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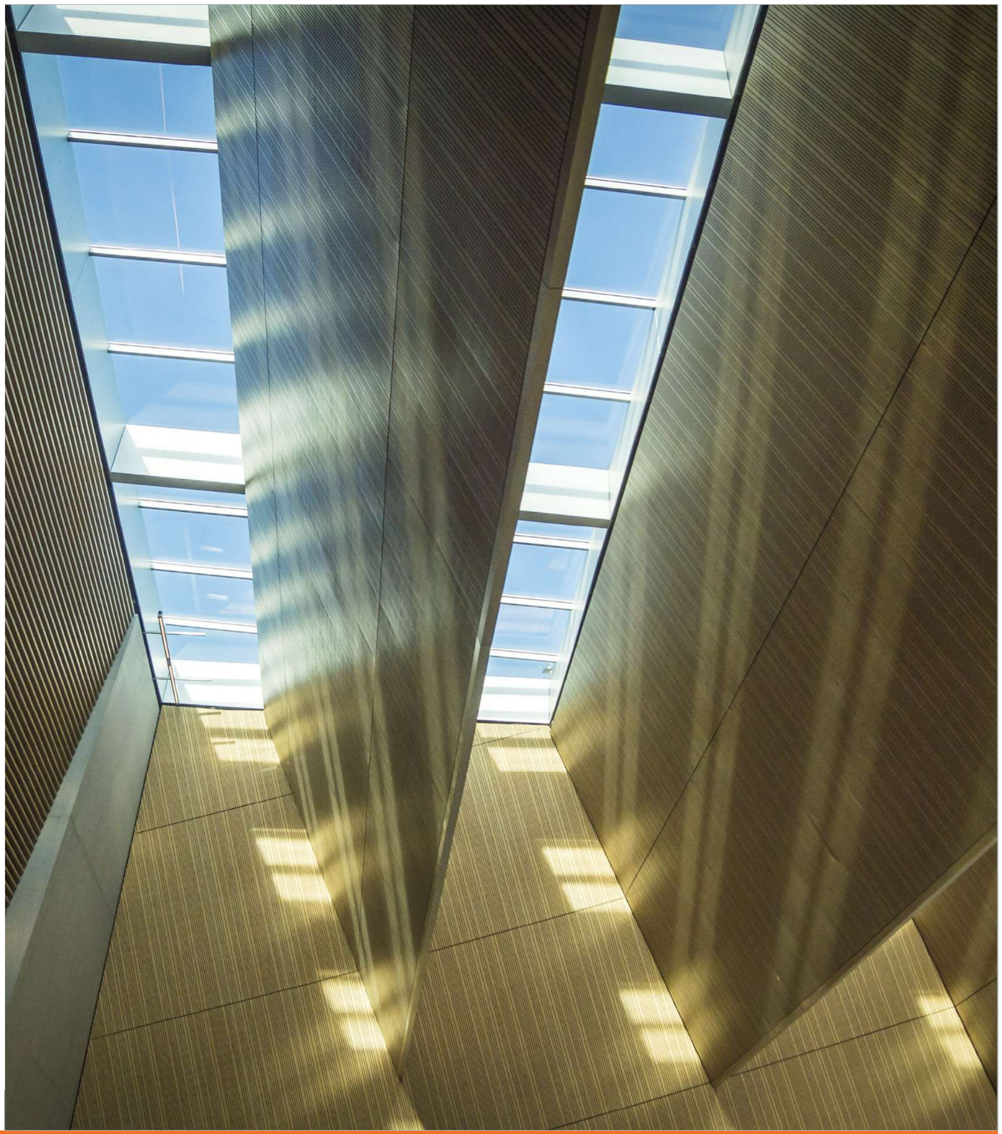

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Vol 4 – Modeling and Prediction

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A NEW VIRTUAL FIBER MODELING APPROACH TO PREDICT THE KINEMATIC AND MECHANICAL BEHAVIOR OF THROUGH-THICKNESS FABRIC COMPRESSION

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Abstract: *We propose a new modeling strategy based on hybrid elements for virtual fiber modeling (also known as the digital element method) to predict both kinematics as well as mechanics of woven fabrics. In virtual fiber modeling, yarns are modeled consisting of a number of discrete fibers. We show that through the development of a modeling strategy based on hybrid elements, we are able to impose correct properties in the fiber direction, as well as out-of-plane properties thanks to the inclusion of fiber bending stiffness. This approach accurately predicts the through thickness compression of a 2x2 twill glass fiber woven fabric. Both kinematically, as well as mechanically, good agreement between experiment and simulation is obtained. Ultimately, these kinds of models could allow faster virtual prototyping as the amount of experimental input is very low and can usually be found in the datasheet.*

