VIRTUAL MECHANICAL TESTING OF A COMPLEX 3D WOVEN FABRIC: A UNIFIED SIMULATION METHODOLOGY FOR DEFORMATION MECHANICS OF TEXTILE STRUCTURES DURING TENSION, SHEAR AND DRAPING

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Abstract

The most common method of modelling the behaviour of fibrous materials such as yarns and woven fabrics, is to treat them as continuous solids. The fibrous behaviour is then taken into account by appropriate constitutive laws. These constitutive laws are however very difficult to develop due to the complex behaviour (non-linearity, large displacements, anisotropy, crushing, …). Here, we show a more viable simulation methodology which allows for the virtual testing of fibrous materials. In this method, yarns are modelled as a bundle of (virtual) fibres which can realign themselves. Hence, the fibrous behaviour is taken into account in a very natural manner. The methodology is applied to study the mechanical behaviour of a complex 3D woven fabric under tensile and shear loadings. This allows for the virtual determination of tensile and shearing properties of the fabric without the need to produce or test the actual fabric. Especially in the case of 3D woven fabrics, where production and testing can be costly and time-consuming, virtual testing can result in large cost-savings. Furthermore, the proposed method is very versatile and we show that it can also be used for weaving, stitching and draping simulations when high detail is required.

1. Introduction

Recently, the use of 3D woven fabrics as the reinforcement for structural composites has gained a lot of interest in the composites community. As compared to traditional composite laminates, which are made by a stacking of 2D fibre architectures and have relatively low out-of-plane properties, 3D woven fabrics provide a reinforcement in the through-the-thickness direction. This results in higher out-of-plane properties compared to 2D fabric based composites and it can increase the delamination resistance [1]. Furthermore, the technique of 3D weaving enables the production of relatively thick reinforcements with fibres aligned in each of the three major directions, making the tedious and time-consuming process of stacking plies redundant. Combined with the continuous production of these reinforcements on weaving machines, the production of structural composites based on 3D woven fabrics can result in serious cost savings and fast production processes.

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A numerical framework which has the capability to simulate and predict the as-woven geometry of the 3D fabric and its behaviour under loadings such as tension and shear in a realistic manner would be a helpful tool in order to optimise the 3D fabric architecture for composite applications. However, the numerical modelling of 3D woven fabrics, and textile materials in general, is very complex due to their fibrous constitution and multi-scaled nature. Recently, a viable method of modelling textile materials has gained a lot of attention: the digital element method [2–14]. It was first developed by Wang et al. [7,8] and is based on the concept of virtual fibres. Instead of treating yarns as continuous materials, the yarn is divided into several virtual fibres. Although the amount of virtual fibres is usually smaller than the actual amount of fibres in a real yarn, the method is still able to capture the fibrous behaviour of the yarns in a very realistic and natural manner.

In this article, a numerical modelling methodology based on the concept of virtual fibres is proposed to simulate as-woven geometries and yarn mechanics in dry fabrics. The method allows for virtual testing of very complex fabrics and it is applied to a 3D woven fabric with a relatively complex internal architecture.

2. Modelling approach

The basic approach that is followed in this article to simulate the as-woven structure and yarn mechanics is shown in Figure 1. It consists out of following steps:

1) A piece of fabric is rendered according to an idealised unit cell by a Python script and written to an Abaqus input file. The yarns are assumed to have a circular cross section by default. An idealised "loose" fabric is then generated.
2) The as-woven fabric is generated in Abaqus/Explicit by applying a thermal crimp to the binder yarns in the idealised fabric similar to the approach followed by Green et al. [3]. This results in tensioning and realigning of the fibres similar to a realistic weaving process.
3) A Python script uses the as-woven geometry of the fabric in order to "cut out" coupons which are used to simulate mechanical tests, much like the experimental process in which coupons are also cut from a larger piece of fabric.

