**Dieses Dokument ist eine Zweitveröffentlichung (Verlagsversion) /
This is a self-archiving document (published version):**

Oliver Döbrich, Thomas Gereke, Olaf Diestel, Sybille Krzywinski, Chokri Cherif

**Decoupling the bending behavior and the membrane properties of
finite shell elements for a correct description of the mechanical
behavior of textiles with a laminate formulation**

Erstveröffentlichung in / First published in:

Journal of industrial textiles. 2014, 44(1), S. 70 - 84 [Zugriff am: 09.08.2019]. SAGE journals.
ISSN 1530-8057.

DOI: <https://doi.org/10.1177/1528083713477442>

Diese Version ist verfügbar / This version is available on:

<https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa2-356088>

„Dieser Beitrag ist mit Zustimmung des Rechteinhabers aufgrund einer (DFGgeförderten) Allianz- bzw. Nationallizenz frei zugänglich.“

This publication is openly accessible with the permission of the copyright owner. The permission is granted within a nationwide license, supported by the German Research Foundation (abbr. in German DFG).

www.nationallizenzen.de/

Decoupling the bending behavior and the membrane properties of finite shell elements for a correct description of the mechanical behavior of textiles with a laminate formulation

2014, Vol. 44(1) 70–84

© The Author(s) 2013

Reprints and permissions:

sagepub.co.uk/journalsPermissions.nav

DOI: 10.1177/1528083713477442

jit.sagepub.com

**Oliver Döbrich, Thomas Gereke, Olaf Diestel,
Sybille Krzywinski and Chokri Cherif**

Abstract

Drape simulation of textiles is a field of research, which is known in the clothing sector for a long time. The ongoing development of high-performance composites made of textile reinforcements and matrix materials focus the interests on a serial production in many industrial sectors, such as aviation and automotive industries. Challenges occur mainly in the serial production technologies and in supplying concepts for the preform architecture and shape. Research aims on the acceleration of preform manufacturing and the reduction of expensive pretests. Numerical simulation models can help to improve the composite development chain with structure and process simulation. A special challenge in drape modeling is the bending behavior of textiles. This study introduces a novel approach for modeling single textile layers as laminates to gain a correct mechanical behavior, where all deformation mechanisms are uncoupled. The implementation in the finite element software LS-DYNA® is described. An algorithm is introduced which provides the membrane stiffness for each layer of a laminate to fit the measured cantilever bending stiffness of textiles in every bending direction and bending side. The calculated parameters for the laminate formulation result in the requested

Technische Universität Dresden, Fakultät Maschinenwesen, Dresden, Germany

Corresponding author:

Oliver Döbrich, Technische Universität Dresden, Fakultät Maschinenwesen, Dresden 01062, Germany.

Email: oliver.doebrich@tu-dresden.de

bending stiffness for the textile layer. The cantilever bending stiffness can be used directly for dimensioning the model.

Keywords

Fabrics/textiles, anisotropy, finite element analysis, laminate mechanics

Introduction

The steadily increasing usage of fiber reinforced composites requires improved production technologies to handle the increasing quality demands and to reduce the development time for novel structural parts. The manufacturing of composites with textile reinforcements typically requires the preforming of the dry textile and the subsequent resin infusion and consolidation. This preforming requires decisions on the applied textiles, on their positioning in the forming tool and, if applicable, on zones for special pre-treatments such as structural fixation with binders or stitches. The development of the preform design, the shape and zones for pretreatment with experimental design is very time-consuming and expensive. Numerical forming simulations assist with decisions in the preform development process. Forming or draping simulation is a tool in the development chain of structural composites made of reinforcing fiber materials.

