Textile and Composite Modelling on a near Micro-scale: Possibilities and Benefits

Oliver Döbrich[1], Thomas Gereke[1], Chokri Cherif[1]

[1] Technische Universität Dresden,
Institute of Textile Machinery and High Performance Material Technology,
Hohe Straße 6,
01069 Dresden,
Germany

1 Introduction

Textile materials are increasingly used in engineering for the reinforcement of high performance composites and membranes or for the filtration of contaminated media. Therefore, the demand for accurate numerical models which are able to predict the textile mechanics and the forming behaviour of dry and resin consolidated textiles and the requirements on the model accuracy and fineness. are increasing There is also a need for accurate models which are able to predict the geometry of fiber based materials. Examples are the determination of the packing density or the porosity.
Many numerical models have been introduced in the literature for the different levels of objectivity that are shown in Figure 1. The use for a certain resolution depends on the targeted result. For macro-scale models, complex material models were developed that account for the various deformation mechanisms and the anisotropic mechanics of textile fabrics. Macro models are e. g. preferable for forming simulations, where wrinkles and shear angles of the reinforcement textile shall be analyzed. The advantage of such models is there high cost efficiency in terms of low computation time. They are especially suited for forming process investigations in composite production. The drawback of macro models is that they are not able to account for every deformation mechanism, especially regarding the failure mechanisms such as fiber sliding or the formation of gaps.
Structural analyses can be carried out on the meso-scale. Here, the textile construction is visible and the trace of the yarns is modelled explicitly. For meso-scale models, the quality of the geometrical model is mainly influencing the simulation results. The quality of a numerical simulation in general strongly depends on the model accuracy. Therefore, providing an accurate model is the key factor for a successful simulation. Most models on the meso-scale are carried out in the dimension of the textile unit-cell. Examinations on this small periodic geometry are suitable for most simulations such as virtual tests of structural properties or permeability investigations. But also large scale simulations such as drape simulations of entire structural parts can be carried out on this level of objectivity.
Simulations on the micro-scale enable the analysis of micro effects in textile materials like filament spreading, fiber damage or micro stress distribution. Models on the micro-scale are carried out in unit-cell dimension due to the high detail of the models. For high performance textile modelling, where nearly straight aligned filaments are composed to yarns, the biggest challenge is the implementation of the textile construction. Methods and approaches regarding this topic are explained in Section 4. For textile micro-scale modelling, the digital-element approach was introduced to account for the typical behaviour of technical multifilament yarns [1], i.e. high tensile stiffness, low bending stiffness and nearly unresisting yarn spreading. This approach is used for the examinations done in this paper and is explained in Section 2.

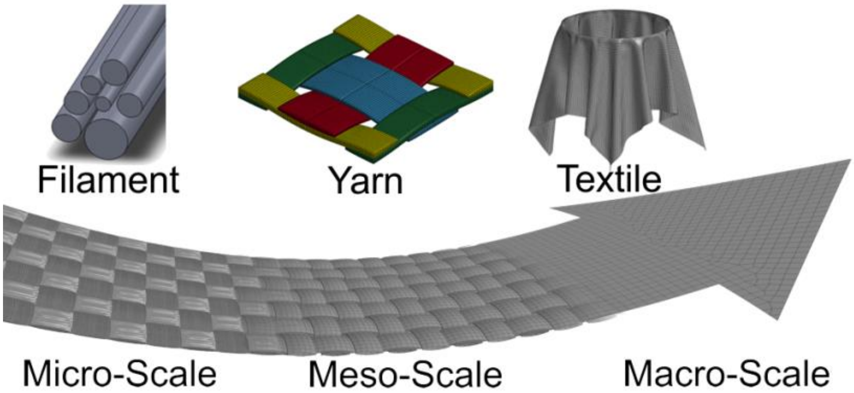


Fig.1: Levels of objectivity in textile modelling

2 The digital-element approach

2.1 General information

Digital elements are simplified beam elements which are pin-jointed to build an element-chain. From the mechanical point of view, they act like a tow. They were firstly referenced by Wang and Sun in 2001 [1]. This simulation technique was already introduced for textile structure simulations. Digital elements are characterised by a reduced stiffness matrix, *K*, as:

$$K = \frac{E \cdot A}{\Delta L} \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} G & 0 & 0 & -G & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -G & 0 & 0 & G & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{1}$$

