Modeling non-isothermal thermoforming of fabric-reinforced thermoplastic composites

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Abstract

The correct modeling of the sheet forming of fabric reinforced thermoplastic composites, so called organosheets, is still a challenge. In the past, it was only possible to predict accurately and efficiently the fiber orientation during the draping of dry reinforcement or constant temperature organosheet (reinforcement and molten polymer) using the explicit FEM-Software LS-DYNA®. The developed model was only able to simulate the right material behavior for a purely isothermal process. With several enhancements, it is now possible to implement temperature dependent shear and bending stiffness of the thermoplastic material into the model. This allows the modeling of a non-isothermal forming process. The method is based on a "hybrid unit-cell" modeling approach which uses a combination of shell and beam elements. With the new extended modeling approach, is it possible to predict fiber orientation and occurring defects, such as wrinkling, even more accurately. Many defects which occur during thermoforming are caused and can even be controlled by temperature changes due to the ongoing tool contact which can now be considered in the calculation. The verification of the developed modeling approach is carried out through the simulation of material characterization tests (shear and bending behavior) for a commonly used commercially available organosheet material TEPEX® dynalite 102. *The material model parameters derived from the verification models are used to simulate the forming behavior of a novel automotive crash element geometry.*

1 Introduction

In the automotive and aerospace industries, woven fabrics are one of the most widely used of all the textile reinforcement structures in polymer based fiber reinforced composite materials. Especially in the automotive sector, continuous fiber reinforced thermoplastic sheet material, or so called organosheets, are beginning to be used more frequently. The high stiffness, strength and energy absorption capacity with a low density qualifies this material for lightweight constructions. When using an organosheet for a lightweight application, the prediction of the fiber orientation inside the part is a very important task. During manufacturing, the fiber orientation has a great influence on the drapability and the formation of wrinkling defects in the component. In the resulting part, the fiber orientation influences the local and overall mechanical properties.

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, the 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. One disadvantage of this modeling method is the restriction that only dry fabric draping or isothermal organosheet thermoforming can be modeled. It is therefore not able to simulate a realistic fully non-isothermal forming process.
A standard organosheet thermoforming procedure is a non-isothermal process since the organosheet is drastically cooled down upon contact with the tooling. The viscosity of the thermoplastic resin is highly dependent on the temperature, especially when it comes near to or goes below the melting temperature. Therefore these thermal effects have to be taken into account when trying to predict fiber orientation or any possible defects. This work will show how the existing method developed in [1] can be extended to model a fully non-isothermal forming process.

Before an actual simulation of the forming process on the part level can be carried out it is necessary to characterize the material behavior. During the draping process, the textile reinforcement will begin to shear. The shear behavior of the fabric in combination with the thermoplastic resin will change with temperature. For the characterization, a horizontal picture frame test is carried out. In this test, the specimen is heated to a constant temperature in an expected forming temperature range and then deformed in shear.

Independently of the shearing, bending of the organosheet will also occur. Within the forming temperature range, the bending behavior is mostly defined by the fabric structure and only minimally influenced by the temperature and strain rate dependency of the polymer. One method for an efficient determination of bending stiffness is a simple three-point bending test performed at elevated temperature inside a heating chamber.

Another interesting influence on the manufacturing process can be given by the friction between the tooling and the organosheet. This tool-ply friction is influenced by the normal force on the sheet and the velocity of the sheet relative to the tooling surface. A glue effect between the molten polymer and the tool can also influence the movement of the organosheet. For the simulation, this additional effect can firstly be simplified as a Coulomb friction influence. This work will show a friction test which can be used to characterize the friction coefficient using modified scratch testing equipment.

2 Modeling of non-isothermal Thermoforming

2.1 Macro scale Unit cell model

For an accurate modeling of the thermoforming manufacturing process of an organosheet, the shear and bending behavior of the fabric reinforcement in combination with the polymer resin has to be taken into consideration. For this approach, a macro scale model based on a unit cell that is represented by shell and beam elements which share specific common nodes is created. Hereby, the beam elements represent the bending stiffness of the composite material, which is mostly defined by the properties and the direction of the fabric. That is why the beam elements lie in the fiber direction and represent the actual yarns of the fabric. Fig.1: shows that crossing beam elements are connected with the four nodes of every second shell element and have no common node to each other. This arrangement guarantees a free relative sliding movement of the beams during shearing of the organosheet. The shearing stiffness of the composite is mostly represented by the properties of the resin. For this purpose, shell elements are defined to take this effect into consideration.

