Modeling composite materials with respect to reinforcement textile construction

P. Böhler[1], M. Gubser[1], J. Ravic[1], O. Döbrich[1,*]

[1] ZHAW Zurich University of Applied Science,
School of Engineering, Institute of Materials and Process Engineering
Technikumstrasse 9, 8401 Winterthur, Switzerland

*oliver.doebrich@zhaw.ch

1 Abstract

To address the ongoing efforts to virtually design complex composite materials and their high-performance structures and to contribute to the increasing developments towards Industry 4.0, research and development of fiber-reinforced composites is shifting from an experimental domain to a virtually controlled environment. Material models to account for the specific failure mechanisms of layered fiber-reinforced materials have been developed and can be used for largescale numerical structural simulations. However, these models do not account for the individual properties of the reinforcing materials and therefore lack information on microstructural effects and behavior. A near-microscale approach for modeling textile and fiber-based reinforcement structures is presented that allows studies based on the individual textile structure. The digital beam approach is well established in literature for modeling textile processes and textile unit-cells. It allows simulations where the parameters of the manufacturing process are considered, and the resulting reinforcement structure is obtained because of these simulations. This paper addresses such microscale geometric models of reinforcement textiles for use in a virtual composite development chain. The resulting mechanical properties can be predicted for the dry reinforcement textiles by virtual testing and are available as material input parameters for further investigations, such as textile drape simulations. In addition, an approach is presented in which the textile models are used directly for composite modeling. Superimposed models are presented that take advantage of LS-DYNA's ability to Lagrangian-couple solids and provide information about the mechanical behavior of textile-reinforced composites. In addition to the homogenized mechanical properties, additional information such as load distribution within the fibers and other properties based on the specific design of the reinforcement textile can be derived and analyzed.

2 Introduction

The applicability of digital methods for component design and production is combined in the marketing term "Industry 4.0". Modern communication structures are to be used to enable the self-organized production of goods through networking of digital systems. In the "smart factories" of the future, information will be processed and made available for further processing steps. Here, it will be irrelevant whether the goods are mass-produced or single items. Each production step will be optimized on a component-specific basis and virtually tailored in advance using model-based processes, which will allow the production of individual items at the price of mass-produced goods. The intervention of digitization in the modern component cycle is expected to extend along the entire value chain, from development, through production and use, to recycling.
The demands for inhomogeneous reinforcement structures, for the targeted and load-adapted development of high-performance fiber composite structures based on the lightweight principle, correspond to the opportunities presented by digitalization in an Industrial Environment 4.0. The multi-scale simulation of the textile reinforcement structure in the form of a virtual composite process chain is seen as promising for the transition of the fiber composite industry into the field of Industry 4.0.

3 Process dependent modelling of fiber-based reinforcements

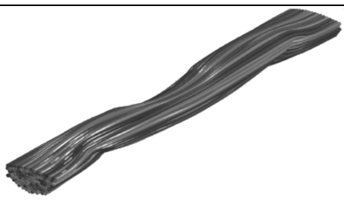
The building of virtual models representing textile-based reinforcement structures and their composites for use with the finite element method can be carried out at different levels of objectivity. These are distinguished according to their degree of resolution and the associated representation. The individual abstraction levels are referred to as macro, meso and micro levels. A fundamental challenge is to provide material models for yarn or textile and to provide a correct geometrical model of the textiles on meso and micro level. While the macroscale approach represents the textile in a homogenized manner, geometrical modeling at the meso and micro levels is given special importance and can be seen as a separate discipline in the field of textile simulation.

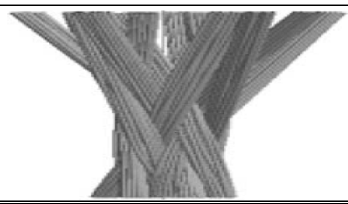
At the micro level, the existing semi-finished product is represented in the highest level of structural detail, up to every individual filament. Simplifications on the models are to be avoided or limited to the necessary. The modeling is done on the microscale mostly on the size of the smallest representative unit-cell, which can be repeated periodically.