The accurate prediction of wrinkles is one of the most important challenges in a drape simulation. Complex textile structures induce high deformational rates into the fabric while forming. These strains lead to local or global shearing and bending effects. Wrinkles can be seen as a local buckling problem. Boisse et al. [1] characterized the importance of a correctly described shearing and bending behavior for the propagation of wrinkles and mentioned that the formation of wrinkles reduces the internal strain energy. The increase of the shear stiffness above the critical locking angle was identified as the main reason for wrinkle forming. Boisse et al. [2] also stated that there is no direct relationship between the local shear angle and the forming of wrinkles. The bending stiffness and the interaction of shearing and bending stiffness, respectively, were accounted for the wrinkle size and the number of wrinkles formed. Thus, numerical drape simulations with membrane elements are unsatisfying for the simulation of wrinkling. Hedfi et al. [3] also indicated the necessity of a correct description of the textile bending stiffness in a numerical model for an accurate prediction of wrinkling [3].

This article introduces a finite element model, which reproduces all main deformation mechanisms of textile reinforcements and their nonlinear character. The presented approach configures the textile structure as laminate. Thus, all resulting deformation mechanisms are treated correctly and the membrane and the bending rigidities are decoupled. Furthermore, the material model considers the different bending rigidities of textiles, which depend on the bending direction and the bending side. With this novel approach of a fabric material model

considering the bending stiffness of textiles an implementation into commercial finite element analysis (FEA) software is possible.

Modeling approaches

In the clothing industry many techniques are known for predesigning precuts and laying up 2D textiles into 3D shaped forms [4–6]. Kinematic or fish-net algorithms were used. However, those approaches do not account for stresses within the structure and are not able to commit on the microscopic layout of the textiles. The alternative is a mechanical model that represents the non-linear material behavior of textile reinforcements [7–11]. Technical reinforcement textiles exhibit low bending and large tensile rigidities. This differentiates them clearly from traditional construction materials, such as metals. One of the challenges of the continuum mechanics approach is the decoupling of the bending and the membrane rigidities in the constitutive law.

In continuum mechanics approaches in the scope of the FEA the low bending stiffness was often neglected and membrane elements were used [12]. The correct prediction of wrinkling while forming is necessary for a successful fabric drape simulation. The forming of wrinkles leads to a lower level of internal energy compared to a further shearing of the fabric. Thus, the neglecting of the bending rigidities, as most FE textile models do, is inappropriate for the simulation of textile material forming.

Sriram and Wagoner [8] introduced a membrane element, which considered the bending energy. Chen et al. [11] considered this energy through the change in the angle to neighboring elements. Hamila et al. [9] proposed a triangular shell element for textile forming simulation, where internal virtual work was included in dependence of tension, shear and bending moments. The bending moment was obtained from the displacement of neighboring elements. Another solution was introduced in references [13,14] where a beam model was proposed that considered all deformation mechanisms. The bending rigidities were defined through the cross section of the beams. Jannski and Ulbricht [15] also refer to the problem of decoupling the bending and the membrane rigidities of shell elements. They presented a shell element based on the Cosserat theory, where all shell rigidities were independent of each other. However, the determination of the material input parameters from mechanical tests is challenging. A simplifying but common assumption based on the bending theory of classical materials was acquainted in references [16–19]. The Young's modulus was arranged such that the resultant bending stiffness was identical to the one measured with a mechanical cantilever bending test. Such a change of the membrane tension stiffness of technical textiles is mostly uncritical for drape simulations but insufficient for a general material model.

Another possibility of modeling the drape behavior of textile structures is a particle-based assumption [20–22]. Particles were often placed in crossover points of weft and warp yarns. An energy potential defined the interaction of the particles, which contained e.g. tension and bending energies. Particles which move out of the

plane determined the amount of the bending energy. Wagoner et al. [23] introduced an element bending group technique that allowed the membrane elements to account for bending.

Gereke et al. [24] gives a literature review dealing with the state-of-the-art in textile forming, characterizing and simulation. Multiple papers are discussed which account for several problems of drape simulation.

The bending behavior of textiles – Characteristics of fixed and unfixed structures

The bending behavior of textiles differs significantly from those of classic materials such as metals. The bending rigidity of textile structures does not directly depend on the Young's modulus and the cross section. The possible motion between the yarns yields a very small textile bending stiffness, which results from the yarn rigidity and inner frictional effects due to crossing of the yarns. The effects of friction and yarn compression cannot be determined theoretically.