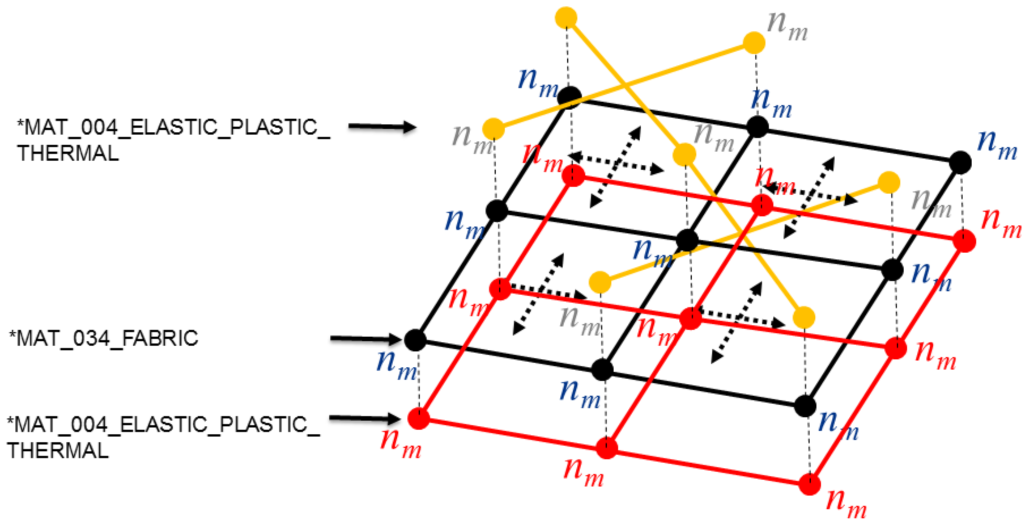


Fig.1: Finite element mesh unit cell used to represent the forming behavior of a thermoplastic organosheet material

A shearing of the composite leads to a rotation of the beams and a tension/compression of the shell elements. This effect avoids great 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 represented by the tensile stiffness of the shells.

2.2 Yarns

A beam element formulation with a simple elastic plastic material model (**`*MAT_004_ELASTIC_PLASTIC_THERMAL`**) is used to represent the longitudinal behavior of the yarns. It is possible to derive the tensile modulus and the bending stiffness by using a three point bending test or a cantilever test [3]. Some customized methods have also been developed and have recently appeared [4]. Because the overall time step is dependent on the tensile modulus, it is possible to use the cross-sectional area of the beams to reduce the tensile modulus but achieve the same stiffness as before. This helps to reduce the necessary calculation times when simulating large full scale parts.

2.3 Resin

The material law for the shear stiffness response of the organosheet can be simplified into a tri-linear stress-strain curve as shown in Fig.2:.

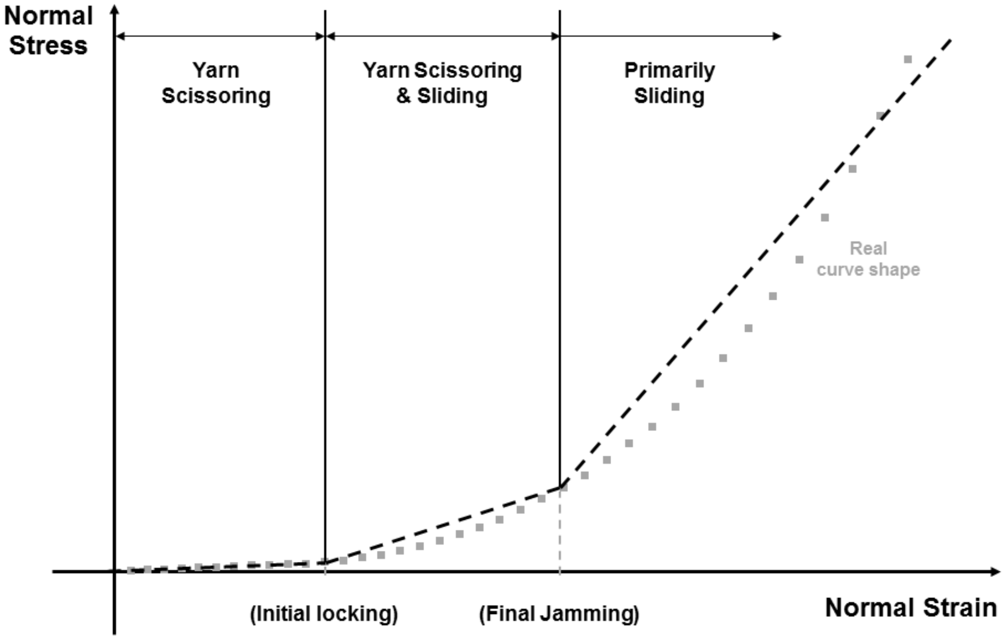


Fig.2: Tri-linear normal stress-strain relationship represented by shell elements [2]

It is possible to divide the actual shear stress versus shear strain curve into three simplified linear sections that represent the different interacting mechanics of yarn scissoring and sliding, in the fabric material when shearing. The transitions of one to another section are defined by the initial and locking jamming angle. When a molten thermoplastic resin is present, the stress will increase in dependence of the viscosity of the polymer.

This information can be implemented in LS-DYNA® by using the airbag fabric material model (**`*MAT_034_FABRIC`**). The required information can be extracted by performing a picture frame test and then implemented as tensile stress strain curves in the parameters LCA and LCB of the material card.