Although models are known in which three-dimensional elements have been used to discretize individual filaments [1], currently the most common representation of textile structures at the (near) micro-scale is by beam or other two-dimensional elements defined primarily by their axial properties [2, 3]. These beam models are computationally efficient and provide very good geometrical models. Their suitability for performing virtual tests is demonstrated in this contribution.

Isotropic material model *MAT_001 is applied for the material parameterization of the beam models. In the work of [2, 4] the so-called digital element approach was used. Here, a reduced stiffness matrix is introduced, which corresponds to the mechanics of a cable element and can be seen in Figure 1. The bending stiffness of the elements is completely neglected. The digital elements are connected in chains to form element-chains. A multitude of parallel element-chains then forms a multi-element-chain and is suitable for modeling technical multifilament yarns [5].

$$K = \frac{EA}{\Delta L}\begin{bmatrix} G & 0 & 0 & -G & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -G & 0 & 0 & G & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$





Digital-element stiffness matrix	Distorted yarn from multiple beam-chain-elements	Braiding simulation with digital-element-approach [5]

Figure 1 Digital-elements for micro-scale modelling of technical textiles.

For the provision of a textile microstructure model, the process simulation of textile processing procedures is suitable in addition to the unit-cell generation methods [6]. Depending on the process parameters, models of the textile structure can be generated here [2, 7]. This method enables process and structure analyses and provides the basis for a virtual process chain. With a reliably validated simulation, models of textile structures can be generated and virtually tested that were not actually manufactured in advance. However, process simulations on a microscale basis have high numerical costs.

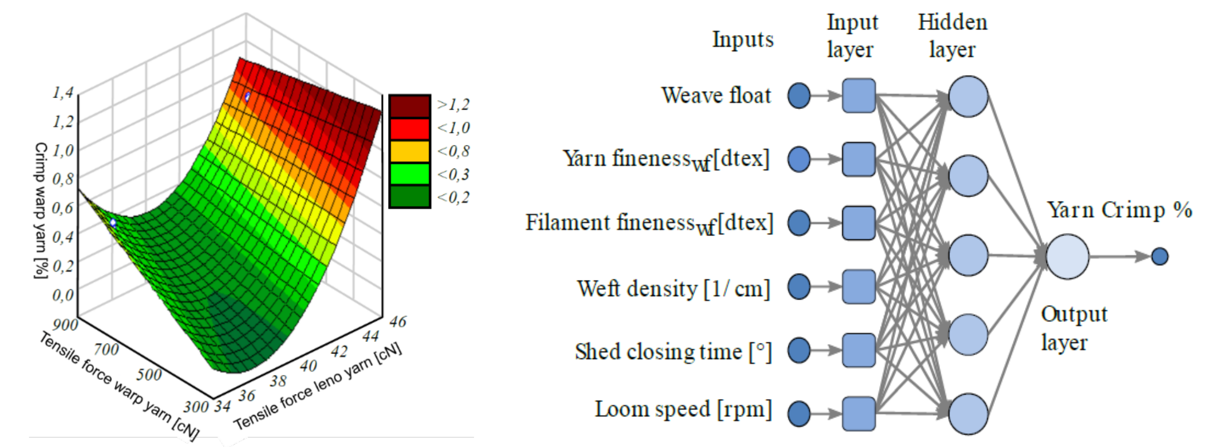
Established modeling methods require input parameters that must be obtained from the textile itself to be modeled successfully. Those may be the yarn count or information about the yarn cross-section geometry. However, for the intended virtual development of composite materials, according to the idea of Industry 4.0, models of textile reinforcement structures should be generatable without an already existing sample. In the context of a textile process simulation, all machine parameters influencing the structure are directly considered [8]. However, since the numerical costs of this modeling method are high, it is considered unsuitable for a flexible virtual development chain at the present time.

The consideration of yarn tensions and other production parameters, such as main shaft speed, cannot be done directly outside a process simulation. Therefore, methods are presented in the following which allow indirect inclusion of the textile production parameters. The production parameters of textile surface formation result in a certain specific yarn consumption, which can be determined within the dimension of a unit cell. This yarn consumption corresponds to the crimp.

