VIRTUAL FIBER MODELLING: A VIABLE MULTI-SCALE APPROACH FOR MECHANICAL MODELLING OF TEXTILE MATERIALS

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ABSTRACT

The use of fiber and textile materials poses a difficult problem for engineers in the composites sector. While these materials offer a unique mechanical performance, typically combining high mechanical properties in the fiber direction, while remaining flexible in the other directions, their mechanical behavior is non-linear and complex. New modelling tools are required for more performant virtual prototyping and testing. One of the most recent innovations in textile modelling is the virtual fiber approach which allows to include the fibrous nature of textile materials such as yarns, weaves, knits, braids, … by explicitly modelling the textile as being made up of multiple fibers. Compared to reality however, the number of fibers in the virtual fiber approach is limited to 50 – 100. Here, we propose our take on the virtual fiber modelling approach that is capable of predicting the kinematic and mechanical response of different textile structures and manufacturing processes. This approach is a predictive near-microscale (virtual fiber scale) technique for textile materials. The required input properties can usually be found in the datasheet of the fibers/yarns or are easily obtainable through experiments.

1. INTRODUCTION

The use of textile materials has seen a steady increase in technical sectors. Typically used for their high mechanical performance in certain directions while remaining flexible in other directions, textile materials offer an interesting mechanical behavior for a variety of applications. For example, coated stretchable fabrics for use in architectural design. Another example is the use of textile reinforcements for composite materials.

Textile materials have an hierarchical structure, where at the smallest scale (microscale) individual fibers are considered, these fibers are then combined into tows or yarns at the mesoscale to form a macroscopic structure like a woven or knitted fabric at the macroscale. Currently, the modelling of textile materials goes hand in hand with the homogenization of the microscale, resulting in mesoscale models where individual yarns are considered or macroscale models in which the yarn-scale is homogenized. These models certainly have their merits, but the homogenization approach necessitates input parameters that are based on experimental measurements at the yarn (meso) and fabric (macro) level. Similar to the multiscale modelling approach which is already well known for (consolidated) composite materials, the addition of (near-)microscale modelling of textile materials offers the possibility to have a virtual workflow building up from fiber, to yarn, to fabric level. In addition, as the fibers can be considered to be the building blocks of textiles, modelling at this level offer predictive simulations that mainly require input parameters measured on the fiber level, which reduces the amount of variables considerably.

The digital element modelling approach for textile materials does just that. First published by Wang et al. in 2001 [1,2], in this approach fibers are modelled using truss- or beam-like finite elements. Instead of modelling all the fibers within a yarn, which can easily exceed thousands of fibers, only a limited number of fibers is considered in the digital element approach, typically between 50 – 150. Therefor, these fibers are referred to as virtual fibers as they are larger than the physical fibers they are representing. Nevertheless, the use of virtual fibers allows to implement the typical fibrous characteristics, e.g. fiber realignment, discretization of yarn, fiber orientation, into the simulations in a natural way without requiring specific constitutive material models. The method is often also referred to as the virtual fiber modelling method, referring to the key use of virtual fibers.

Since its introduction in 2001, the virtual fiber modelling method has been successfully used in a variety of manners for different materials [3–12]. Overall, some of the major differences between all of these studies can be summarized as follows:

- Truss- or beam-like elements to make up the virtual fibers;
- Kinematics of fibers or both kinematics and mechanics of fibers;
- Physics based input parameters or input parameters derived from fitting the simulation outcome on experimental data (inverse procedure).

The results achieved using a virtual fiber approach in the past decade have shown great potential for the method to become one of the key tools in the field of textile mechanical modelling. Nevertheless, there are still some questions left unanswered in the current state-of-the-art: (i) how effective is the method in predicting mechanical properties of textile materials (virtual testing), (ii) which input parameters are required, (iii) is dedicated virtual fiber modelling software required or can the method be implemented in current commercially available finite element analysis software?