2.4 Non-isothermal modeling

Until now, only the requirements for isothermal modeling have been shown. But as mentioned before, thermoforming is a highly non-isothermal process with great influence from the viscosity of the polymer resin. So it is of great importance to implement the non-isothermal effects on the stiffness of the material into the modelling method. For this purpose a second shell layer that shares common nodes with the first layer is included into the unit cell, as shown in Fig.1:. It is important to note that the layer is formulated by defining a thermal elastic material model, such as **`*MAT_004_ELASTIC_PLASTIC_THERMAL`**. The tensile modulus of this layer can be used as a scaling factor to represent stiffness changes with temperature.

3 Material Characterization of Organosheets

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. As an example, the material characterization of a commercial available TEPEX® dynalite material is shown here.

3.1 Shear Behavior: Picture Frame Test

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. Fig.3: 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.

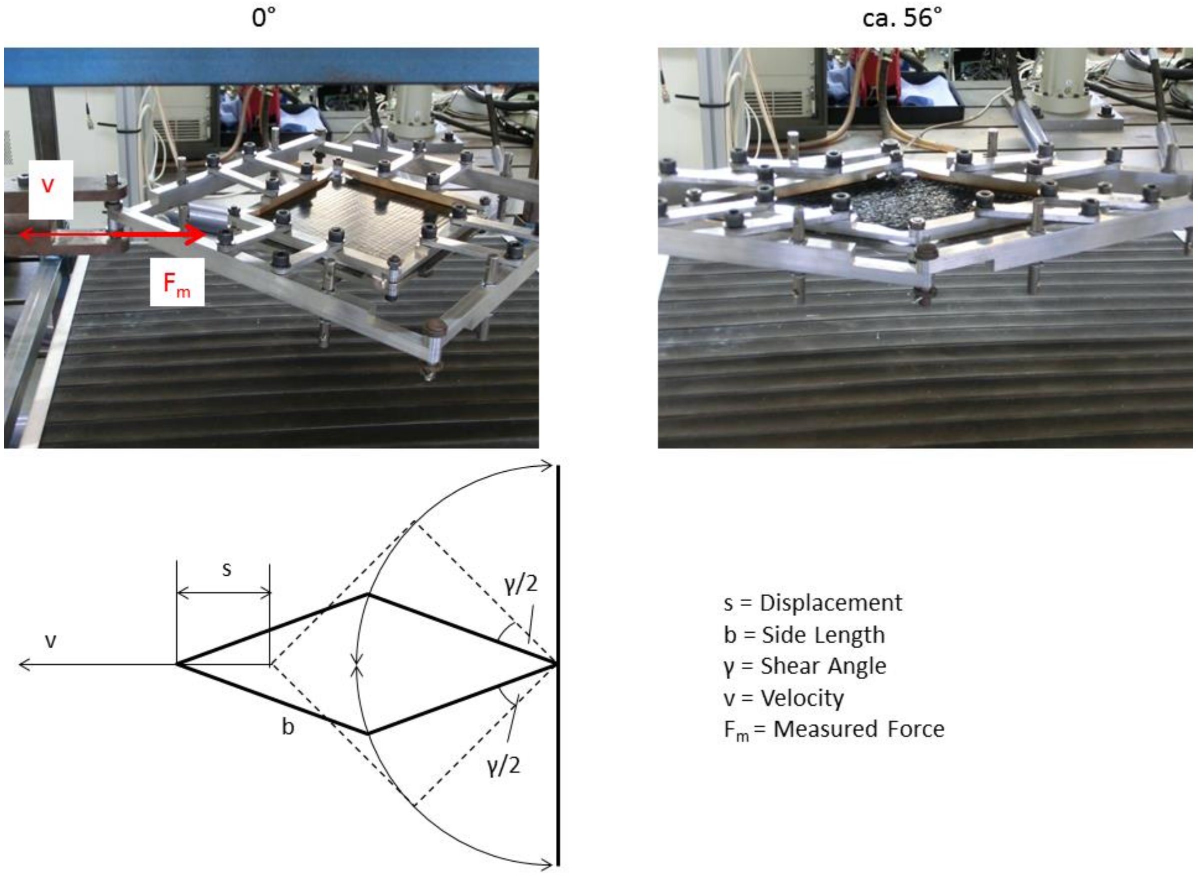


Fig.3: Horizontal Picture Frame test (top: experimental, bottom: schematic)

The direct output of this test is a force versus displacement curve (F_m-s). This F_m-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):

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

In (3) l is the side length and t the thickness of the specimen. Fig.4:shows resulting curves at two different testing temperatures for the glass fiber PA 6 based TEPEX® material. At lower temperature, the higher viscosity of the polymer results in the higher shear stress.