In classic materials the Young's modulus, E , and the moment of inertia, I , typically define the bending stiffness, B , as

$$B_{\text{classic}} = E \cdot I. \quad (1)$$

In fibrous structures and for measured bending stiffness this would lead to a Young's modulus of textile structures, which is much lower than the actual one. This approach can only be used if the membrane stiffness can be neglected [16,25]. It is suitable for analyzing the folding behavior of textiles under gravity loads. However, in technical forming tools with blank holders the nonlinear membrane stiffness has to be taken into account in a realistic model.

The approach presented in equation (1) is insufficient for a general textile material model since most technical reinforcement textiles exhibit very high tension stiffness and a nearly negligible bending stiffness. Challenges occur in textiles with an asymmetrical layout or an asymmetrical state of pre-stress. As an example, the meso-structure of a biaxial reinforced multilayer knitted fabric is shown in Figure 1. Here the asymmetrical layout and the asymmetrical knit yarn system cause the bending stiffness to depend on the bending side (top and bottom side, see Figure 1) and the bending direction (x - or y -direction).

Another challenge for a realistic model is the influence of interventions in the mesoscopic design, such as structural pre-fixation. Girdauskaite [26] described a textile pre-fixation with thermoplastic binders. Cherif et al. [27] melted and consolidated the thermoplastic part of hybrid yarns that were integrated into the textile and, thus, achieved a structural fixation of the fabric. It was shown that fixed textiles are much stiffer in their bending and shearing behavior than unfixed ones. The effect on the tensile stiffness and the structural layout was negligible. Most of the pre-fixations substituted the yarn–yarn friction with a yarn–yarn

Figure 1. Model of a biaxial reinforced multilayer knit.

Figure 2. Effect of structural fixation on the bending behavior of a biaxial reinforced knitted fabric.

adhesion. This resulted in a significant increase in the structural bending stiffness. The effect of such a pre-fixation can be seen in Figure 2.

Material

For the experimental tests and material simulations a biaxial reinforced knitted fabric made of glass filament yarn (GF) was used. With its knit yarn system made of polyethylene (PE), it is suitable for a fixation as described in reference [27]. The knitted fabric is schematically shown in Figure 1. Table 1 summarizes the characteristics of the yarns and the knitted fabric.

Methods

Determination of the bending behavior

The bending behavior was measured with a cantilever bending test according to DIN 53362 [28]. The device is schematically shown in Figure 3 and the determination of the overhang length is illustrated in Figure 4. In this test a strip specimen is

Table 1. Layout of biaxial reinforced multilayer knitted fabric.

	Material	Yarn distance
Weft yarn	GF-EC (900 tex)	3.56 mm
Warp yarn	GF-EC (900 tex)	3.56 mm
Knit yarn	PE/GF-HY (137 tex)	
Mass per area	578.7 g/m ²	
Fabric thickness	1.03 mm (according to DIN EN ISO 5048) [34]	
Yarns Young’s modulus	69.8 GPa	

GF: glass fiber; EC: E glass; HY: hybrid yarn.

Figure 3. Experimental setup of cantilever bending test (according to reference [28]).

Figure 4. Deflection of specimen strip at $l = l_0$.

pushed over an edge at a constant velocity. This edge is a reference for the overhang length, l_o . Owing to gravity the strip bends depending on the current overhang length. If the sample reaches an imaginary line which is in 41.5° angle from the tip of the sample to the reference edge, the overhang length is determined. The deflection results from the overhang length.

With

$$\frac{B}{b} = \frac{g \cdot m}{l \cdot b} \cdot \frac{l_o^3}{8} \quad (2)$$

the overhang length, l_o , can be converted into a width-scaled bending stiffness [28]. In equation (2), B denotes the bending stiffness (Nmm^2), b is the sample width (mm), g is Newton's constant (m/s^2), m is the sample mass (kg) and l is the sample length (mm). The derivation of this equation can be found in reference [29].

