Drape Simulation: Textile Material Model for Correct Property Reproduction to Improve the Preform Development Process of Fiber-Reinforced Structures.

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Abstract

The deformation behavior of textiles requires unconventional assumptions for successful drape simulation. The special performances in shearing, stretching and bending were implemented in LS-DYNA® with user friendly subroutines. The general deformation behavior was considered by particular strain rates. A fully nonlinear and orthotropic material model was implemented to reproduce the character of the deformation mechanisms, shearing and stretching. The nearly negligible bending resistance was realized within a laminate formulation, which allows to set up an independent bending performance. Additional features such as pseudo-plastic shearing deformation or bending rigidity controlled by the bending side and direction was included. The simulation model was used to carry out complex drape simulations. A special afford was made in dealing with textile pre-treatments, which have local effects on the deformation behavior. Fixations affect the drapability and improve the handling of textile preforms. The material model and consequently the drape simulation are tools for a complex development process for textile preforms. The complete virtual development chain can lead from the textile good, with its special mechanical behavior, over the caused localization for special pre-treatment zones to a fully shaped and self-stable preform for complex shaped fiber-reinforced structures. An approach for composing this development chain will be introduced and presented.

Introduction

Composites made of reinforcing fibers and plastic matrixes are used increasingly for highly stressed structural parts. The design and the use of the material distanced itself from simple shaped parts and develops to the use in high performance parts. Mostly technical textiles like glass or carbon woven are chosen for adjustable reinforcement because of their enormous strength and favorable lightweight character.

The process of composite manufacturing often includes a textile preforming step. The textile good is formed into a preform which will become a structural part after the process of matrix consolidation. To improve the manufacturing process with regard to serial production the preform process has to be improved. Many textiles with a good drapability have a very unstable behavior. This leads to quality problems and uncertainties about the reinforcement orientation. The fiber orientation is the most important characteristic for the structural stiffness and load bearing capacity. Little deviations of the reinforcement orientation to the load direction lead to a significant loss of strength.

For structural lightweight design the fiber orientation after the draping is of higher interest. Insecurities in fiber orientation can only be compensated by expensive experiments or additional reinforcing fibers. Pre-trials can become very time- and cost expensive and additional fiber material leads to a worse lightweight character.

To improve the developing process of preforming a material model was implemented in LS-DYNA. It reproduces the classic deformation mechanisms of textiles. The developed model allows the prediction of fiber orientation during and after draping and is able to generate a first near net shaped pre-cut.

Characteristics of textile mechanical behavior – Requirements on a material model

The mechanical behavior of textiles can be characterized on different levels of consideration. The macroscopic behavior is characterized through the mesoscopic assembly. A structure homogenization is described and used very often. For complex simulations, such as drape simulations, a homogenized macroscopic approach is preferable because of the very efficient shell elements which can be used.

For describing the deformation of textiles [1] introduced the classic deformation mechanisms. These are extension/stretching, shearing and bending as shown in Table 1. To implement a successful material model for textiles these mechanisms and their nonlinear character have to be considered.

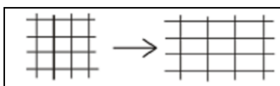
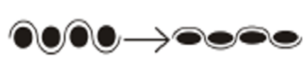
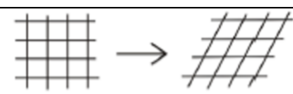
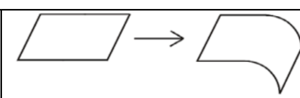
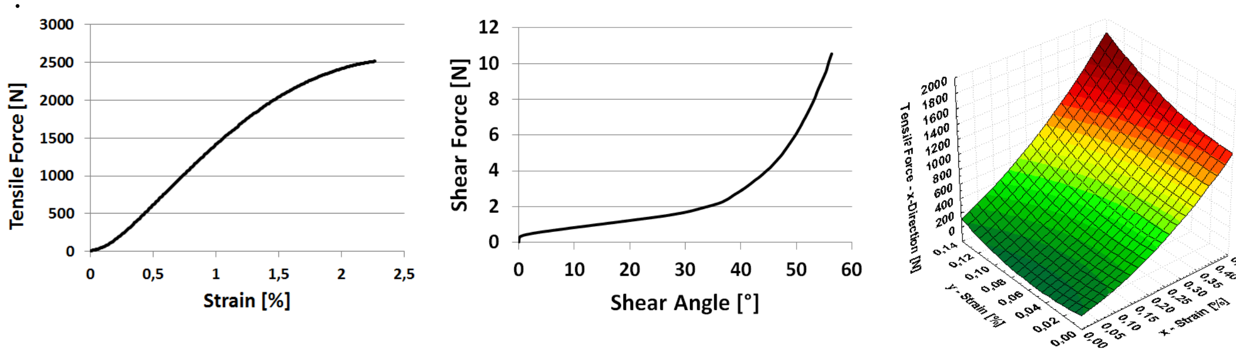
			