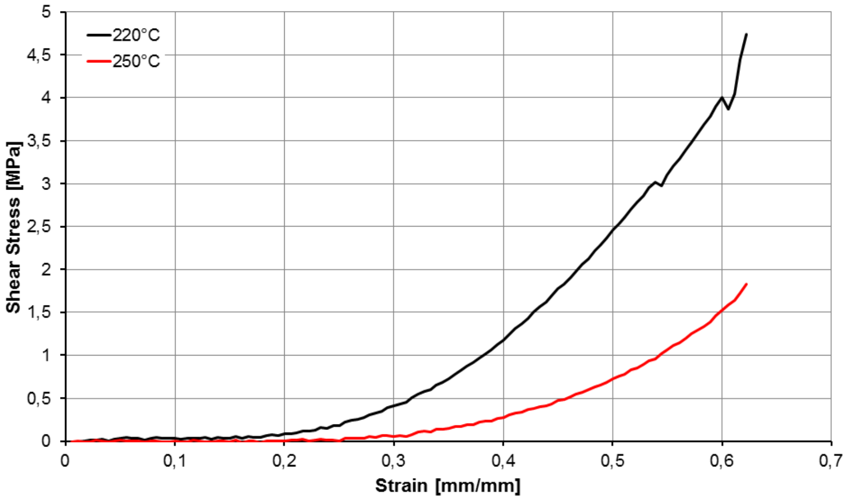


Fig.4: Example shear stress-strain curve at different temperatures for TEPEX® dynalite 102 RG600

To calibrate a material model for this 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 stress-strain curve for 250°C serves in this example as the original input curve for the material model. To compensate for the nonexistence of some real physical effects in the material model a short fitting process is necessary. The outcome of this calibration process is shown in Fig.5:. The simulated shear response for a temperature of 250°C fits perfectly onto the experimental result. By using the stiffness of the second shell layer it was possible to find a reasonable approximation for the lower temperature of 220°C.

The comparison of the resulting specimen in experiment and simulation shows an almost identical shape. 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.

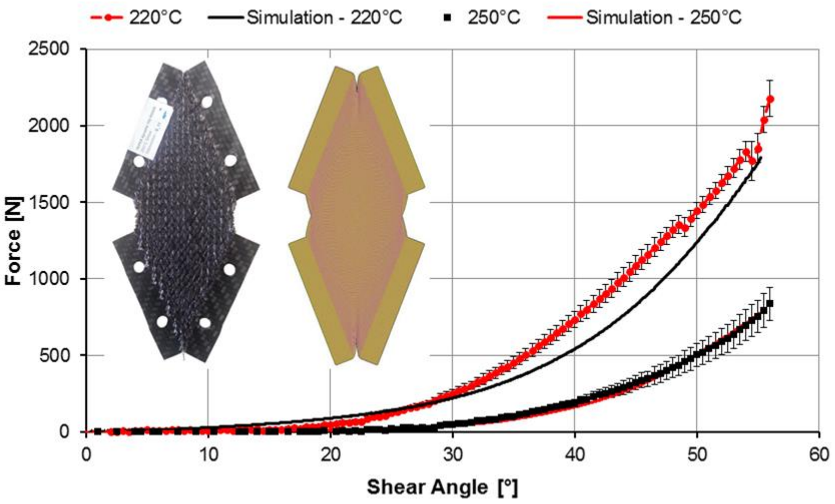
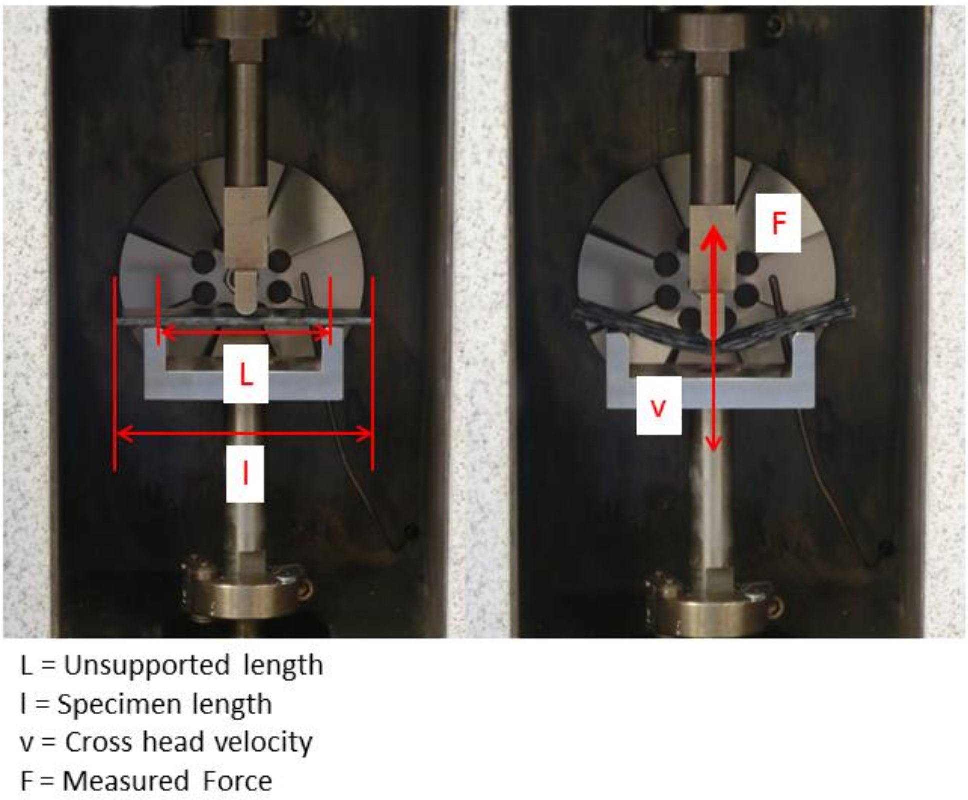