Material model based on the laminate theory

The laminate theory consists of some basic computation rules that allow the calculation of the mechanical properties of layered material. In the current approach the laminate theory is used to describe the characteristic anisotropic behavior of one single textile layer (one warp and one weft layer). The resulting macromechanical properties are known from mechanical standard tests, such as the strip tension test according to DIN EN ISO 13934-1 [30], the picture frame shear test as described e.g. in reference [31] and the cantilever bending test according to DIN 53362 [28]. In the presented model a laminate replaces one single textile layer containing one weft and one warp yarn layer. A schematic representation of the assembly of a symmetric laminate is shown in Figure 5.

The layered formulation given below assists in correctly generating all resulting deformation mechanisms.

Figure 5. Example of laminate design.

Figure 6. Bending behavior of laminates.

The following basic equations are used for the computations. The resulting Young's modulus of the laminate is given by the rule of mixture as

$$E_{x, \text{ laminate}} = E_{x,1} \cdot \varphi_1 + E_{x,2} \cdot \varphi_2 + \dots + E_{x,n} \cdot \varphi_n \quad (3)$$

with

$$\varphi_n = t_n/h \text{ and } \sum \varphi_n = 1 \text{ (y-direction analogous to this).}$$

The layer thickness of the n th layer is denoted as t_n , the thickness of the laminate is given by h , and the volume fraction of the n th layer is symbolized by φ_n . Similar to equation (3) the resulting shear modulus, G_{xy} , of the laminate is determined as

$$G_{xy, \text{ laminate}} = G_{xy,1} \cdot \varphi_1 + G_{xy,2} \cdot \varphi_2 + \dots + G_{xy,n} \cdot \varphi_n. \quad (4)$$

As illustrated in Figure 6 bending causes tension on one side of a plate and compression on the opposite side. Those bending sides cannot be considered within equation (1). For classic materials and small deflections the stress–strain behavior is the same for tension and compression loads. However, this is not the case for fibrous materials. Thus, the current material formulation considers the bending side with the integral over the thickness of the plate (equation (5)). The laminate bending stiffness is computed as follows

$$B_{\text{laminate}} = \int_{-\frac{h}{2}}^{\frac{h}{2}} E \cdot z^2 dz = \frac{1}{3} \sum E_i \cdot (z_i^3 - z_{i-1}^3) \quad (5)$$

where z is the thickness direction, h is the laminate thickness, E is the Young's modulus and φ_n is the layer fraction.

To allow for different bending rigidities on both bending sides (top and bottom side) different stress–strain behaviors for several layers have to be defined. Otherwise, the laminate bending stiffness given in equation (5) would be independent of the bending side.

Commercial FEA codes offer some possibilities to handle layered materials. Shell elements, which are based on a solid material law, are pre-integrated in the thickness direction. Thus, the volume integral of the stiffness matrix, C_{ijkl} , becomes an area integral [32]

$$\int_V C_{ijkl} dV = \int_A C_{ijkl} \cdot z \cdot \frac{h}{2} dz dA. \quad (6)$$

With this integration the static variables of the membrane forces, transverse force and moments are calculated. The solution for the moments, m_{ij} , according to equation (6) can be defined as

$$m_{ij} = \int_{-1}^1 z \cdot S_{ij} \frac{h^2}{4} dz. \quad (7)$$

The pre-integration happens numerically at certain integration points, which are presented together with the integration limits in Figure 5.

Material parameters and calculation

According to reference [33] the primary deformation mechanisms of textiles are stretching, shearing and bending. The engineering constants, which correspond to them, are the Young's modulus E , the shear modulus G and the bending stiffness B . The calculated layer parameters of the laminate model for influencing the bending behavior must not affect any of the other deformation mechanisms. Thus, the layer material parameters have to be defined in a way that they result in the textile macroscopic behavior. For reasons mentioned earlier, this is not possible with only one layer. A minimum of three layers has to be assumed in the laminate formulation. This leads to $n=3$ and the consideration of the bending side independent stiffness for the x -direction leads to: $E_{x,1}^{compression} \neq E_{x,3}^{tension}$. The assumption $E_{x,1}^{tension} = E_{x,3}^{tension}$ is beneficial because of occurring bimoments that otherwise cause areal distortion under tensile loading. For a three-layered laminate equation (5) becomes

$$B_{laminate} = \frac{1}{3} \left[E_{1,1} \cdot \left(\frac{h^3}{8} - \frac{d^3}{8} \right) + E_{1,2} \cdot \left(\frac{t^3}{4} \right) + E_{1,3} \cdot \left(\frac{-t^2}{8} - \frac{h^3}{8} \right) \right]. \quad (8)$$

Here, $E_{x,n}$ is the Young's modulus of the n th layer and the geometrical parameters t and d are given in Figure 5.