extension	stretching	shearing	bending

Table 1 Characteristic deformation mechanisms of textiles [1]

Ondulations of the reinforcing fibers, which occur in dependence of the fiber formation, lead to a nonlinear behavior in membrane tension stiffness. Membrane tensile load in reinforcement direction leads to a stretching of the yarns. The stiffness increases until the ondulations are compensated. The typical tensile behavior of wovens is shown in Figure 1a). Furthermore the strain behavior in one direction of crossed yarn systems is affected by the other direction. The tensile behavior of one direction depends on the tensile force in the other direction. The relationship can be determined by biaxial tension tests and is shown for a woven in one direction in Figure 1c).

The most important textile deformation mechanism for draping is shearing. The resistance against a change of the shear angle is mostly very little; a large in-plane deformation is possible. The shear modulus is an important factor for drapability. Its character is strongly nonlinear for almost all textiles. The resistance against shearing is controlled by internal yarn-yarn friction. Above a critical shear angle γ_{crit} the shear modulus increases significantly because of internal yarn contact or distorted loop threads. The critical shear angel is often pointed as the angle where first wrinkles occur [2]. A typical shear character is plotted in Figure 1b). The shear modulus can also be expressed in dependence of membrane tensile strain as $G_{xy}(\gamma_{xy}, \varepsilon_x, \varepsilon_y)$.



a) Tensile force vs. strain b) Shear force vs. shear angle c) $F_x(\varepsilon_x, \varepsilon_y)$

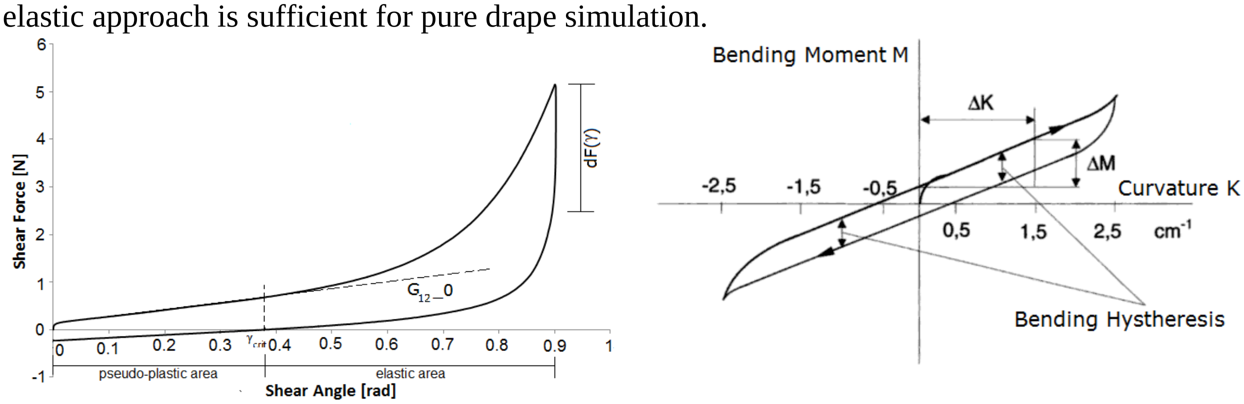
Fabric – plain weave, glass fiber 900 tex

Figure 1 Tensile- and shear properties of textiles

Bending is the only spatial deformation mechanism in textiles. The resistance against textile bending results from the yarn characteristics and the textile construction. The macroscopic behavior can only hardly be determined theoretically. The bending stiffness of textiles is mostly very low and so it is often neglected [3]. A special problem in developing a material model is the decoupling of bending- and membrane stiffness. For this problem some approaches were introduced. A special problem of unsymmetrical textile bending behavior is the different bending stiffness in dependence of the bending side and direction.