In this paper, we show our take on the virtual fiber modelling approach and try to give a concise answer to the current shortcomings and question that remain in the state-of-the-art. Therefor, the paper consist out of two major sections. First, we discuss the general simulation concept and details (e.g. element types, geometry, used software, …). Then, we discuss several cases in which the virtual fiber method is utilized to simulate a textile material and or loading that would be challenging using traditional meso- or macroscale modelling techniques.

2. SIMULATION DETAILS

2.1 Concept of virtual fiber modelling

The virtual fiber modelling concept is schematically shown in **Figure 1** for woven textile materials. The smallest feature considered is the virtual fiber, which subsequently makes up the yarn (or tow) scale, the fabric scale and the application scale. The virtual fiber method is thus capable of multiscale simulations, e.g. for modelling at the mesoscale (yarn and tow level) and at the macroscale (fabric and application level). However, the requirement of many virtual fibers, which results in even more (possible) contact points between the fibers, means that the simulations are often still limited to one or several unit cells due to computing time.

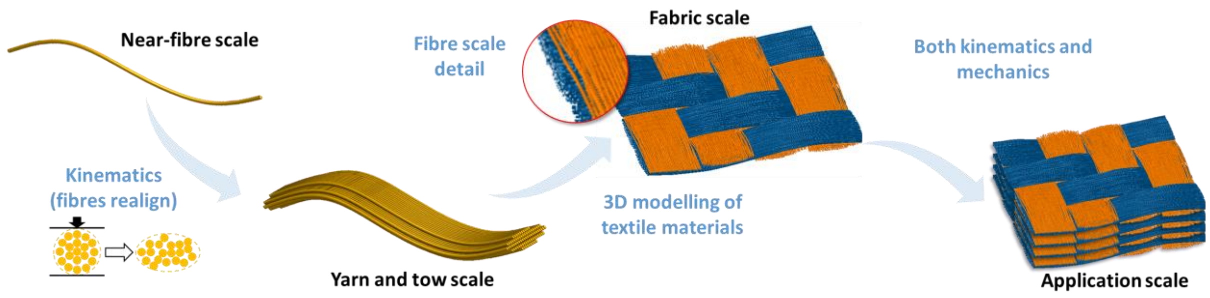

Figure 1 - Concept of the virtual fiber approach, from yarn/tow scale to fabric scale to application scale. Yarns and tows are discretized into a discrete number of virtual fibers. This way, there is no need for complex constitutive material models, rather, the fibrous behavior of the textile is implemented in a natural manner.

2.2 Implementation in finite element analysis software

Each virtual fiber typically consists of a chain of truss-, or beam-like finite elements or even a combination of both (see **Figure 2**). The elements are connected to each other by their end nodes. In comparison to traditional finite element modelling however, the "flexibility" of the virtual fiber is induced by the size of the finite elements that make up the fiber, especially in the case of truss-like elements. As no moments are transmitted between truss elements, their nodes act as frictionless pins between the elements. Hence, the chain of elements becomes flexible and its behavior represents an (ideal) string for infinitesimally short elements. For many textile materials this inherent lack of bending stiffness corresponds well with the very small bending stiffness of fibers, and even yarns. In those cases where the bending stiffness of virtual fibers should be considered, beam-like elements or hybrid elements consisting of truss- and beam-like elements are a solution. These elements are part of (almost) every commercial finite element analysis (FEA) software package, and the virtual fiber methodology can thus be implemented in current FEA software. The main requirement however is that contact can be defined on the outer radius of the truss or beam elements to enable contact between virtual fibers. In our simulations, the Abaqus Finite Element Analysis environment with an explicit solver is used.