The amount of unknown variables requires some assumptions. Choosing constitute layer thicknesses leads to a closed-form solution. These assumptions allow for a free choice of the bending stiffness with simultaneously constant membrane stiffness. Thus, it is possible to justify the complex bending behavior of unfixed and fixed textiles. An orthotropic formulation allows the handling of different bending rigidities in the different bending directions (0° and 90° orientation). A unique Young's modulus in tension and compression for the outer laminate layers allows for the correct bending side dependent bending behavior (top and bottom side). The Young's modulus of the inner layer adjusts the resulting in-plane stiffness.

Results and discussion

Cantilever bending test

Table 2 lists the characteristic overhang lengths determined for different bending directions, different bending sides and for unfixed and fixed samples. Differences between the x - and y -directions are significant for unfixed and fixed samples. As mentioned earlier fixed samples are clearly stiffer in bending than unfixed samples. This is represented by a larger bending stiffness as shown in Table 3 and by the bending behavior as illustrated in Figure 2. The different bending rigidities between the top and the bottom side in x - and y -direction results from the asymmetric structure of the textile, as illustrated in Figure 1.

Model application and examples

Table 4 contains the laminate parameters for the used specimens, which were calculated according to equations (3) and (8). It contains the measured bending stiffness, as described, and a normalized Young’s modulus for the in-plane

Table 2. Overhang length of unfixed and fixed samples according to DIN 53362 [28].

	x-direction bottom side	x-direction top side	y-direction bottom side	y-direction top side

Overhang length – unfixed	118 mm	106 mm	123 mm	124 mm
Overhang length – fixed	171 mm	176 mm	140 mm	154 mm

Table 3. Bending stiffness of unfixed and fixed samples according to DIN 53362 [28].

Bending direction – side	Unfixed	Fixed
x-direction – bottom side	138 mNcm	346 mNcm
x-direction – top side	99 mNcm	448 mNcm
y-direction – bottom side	162 mNcm	253 mNcm
y-direction – top side	163 mNcm	294 mNcm

rigidities. The Young’s modulus is the stiffness which accounts for the cross section of the shell element. The assumed cross section of the shell element is bigger than the actual load-bearing cross section of the yarns, which makes the assumed Young’s modulus lower than the actual tensile stiffness. The moduli for core and cover layer were calculated as described, to match the resulting rigidities for bending and in-plane tension.

The calculated layer parameters were checked for their correctness with a cantilever beam simulation. In the FEA model that was implemented in LS-DYNA® a strip sample with the length l_0 was clamped at one side and loaded with a gravitational load. Figure 7 plots the results of the cantilever simulations. The deflections of the shell elements with a classic formulation (equation (1)) and the modified shell formulation are referenced.

As can be seen in Figure 7 the application of a classic shell element formulation results in a large deflection error. The deflections of the modified laminates coincide

Table 4. Bending stiffness and Young’s modulus for each layer in laminate formulation.

Direction	B_{result} (mNcm)	E_{result} (MPa)	E_{core} (MPa)	E_{cover} (MPa)
x-direction	138.5	1036	103,100	5.11
y-direction	162.9	1280	127,400	6.03
x-direction fixed sample	346.3	840	82,710	13.00
y-direction fixed sample	253.8	590	58,060	9.53

Figure 7. Solution of the cantilever simulations.

Figure 8. Comparison of drape simulation with classic and novel shell formulation.

Figure 9. Forming of wrinkles.

with the real deflections measured by means of the cantilever bending test. Furthermore, with the developed approach it is possible to handle the deflections as a function of the bending side.