Additional to the elastic behavior of textile deformation a pseudo-plastic behavior has to be mentioned. The resistance against shearing and bending does not result from elastic material behavior but from deformation of the yarn construction and internal friction. These effects are described in [4]. Shearing below the critical shear angle without a proper counterforce can be seen as irreversible and pseudo-plastic. Shearing above this angle leads to elastic deformation effects which cause reversible forming back to γ_{crit}. Reversible forming back to an orthonormal state requires an amount of energy to compose internal friction below $\gamma_{crit.}$

Textile bending leads to slip in the yarn system which leads to inelastic behavior because of internal friction. The characteristic of deformation hysteresis of shearing and bending behavior is shown in Figure 2. The pseudo-plastic behavior influences the shape and preform stability. An elastic approach is sufficient for pure drape simulation.



Shear force vs. shear angle hysteresis Bending moment vs. curvature hysteresis [5]

Figure 2 Hysteresis in bending- and shear loading

The mechanical input parameters are gained by physical examinations such as strip tension test, picture frame shearing test and the cantilever bending test.

Appropriate material models in LS-DYNA

Many material models are implemented into LS-DYNA. However, none of them fulfills all the mentioned conditions. The models that fit mostly are listed and evaluated in Table 3.

# Mat	Material name	Anisotropic	Nonlinearity
_002	_ORTHOTROPIC_ELASTIC	Anisotropic	---
_022	_COMPOSITE_DAMAGE	Orthotropic	---
_034	_FABRIC	Orthotropic	---
_040	_NONLINEAR_ORTHOTROPIC	Orthotropic	in tension
_058	_LAMINATED_COMPOSITE_FABRIC	Orthotropic	in shear
_108	_ORTHO_ELASTIC_PLASTIC	Orthotropic	---
_116	_COMPOSITE_LAYUP	Orthotropic	---
_158	_RATE_SENSITIVE_COMPOSITE	Orthotropic	in shear

Table 2 Appropriate LS-DYNA material models

As shown, none of the material models can handle nonlinear behavior in shearing and tension. User-specific integration rules in thickness direction enable adjusting of the bending behavior. These can be used for every material in LS-DYNA.

Implementation of the textile material law in LS-DYNA

For considering the deformation behavior and the special characteristics of deformation mechanisms a material model was implemented into an LS-DYNA user subroutine. The Green-Lagrange strain is used as strain rate for handling large deformations:

