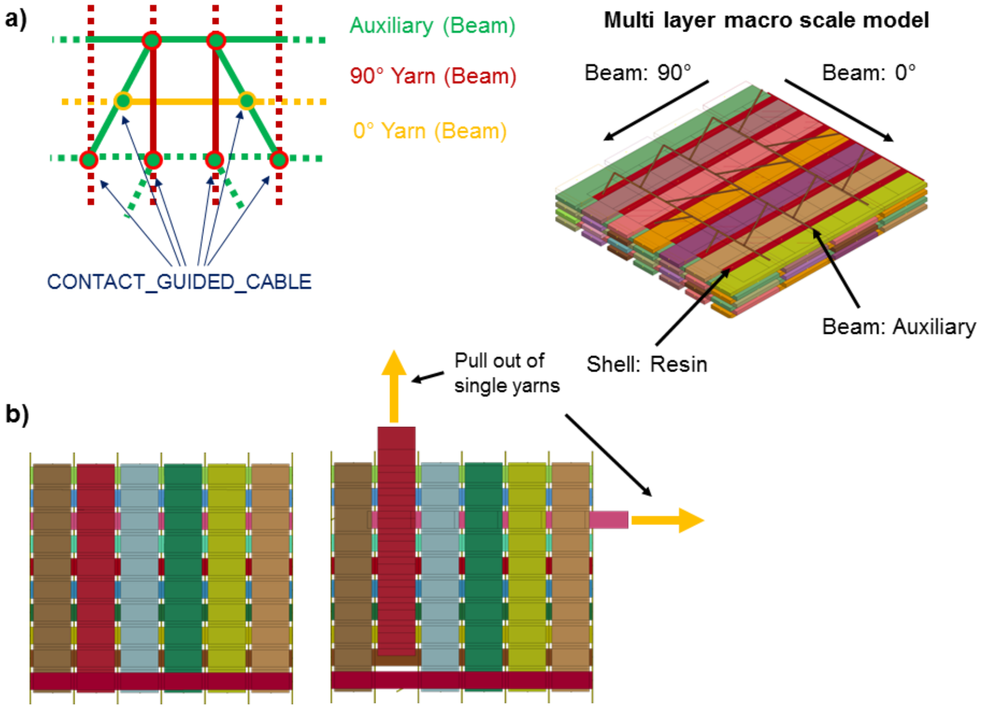

Figure 4. Simulative description of dry DRAPFIX NCF (left) and a complete macro scale model of a multilayered organosheet PES/Drapfix (right)

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In this case, as material model for the beam elements, a purely elastic model is used to simplify the mechanical behavior of the carbon fibers. For the shell elements a temperature dependent, elastic-viscoplastic material model is chosen where it is possible to directly define a stress-strain curve to describe the plasticity of the material. As in the fabric material before, it is possible to input a shear stress vs shear strain curve measured by a picture frame test to describe the tensile behavior of the elements. Because the material model is already temperature dependent, it is possible to spare a second shell layer.

3. Material characterization of the shear behavior

Material characterization is the most important part of process simulation. Here, the many parameters necessary for the creation of accurate simulation models are collected and organized into the inputs required for general or application specific finite element software codes. For the calibration and verification of the material models, the data is first used in simulations of the tests itself to check that material behavior has been captured correctly. Dependent on the overall structure of the organosheet more or less characterization tests are necessary. As an example, here will be shown the picture frame test on an organosheet with a “Drapfix Carbon” reinforcement structure from “Gerster TechTex” and a PA6 polymer matrix.

The picture frame test is used to measure the necessary shear stiffness response for the composite material. Here a horizontal setup is used where the specimen is heated between two infrared panels. The surface temperature is optically controlled by a thermal camera. Figure 5 shows the setup for this test. It can be seen that one corner of the rig is fixed while the opposite corner is pulled with a defined velocity. γ here is defined as the shear angle and is the difference between the initial inner frame angle (90°) and the actual inner angle.