Fig.5: Comparison between experiment and simulation of the picture frame test using the example of TEPEX® dynalite 102 RG600

3.2 Bending Behavior: Three point bending test

As an example of how to characterize the bending stiffness of an organosheet material at elevated temperature, a three point bending test procedure will be demonstrated here. This simple test is based on the description of a bending test using the DIN EN ISO 14125 standard for fiber reinforced materials. It is important to note that unlike the usual test, the organosheet material's response to bending at the test temperatures results in very low forces. A reason for this is that in the molten state bending is almost completely absorbed by the fabric reinforcement.



L = Unsupported length
l = Specimen length
v = Cross head velocity
F = Measured Force

Fig.6: Three point bending test inside a heating chamber at elevated temperature

The goal of this test is to determine the bending stiffness as a product of bending modulus E_B and the area moment of inertia I.

$$I = \frac{b \cdot h^3}{12} \tag{4}$$

Equation (4) calculates the area moment of inertia for a rectangular cross section where b is the width of the specimen and h the thickness. The bending modulus can be found as the slope of a bending stress σ_b versus the outer fiber strain ε_f curve.

$$\varepsilon_f = \frac{6 \cdot s \cdot h}{L^2} \tag{5}$$

$$\sigma_f = \frac{3 \cdot F \cdot L}{2 \cdot b \cdot h^2} \tag{6}$$

Note that in the simulation the bending stiffness of the specimen is the sum of the bending stiffness of all beams in the bending direction. In the equation shown in Fig.7: I_i uses Equation (4) and assumes a rectangular cross section of the single beams (width b and thickness h of the beam). The comparison given in Fig.8: shows a good approximation of the experimental and the simulated curves.

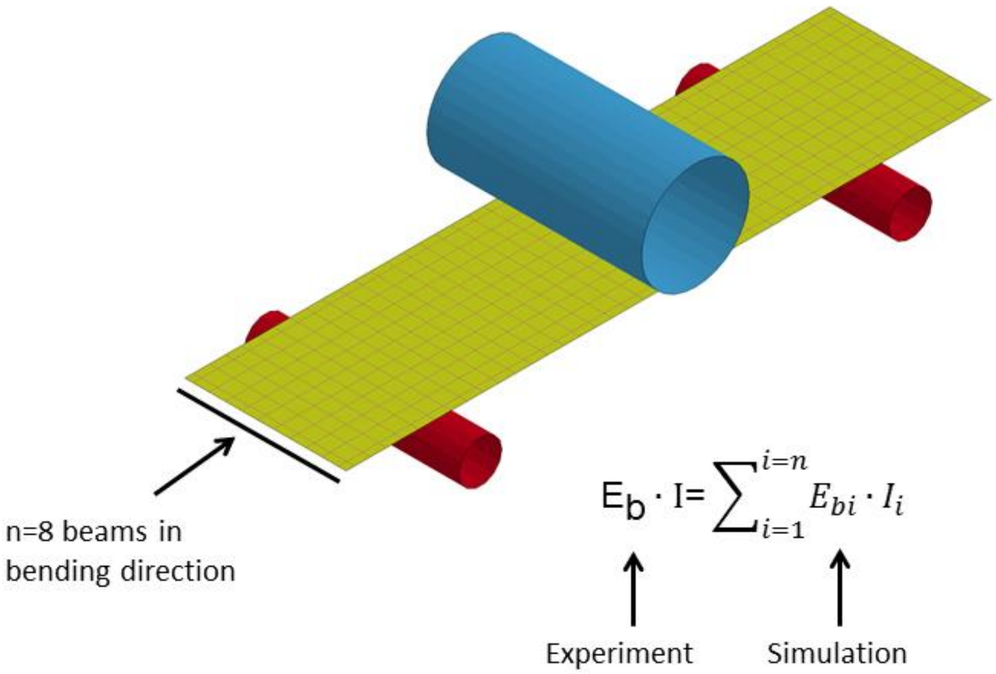


Fig.7: Calculation of simulative bending stiffness from the experimental bending stiffness