Industrial producers are often specialized in the manufacturing of a specific textile semi-finished product, so that producers have many years of extensive experience in varying process parameters. Nevertheless, products are constantly changed and adapted according to the requirements found in the market. A production analysis using statistical design-of-experiments (DOE) can directly transfer the effect of production parameters and source materials onto semi-finished product properties [9]. DOE allows to interpolate between the sample points spanning the experimental plan and thus to obtain information about previously unmanufactured goods (Figure 2 left). This information is then available for a statistically validated virtual structure analysis.

The application of DOE to a complex process, such as textile semifinished product production is only reliable if many boundary conditions remain constant. However, the geometry of a textile structure depends on many variable input parameters. To be able to analyze generally valid statements about structural parameters, such as the thread incorporation, as a function of the totality of input parameters, the use of artificial neural networks (ANN) is an option. These can establish a non-analytical relationship between many input values and an output value.

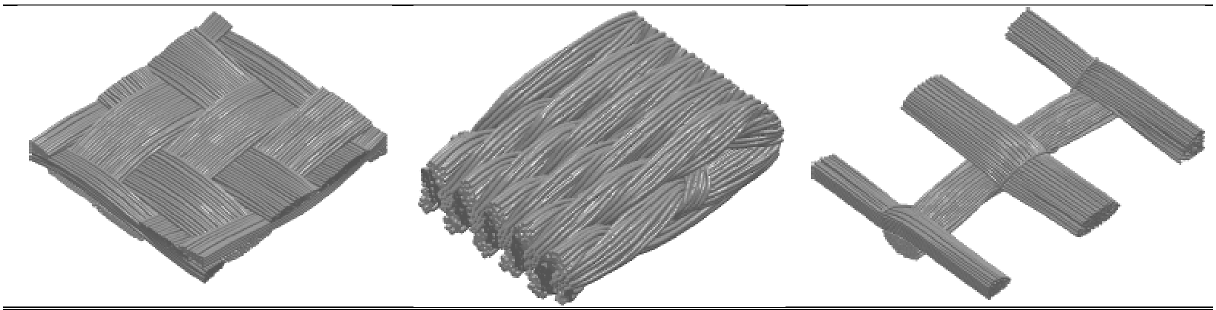
Thus, it was shown in [10] that ANN can establish weaving machine-independent and cross-material regularities between production parameters and crimp in high-density fabrics (Figure 2 right). Figure 2 shows the schematic of a neural network containing all considered input parameters for the analysis of yarn crimp. The large number of connected input parameters becomes clear here.



DOE predicting crimp in leno-weave [9]	*ANN predicting crimp in weaving process [10]*

Figure 2 DOE result and ANN to predict production parameter dependent crimp.

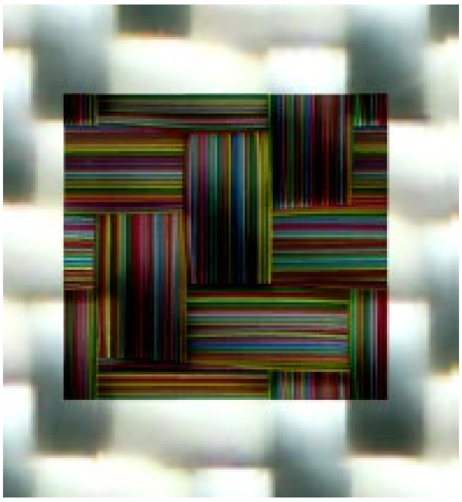
The basis of the presented modeling method is the assumption that yarn segments of a certain length (crimp) arrange themselves in an equilibrium state in a limited space (unit-cell) determined by a prescribed structure (construction). The unit cell size (warp distance × weft distance) can be determined by the production parameters. Consideration of elastic fabric shrinkage, which occurs mainly in knitted fabrics with stretchable yarns, can be neglected when considering high-performance technical fabrics. The structure generation method is furtherly described in [9] and is generally applicable to all textile constructions, as shown in Figure 3.