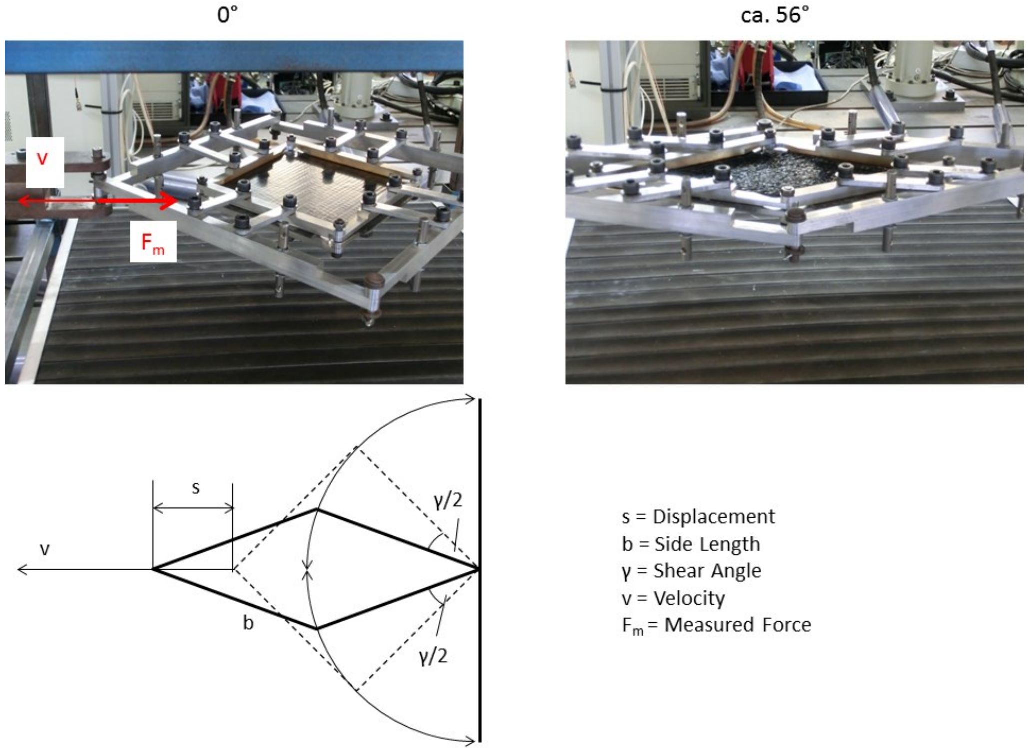

Figure 5. Horizontal picture frame test (top: experimental, bottom: schematic).

The direct output of this test is a force versus displacement curve (F_m-s). This Fm-s curve can then be converted into the stress-strain curve (τ-ε) that is given in the material model. First the resulting shear angle has to be calculated by the crosshead displacement s and the frame side length b.

$$\gamma = 90° - 2 \cdot \cos^{-1}\left(\frac{s}{2b} + \frac{1}{\sqrt{2}}\right) \tag{1}$$

The tension ε inside an element can then be simplified as (2):

$$\varepsilon = {}^{\gamma}/_{90°} \tag{2}$$

The shear stress τ results from the shear force F_S and the sheared area A. This results into (3):

$$\tau = \frac{F_S}{A} = \frac{F}{2 \cdot l \cdot t \cdot \cos\left(45° - \frac{\gamma}{2}\right)} \tag{3}$$

In (3) l is the side length and t the thickness of the specimen.

To calibrate a material model for the shear behavior, the picture frame test itself is remodeled in LS-DYNA®. For this simulation, the original size of the specimen and the picture frame is rebuilt and the simulation reproduces the movement of the frame. The result of the simulation can be evaluated in the same way as the real experiment.