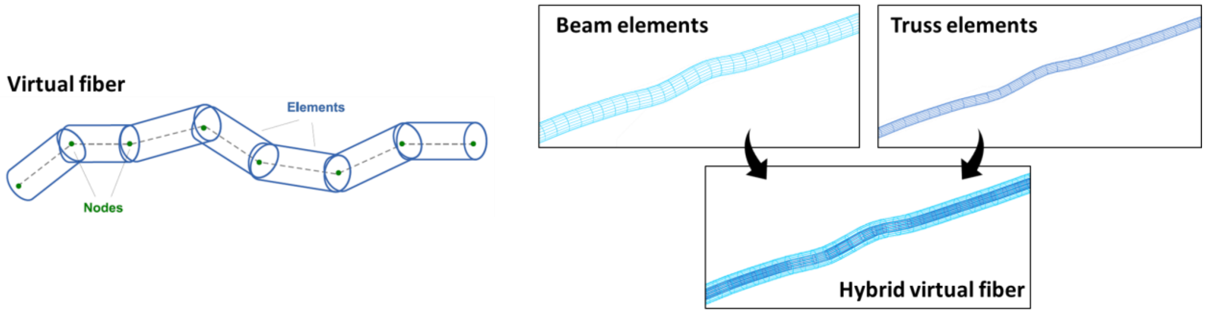

Figure 2 - A virtual fiber consist of a chain of truss- and/or beam-like elements.

Here, the virtual fibers consist of chains of linear elastic truss elements (T3D2 elements, Abaqus\Explicit) with properties representing those of the actual fiber material (e.g. glass fiber, carbon fiber, …). All input properties that are used are related to actual physical and measurable parameters (see Error! Reference source not found.**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 diameter of the virtual fibers D_{vf} (circular cross-section) is set to a value resulting in an equal cross-sectional area of the virtual and of the real yarn, A_{vy} and A_{ry}:

$$A_{vy} = n_{vf}\frac{\pi}{4}D_{vf}^2 = A_{ry} = n_{rf}\frac{\pi}{4}D_{rf}^2 \rightarrow D_{vf} \quad (1)$$

where n_{vf} and n_{ry} are the number of fibers in the virtual and in the real yarn, and, D_{rf} is the diameter of the fibers in the real yarn.

Table 1 - Typical input properties (and an example of how to determine them) required in the virtual fiber modelling method.

Property	Property determination
FIBERS	
Linear density (dTex)	Measure according to ISO 1973.
Average fiber diameter (µm)	Calculate from linear density and volumetric density.
Volumetric density (kg m-3)	Literature value.
E-modulus (cN/dTex | GPa)	Measure according to ASTM D3822.
YARNS	
Linear density (Tex)	Measure according to ISO 7211-5.
Fibers per yarn (-)	Calculate from linear densities of yarn and fiber.
Bending stiffness (10-7 Nm²)	Measure according to ASTM D1388.

2.3 Simulating as-woven microstructure of woven fabrics

Woven fabrics form a major class of engineering textile materials. In traditional modelling strategies, the initial fabric state is usually imported from experimental data (e.g. micro-computed tomography (µCT) scans) or based on idealized unit cell formulations. Using virtual fiber modeling, the initial fabric structure, here referred to as the as-woven state, can be directly simulated. And idealized "loose" state of the fabric is created based on the weaving parameters (i.e. thread count, weave schematic). A shrinkage step is applied to the virtual fibers, resulting in tensile forces in the yarns that are similar to those in the actual weaving process. The tension in the yarns results in flattening and realignment of the fibers. At the point at which the crimp of the virtual yarns equals that of the real yarns, the simulation is stopped, resulting in the as-woven state of the fabric. This is represented for a 2x2 twill glass fiber fabric unit cell (linear elastic T3D2 truss elements, Abaqus\Explicit) in **Figure 3** for three different amounts of virtual fibers per yarn. The overlay with a µCT image of the same fabric shows that the predicted microstructure corresponds well to the actual microstructure of the fabric. The boundary conditions for these simulations are relatively simple as the fiber ends are constrained not to move in the fiber direction. Periodicity of the unit cell can be ensured using periodic boundary conditions with slave yarns as detailed in Ref. [8,12].