where *E* is the Young´s modulus and *A* is the cross-sectional area of an element-chain. According to Wang and Sun [1] the values of the occupied terms *G* are not to be regarded as the classical stiffness matrix terms. Every term has to be “a large positive value” [1]. This comment disqualifies the digital-element approach for mechanical examinations. Additional terms are added to the matrix to prevent singularity. Another assumption is the pin-jointed connection between the elements. The bending stiffness of a single filament is negligible. Therefore, a pin-joint assumption is a consequent simplification. The digital elements are not as cost extensive as normal beam elements, which has benefits in large models with a multitude of interacting filaments. Zhou et al. [2] introduced multi-chain digital elements in 2003. These chains are bundles of single filament models to represent multifilament yarns. These yarns consist of hundreds of single filaments. Discretizing a single yarn into these hundreds of single filaments is unusual due to the large amount of interactions, the enormous pre-processing effort and, thus, the high computational costs. Miao et al. [3] examined the amount of digital chains, which are necessary for a multifilament yarn discretization. Miao et al. also showed that there is no need in discretizing a multifilament yarn with the exact number of existing filaments. The number of element-chains rather has to be merely large enough to provide “sufficient accuracy” [3]. For braiding simulations, satisfactory results were achieved with the usage of 19 chains per yarn. A weaving simulation delivered accurate results by using 50 to 70 chains per yarn [3]. Thus, the multi-chain digital element models are beneficial for modelling multifilament yarns on a level of objectivity which is “near to filament” [3].

2.2 Implementation in LS-DYNA®

For the realization of these ropy elements in LS-DYNA, a couple of necessities has to be fulfilled to guaranty the usability of the introduced approach. The restriction to the software environment leads to the following solution which is easy to implement. In the following, the main assumptions are listed which are mandatory for the numerical modelling and the simulation:

1. The reduced beam elements need to be circular in cross-section,
2. The reduced beam elements need a defined cross-section area,
3. When in contact, the circular cross section has to determine the space between two elements,
4. The energy consumed under tensile load has to be identical to the real yarn,
5. The consumed energy per yarn has to be independent from the number of element chains used to represent a yarn,
6. Bending stiffness between two coupled elements is zero,
7. Under dense packing, a multi-chain element has to take the same space as the real yarn does,
8. Element-chains have to be able to stick together or slide upon each other,
9. Friction has to be included.

To realize these terms under the restrictions of LS-DYNA, several approaches are possible. As specified in [4], the discrete elements **`ELFORM=6`** are equipped with a stiffness matrix as stated in Equation 1. But as the section definition for discrete elements requests, only a beam volume can be defined. There is no way to ensure a circular cross section which is one of the mandatory terms listed above.

The easiest way to achieve a beam element behaviour which fulfils all of the listed requirements is the use of classic LS-DYNA beams with a reduced integration. Here, the predefined **STYPE** cross-sections can be chosen and the implemented contact algorithms can be used. By defining **QR/IRID=1**, the bending rigidity is eliminated and a ropy mechanic is realized. This is very important due to the fact that the bending stiffness of fibre material is many dimensions lower than the tensile stiffness. Thus, a reduction to zero is a quite consequential simplification for some approaches. The use of underintegrated beam elements has the additional advantage of numerical robustness. Whereas a classical tow element would numerically collapse when loaded with a compressive force, these elements buckle away from the load direction.
An additional variation from the classical digital-element theory is the values inside the stiffness matrix. When loaded with a tensile force, the elongation of a yarn model shall behave like the real yarn. Therefore, an adaptation of the Young's modulus in the material card is mandatory in dependence of the discretization. Regarding the number of chain elements used to represent a single fibre yarn, the loaded cross-section differs from the real multifilament yarn cross section. Only if the number of modelled filaments equals the number of filaments in the real yarn, the stiffness values can be chosen according to a tensile test with the real yarn. If one single element chain is chosen to represent a multifilament yarn, and the occupied space of this yarn model is the same as the space of the real yarn, the cross sectional area will be much larger. Due to this effect, the tensile modulus has to be adapted to the number of element chains chosen. The cross sectional diameter of every single element chain has to be defined regarding the packing properties. The resulting area under densest packing must not exceed the area of the real yarn. With this approach, limp bending beam elements are enabled which are able to simulate the energy absorption under tensile load. An example for a section keyword to realize digital-element behaviour in LS-DYNA is listed below:

```
*SECTION_BEAM
  1SECID   2ELFORM     3SHRF  4QR/IRID      5CST    6SCOOR       7NSM
       1         1         1         1         1         0         0
     1TS1      2TS2      3TT1      4TT2    5NSLOC    6NTLOC
      0.3       0.3         0         0
```

2.3 Benefits of the digital-element approach

The most outstanding benefit when using the digital-element approach is the representation of every possible deformation mechanism of a technical multifilament yarn without complex material models. Most technical fibres can be regarded as linear elastic. But to account for every deformation mechanism of multifilament yarns, i. e. spreading, shearing, elongating and bending, the material model becomes very complex and insufficient for simulations with large deformations. Especially the yarn spreading, which may occur without a nameable force, the compression of the tow and the involved displacement of fibres are mostly not considered within a continuum mechanical approach. An important advantage of this approach is the ability of enabling force distribution investigations. Tow-elements can only carry tensile load. If multiple elements are arranged next to each other, every element carries a specific load. This enables the visualization of the load distribution within a single yarn. This is one of the largest advantages. Figure 4 shows an example of a woven unit cell loaded in tension.