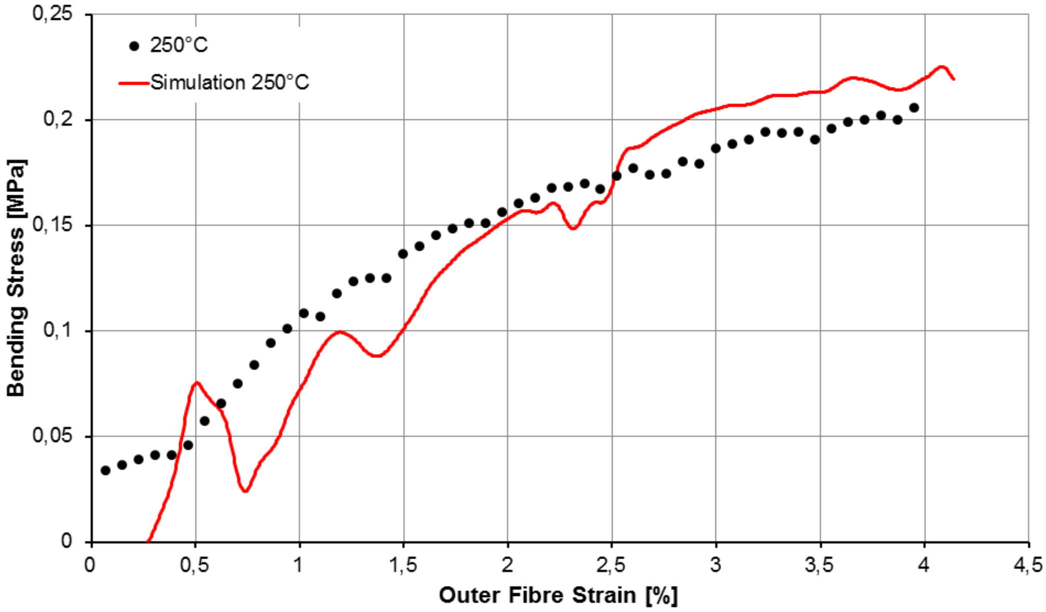
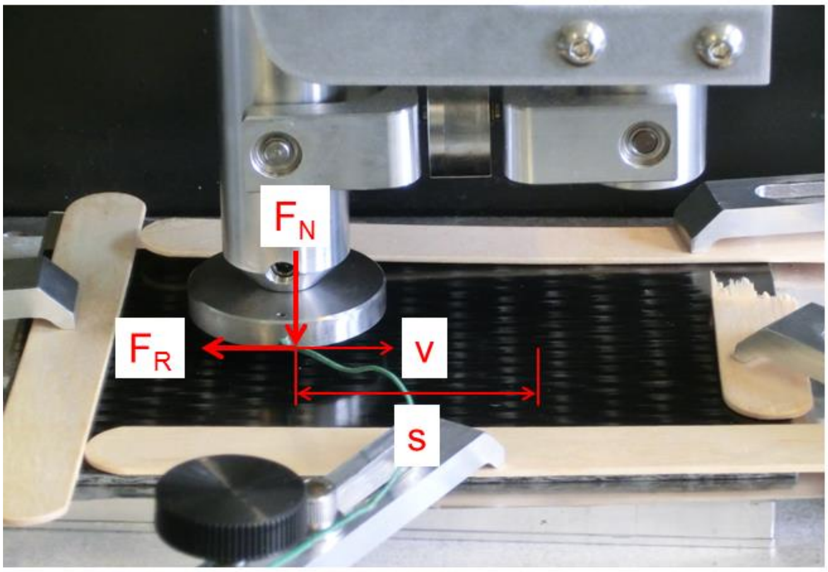


Fig.8: Comparison of three point bending curves from experiment and simulation using the example of TEPEX® dynalite 102 RG600

3.3 Tool-Ply friction: Friction test

To determine the friction coefficient between tool and organosheet modified scratch testing equipment is used (Fig.9:). Here the organosheet is first heated to the desired test temperature using a heating plate on its underside. A flat blank steel tool (whose surface temperature can also be set) with a prescribed surface roughness and a defined normal force F_N is moved over the surface of the sheet. By measuring the resulting friction force F_R, the friction coefficient μ_R can be determined (7).



- v = Tool velocity
- s = Distance
- F_N = Normal force
- F_R = Friction force

Fig.9: Elevated temperature tool-ply friction test performed using modified scratch testing equipment

$$\mu_R = {}^{F_R}/_{F_N} \tag{7}$$

This test is performed in the two directions of the fabric yarns (0° and 90°) and a diagonal direction (45°) (Fig.10:). Note that the example results shown here are for TEPEX® dynalite 104.