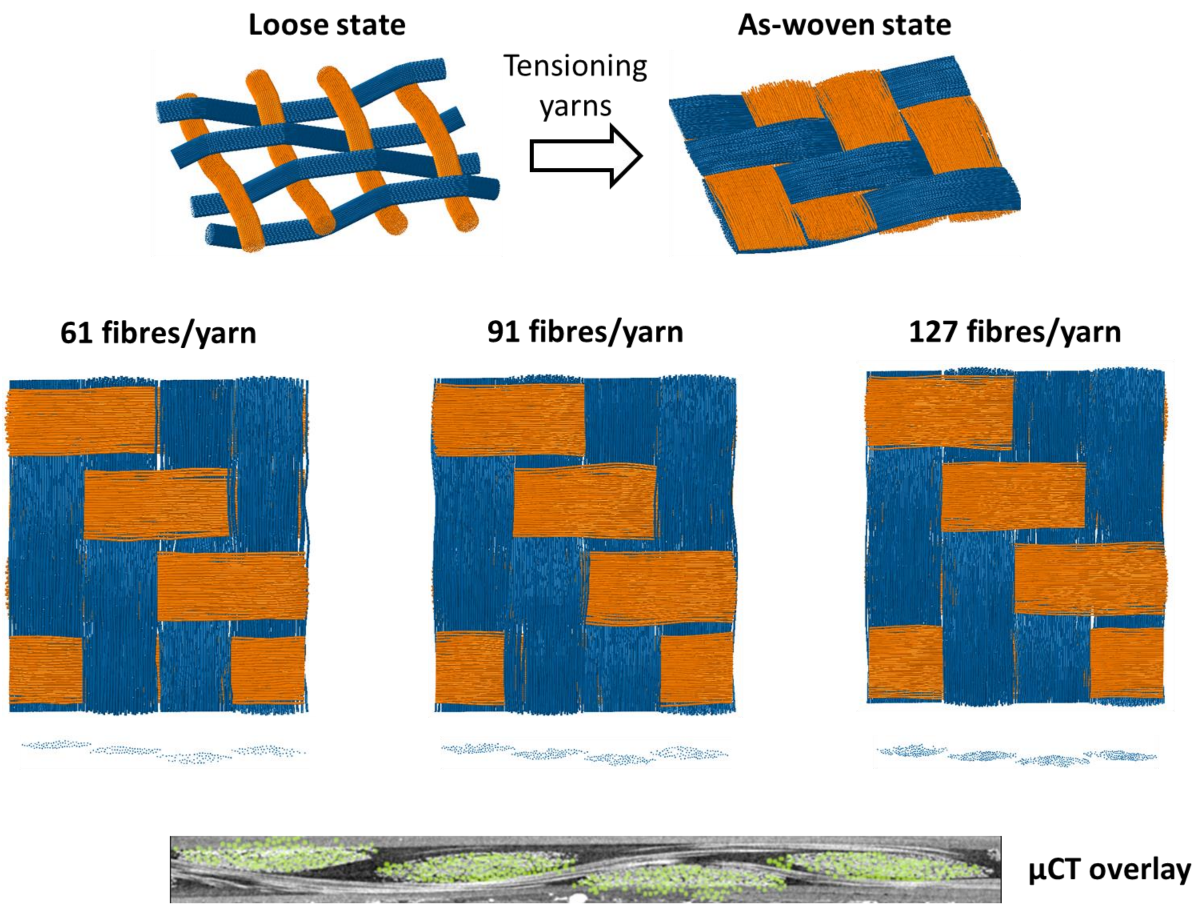

Figure 3 - The as-woven state of the fabric is modelled based on the tensioning of an idealized fabric (here a 2x2 twill weave). The results for different amounts of virtual fibers per yarn show that discretization into 61 fibers/yarn suffices to predict the overall as-woven geometry.

Comparison with a µCT scan of the fabric shows that the simulations predicts the inner microstructure of the fabric well.

3. RESULTS

3.1 Yarn behavior in textile manufacturing processes

Many textile manufacturing processes consist of interlocking yarns making up the larger-scale textile, e.g. knitting, weaving, braiding, stitching or tufting. In these processes the yarns are moved by the production machine, usually at relatively high velocities, and their (dynamic) behavior determines the quality and structure of the end product. **Figure 4** illustrates the use of the virtual fiber approach for modelling the stitching process of foam core panels (application: stitched composite sandwich panels). Here, the yarn was modelled with only one virtual fiber (i.e. the virtual fiber corresponds to the virtual yarn, neglecting any cross-sectional deformation by fiber realignment) to study the yarn path behavior during these dynamic processes. This analysis can then be extended by discretizing the yarn further into virtual fibers to incorporate cross-sectional deformations of the yarn.