3 Material

The results presented in this paper are obtained by analysing a plain woven fabric made of 900 tex glass multifilament yarns (900 tex EC-GF). The results of the optical analysis from the examined fabric and the used yarn material are presented in Table 1. The geometrical parameters obtained by optical analyses of scanner and micrograph data are used as input values for the unit cell construction.

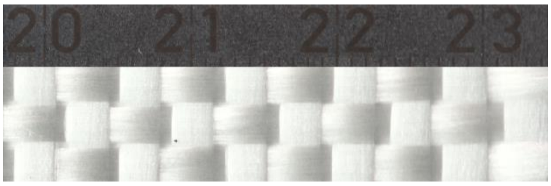
	Material properties		Microscope and scanning images
Yarn Material: 900tex EC-GF	Yarn height weft Yarn width weft: Yarn height warp Yarn width warp Cross-sec. area weft Cross-sec. area warp	0.2675 mm 3.1715 mm 0.3016 mm 2.8258 mm 2.6653 mm² 2.6775 mm²	
Fabric material: Plain woven fabric	Fabric thickness Crimp of weft yarns Crimp of warp yarns Weft distance Warp distance	0.5517 mm 0.3454 % 0.17285 % ~3.33 mm ~3.63 mm	

Table 1: Glass yarn characteristics and examined plain woven fabric

4 Modelling technical textiles on a near micro-scale

4.1 Textile structure modelling techniques from literature

4.1.1 Mathematical approach

The most common approach for defining the geometry of a textile is the mathematical approach. Here, the geometry of the yarns is determined by mathematical functions, which define the trace of the yarns. The most referenced literature on this topic is [5]. McBride and Chen developed equations for the determination of the trace of the yarns for a plain woven fabric from geometrical relationships, for example. Four sinusoidal curves are required to define the shape of the yarns in the unit-cell. These equations are commonly used for a mathematical geometry description of a plain woven unit-cell [6].

4.1.2 Microscopic and microtome optical analyses

Another approach for gaining information about the textiles geometry is by optical analysis. This approach has the benefit that the dimensions and the geometry are reproduced accurately from an actual textile. The disadvantage is that a sample of the examined material is required. Rief et al. [7] describe the method of a microtome sectioning analysis. Slices of an embedded textile are cut in the direction of the cross section and two-dimensional images were taken from every slice. Finally, image processing reproduced the three-dimensional structure of the examined textile [7].
Another possibility is to examine the woven geometry by microscopic analysis, as in Hivet and Boisse [8]. The conditions are equal to the microtome analysis. Some important concerns are stated in the paper. It is known, that the injection of a dry fabric with resin influences the observed sample. As seen from the resulting images, resin infiltrates the fabric and the filaments of the multi-filament yarn. Therefore, the results of a microtome or a microscopic measurement are not identical as for a dry fabric. This disadvantage is known but accepted for most examinations.
As mentioned, there is no chance to do microscopic or microtome analysis without manufacturing the actual fabric. This is disadvantageous for developing new textiles or optimizing textile structures in accordance to their mechanical requirements. However, after an examination of existing structures the resulting three-dimensional geometry data fits the actual structure with good correlation. Certainly, the obtained input data for yarn alignments from this method delivers no information on inner states of stress. The influence of the resin, which is used to fix the dry fabric before cutting the samples for optical measurement, has to be checked.

4.1.3 Generating unit cells of textile structures

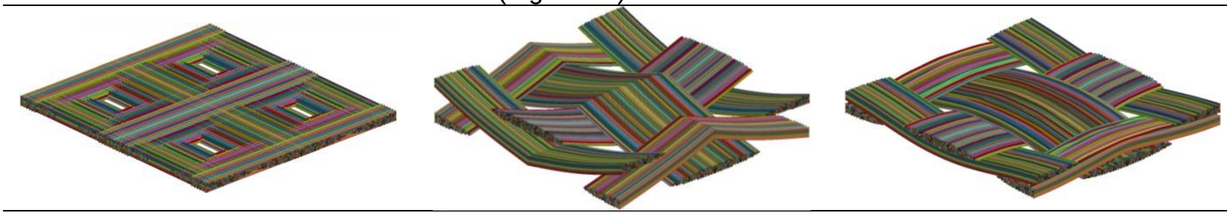
Several other approaches for generating unit cell geometries, or at least substitution models, were introduced in the past. Tan et al. [9] introduced a method to compound a woven unit cell out of micro- and macro-blocks. Each block has another mechanical property, according to its position in the unit cell. A combination of these blocks results in a substitution continuum for predicting the mechanical values of fabrics.