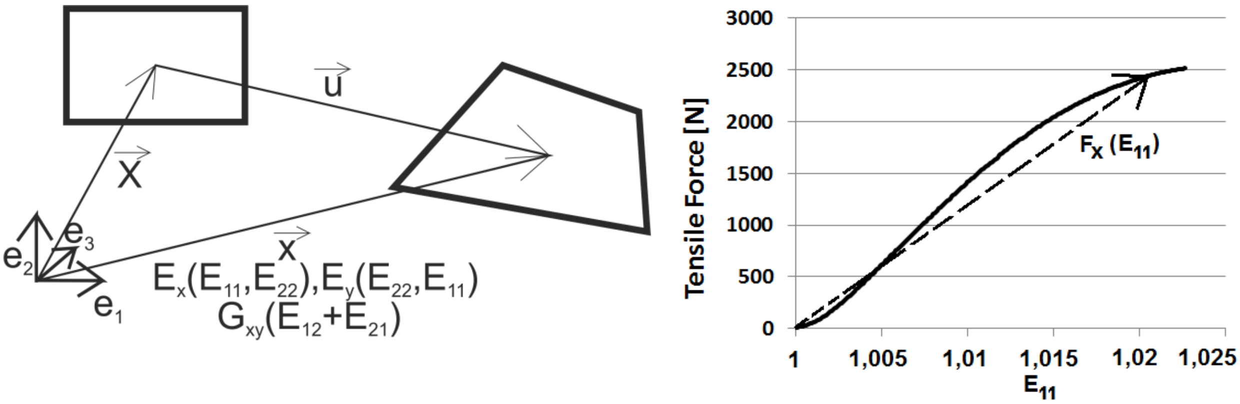
$$E_{ij} = ½ (F_{ij}^T F_{ij} – I)$$

Another advantage of Green-Lagrange strain is the fact that the strain of the current configuration refers completely to a stressless reference configuration as shown in Figure 3. A total strain can be listed for every time step. So a strain rate dependent modulus can be formulated for every time step. This modulus differs from the tangent modulus. A nonlinear formulation is very easy with a different modulus for every time step if material parameters are given in the form: $E_x(E_{11})$, $E_y(E_{22})$ and $G_{xy}(E_{12}+E_{21})$. The material parameters are included in the material tensor C_{ijkl} and affect the 2. Piola-Kirchhoff stress S_{ij}:

$$S_{ij} = C_{ijkl} : E_{ij}$$

The Young's and the shearing moduli are given in dependence of the current strain state as measured in the physical tests. The parameters are included as internal *LOAD_CURVE. The determination of this special modulus is shown in Figure 3. To realize the pseudo-plastic behavior in shearing, a load criterion is introduced. The shearing behavior is known from the picture frame test. It is mostly nonlinear and so no hardening modulus can be introduced like it is done with isotropic hardening, for example. Depending on loading or unloading, $dF_{ij} > 0$ or dF_{ij}

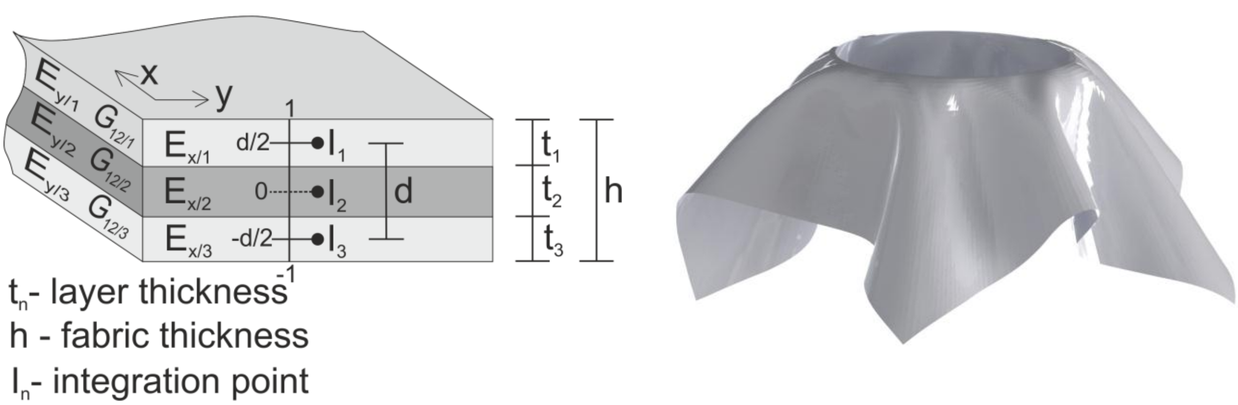
< 0 with i,j = 1,2 ; i ≠ j, a 'virtual' modulus is selected. With relieving load this one can lead to a negative modulus. With this effect the pseudo-plastic behavior below γ_{crit} is realized.



Configurations of deformation Virtual modulus

Figure 3 Configurations

Bending stiffness has to be independent of membrane stresses. Most technical reinforcement textiles are known for their high Young's modulus and their nearly negligible bending stiffness. This is considered within a user-specific integration rule in thickness direction. Formulating the mechanical behavior of one textile layer with a laminate formulation out of more than one different layer leads to a decoupled forming behavior. Different strain rate dependent Young's moduli for tensional and compressional loading lead to different bending behavior in dependence of the bending side. Different bending behavior in dependence of the bending direction is realized with an orthotropic formulation. A sketch of the laminate assembly is shown in Figure 4.



Laminate assembly Demonstration of limp bending behavior

Figure 4 Laminate assembly and limp bending behavior

The preform development chain

The development of structural parts reinforced with endless fibers is a complex process. If the lightweight potential of composites should be as high as possible the fiber orientation has to be known at the point of structural construction because reinforcing fibers can only accommodate load in direction of their orientation. Other advantages are preform designs with nearly net shaped pre-cuts. Preforms which are made of as less pre-cuts as possible are preferable. Besides that a wrinkle free forming has to be possible. The numerical drape simulation is a tool which generates proposed solutions without great practical effort.