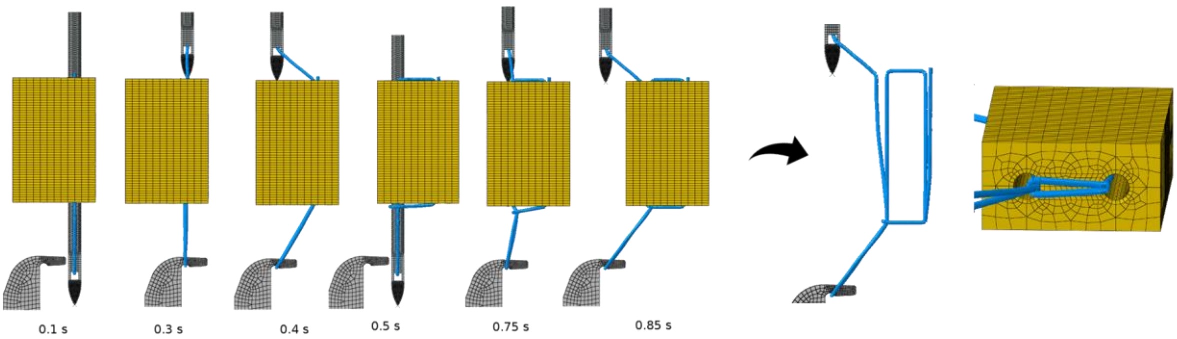

Figure 4 - Yarn behavior and final yarn path in the stitching of a foam panel.

3.2 In-plane mechanical behavior of a 3D woven fabric

The in-plane mechanical behavior is simulated for a woven fabric with a 3D architecture in which multiple layers of warp and weft yarns are interlocked by binder yarns. The 3D woven fabric is one of the architectures that were developed in the European FP7 project 3D-Light Trans and was awarded the JEC innovation Award 2015 in the Reinforcements category. It is rather complex with a unit cell consisting out of 40 weft yarns, 8 warp yarns and 8 binder yarns. The yarns consist out of glass/PET comingled fibers with a Young's modulus of approximately 30 GPa.

A more detailed discussion can be found in Ref. [3]. Briefly, the explicit solver Abaqus/Explicit is used as it is more suited to handle the complex non-linear behavior, large displacements of the virtual fibers and the large amount of contact definitions. The time-scale of the simulations is chosen in order to have a quasi-static response of the fabric without inertial effects. Each virtual fiber is made up of T3D2 truss elements with an initial length comparable to that of the yarn diameter. The experimentally determined Young's modulus of the yarn is used to define the stiffness of the truss elements. Fiber-fiber contacts were handled by Abaqus' general contact algorithm using a Coulomb friction law.

A rectangular coupon was selected from a large piece of simulated as-woven fabric in order to simulate tensile and picture frame shearing loadings. The coupon geometry, boundary conditions and results are given in **Figure 5**. The tensile coupon measured approximately 120 x 50 mm², the shearing coupon approximately 40 x 40 mm². There is good agreement between the force versus elongation curves obtained in the experiment and in the simulations. This indicates that the virtual fiber method accurately captures the yarn mechanics for fabrics under tension and shearing, e.g. (i) yarn/yarn contact, (ii) yarn/yarn sliding, (iii) yarn tensioning, (iv) fiber realignment, (v) fabric compaction, and (vi) shear locking of the fabric. They are responsible for the highly non-linear behavior of load-displacement curve. This results in a relatively low stiffness behavior at small strains of the 3D fabric. At higher strains, the response of the fabric changes due to straightening of the warp yarns for the tensile locking and shear locking of the yarns for the shear loading, resulting in an overall stiffer response.