Wang et al. [10] presented an approach comparable to the one introduced in the current paper. Digital elements were used, which are known to be adequate for discretizing multifilament yarns. Digital elements are an alternative to solid or shell elements. A non-continuum approach was realized, which enabled a “near filament-level resolution” [10]. An initial geometry was built by pre-processing. The final woven geometry was obtained by a relaxation process, where the yarn cross-sections and the trace of the yarns achieve a static equilibrium. By applying a pre-tensile load to the yarns an initial impulse is generated to change the yarn geometry. The obtained geometry contains compressed yarns due to contact. The contact forces are due to the pre-tension. It is possible that the amount of forces used for pre-tensioning the initial configuration has only a negligible effect on the resulting geometry. However, the resulting contact forces are not realistic due to the freely chosen value for the pre-tensile forces.

4.2 Textile structures as result from process like simulation

4.2.1 Method

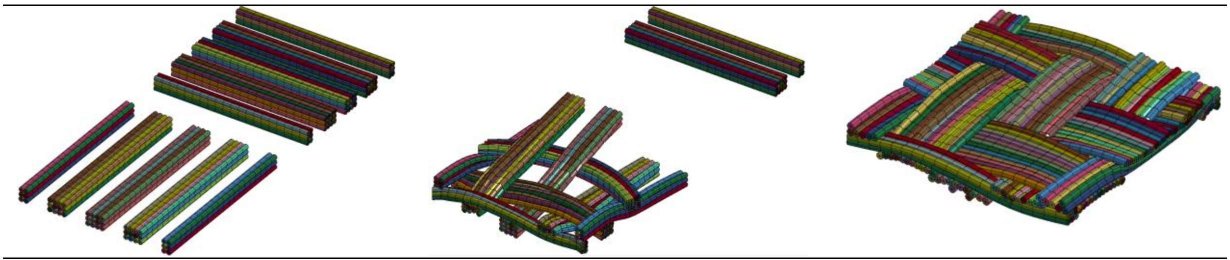
As mentioned before, this method was already introduced with a continual approach for the multifilament yarn mechanics [11]. The aim of the introduced method is to achieve a yarn configuration which equates the one of the examined textile in its static equilibrium. The benefit of the introduced method is that the yarn is straight and stressless in the beginning of the simulation. Here, no strains are applied. Afterwards, the aligned yarn segments are forced to come up with the textiles yarn construction by prescribed motions. Preliminary tests showed that the sequence of prescribed motions is secondary as long as the boundaries are correct; at least as the yarns material model is purely elastic as it is for the examinations in this study. Firstly, all geometric dimensions of the examined textiles have to be known. These parameters are the warp and weft density, the yarn crimp in every direction and the yarn dimension. Figure 2 describes this approach demonstratively for the generation of a plain woven unit cell. Figure 2a shows the initial alignment of the yarns before the unit cell construction begins. All contacts are disabled at this state because of the yarn penetrations. The unit cell borders are defined and correspond to the warp and weft densities previously determined by optical analysis. The borders are fixed and represent the boundaries for the symmetric conditions. The crimp of the yarns is also considered. After aligning the yarns regarding the textile construction (Figure 2b), the boundaries of prescribed motion are disabled and reduced to a minimum required for realising the symmetry conditions. After releasing the unnecessary boundary conditions, a static equilibrium establishes after a moment of relaxation (Figure 2c).



a) Initial configuration b) Prescribed configuration c) Static equilibrium

Fig. 2: Steps of plain woven fabric unit cell generation process

This simple generation process is not applicable for more complex textile constructions. Multilayer weaves, for example, demand a construction process according to the real manufacturing sequence. Even for the construction of a twill weave model it is more suitable to use a process generation method. The conditions are the same. An example of such a generation process which is near the real production sequence is shown in Figure 3. The warp yarns are lifted and lowered according to the construction and the weft yarn is inserted into the shed. After a relaxation process, the unit cell geometry is obtained.



a) Initial configuration b) Prescribed motion c) Static equilibrium

Fig. 3: Steps of twill woven fabric unit cell model generation process

The quality of the introduced model depends on the number of element-chains per yarn as well as on the element size used for modelling an element-chain. The number and size of elements has to be as low as possible due to the numerical costs but large enough to account for the occurring effects. An examination on the convergence for the introduced examples of modelling single layer weaves is presented in Section 6.