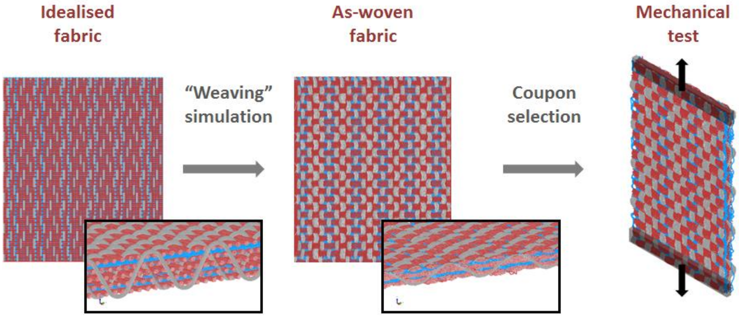

Figure 1. Followed modeling approach.

All simulations are done with the finite element analysis software Abaqus 6.14©. The explicit solver Abaqus/Explicit is used as it is more suited to handle the complex non-linear behaviour, large displacements of the virtual fibres 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 fibre 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. Fibre-fibre contacts were handled by Abaqus' general contact algorithm using a Coulomb friction law.

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3. 3D woven fabric architecture

The fabric under consideration has 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. The idealised unit cell (UC) and fabric architecture are shown in Figure 2. The 3D woven fabric under consideration is rather complex with a UC consisting out of 40 weft yarns, 8 warp yarns and 8 binder yarns. The yarns consist out of glass/PET comingled fibres with a Young's modulus of approximately 30 GPa.

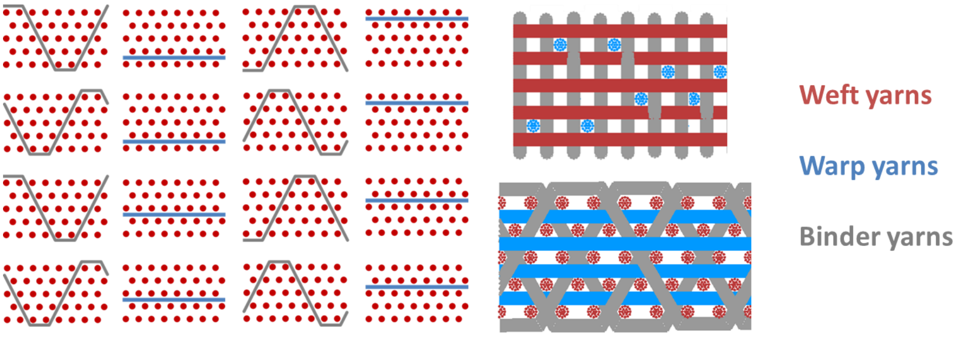

Figure 2. unit cell architecture of the 3D woven fabric under consideration.

4. As-woven simulation

A relatively large piece of fabric consisting out of 6x6 unit cells is used in order to generate a relatively large piece of as-woven fabric. The microgeometry of the as-woven fabric is simulated by fixing the nodes at each yarn end in all degrees of freedom, while applying a crimp to the binder yarns. The crimping process generates a tensile stress in the binder yarns making them contract which in turn compacts the fabric. At the same time, the circular cross-sections of the yarns are deformed due to the realignment of the fibres due to tension in the yarns and contact with other fibres. Since the warp and the weft yarns are initially straight, they are allowed to expand in order to compensate for the longer yarn length due to the waviness of the yarns after weaving. The boundary conditions that were used result in a relatively small zone of edge effects. These zones where not used for subsequent simulations and hence posed no problem.

The microgeometry of the simulated as-woven fabric was compared with micro-CT images of the 3D woven fabric. The thermal expansion coefficients of the crimping process were subsequently adjusted if necessary in order to improve the agreement between the real and simulated microstructure. Two iterations were necessary for the fabric under consideration. The microstructure of the simulated fabric showed good agreement with micro-CT images of the real fabric, see Figure 3. The curvature of the yarn paths is accurately captured by the simulations. Furthermore, since the microgeometry of the fabric can be studied at any point during the simulation, one can link the microgeometry to the applied yarn tension. Thus, the weaving process can be optimised based upon the results of these simulations.