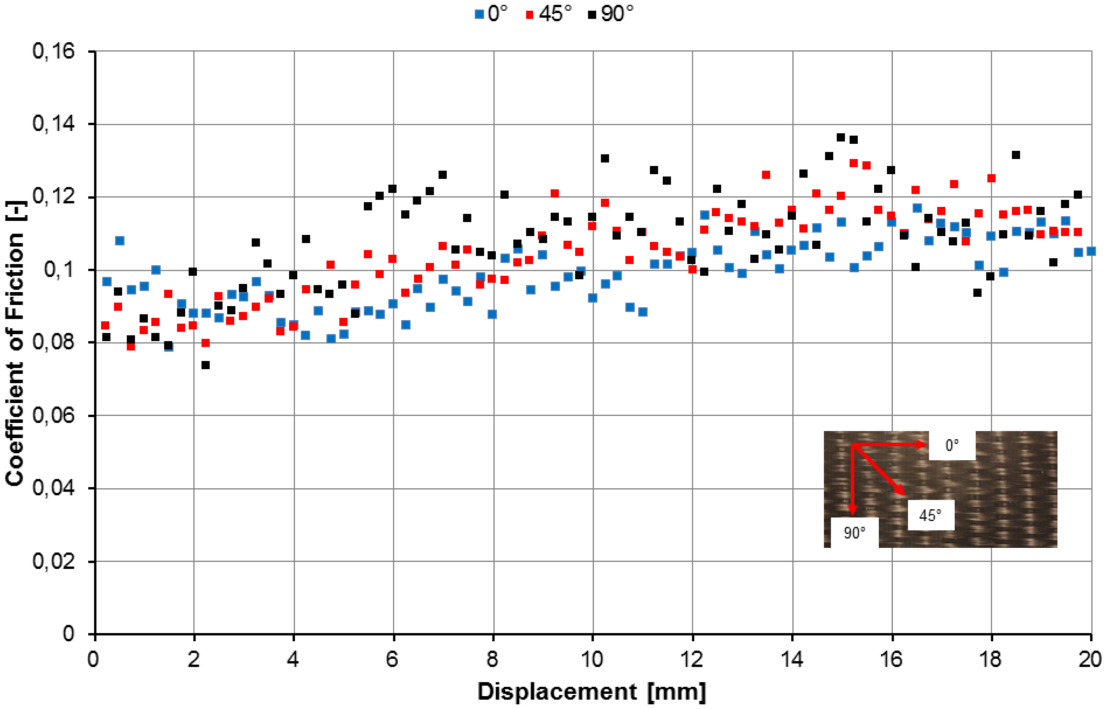


Fig.10: Coefficient of friction versus displacement for tool-ply friction in three directions (0°, 45°, 90°) at a material temperature of 190°C and friction probe surface temperature of 80°C (TEPEX® dynalite 104)

It can be seen that the coefficient of friction for all three cases float around a value of 0,1 over the whole test displacement. As a conclusion, a typical coefficient of friction value of 0,1 can be chosen as a first approximation for the contact definition keycards for the tool-ply friction for these types of materials.

4 Forming simulation example: “Crash Muffin”

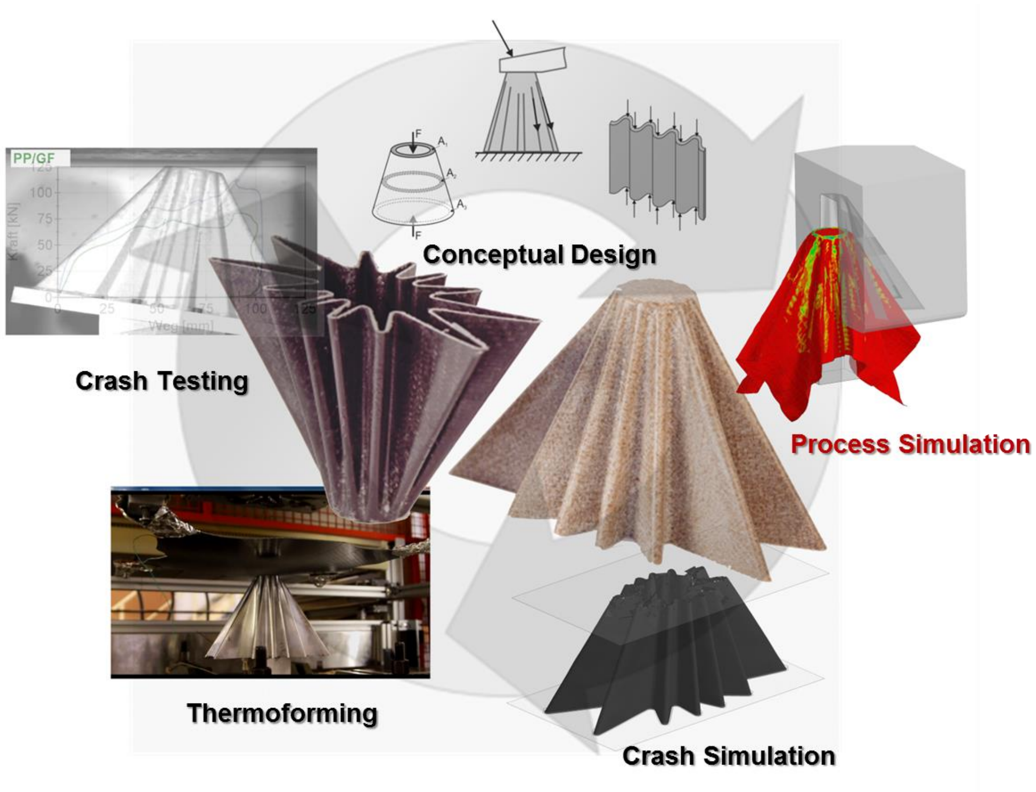
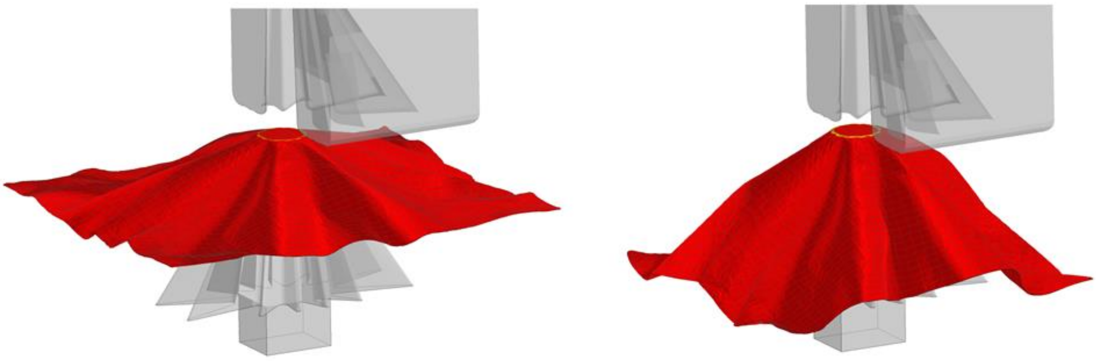