Keywords: finite element modelling; textile mechanics; predictive simulation; forming

1. Introduction

Liquid Composite Molding (LCM) processes such as Vacuum Assisted Resin Transfer Molding (VARTM), Resin Transfer Molding (RTM), or Injection Compression Molding (ICM), are composite manufacturing processes in which a dry fibrous reinforcement is infused with liquid resin. The reinforcement is often compressed between two mold halves (or between a mold and a vacuum bag) in these processes and its microstructure hence changes because of the applied pressure (e.g. tow compaction). Hence, understanding and predicting the through-thickness compression behavior of reinforcements is one of the crucial factors in the manufacturing of high-quality composite parts through LCM processes.

Modeling techniques would provide a good alternative to cumbersome experimental techniques such as high-resolution X-ray microcomputed tomography (µCT). One of the main goals is to gain insight into microstructural changes of the fiber reinforcements that could for example influence the permeability of the reinforcements [1]. Although macro- and mesoscale models exist, these are usually fitted with specific constitutive laws based on experimentally determined through-thickness input properties [2]. In addition, they do not reveal conclusions about the micro-level which would be relevant for microscale permeability.

Microscale models offer the possibility to analyze the through-thickness compression at the reinforcement level while taking into account the microscale deformation mechanisms. Most notably, the virtual fiber modeling method, initially conceived by Wang et al. [3,4], is proving to be one of the most viable options. Often referred to as the digital element method, this method is centered around the modeling of fibers through a chain of truss-like elements (digital

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elements), simulating the textile material as made up of a relatively small amount of such "virtual" fibers (up to 100-200). The virtual fiber method thus explicitly takes into account the fibrous behavior of the reinforcements at near-microscale, see Figure 1.

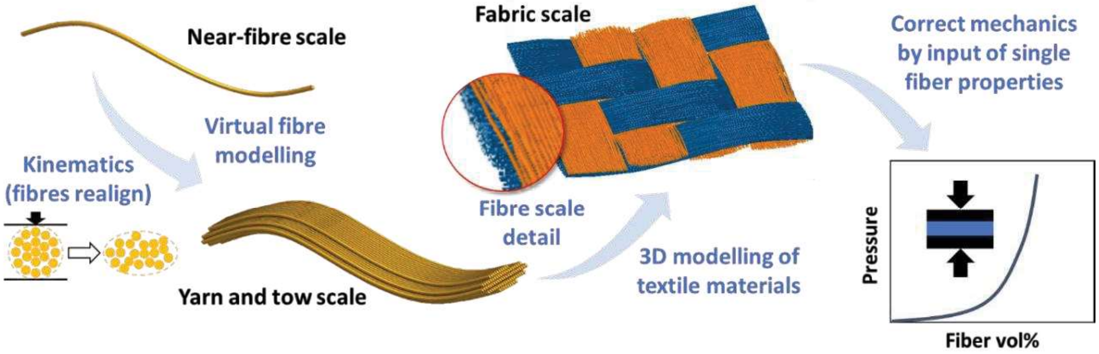

Figure 1 – Concept of virtual fiber modelling to determine the through thickness compression of textile materials.

The virtual fiber modeling method has recently been applied to through-thickness compression of woven fabrics with successful validation of the microstructure (e.g. yarn compaction, yarn paths, …) to experimental data [5,6]. Yet in both cases, the modeling is kinematic only in that the compaction in the models is realized without taking the actual pressure level into account. Although this enables meso-scale models to include the correct mechanical behavior by using the predicted microstructures [6], virtual fiber modeling with correct out-of-plane mechanics might provide a more efficient route for virtual mechanical analysis of textile reinforcements. In the case of in-plane loadings, the response is dominated by tensile loading in the fiber directions and we have previously reported a successful correlation between kinematics and mechanics for these cases [7,8].