Preforming is an interim step in composite production. Currently this step has a large amount of manual work. Handling textile preforms leads to fiber sliding and distortions and with that to a lack of quality. For a preform serial production this step hast to be fully reproducible and verifiable. Here, a prefixation of the textile structure is a good approach for improving this production step. A fixation can increase the shearing stiffness locally or globally and is able to affect the drapability towards a fiber orientation in force direction. Possibilities for such fixations are mentioned in [6].

The numerical drape simulation can determine zones with no or less shearing after forming a planar textile into a complex shape. A fixation of zones where no shearing occurs has no influence on the fiber orientation after forming. Handling, transport and storage problems are decreased. There is also the possibility to influence the fiber orientation with zone fixation. Zones of large distortions can be adjusted into areas where no shearing occurs. So influencing the fiber orientation is possible and the orientation can be adjusted to load orientation. Figure 5 shows the development chain of preform production with numerical drape simulation.

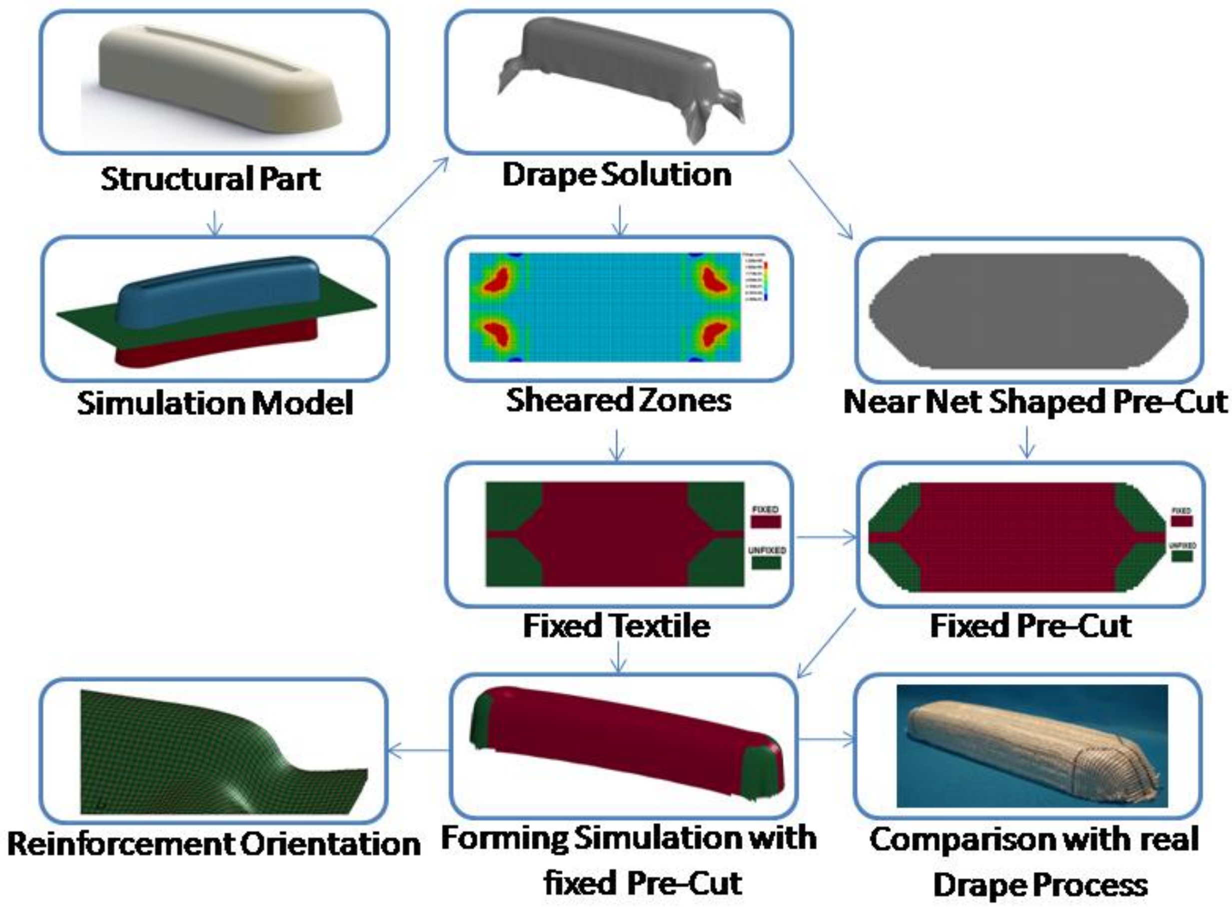