Fig.11: Process Simulation as part of the complete design cycle of the crash muffin

The Institute for Composite Materials (IVW) together with Stadco Saarlouis Ltd. & Co. KG have developed a new crash absorber consisting of a glass fiber reinforced thermoplastic composite. This crash absorber is an excellent example for the usage of the high energy absorption capacity and lightweight properties of an organosheet material in the automotive industry.[6]
Fig.11: shows the importance of process simulation as a part of the complete design process. The process simulation models the thermoforming procedure and gives as results the draped geometry, the fiber orientation, stress and strain information and temperature development during forming of the part. Some of this information is then mapped into a structural mesh and a crash simulation of the resulting crash absorber is performed.

After fulfilling the complete material characterization process, the developed unit cell (which was shown in Fig. 1) is tessellated to a square sheet the size of the blank material (Fig.12:). At the initial temperature, the stiffness of the organosheet is very low. Therefore, the sheet only falls onto the bottom tool and is pre-draped over the tool by the effects of gravity. The actual forming process will begin when the top tool comes into contact. The temperature fringe shown in Fig.12: shows clearly that the material temperature drops upon initial contact with the bottom tool before the actual tooling is completely closed. This effect shows why it is very important to implement non-isothermal effects into the model.



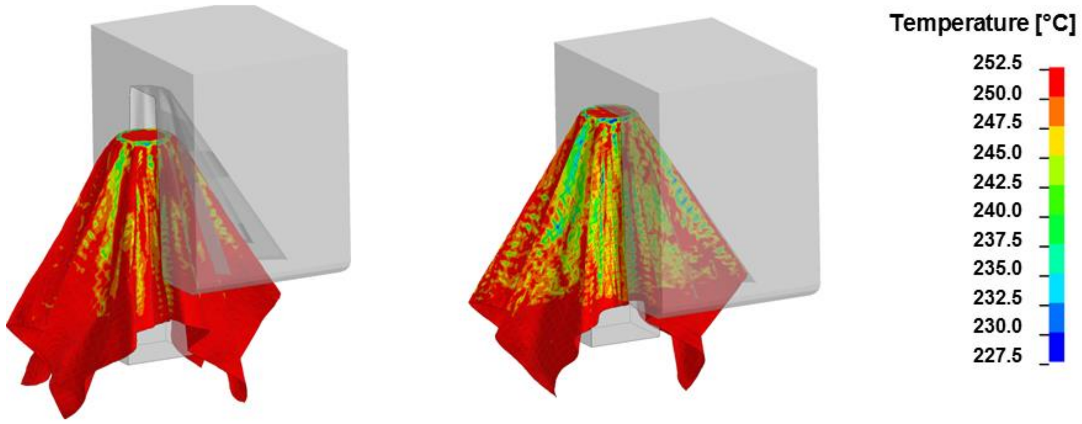


Fig.12: Temperature contours of non-isothermal thermoforming process of a crash absorber performed in LS-DYNA®

5 Summary

This paper combines a developed modeling method and the experimental material characterization to represent the mechanical properties of a fiber reinforced composite material that come into play during the thermoforming process. The modeling method is based on a repeating macro scale unit cell represented using a combination of beam and shell elements. By applying a second layer of shell elements, it was possible to scale the shear stiffness response with temperature. This is a very important feature of the model as the thermoforming process is a strongly non-isothermal procedure.

The mechanical properties that come into consideration for thermoforming are mostly the shear and the bending behavior of the organosheet. These parameters can be very well characterized by elevated temperature picture frame and three point bending tests. To calibrate the material models these two characterization tests are remodeled in LS-DYNA® and show a very good approximation to the real experimental results. For some cases of tooling it could also be interesting to have knowledge about the tool-ply friction. To characterize the coefficient of friction,, a friction test performed by using modified scratch testing equipment has been shown. The tool is represented by a flat disc shaped probe having the same surface roughness as the actual steel tool. Here it was shown that the coefficient of friction is in all moving directions almost the same.

To highlight the importance of the material characterization and the following process simulation as a part of a complete design circle, an example of a newly developed crash absorber was shown. In this example, it becomes clear why the implementation of non-isothermal effects is a necessary step on the way to achieving accurate thermoplastic organosheet thermoforming simulation results.

6 Literature

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