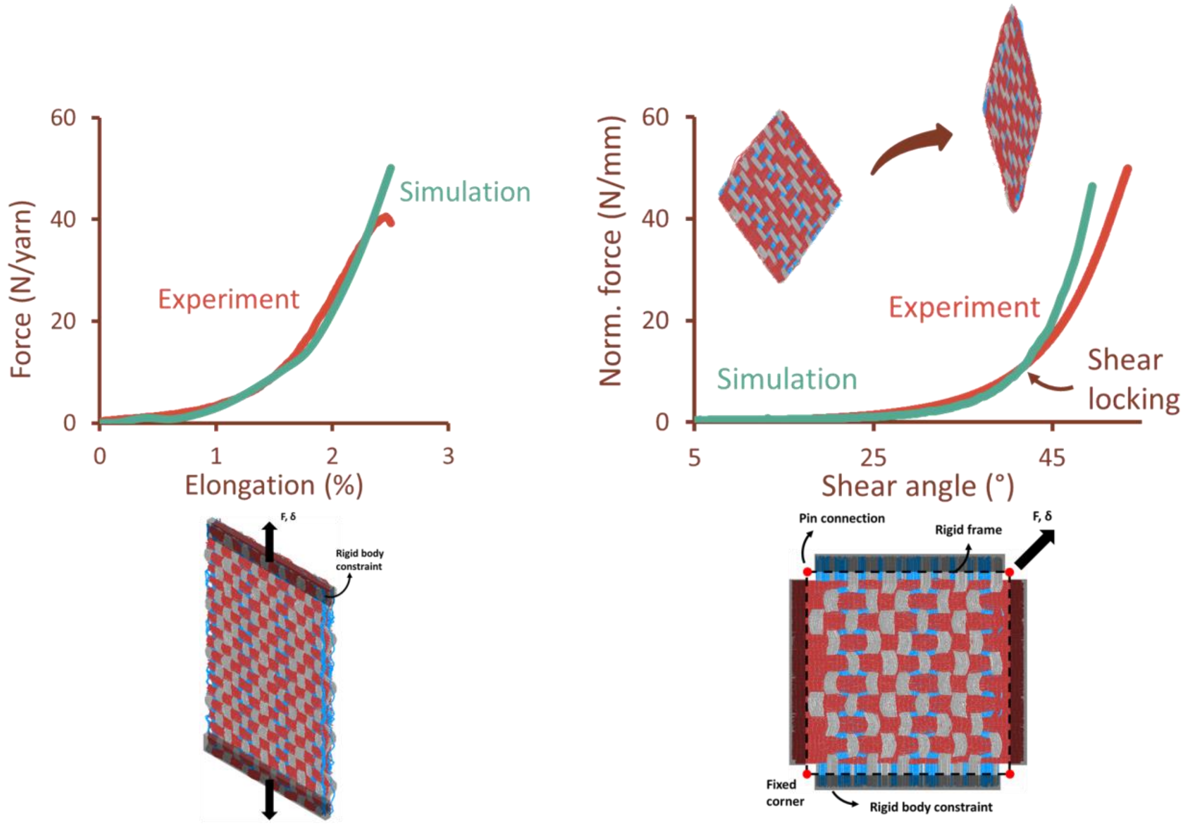

Figure 5 - Tensile test simulation and the resulting force versus elongation diagram (left). Picture frame simulation and the resulting force versus shear angle diagram (right).

3.3 Out-of-plane mechanical behavior of a 2D woven fabric

One of the important out-of-plane properties for fabrics is their through-thickness compression. This property is for example crucial in Liquid Composite Molding manufacturing processes where a dry reinforcement fabric is infused with liquid resin. The pressure of the mold changes the microstructure, and thus permeability, of the reinforcement which affects the quality of the final composite product. In comparison to in-plane loadings such as tensile and shearing (Section 3.2), the through-thickness compression is not dominated by (tensile) stresses in the yarn directions. Rather, it is dominated by fiber realignment, fiber (and yarn) bending and transversal compaction.