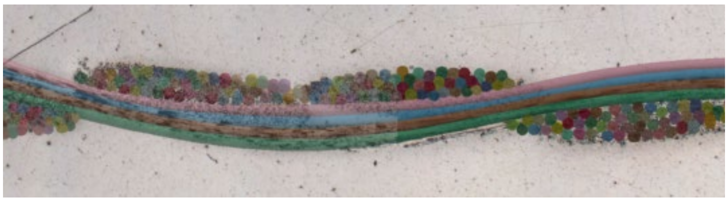
Twill-weave	Narrow-fabric	Leno-fabric

Figure 3 Examples of digital-element models of fiber-based reinforcements.

For the geometric validation of the generation method, the textile structure models obtained are visually compared with the actual manufactured semi-finished products. This can be done a simple view of the textile surface using microscopy or scanner images, or by comparing the cross-section formed by the individual yarns. For this purpose, section cuts are compared with the generated digital models. Here, the cross-sections and the traces of the yarns can be evaluated. Figure 4 shows the optical comparisons of real images (top view, section cut in warp direction, section cut in weft direction) with the models of the respective fabric structures. As can be seen, the assumptions taken within the generation method result in a very realistic geometrical representation. Both the position, the cross-sections and the yarn courses of the generated models correspond very well to the real models.



Section cut in warp direction



Top view

Section cut in weft direction

300 tex glass fiber twill weave

Figure 4 Geometrical validation of unit-cell model for 300 tex plain woven fabric.

4 Composite modelling by Lagrangian coupling

The models of textile structures should be able to be used directly in a virtual composite development chain to predict the respective composite properties. For this purpose, a microscale modeling method for fiber-reinforced composites was introduced in [11]. The basis of this method are the introduced beam models for textile structures. The beam elements are kinematically coupled to solid elements, which represent the matrix material using *CONSTRAINED_LAGRANGE_IN_SOLID keyword (Figure 5). A deformation of the matrix is thus transferred to the beam elements without changing their relative position in the solid element. This principle is illustrated in Figure 6.

1	COUPID	TITLE						
	0							
2	LSTRSID	ALESID	LSTRSTYP	ALESTYP	NQUAD	CTYPE	DIREC	MCOUP
	6	362	0	1	0	2	3	0
3	START	END	PFAC	FRIC	FRCMIN	NORM	NORMTYP	DAMP
	0.0	1.000e+10	0.1000000	0.0	0.5000000	0	0	0.0
4	K	HMIN	HMAX	ILEAK	PLEAK	LCIDPOR	NVENT	BLOCKAGE
	0.0	0.0	0.0	0	0.1000000	0	0	0
5	IBOXID	IPENCHK	INTFORC	IALESOF	LAGMUL	PFACMM	THKF	
	0	0	0	0	0.0	0	0.0	

*Figure 5 *CONSTRAINED_LAGRANGE_IN_SOLID Keyword*

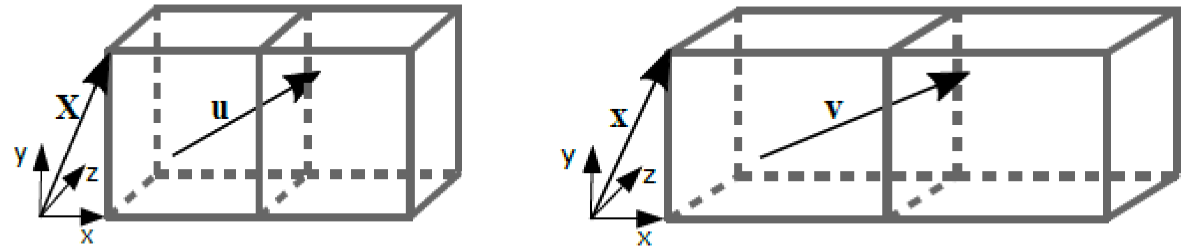
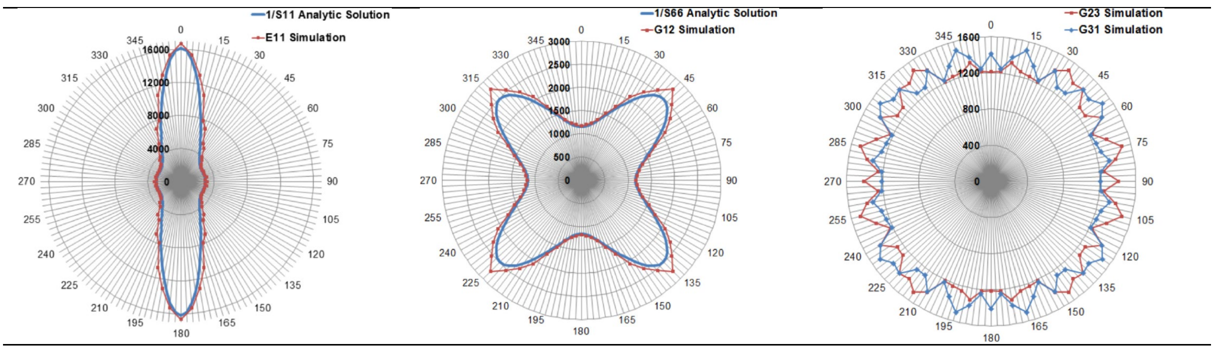