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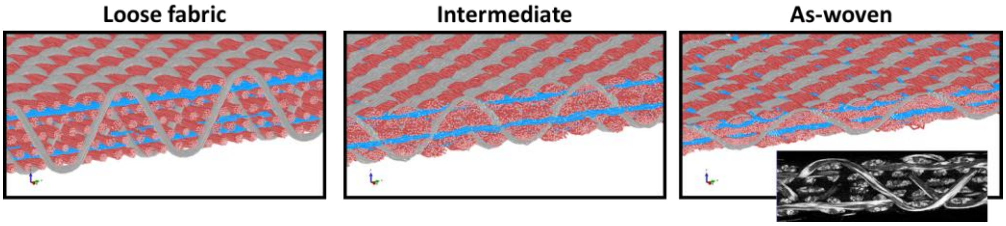


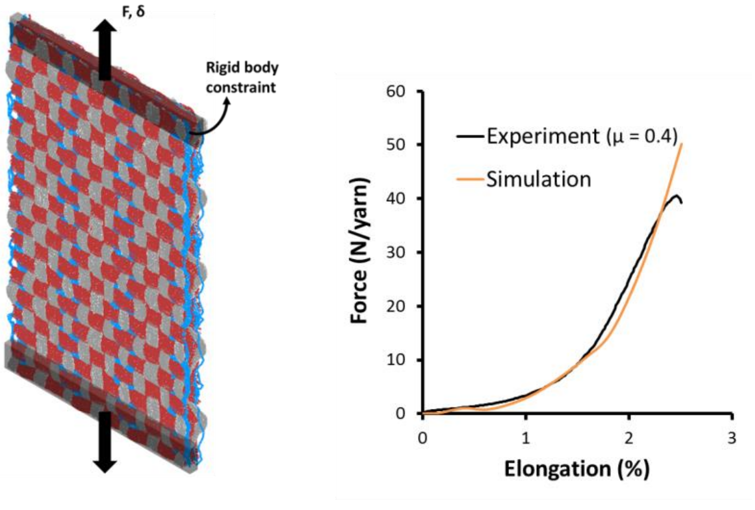
Figure 3. Generation of the as-woven fabric by crimping the binder yarns.

5. Virtual mechanical testing

5.1 Uniaxial tension

A rectangular coupon was selected from the as-woven fabric in order to perform tensile simulations. The coupon geometry and boundary conditions are given in Figure 4a. In accordance with the experimental procedure for 3D woven fabrics where clamped coupon ends are embedded in epoxy in order to transfer the load from the tensile machine to the fabric, a rigid body constraint was applied to all the elements that were present in the clamped area. Tensile stress was then applied to the fabric by a displacement of the rigid ends in opposite direction, while disabling their movement in the other directions. The coupon had a size of approximately 120 x 50 mm which corresponds to about 4.5 x 3 unit cells.

The force versus elongation curves obtained in the experiment and simulation are shown in Figure 4b. There is good agreement with the experimental data, indicating that the virtual fibre concept accurately describes the yarn mechanics for fabrics under tension. These yarn mechanics include (i) yarn/yarn contact, (ii) yarn/yarn sliding, (iii) cross-section deformation due to realigning fibres, and (iv) fabric compaction due to yarn tension. They are responsible for the highly non-linear behaviour of the fabric under tensile loadings. As the yarns in the warp direction had high undulations in the as-woven fabric, they realign themselves in the direction of load at small elongations. This results in a relatively low stiffness behaviour at small elongations of the 3D fabric. At higher elongations of 1 – 1.5%, the response of the fabric changes, resulting in a higher observed stiffness.