The comparison of the resulting specimen in experiment and simulation shows an almost identical shape (see Figure 6). The wrinkling of the material in the corners in the direction of the cross head movement is represented very well. The material in the other two corners shows the same stretching in both cases. The approach taken here therefore compensates for the fact that the shear test does not and cannot apply a “pure shear” deformation condition to the organosheet specimen.

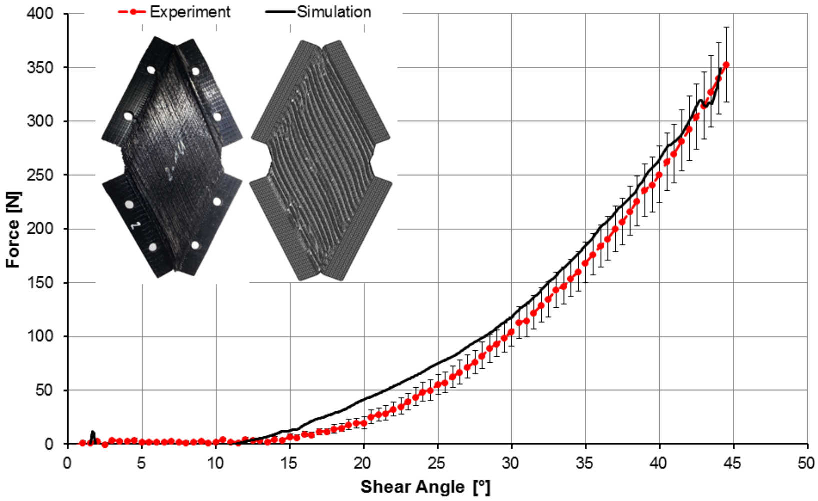

Figure 6. Comparison between experiment and simulation of the picture frame teston a 5-layered organosheet.

4. Simulation example

The functionality of the model will be demonstrated on a simple dome forming model, shown in Figure 7. Here a 5-layered organosheet sample with a size of 250x250 mm is positioned between a die and a binder tool. The toolings are so positioned that wrinkling effects are avoided. The movement of the punch then forms the dome geometry.

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Table 1 gives an overview regarding the utilized computer ressources. The calculation time mentioned here refers to a speed up factor for the punch velocity of 10. No other methods to speed up the simulation, such as mass or time step scaling etc., have been used here.

Table 1. Computer resources used to run the 5-layered organosheet dome forming simulation

Operating system	Windows 7 Enterprise (64-Bit)
Processor	Intel® Core^{TM} i7-4930K CPU @ 3.40 GHz (12 cores
Memory (RAM)	64.0 GB
FEM-Solver	LS-DYNA® smp s 7.1.2
Calculation Time	3 hours 55 minutes 32 seconds

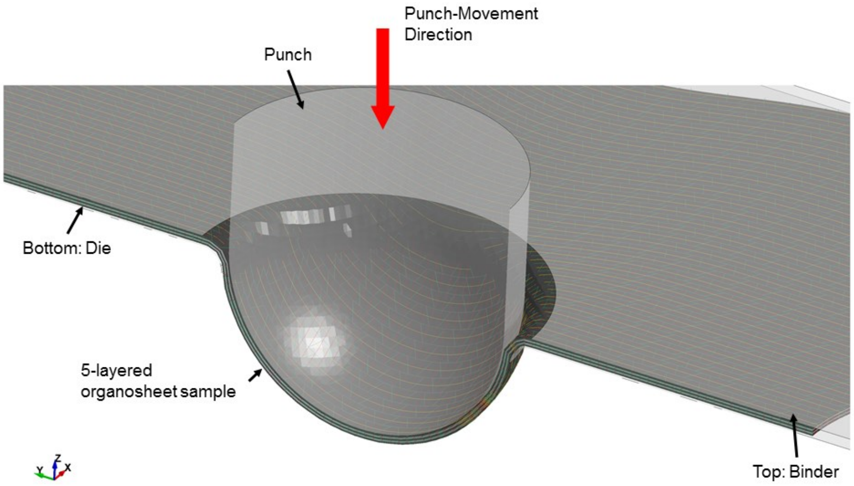

Figure 7. Cross section of dome-forming simulation with a multi-layered organosheet sample