Figure 5 Process chain for preform development

Application and drape simulations

In the following an example of preform development with numerical drape simulation is introduced. A structural part and a technical reinforcement textile are given. The development process is shown in Figure 5. A fixed preform pre-cut which is kind of self-stable and able to form the shape of the structural part is the result of the development process.

A double-curved structural demonstrator which shall be reinforced with textile goods made out of endless fibers is given. It is shown in Figure 6.

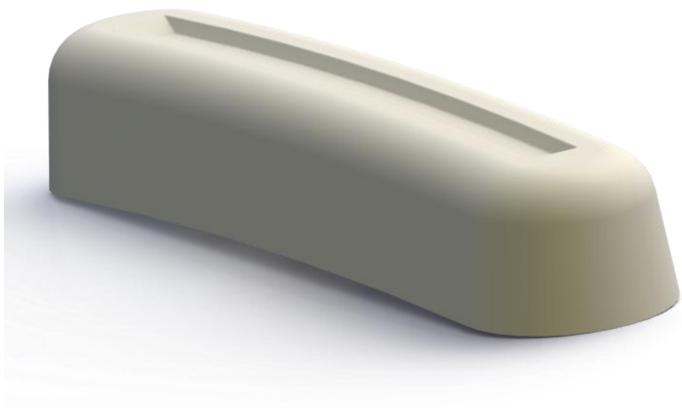
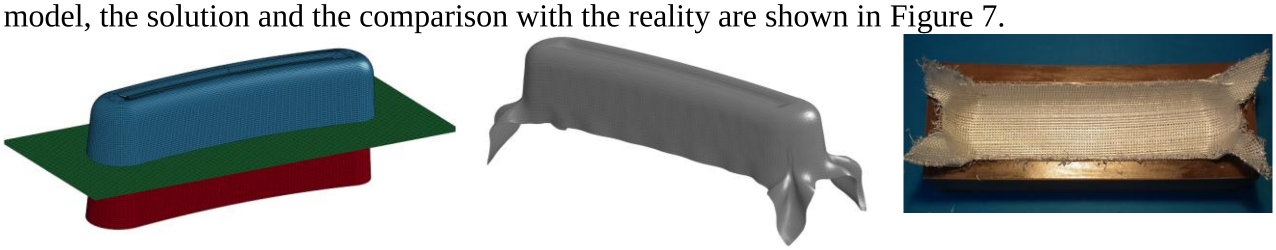


Figure 6 Structural part

According to the scheme of Figure 5 a drape simulation is performed according to the real production process. The forming is done with a negative and a positive tool. The discretized model, the solution and the comparison with the reality are shown in Figure 7.



Simulation model | Solution of drape simulation | Solution of real drape process

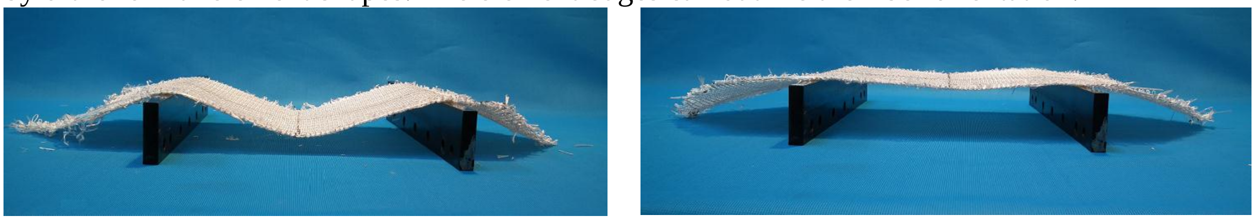
Figure 7 Solution of first drape simulation

Knowledge about fiber orientation and sheared zones while forming are solution of the drape simulation. These solutions are shown in Figure 8.