(a) (b)

Figure 4. Tensile test simulation (a) and the resulting force versus elongation diagram (b).

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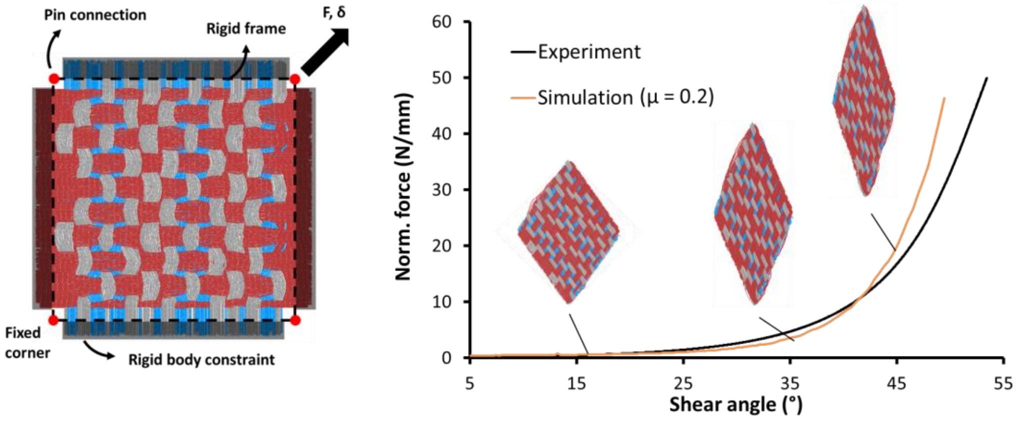
5.2 Shearing: picture frame

The picture frame shearing experiment consists out of a rigid frame with hinged connections in its corners. A square piece of fabric is clamped in the frame. By displacing the frame corners, shear is applied to the fabric. In order to have good load transfer to the fabric without compressing it, the clamped edges of the fabric were embedded in epoxy resin before clamping. The arm length is slightly larger than the specimen length in order not to restrict movement of the yarns in the corners which would result in an underestimation of the shear locking angle. The simulations were performed on a smaller piece of fabric in order to reduce computational costs. In order to compare picture frame data from frames with different sizes, e.g. simulation versus experiment, the reaction force was normalised by the coupon length according to Ref. [15]. The shear angle was measured by the displacement of the frame. The boundary conditions for the picture frame simulations are illustrated in Figure 5a. The frame was modelled by applying a rigid boundary condition to all the truss elements that are clamped in the frame. The rigid bodies were connected to each other with a pin connection allowing rotation in the plane of the frame. The bottom left corner of the frame was fixed in space, while the opposite corner was displaced in order to produce shear loading in the fabric. All rigid bodies and pin connection nodes were allowed to move in the in-plane direction, but were fixed in the out-of-plane direction. No boundary conditions were however applied to the unclamped fabric allowing freedom in all directions. The reaction force on the corner node is compared with the experimentally determined one. A preload was applied to the fabric in the experiments due to the clamping mechanism of the picture frame [16,17]. This preloading was mimicked in the simulations by applying a small crimp to the unclamped elements before shearing.

The results of a typical picture frame simulation are illustrated in Figure 5b. No wrinkling of the 3D woven fabric was observed during the simulations and experiments even at very high shear angles. This is probably due to the inherent thickness and 3D woven architecture of the fabric which increases the bending stiffness of the fabric considerably compared to 2D fabrics where wrinkling is often observed at high shearing angles. The reaction force on the picture frame is relatively low until shear locking takes place in the fabric. At a certain angle of shear, the yarns become restricted in their in-plane movement due to their neighbouring yarns, and the reaction force on the picture frame rises quickly, i.e. shear locking takes place. Good agreement of the shearing behaviour was observed for the simulation. Similar to the tensile tests, this indicates that the simulation method with truss element-based virtual fibres accurately describes the yarn mechanics under shear loading for the 3D woven fabric under consideration. These include for example (i) yarn/yarn contact, (ii) yarn/yarn sliding, (iii) yarn tensioning, (iv) fibre realignment, (v) fabric compaction, and (vi) shear locking of the fabric.