The contour pattern, shown in Figure 8 on the left side, shows different pull-in distances (red arrows) on the edges of the sample. This is dependent on the lay-up structure of the "Drapfix" fabric in 0° and 90° as the size of the yarns in the two directions in a single layer of the material are different and the pattern formed by the auxiliary yarns shows a different connection geometry to the yarns in different directions. That is the reason why the smaller yarns in 90° orientation shows a smaller pull-in effect. Also the effective plastic strain on the right side shows a different pattern in the two directions giving a very plausible result.

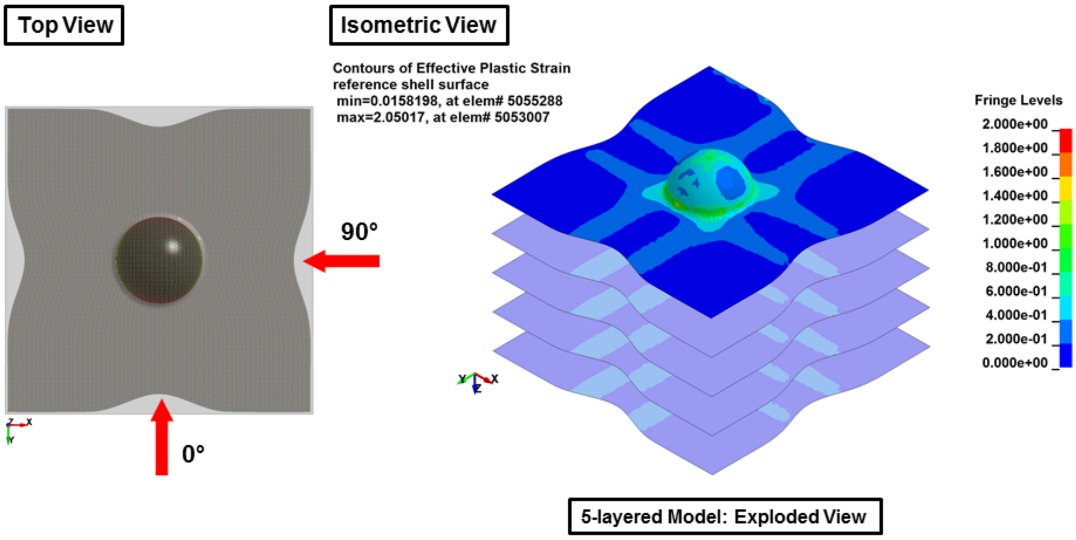

Figure 8. Result dome forming simulation: Top View (left), Contours of effective plastic strain (right)

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5. Summary

This paper shows the setup of a simulation modeling method, that can be used to represent any textile reinforcement structure that could arise in the thermoforming process. An older solution was already capable of a very accurate prediction of fiber orientations for weave structures in a non-isothermal forming simulation. But because of the used material models and the restriction in possible setup geometries, it was necessary to make some modification to open this hybrid modeling technique to a much wider field of now available reinforcement structures. On the example of a “DRAPFIX Carbon Highly Drapable Non-Crimp Fabric” produced by “Gerster TechTex” the setup and the potential of this method has been demonstrated. One of the most important parts of every process simulation is the material characterization. As an example, it has been shown that the picture frame test can be used to characterize the shear behavior of a non-woven layered organosheet. The resulting shear stress vs. shear strain curve is a direct input into the material model used in the simulation. The dome-forming simulation shows the possibilities of the developed hybrid simulation method. Even with a full description of all organosheet layers, it is possible to achieve a good prediction of the mechanical behavior of the material also within a reasonable calculation time.

Acknowledgments

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