Figure 6 Left: Initial condition, Right: Deformed condition.

To validate the introduced modeling approach, composite models with unidirectional (UD) reinforcement structure were set up and virtually tested. The results could then be compared with existing analytical solutions for composite stiffnesses to evaluate the performance of the modeling method. This has been done in [11].

The stiffnesses determined virtually by these tests are shown in Figure 7 as a function of the fiber angle in a polar diagram, together with the analytical solutions. As can be seen from the virtually determined composite stiffnesses, the introduced composite material model is able to correctly reproduce the in-plane stiffness behavior. The determined values for the transverse shear stiffnesses G_{yz} and G_{zx} correspond to the shear stiffness of the isotropic matrix with no contribution of the reinforcement fibers. The beam elements coupled into the matrix therefore do not influence the transverse shear stiffnesses of the UD models.



Tensile stiffness E_{11}	Shear stiffness G_{12}	Shear stiffness G_{31} +G_{23}

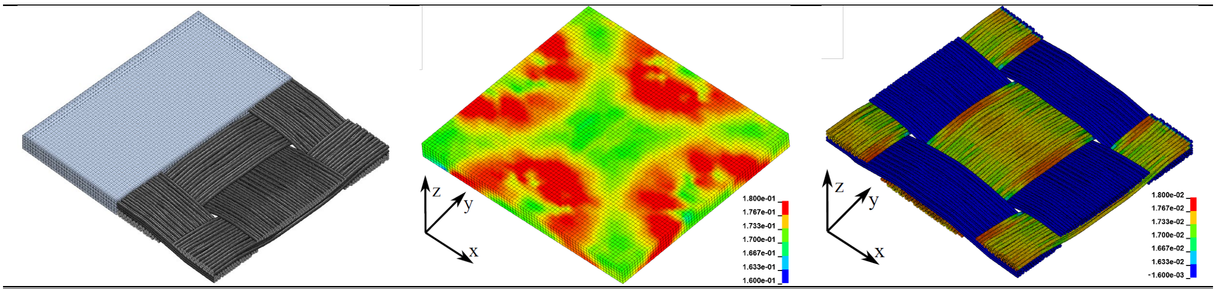
Figure 7 Polar-diagram for UD stiffness - virtual model compared with analytical solution.

5 Examples

The model of the composite is generated by kinematically coupling the textile model with an isotropic matrix model from solid elements, analogous to Figure 6. This is illustrated in Figure 8.

Figure 8 Model composition - Digital-element model and solid element matrix.

Figure 9 shows the results of a uniaxial loading simulation of the introduced plain woven reinforced composite model. In addition to the predicted stiffness, virtual analyses can provide information about the loaded composite that cannot be obtained easily from real world experiments. In Figure 9 both the stress distribution in the matrix and the force distribution in the reinforcing fabric are shown.



Composite model | Von-Mises-Stress in matrix | Axial fiber load in weave

Figure 9 Result of composite tensile simulation.