(a) (b)

Figure 5. Picture frame simulation (a) and the resulting force versus shear angle diagram (b).

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5.3 Draping

A typical draping simulation was performed with a hemispherical punch (50 mm radius). However, this required a relatively large coupon size for the 3D woven fabric, which led to very high computational costs. Therefore, we decided to perform the draping simulations on a hypothetical 2x2 plain weave fabric with similar yarns to the ones used for simulating the 3D woven fabric. This reduced the computational costs substantially which made it possible to perform the whole draping simulation. A relatively loose woven structure was generated in order to allow high shearing angles during draping. Only one quarter was simulated due to symmetry of the problem. The nodes of the fibre ends were fixed in the symmetry plane similar to conventional symmetric boundary conditions. The hemispherical punch was modeled as a rigid body and was moved in the directions transverse to the fabric. Figure 6 shows the simulated fabric after draping. This shows that the simulation captures the typical fabric deformations expected during draping.

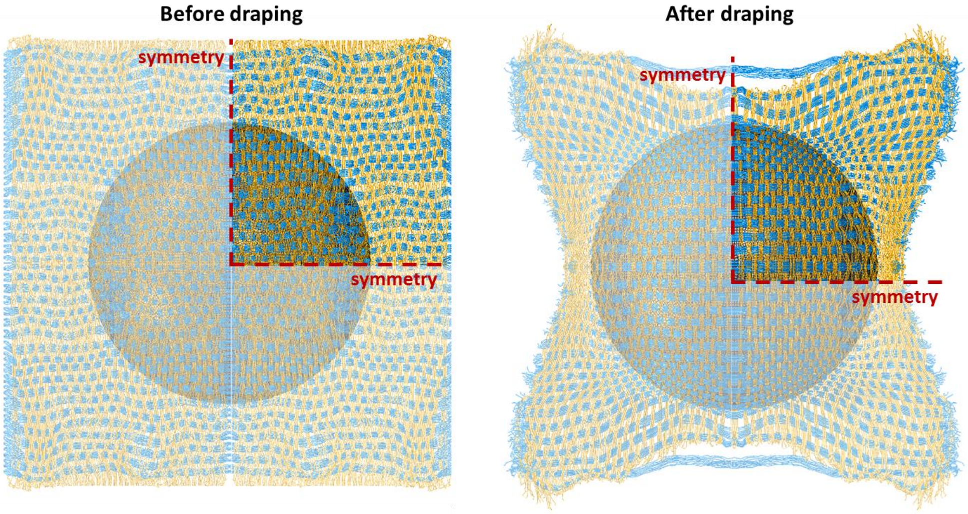

Figure 6. Resulting fabric morphology before and after draping simulation.

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6. Conclusion

A simulation methodology based on the concept of virtual fibres was applied to model the as-woven microgeometry and yarn mechanics in a complex 3D woven fabric. By using virtual fibres consisting out of chains of truss elements, realistic material properties can be used without affecting the flexibility of the virtual fibres. It was seen that this method provides very good agreement with experimental results indicating that the method takes the fibrous behaviour of fabrics into account in a very natural and realistic manner. The proposed simulation methodology provides a viable and versatile way for the virtual testing of 3D woven fabrics, and textile materials in general.

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References

[1] Gerlach R, Siviour CR, Wiegand J, Petrinic N. In-plane and through-thickness properties, failure modes, damage and delamination in 3D woven carbon fibre composites subjected to impact loading. Composites Science and Technology 2012;72:397–411. doi:10.1016/j.compscitech.2011.11.032.