Reinforcement orientation | Near-net-shaped pre-cut | Zones of shearing

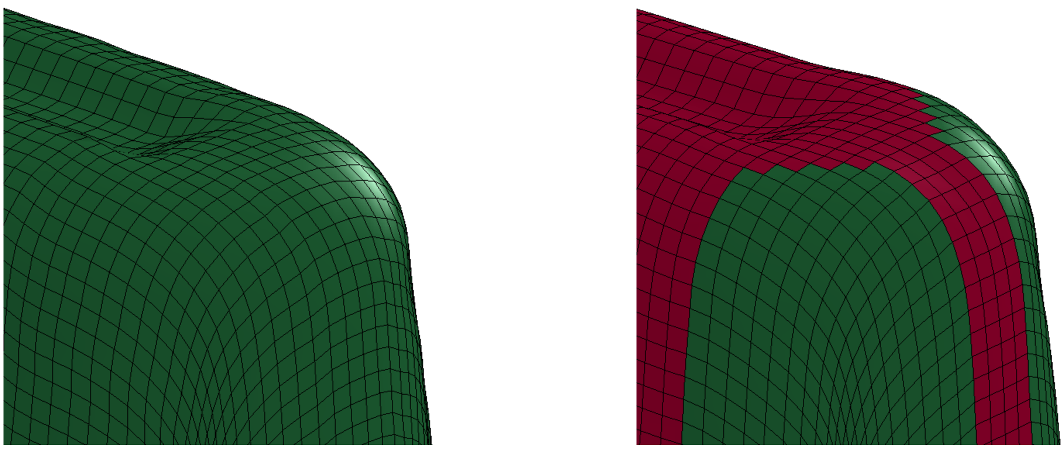
Figure 8 Near-net-shaped pre-cut and zones of shearing

Unsheared zones are preferable for a fixation which shall not affect the fiber orientation. Figure 9 shows a comparison of the unfixed and prefixed preform stability. It is clear to see that prefixation increases the preform stability. The control simulation with forming the prefixed textile shows that such a fixation has no influence on fiber orientation after draping. This is shown in Figure 10. Referring the fiber orientation of orthonormal constructed textiles happens by orthonormal element shapes. The element edges can outline the fiber orientation.



Unfixed preform Fixed preform

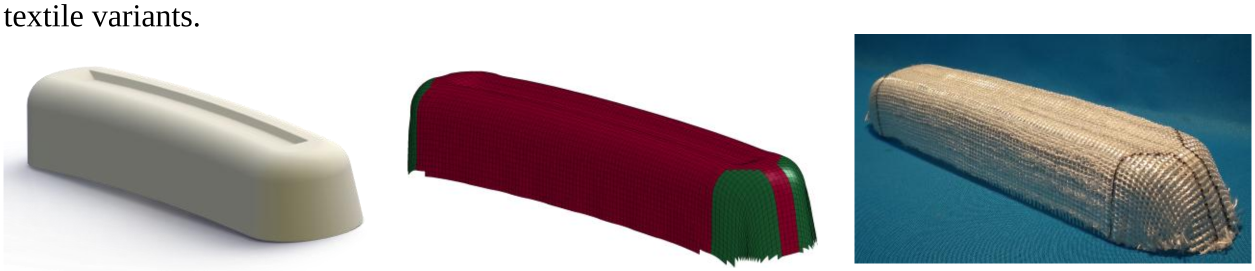
Figure 9 Comparison of preform stability (unfixed and fixed preform)



Unfixed preform Fixed preform

Figure 10 Comparison of reinforcement orientation (unfixed and fixed preform – gravitational load)

The advantages of preform fixation are clear to see. The textile good is much more self-stable than the unfixed one and with that the handling increases. Unwanted fiber distortions are prevented in the fixed areas. It was shown that the preform development can be very complex and can take a large manual effort. The numerical drape simulation can be an important tool which reduces effort, the costs of preform development and it enables the easy analysis of many textile variants.



Structural part Draped fixed preform Draped fixed preform (real)

Figure 11 Comparison of structural part and drape simulation

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