4.2.2 Benefits

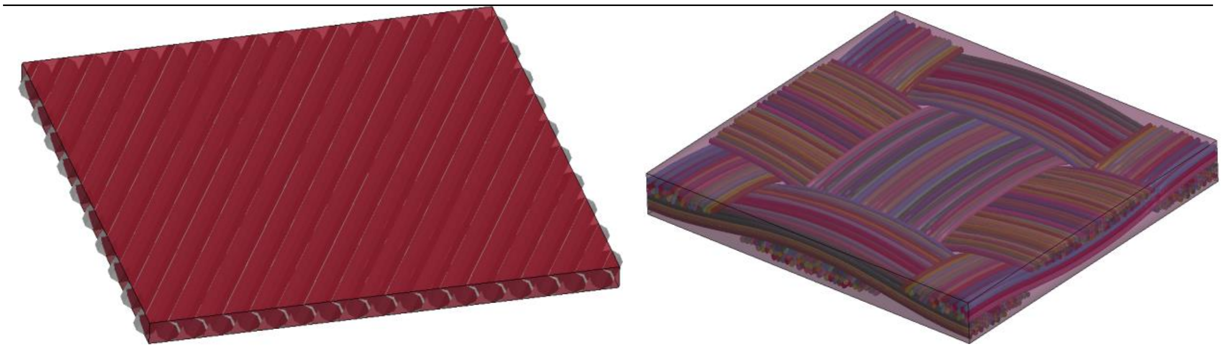
As result from a textile structure generating process which is aligned to a forming simulation itself, a unit cell is obtained where all interacting components are arranged in a natural manner to fit the static equilibrium. The cross-section and the trace of single yarns are complex and do not result from mathematical equations. The input parameters can be related to manufacturing parameters, as it was done in [12]. For this case, process related variations can be carried out and their influence on the structure geometry can be examined. Compared to microscopic methods, this is a effective way to achieve accurate models of textile structures on a microscopic level. The microscopic model is suitable for investigations of geometry, porosity and mechanical behaviour.

5 Modelling textile reinforced composites on a near micro-scale

An approach to model composites which is able to include the introduced micro-scale models of textile materials, is to kinematically couple the beam elements into a solid element matrix. Under deformation the nodes of the beam elements are displaced according to the solid elements and the beam elements have to carry load so they can act as reinforcement as fibres do in composites. A way to realize such a kinematical coupling in LS-DYNA is given by the keyword **`*CONSTRAINED_LAGRANGE_IN_SOLID`**. The used keyword to couple the microscopic beam structure of a textile fabric in a solid element matrix is shown in detail below:

```
*CONSTRAINED_LAGRANGE_IN_SOLID
   SLAVE    MASTER     SSTYP     MSTYP     NQUAD     CTYPE     DIREC     MCOUP
       1         2         0         1         0         1         1         0
   START       END      PFAC      FRIC    FRCMIN      NORM   NORMTYP      DAMP
     0.3       0.3         0         0       0.5         0         0         0
      CQ      HMIN      HMAX    ILEAK     PLEAK   LCIDPOR     NVENT  BLOCKAGE
       0         0         0         0       0.1         0         0         0
  IBOXID   IPENCHK   INTFORC   IALESOF    LAGMUR    PFACMM      THKF
```

A picture of the assembly of the introduced composite model for a 30° unidirectional reinforced plastic and a weave reinforced composite is given in Figure 4.



a) 30° unidirectional reinforced composite b) Plain woven reinforced composite

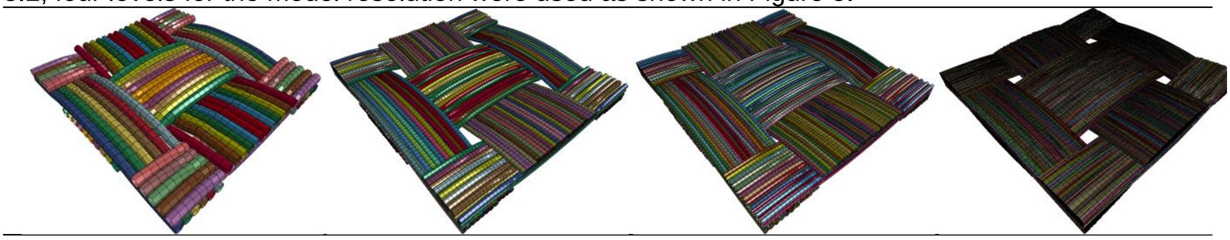
Fig. 4: Model of a) unidirectional reinforced composite and b) plain woven reinforced composite

6 Validation of the textile and the composite model

6.1 Validation of the dry textile model

The quality of the generated dry textile model can be determined by a geometric comparison of the virtual and the real fabric as well as by a comparison of the fabric mechanics. A comparison with the