[2] El Said B, Green S, Hallett SR. Kinematic modelling of 3D woven fabric deformation for structural scale features. Composites Part A: Applied Science and Manufacturing 2014;57:95–107. doi:10.1016/j.compositesa.2013.11.006.

[3] Green SD, Long AC, El Said BSF, Hallett SR. Numerical modelling of 3D woven preform deformations. Composite Structures 2014;108:747–56. doi:10.1016/j.compstruct.2013.10.015.

[4] Green SD, Matveev MY, Long AC, Ivanov D, Hallett SR. Mechanical modelling of 3D woven composites considering realistic unit cell geometry. Composite Structures 2014;118:284–93. doi:10.1016/j.compstruct.2014.07.005.

[5] Huang L, Wang Y, Miao Y, Swenson D, Ma Y, Yen C-F. Dynamic relaxation approach with periodic boundary conditions in determining the 3-D woven textile micro-geometry. Composite Structures 2013;106:417–25. doi:10.1016/j.compstruct.2013.05.057.

[6] Mahadik Y, Hallett SR. Finite element modelling of tow geometry in 3D woven fabrics. Composites Part A: Applied Science and Manufacturing 2010;41:1192–200. doi:10.1016/j.compositesa.2010.05.001.

[7] Wang Y, Sun X. Digital-element simulation of textile processes. Composites Science and Technology 2001;61:311–9. doi:10.1016/S0266-3538(00)00223-2.

[8] Zhou G, Sun X, Wang Y. Multi-chain digital element analysis in textile mechanics. Composites Science and Technology 2004;64:239–44. doi:10.1016/S0266-3538(03)00258-6.

[9] Wang Y, Miao Y, Swenson D, Cheeseman BA, Yen C-F, LaMattina B. Digital element approach for simulating impact and penetration of textiles. International Journal of Impact Engineering 2010;37:552–60. doi:10.1016/j.ijimpeng.2009.10.009.

[10] Miao Y, Zhou E, Wang Y, Cheeseman BA. Mechanics of textile composites: Micro-geometry. Composites Science and Technology 2008;68:1671–8. doi:10.1016/j.compscitech.2008.02.018.

[11] Durville D. Contact-friction modeling within elastic beam assemblies: an application to knot tightening. Computational Mechanics 2012;49:687–707. doi:10.1007/s00466-012-0683-0.

[12] Durville D. Simulation of the mechanical behaviour of woven fabrics at the scale of fibers. International Journal of Material Forming 2010;3:1241–51. doi:10.1007/s12289-009-0674-7.

[13] Ganghoffer J-F, Pastrone F, editors. Mechanics of Microstructured Solids. vol. 46. Berlin, Heidelberg: Springer Berlin Heidelberg; 2009. doi:10.1007/978-3-642-00911-2.

[14] Laurent CP, Durville D, Mainard D, Ganghoffer J-F, Rahouadj R. A multilayer braided

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scaffold for Anterior Cruciate Ligament: mechanical modeling at the fiber scale. Journal of the Mechanical Behavior of Biomedical Materials 2012;12:184–96. doi:10.1016/j.jmbbm.2012.03.005.

[15] Harrison P, Clifford MJ, Long AC. Shear characterisation of viscous woven textile composites: a comparison between picture frame and bias extension experiments. Composites Science and Technology 2004;64:1453–65. doi:10.1016/j.compscitech.2003.10.015.

[16] Cao J, Akkerman R, Boisse P, Chen J, Cheng HS, de Graaf EF, et al. Characterization of mechanical behavior of woven fabrics: Experimental methods and benchmark results. Composites Part A: Applied Science and Manufacturing 2008;39:1037–53. doi:10.1016/j.compositesa.2008.02.016.

[17] Launay J, Hivet G, Duong A V., Boisse P. Experimental analysis of the influence of tensions on in plane shear behaviour of woven composite reinforcements. Composites Science and Technology 2008;68:506–15. doi:10.1016/j.compscitech.2007.06.021.

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