In this work, we describe a framework to enable the correct inclusion of fiber bending into the virtual fiber modeling approach, to predict the through-thickness compression of a twill woven glass fiber fabric reinforcement. It is based on an overlay mesh-element technique, combining both (i) finite elements that determine the in-plane fiber properties as well as (ii) finite elements that determine out-of-plane fiber bending. This method is applied to the through-thickness compression of a single layer of dry fabric reinforcement to exclude any effects by the nesting of multiple layers. To validate the model, two different test methods are used to determine the pressure-compaction relationship for a single reinforcement ply with adequate resolution.

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2. Simulation set-up

The simulation details are fully explained in Ref. [9]. Briefly, an idealized and "loose" unit cell geometry is created within the Abaqus 2019 Finite Element Analysis environment. A shrinkage step then creates tensile forces in the yarns similar to those present in an actual weaving step. By tensioning the yarns, the fibers will realign and spread out, creating the typical lenticular yarn cross-sectional shapes. This results in the as-woven state of the fabric. Periodicity of the unit cell is ensured using periodic boundary conditions proposed by Green et al. [10], consisting of periodicity imposed at individual fiber ends as well as slave yarns that provide a contact surface at the unit cell edges. This is illustrated in Figure 2.

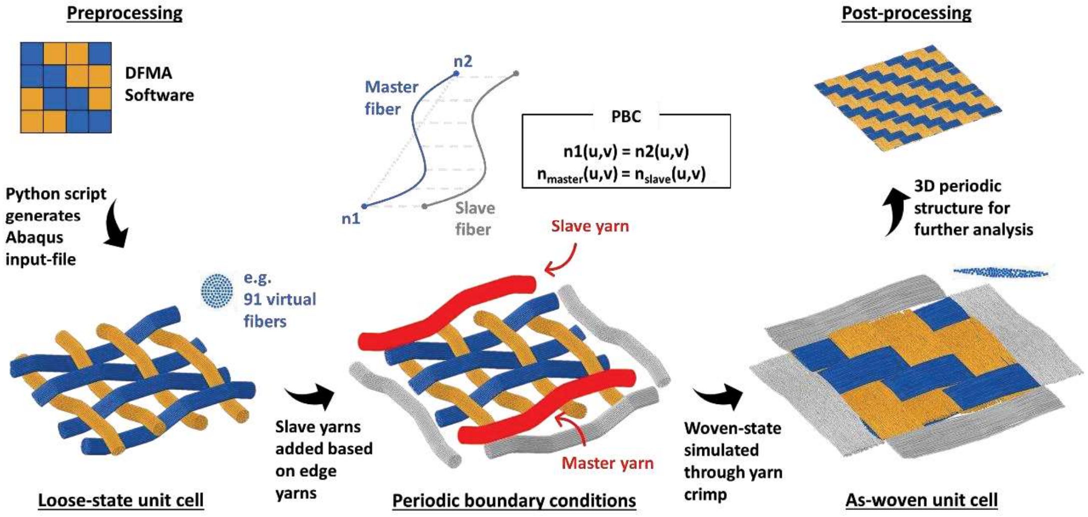

Figure 2 – Conceptual overview of the as-woven fabric generation using the virtual fiber principle and periodic boundary conditions (figure taken from Ref. [9])

Here, the virtual fibers consist of chains of linear elastic truss elements (T3D2 elements, Abaqus/Explicit) with properties representing glass fiber properties. All input properties that are used are related to actual physical and measurable parameters (see Table 1). Note that the majority of these parameters can already be found in the datasheets of the fiber and fabric material, making extended experimental characterization unnecessary. The idealized unit cell geometry is created through the Dynamic Fabric Mechanical Analyzer (DFMA, www.fabricmechanics.com) from the Fabric Mechanics group at Kansas State University (Wang et al.). The DFMA software was used only as a pre-processor; the idealized geometry is generated in DFMA and then exported through a dedicated python script to an Abaqus 2019 input file for the as-woven simulation.