Figure 6 shows the simulated through-thickness response for a 2x2 twill glass fiber woven fabric simulated using the virtual fiber approach with 61 fibers per yarn. Two simulation cases where considered, one without implementation of bending stiffness of the fibers (using only T3D2 truss elements) and one with implementation of bending stiffness (using hybrid virtual fibers consisting of a superposition of truss T3D2 and beam B31 elements). The results clearly illustrate the need for implementing bending stiffness when out-of-plane loads are considered as only the simulated response with bending stiffness included corresponds well to the experimentally determined response. The pressure-thickness curves show that the major effect of implementing bending stiffness is in the low compaction / low pressure region. In this region, the fibrous mechanics consist of fiber and yarn bending and realignment. At later stages, the fibers are compacted to such a degree that realignment becomes less prominent and higher through-thickness compression stresses can develop by transversal compaction of the fibers.

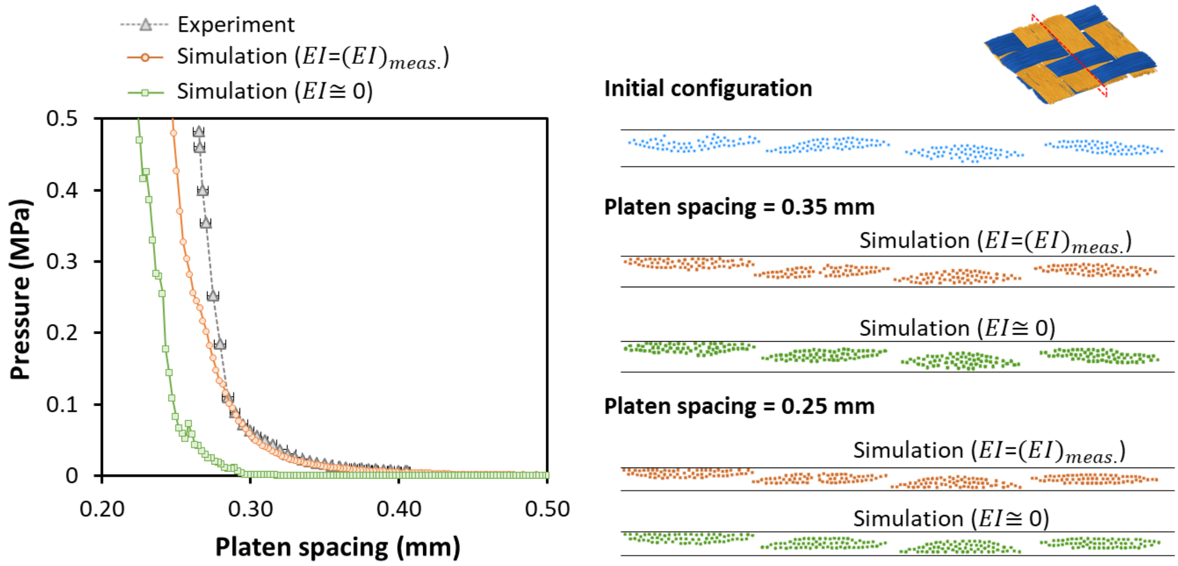

Figure 6 - Compressive response of fabric simulated with and without bending stiffness of the virtual fibers show that while kinematically similar (yarn cross-sections are visualized on the right-hand side), the mechanical response (left-hand side) is better predicted when bending stiffness is considered.

4. CONCLUSIONS

Virtual fiber modelling has great potential to become a staple methodology for modelling textile materials. As each yarn is discretized into multiple virtual fibers, the fibrous nature is incorporated in a natural manner. The virtual fibers themselves are made up from a chain of truss- and/or beam-like elements. The input parameters required for the simulations are easily obtainable and often already present in the material's datasheet. The method is shown to capture both the kinematics (e.g. fiber realignment, yarn path behavior, …) as well as the mechanics (e.g. in-plane loadings such as shear and tension, out-of-plane loadings such as through-thickness compression). Since the simulations are predictive, they can be used for virtual prototyping and virtual testing of many textile materials.

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