A wrinkling analysis of a free falling table cloth was chosen as an application example of the presented approach. A drape simulation with the modified shell formulation is compared to the classic approach in Figure 8. The forming of the wrinkles at different time steps during a linear increase of the gravitational load can be seen in Figure 9. As can be observed from the figures, the modified formulation leads to a realistic wrinkling behavior of the fabric, whereas with the classic approach the fabric is too stiff in bending.

Conclusions

A novel formulation for shell elements based on the laminate theory has been developed. With this approach it is possible to include the bending stiffness of

fabrics into commercial FEA codes and to adjust the bending stiffness independently of the membrane tensile stiffness. The resistance against bending, for example for fixed and unfixed textiles, can be customized as a function of the bending direction and the bending side. The presented laminate formulation for shell can be implemented into commercial FEA-software, such as LS-DYNA®, easily. Simulation results showed excellent agreement with measured deflections of textile specimens. The calculated layer stiffness, which was derived from the laminate theory, could be used directly to adjust the complicated and tensile stiffness independent textile bending behavior.

Funding

The authors are grateful for the support of the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) and the Allianz Industrie Forschung (AiF) in the scope of the DFG-AiF-Cluster 'Leichtbau und Textilien' ('Lightweight Construction and Textiles') under grants CH 174/16-1, KR 3487/5-1, and 16427 BR. We thank these institutions for the provision of financial resources.

References

- [1] Boisse P, Zouari B and Daniel JL. Importance of in-plane shear rigidity in finite element analyses of woven fabric composite preforming. *Compos Part A - Appl Sci Manuf* 2006; 37(12): 2201–2212.
- [2] Boisse P, Hamila N, Vidal-Salla E, et al. Simulation of wrinkling during textile composite reinforcement forming. Influence of tensile, in-plane shear and bending stiffness. *Compos Sci Technol* 2011; 71(5): 683–692.
- [3] Hedfi H, Ghith A and Salah HBH. Study of dynamic drape behavior of fabric using FEM. *IJEST* 2011; 3(8): 6554–6563.
- [4] Hancock SG and Potter KD. Inverse drape modelling: An investigation of the set of shapes that can be formed from continuous aligned woven fibre reinforcements. *Compos Part A - Appl Sci Manuf* 2005; 36(7): 947–953.
- [5] Wang J, Paton R and Page JR. The draping of woven fabric preforms and prepregs for production of polymer composite components. *Compos Part A - Appl Sci Manuf* 1999; 30(6): 757–765.
- [6] Potter K. Beyond the pin-jointed net: Maximising the deformability of aligned continuous fibre reinforcements. *Compos Part A - Appl Sci Manuf* 2002; 33(5): 677–686.
- [7] Sze KY and Liu XH. Fabric drape simulation by solid-shell finite element method. *Finite Elem Anal Des* 2007; 43(11–12): 819–838.
- [8] Sriram S and Wagoner RH. Adding bending stiffness to 3-D membrane FEM programs. *Int J Mech Sci* 2000; 42(9): 1753–1782.
- [9] Hamila N, Boisse P, Sabourin F, et al. A semi-discrete shell finite element for textile composite reinforcement forming simulation. *Int J Numer Meth Eng* 2009; 79(12): 1443–1466.
- [10] Cherif C. *Drapierbarkeitssimulation von Verstärkungstextilien für den Einsatz in Faserverbundkunststoffen mit der Finite-Elemente-Methode*. PhD Thesis, Institut für Textiltechnik, RWTH Aachen, 1999.
- [11] Chen SF, Hu JL and Teng JG. A finite volume method for contact drape simulation of woven fabrics and garments. *Finite Elem Anal Des* 2001; 37(6–7): 513–531.