Bending stiffness is imposed on the virtual fibers by overlaying the truss elements with beam elements (B31, Abaqus/Explicit) using the same nodes, see Figure 3. This creates hybrid virtual fibers in which the truss elements will determine the properties in the fiber direction (tensile stiffness), while the beam elements are chosen such that they do not affect those properties (negligible Young's modulus), but have a certain bending stiffness EI. The value of that bending stiffness can be set to the required value by changing either the Young's modulus E or the beam element radius which defines its second moment of inertia I $(=\pi r^4)$. Here we opted to fix the Young's modulus such that $E_{truss} = 100\ E_{beam}$ to suppress any effects that might rise from the stiffness of the beam elements. For the range of EI considered, the beam radius was similar to that of the truss elements, ensuring that the overall tensile stiffness of the virtual fibers was barely affected by the superimposed beam elements. The virtual fiber bending stiffness was set as follows

$$n_{vf} E_{beam} I_{vf,beam} = (EI)_{measured} \tag{1}$$

The through-thickness compression is simulated by two rigid platens (rigid shell elements R3D4, Abaqus/Explicit) which move towards each other (displacement-controlled) with the fabric reinforcement in between, see Figure 3. The simulation is performed under quasi-static conditions in Abaqus 2019 Explicit (the internal energy is much higher than the kinetic energy). Contact between the virtual fiber surfaces and their surroundings (other fibers and compression platens) is imposed on the truss elements only and is defined by Abaqus' *General Contact* algorithm. The beam elements are excluded from any contact definition as their radius is dependent on the required bending stiffness and does not represent the fiber radius, the fiber radius is equal to the truss element radius. During compression of the as-woven fabric, the reaction forces on the platens and the distance between them are used to determine the pressure-thickness and pressure-volume fraction curves. The same periodic boundary conditions as before are used.

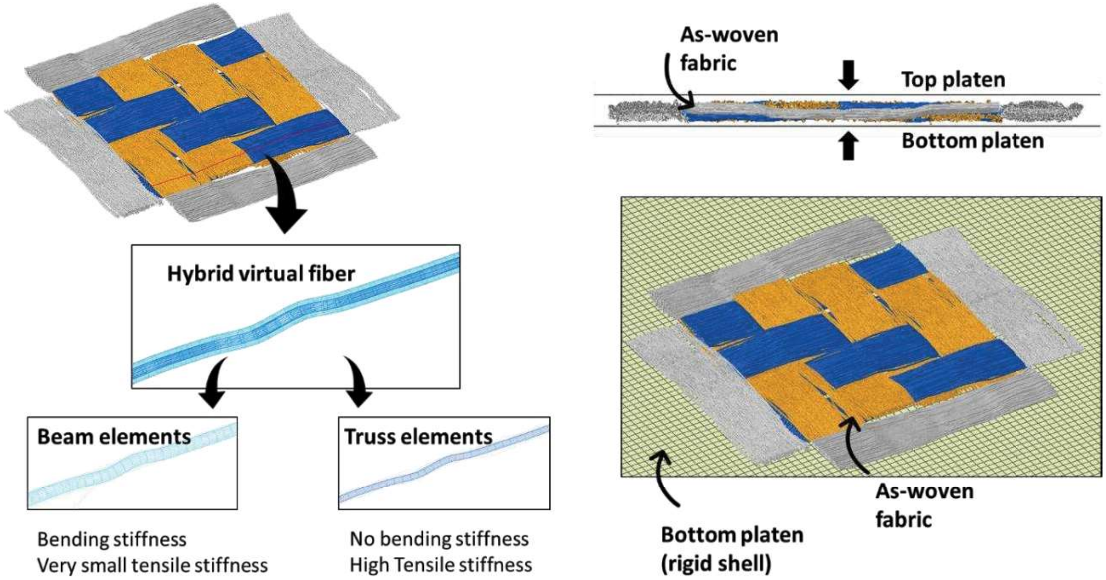

Figure 3 – (a) The fabric is constructed of hybrid virtual fibers that consist of a chain of beam elements for bending stiffness and truss element for tensile stiffness. (b) Overview of the through-thickness compression setup (figure taken from Ref. [9]).

3. Experimental details

Table 1 gives an overview of all the properties of the dry glass fiber twill fabric (Interglas 92140 aero, finish FK 144, 2x2 twill woven, 390 g/m², purchased through R&G Faserverbundwerkstoffe GmbH, Waldenbuch, Germany) that serve as input for the simulations.

Table 1 – Input properties used in the simulations.