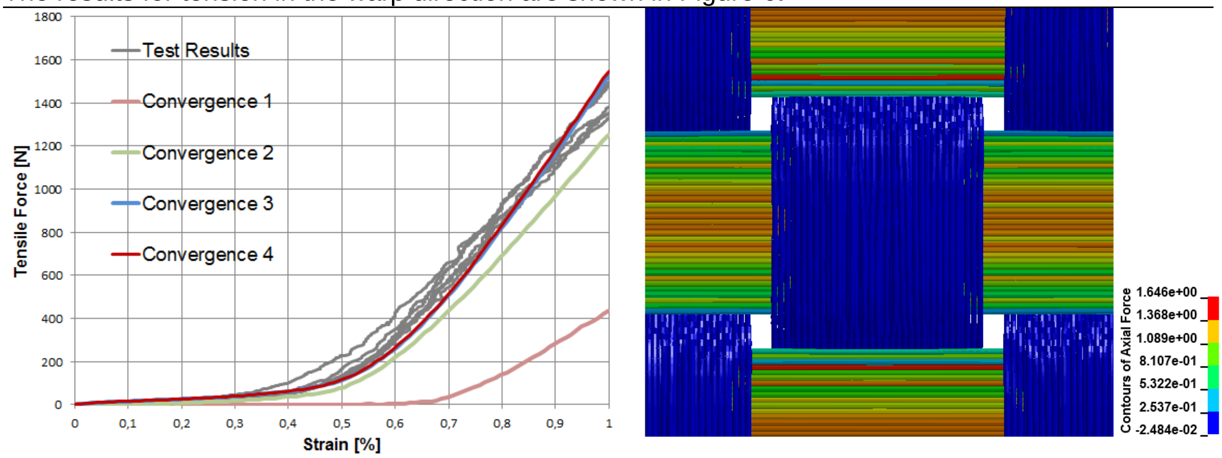
real manufactured fabric is helpful ensure accuracy of the unit cell generating process but it has no significance on the quality of a virtual mechanical test. Thus, validation in this paper is restricted to the mechanical model only. An examination of the convergence is included.
The number of element-chains per yarn is mainly influencing the results. The influence on the resulting geometry was already studied in [2]. The required number of element-chains for an accurate mechanical examination is investigated here. For modeling the single layer weaves shown in Section 3.2, four levels for the model resolution were used as shown in Figure 5.



12 element chains / yarn	30 element chains / yarn	72 element chains / yarn	145 element chains / yarn
Convergence level 1	Convergence level 2	Convergence level 3	Convergence level 4

Fig. 5: Levels of model resolution for the convergence analysis

The mechanical response to unidirectional tension is used as criteria for the model quality. The real manufactured textile was tested under unidirectional tensile load. Unit cell models of the plain woven fabric in the different convergence levels are virtually tested and compared to the actual tensile test. The results for tension in the warp direction are shown in Figure 6.



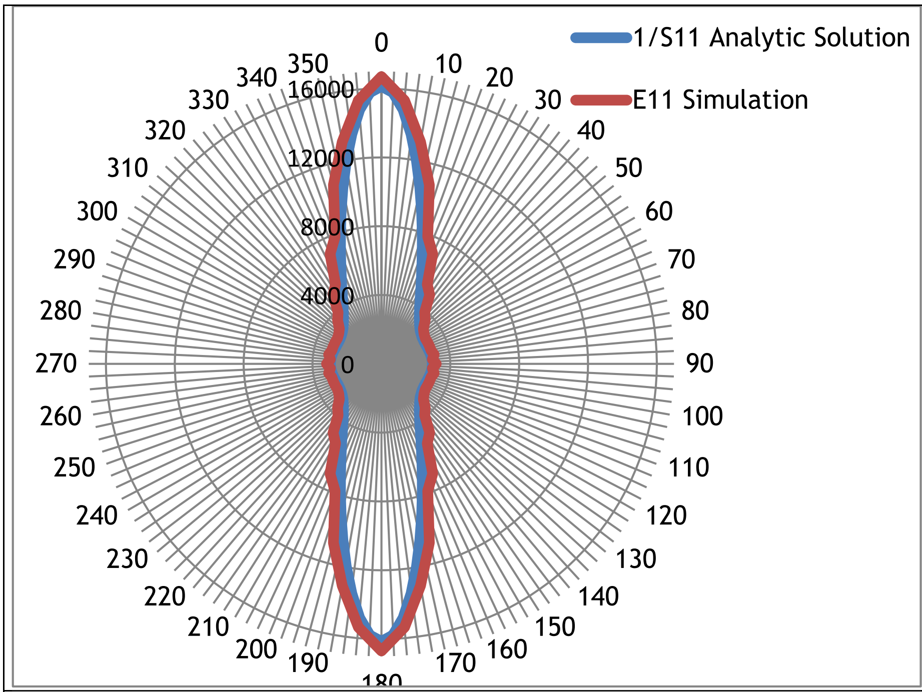
Tensile test in 0° direction	Load distribution in a multifilament yarn