- [12] Collier JR, Collier BJ, O'Toole G, et al. Drape prediction by means of finite-element analysis. *J Text Inst* 1991; 82(1): 96–107.
- [13] Schöne JS and Bölke BS. Drapiersimulation von Preforms für Faserverbundstrukturen mit LS-DYNA. *LS-DYNA Forum* 2011, DYNAMore.
- [14] Ascough J, Bez HE and Bricis AM. A simple finite element model for cloth drape simulation. *Int J Cloth Sci Tech* 1996; 8(3): 59–74.
- [15] Jannski L and Ulbricht V. Numerical simulation of mechanical behaviour of textile surfaces. *Zamm – Z Angew Math ME* 2000; 80(S2): 525–526.
- [16] Seif M. *Bereitstellung von Materialkennwerten für die Simulation von Bekleidungsprodukten*. PhD Thesis, Institut für Textil-und Bekleidungstechnik, Technische Universität Dresden, 2007.
- [17] Eischen JW, Deng S and Clapp TG. Finite-element modeling and control of flexible fabric parts. *Comput Graph Appl* 1996; 16(5): 71–80.
- [18] Chen B and Govindaraj M. A parametric study of fabric drape. *Text Res J* 1996; 66(1): 17–24.
- [19] Tan ST, Wong TN, Zhao YF, et al. A constrained finite element method for modeling cloth deformation. *Visual Comput* 1999; 15: 90–99.
- [20] House D, Devaul RW and Breen DE. Towards simulating cloth dynamics using interacting particles. *Int J Cloth Sci Tech* 1996; 8: 75–94.
- [21] Eberhardt B, Weber A and Strasser W. A fast, flexible particle-system model for cloth draping. *IEEE Comput Graph* 1996; 16(5): 52–59.
- [22] Breen DE, House DH, Wozn MJ, et al. A particle- based model for simulating the draping behavior of woven cloth. *Text Res J* 1994; 64(11): 663–685.
- [23] Wagoner RH, Zhou SSD and Zhou ZD. The element bending group method. *Computational Mechanics*. Berlin: Springer, 1995, pp. 1390–1395.
- [24] Gereke T, Döbrich O, Hübner M, et al. Experimental and computational composite textile reinforcement forming: a review. *Compos Part A - Appl Sci Manuf* 2012.
- [25] Amirbayat J and Hearle JWS. The anatomy of buckling of textile fabrics: Drape and conformability. *J Text Inst* 1989; 80(1): 51–70.
- [26] Girdauskaite L. *Lokale Strukturfixierung im Preformherstellungsprozess für komplex gekrümmte Faserkunststoffverbundbauteile*. PhD Thesis, Institut für Textilmaschinen und Textile Hochleistungswerkstofftechnik, Technische Universität Dresden, 2011.
- [27] Cherif C, Diestel O and Krzywinski S. Strukturfixierung textiler Halbzeuge aus Hybridgarnen für beanspruchungsgerechte Preformen, 3. In: *Symposium für Textilien und Verbundstoffe im Fahrzeugbau*, Chemnitz, 2008.
- [28] DIN 53362. Testing of plastic films and textile fabrics (excluding nonwovens), coated or not coated with plastics – Determination of stiffness in bending – Method according to Cantilever, Standard, 2003.
- [29] Reumann RD. *Prüfverfahren in der Textil und Bekleidungstechnik*. Berlin/Heidelberg: Springer, 2000.
- [30] DIN EN ISO 13934-1 – Textiles – tensile properties of fabrics – Part 1: Determination of maximum force and elongation at maximum force using the strip method (ISO 13934-1:2012), Standard, 2012.
- [31] Orawattanasrikul S. *Experimentelle Analyse der Scherdeformation biaxial verstärkter Mehrlagengestricke*. PhD Thesis, Institut für Textil und Bekleidungstechnik, Technische Universität Dresden, 2006.

- [32] Bischoff M. *Theorie und Numerik einer dreidimensionalen Schalenformulierung*. PhD Thesis, University of Stuttgart, 1999.
- [33] Ermanni P. Composite Technologien - Herbstsemester 2007 - Textile Halbzeuge. Centre of Structure Technologies, ETH Zürich, 2007.
- [34] DIN EN ISO 5084. Textiles – Determination of thickness of textiles and textile products (ISO 5084:1996), Standard, 1996.