Property	Warp	Weft	Property determination
FIBERS			
Linear density (dTex)	1.57		Measured according to ISO 1973 (vibroscope)

Average fiber diameter (µm)	8.9 (9)		Calculated from linear density and volumetric density.
Volumetric density (kg m^{-3})	(2550)		Datasheet value.
E-modulus (cN/dTex | GPa)	292 | 74.6		Measured according to ASTM D3822.
YARNS			
Linear density (Tex)	338 (340)	269 (272)	Measured according to ISO 7211-5.
Fibers per yarn (-)	2148	1708	Calculated from linear densities of yarn and fiber.
Bending stiffness (10^{-7} Nm²)	1.49	0.99	Measured according to ASTM D1388.
FABRIC			
Areal density (g m^{-2})	387 (390)		Measured.
Thread count (cm^{-1})	6.1 (6.0)	6.5 (6.7)	Measured according to ISO 7211-2.
Yarn spacing (cm)	0.164	0.154	Calculated from thread count.
Crimp (%)	0.55	0.75	Measured according to ISO 7211-3.

4. Results and discussion

The need to add virtual fiber bending stiffness to the simulation is illustrated in Figure 4 by the difference in the compression reaction force of the fabric when bending stiffness is and is not present. Simulations performed without any bending stiffness mainly show a kinematic response where initially the reaction force is predominantly determined by the ease with which the (virtual) fibers can be rearranged in the structure by the compression platens (densification). The reaction force on the platens only increases at high compression levels when fiber realignment becomes obstructed and the fibers become transversally loaded. On the other hand, when including fiber bending stiffness, the kinematics remain fairly similar, but an additional compressive reaction force is noted, especially in the low pressure range. At this stage, the platens deform the virtual fibers by bending – as well as realigning – them. The compressive response shows better agreement with the experimentally determined curve, both in terms of its shape and its position.

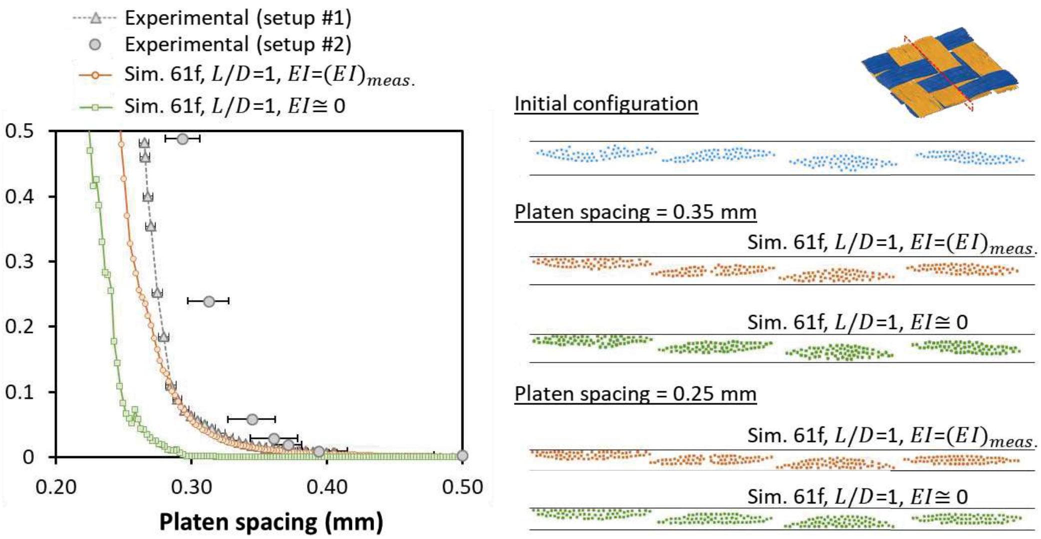

Figure 8 – Compressive response of fabric simulated with and without bending stiffness of the virtual fibers show that while kinematically similar (yarn cross-sections are visualized on the right-hand side), the mechanical response (left-hand side) is better predicted when bending stiffness is considered (figure taken from Ref. [9]: *61f means 61 virtual fibres, L/D is the truss element length over diameter ratio, and EI is the implemented bending stiffness of the virtual fibres).*

5. Conclusion

The results clearly show the potential for the virtual fiber modeling method including fiber bending stiffness as a general textile modeling framework. Taking our previous work on in-plane properties into account, the addition of out-of-plane property simulation capabilities indicates that a large range of textile-relevant loadings can be considered. This approach, fully implemented in the commercial finite element software package Abaqus using the standard element, material and contact libraries, allows research groups with FEA experience but without dedicated virtual fiber tools to implement this type of modeling. Good agreement is obtained between the experimental and the numerical determined pressure-compression behavior. The macroscopic compressive response of the fabric is well predicted for the right set of input parameters.

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