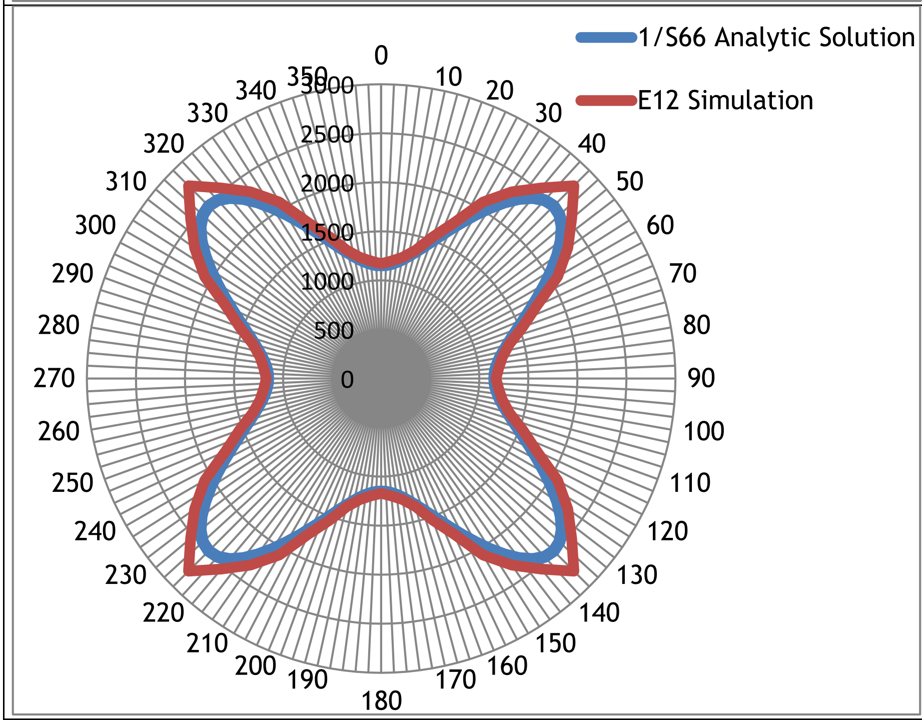
Fig. 6: Tensile load result and load distribution inside a multifilament yarn

It is obvious, that the quality of the model increases with every level of resolution until no significant gain of quality can be observed. At this point, no change in the model response is obtained. The load curve in Figure 6 proofs, that the in-plane results for 145 element chains per yarn are the same as for 72 element chains per yarn. For the reason of numerical costs, all other examinations regarding this model would be carried out on convergence level 3 (72 element chains per yarn). On the righthand side of Figure 6, the load distribution of a multifilament yarn is presented. The possibility of analysing the simulation results for each filament is one of the greatest advantages of the approach. The tensile load increases from the yarn boundary to the middle of the yarns. Such structural knowledge can be very helpful for other textile mechanical investigations and optimizations.

6.2 Validation of the composite model

For validation purpose of the element coupling, a unidirectional composite as shown in Figure 4 is modelled and tested for mechanical behaviour by virtual testing and homogenization methods by applying periodic boundaries to the loaded unit cell. For unidirectional reinforced plastics these results can be compared to analytical values. The virtual composite sample is tested in 72 different angles with a variation of 5°. The examined parameters are the Young's modulus E_{11} and the shear modules G_{12}, G_{23} and G_{31} to check for the mechanical behaviour. The comparison of the analytical and the virtual results is shown in Figure 7 for every examined reinforcement angle.