6 Summary

By considering production-related parameters, a model generation approach for microscale models of textile structures was introduced, which considers the production parameters of the semi-finished product during structural modeling. This modeling approach leads to realistic finite element models of textile reinforcement structures, which are suitable for the analysis of the mechanical behavior. This is particularly determined by the representation of the yarn structure and the yarn mechanics. A method was found to represent the behavior of technical multifilament yarns as a function of the modeling fineness. Due to the very good representation of the structural geometry and the possibility to correctly represent the yarn mechanics, unit-cell models capable of virtual analysis of the mechanical behavior of the high-performance textiles could be generated, making them suitable for use in a virtual composite development chain. The good suitability for predicting the properties of fiber-reinforced structures also suggests future investigation to apply the modeling method to other fiber-based materials such as nonwovens and papers.

7 Outlook

With a view to the aspired virtual composite development chain, target-oriented methods for the virtual design of textile reinforcement structures must be found. The possibilities of the FEA to analyze the behavior of complex mechanical systems is still considered as key technology in development of virtual methods for mechanical applications. The general aim is to gain purely virtual information about the mechanical behavior, the drape properties, and the properties of composites and their structures. The use of microscale models is considered suitable, since they are particularly well suited for geometric modeling of technical reinforcement textiles, and this provides the basis for mechanical structure simulations.
This modelling step enables the coupling of the production parameters of the textile semi-finished product to the resulting composite mechanics. A large number of parameter studies and optimization calculations are thus enabled on a virtual level, again highlighting the advantageous suitability of the microscale models for use in a holistic virtual composite development chain. The introduced methods and models thus provide a basis for the virtual design of the entire composite manufacturing chain, from surface formation to component calculation.

The industrial environment will become increasingly digitally oriented in the coming years and will have a demand for the application of virtual methods. Communication between the individual process stages will become important. The exchange of digital information will shape the image of modern production environments. The methods introduced are ideally suited to this context. They are suitable to enable the application of composites in new fields of application through the information-driven and computer-aided development possibilities. A flexible production environment in the sense of Industry 4.0 will then favor the application in industrial large-scale production, but also for very small series and special productions. The further development of the introduced calculation methods for use by automated optimization algorithms or in the context of machine learning is seen as particularly promising. Future development cycles can be significantly shortened and the real trial-and-error testing effort in the development of new composite structures can be reduced to a minimum.

8 Literature

[1] Nilakantan, Gaurav. "Filament-level modeling of Kevlar KM2 yarns for ballistic impact studies." *Composite Structures* 104 (2013): 1-13.

[2] Wang, Youqi, and Xuekun Sun. "Digital-element simulation of textile processes." *Composites science and technology* 61.2 (2001): 311-319.

[3] Daelemans, Lode, et al. "Finite element simulation of the woven geometry and mechanical behaviour of a 3D woven dry fabric under tensile and shear loading using the digital element method." *Composites Science and Technology* 137 (2016): 177-187.

[4] Miao, Yuyang, et al. "Mechanics of textile composites: Micro-geometry." *Composites Science and Technology* 68.7-8 (2008): 1671-1678.

[5] Zhou, Guangming, Xuekun Sun, and Youqi Wang. "Multi-chain digital element analysis in textile mechanics." *Composites science and Technology* 64.2 (2004): 239-244.

[6] Döbrich, O., T. Gereke, and Ch Cherif. "Virtual Weaving–Construction of a woven representative unitcell." *Proceedings of 13th AUTEX World Textile Conference*. 2013.

[7] AL., H. F.: Prozesssimulation am ITV - Möglichkeiten für Faserverbundstrukturen. Ludwigsburg, Germany, 2012. – Research Report

[8] Gereke, Thomas, et al. "Approaches for process and structural finite element simulations of braided ligament replacements." *Journal of Industrial Textiles* 47.3 (2017): 408-425.

[9] Döbrich, O. ; Gereke, T. ; Cherif, C.: Modelling of textile composite reinforcements on the micro-scale. In: Autex Research Journal 14 (2014), jan, Nr. 1

[10] Malik, Samander Ali, Thomas Gereke, and Chokri Cherif. Prediction of relationships between fabric constructional parameters and composite properties. In: In: Proceedings of 14th AUTEX World Textile Conference, 2014

[11] Döbrich, Oliver, Thomas Gereke, and Chokri Cherif. "Modeling the mechanical properties of textile-reinforced composites with a near micro-scale approach." *Composite Structures* 135 (2016): 1-7.