1/S11 Analytic Solution
E11 Simulation
0
4000
8000
12000
16000


1/S66 Analytic Solution
E12 Simulation
0
500
1000
1500
2000
2500
3000

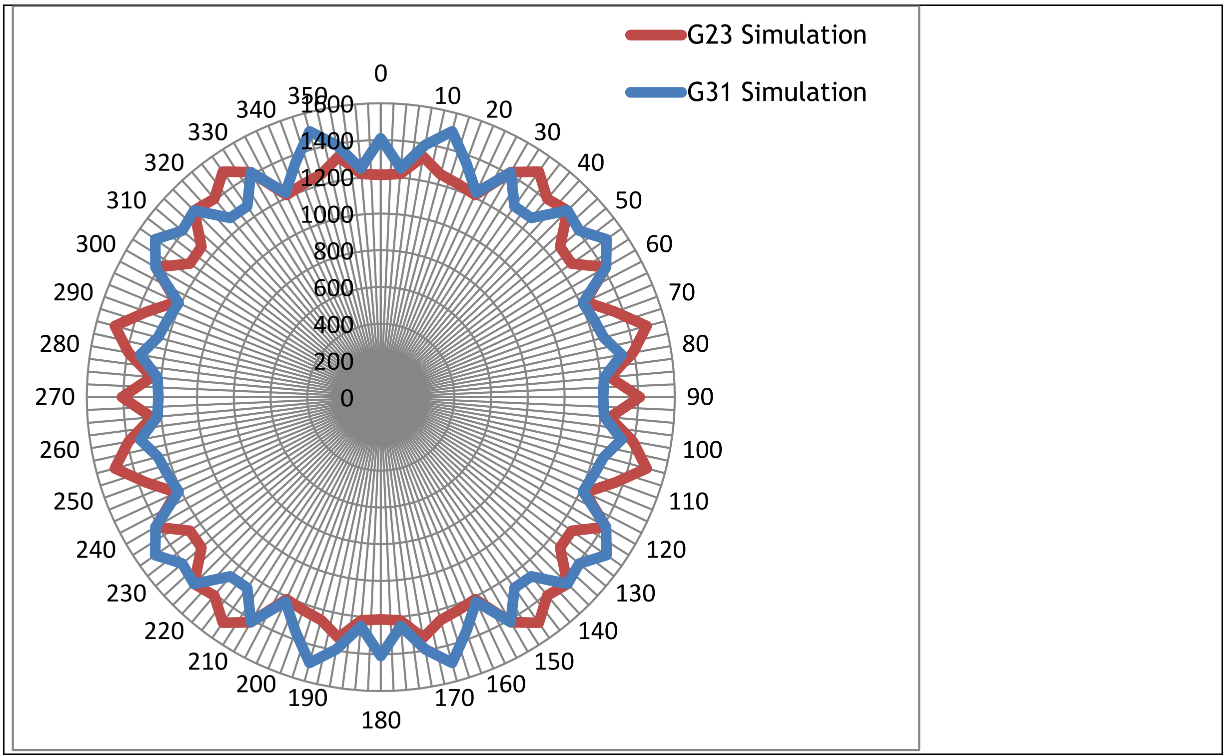


Fig. 7: Comparison of analytical and virtual result for mechanical behavior of UD reinforced composites

The results show an excellent correlation of the model with the analytical result for the Young's modulus E_{11} and the in-plane shear modulus G_{12}. The coupling of beam elements has no effect on the out of plane shear moduli G_{23} and G_{31}. Since the beam element model has no geometric dimension out of the beam axis, there is no influence on the shear behaviour transverse to this axis. The result is independent from the reinforcement angle and equals the shear modulus of the isotropic matrix material.

7 Summary

The digital element approach and the introduced method for generating models of dry textiles and textile reinforced composites are suitable for structural and mechanical examination of high-performance textile reinforced composites on a virtual level. The mechanical validation of the in-plane properties of the implemented models is successful and enables more complex investigations on high performance composite material. Hence, the generating process of the dry textiles unit cell can be related to actual textile manufacturing parameters. The investigation of the influence of the production parameters on the composites mechanics is enabled.

8 Literature

[1] Wang, Y.; Sun, X.: Digital-element simulation of textile processes, Composites Science and Technology, 61(2001)2, pp. 311-319, ISSN 0266-3538

[2] Zhou G., Sun X., Wang Y.: Multi-chain digital element analysis in textile mechanics, Composites Science and Technology, 64(2004)2, pp. 239-244, ISSN 0266-3538

[3] Miao, Y.; Zhou, E.; Wang, Y.; Cheeseman, B. A.: Mechanics of textile composites: Micro-geometry, Composites Science and Technology, 68(2008)7–8, pp. 1671-1678, ISSN 0266-3538

[4] LS-DYNA theory

[5] McBride, T. M.; Chen, J.: Unit-cell geometry in plain-weave fabrics during shear deformations, *Composites Science and Technology*, 57(1997)3, pp. 345-351, ISSN 0266-3538

[6] Aitharaju, V. R.; Averill, R. C.: Three-dimensional properties of woven-fabric composites, *Composites Science and Technology*, 59(1999)12, pp. 1901-1911, 1999, ISSN 0266-3538

[7] Rief, S.; Glatt, E.; Laourine, E.; Aibibu, D.; Cherif, C.; Wiegemann, A.: Modelling and CFD-simulation of woven textiles to determine permeability and retention properties, *AUTEX Textile Research Journal*, 11(2011),3, pp. 78-83

[8] Hivet, G.; Boisse, P.: Consistent 3D geometrical model of fabric elementary cell. Application to a meshing preprocessor for 3D finite element analysis. *Finite Elements in Analysis and Design*, 42(2005)1, pp. 25-49

[9] Tan, P.; Tong, L.; Steven, G. P.: A three-dimensional modeling technique for predicting the linear elastic property of opened-packing woven fabric unit cells, *Composite Structures*, 38(1997)1–4, pp. 261-271, ISSN 0263-8223

[10] Wang, Y.; Miao, Y.; Swenson, D.; Cheeseman, B. A.; Yen, C.-F.; LaMattina, B.: Digital element approach for simulating impact and penetration of textiles, *International Journal of Impact Engineering*, 37(2010)5, pp. 552-560, ISSN 0734-743X

[11] Döbrich O., Gereke T., Cherif Ch.: Virtual Weaving – Construction of a woven representative unit-cell, Proceedings of the 13th AUTEX World Textile Conference, May 22-24, 2013, Dresden, Germany

[12] Döbrich, O.; Weise, D.; Hoffmann, G.; Gereke, T.; Cherif, C.: Simulation-aided development of non-crimped leno fabrics from high-performance coarse yarn. Technical Textiles 57(2014)5, pp. 162-164