NEAR-MICROSCALE MODELLING OF DRY WOVEN FABRICS UNDER IN-PLANE SHEAR LOADING

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ABSTRACT

This article proposes a near micro-scale modelling technique to predict nonlinear shear behaviour of dry woven fabrics in a picture frame test using the digital element method. In the proposed model, the fabric yarns are modelled as bundles of virtual fibres that are then modelled by the truss elements in finite element code. Additionally, our finite element analysis was performed in a repeated unit cell and the contact friction among the fibres is explicitly considered. Especially, we proposed so-called enhanced periodic boundary conditions to capture the mechanical behaviour of fabrics both in the small and large shear angle regimes.

Key Words: PERIODIC BOUNDARY CONDITIONS, FABRIC SHEAR HOMOGENIZATION

1. INTRODUCTION

Woven fabrics have recently received considerable attention because they are involved in different types of structures and materials. A woven fabric is made by interlacing the so-called warp and fill yarns into a certain weave pattern. Classical weave patterns are plain, twill and satin. Indeed, the woven fabric materials have a hierarchically multi-scale nature, i.e., the fabric is composed of the yarns and the yarns are composed of a number of fibres. Therefore, mechanics of woven fabrics can be addressed at three different scales, i.e., the fabric level or macro-scale, yarn level or mesoscale, and fibre level or micro-scale [1]. As a consequence, multiscale modelling is an eligible technique to provide a realistic description of the mechanical behaviour of this kind of materials.

In the literature, woven fabrics can be modelled as an anisotropic shell or membrane structure at the macro-scale. One of the material constitutive laws dedicated to woven fabrics was the hyperelasticity model for 3D woven fabrics proposed by Charmetant et al. [2]. That material model was used to simulate a deep drawing with a hemispherical punch. Compared with the experimental data, that model can provide reasonable results, but discrepancies between them are still visible. At the mesoscale, numerical models of woven fabrics are extensive. There are three different factors that are decisive for the performance of these models, viz., the accuracy of the fabric yarn geometry, material law for the yarns and boundary conditions. In particular, contact between yarns plays a crucial role to predict the behaviour of dry woven fabrics. Thus, the contact surfaces have to be described precisely. Moreover, the constitutive law for the fabric yarn must account for the fibrous and discontinuous nature of the fabric yarns. Charmetant et al. [3] have proposed a material constitutive law for fabric yarns within the hyperelasticity framework. To calibrate this model, a sequence of tests to characterize the aforementioned deformation modes are involved and the parameter identification is not straightforward. Regarding the boundary condition for mesoscale models, the periodic boundary conditions (PBCs) are de facto used. By using these conditions, it is ensured that the displacements among repeated unit cells (RUCs) are continuous and the traction distributions on the opposite faces of any RUC are always the same. Although modelling woven fabrics at the mesoscale is promising and the assumption of variable yarn cross section along the yarn path is a good approach to capture the realistic geometry of woven fabrics, its application for complex fabric structures is limited. Indeed, the yarn shape is affected by the reorganization of the fibre at the micro-scale during loading. Thus, woven fabric geometry can be better captured at the micro-scale, i.e., fibre scale.

The pioneering work in numerical modelling of woven fabrics at micro-scale, i.e., fibre scale, was proposed by Wang and Sun to determine the geometry of 3D braided fabrics [4]. Those authors referred to their method as the digital element method. There are three main concepts in this method, viz., digital fibre, digital yarn, and contact element. While the digital yarn is composed of a bundle of digital fibres, the digital fibre is composed of a sequence of cylinder bars, which are linked by frictionless pins. In order to find the fabric micro geometry, the fabric topology and the targeted yarns prestresses are specified. The prescribed fabric configuration might not be in equilibrium. Such configuration can be efficiently found by using the explicit integration scheme [5]. Moreover, the fabric yarns are composed of hundreds or thousands of fibres in micro-scale. It is thus extremely computationally expensive if all the fibres are included in the model. However, it is not the case when the digital element method is used. In the work of Miao et al. [6], a model that has 19 fibres per yarn was sufficient to predict a 3D braided fabric micro-geometries. In this context, a digital fibre does not represent a single physical fibre, but for a cluster of physical fibres. A similar approach was also proposed by Durville [1]. Recently, Doebrich et al. have used this approach to model the mechanical properties of textile composites. Good results have been reported in [7].

In the present work, we employ the digital element method to simulate the nonlinear shear behaviour of dry woven fabrics in a picture frame test. Additionally, we propose so-called enhanced PBCs to account for the discrete nature of fabric yarns. The outline of this article is as follows. In the next section, the PBCs and the numerical homogenization within finite deformation framework are briefly recalled. Afterwards, simulation of Chomarat 150TB woven fabric under shear load is presented. The article ends with some concluding remarks.

2. ELEMENTS OF THE RUC-BASED HOMOGENIZATION TECHNIQUE

The core of multiscale modelling is the RUC-based homogenization technique. Using this technique the strain from the coarse scale (i.e., the macro-scale) can be transferred to the fine scale (i.e., the micro/mesoscale) as boundary conditions. In return, the stress of the coarse scale can be obtained from the stress fields in the fine scale by using a certain homogenization scheme. In this work, we use PBCs and the numerical homogenization method to exchange information between coarse and fine scales.

2.1 Periodic boundary conditions

In practice, PBCs are normally applied to the opposite surface of the RUC. By using these boundary conditions, the spatial periodicity of the material points on surfaces ABB_1A_1 and BB_1C_1C are respectively linked to the other surfaces DCC_1D_1 and AA_1D_1D and the control points 1, 2, and 3 (cf. fig.) as follows:

$$\boldsymbol{u}^{ABB_1A_1} = \boldsymbol{u}^{DCC_1D_1} - \boldsymbol{u}^1 + \boldsymbol{u}^3 \qquad (1)$$

$$\boldsymbol{u}^{BB_1C_1C} = \boldsymbol{u}^{AA_1D_1D} - \boldsymbol{u}^1 + \boldsymbol{u}^2 \qquad (2)$$

The displacements of the corners 1, 2 and 3 are related to the macroscopic deformation gradient $\boldsymbol{F^M}$ as:

$$\boldsymbol{u^p} = \boldsymbol{x^p} - \boldsymbol{X^p} = (\boldsymbol{F^M} - \boldsymbol{I}) \cdot \boldsymbol{X}^p, \qquad p = 1, 2, 3 \qquad (\mathbf{3})$$

where $\boldsymbol{X}^p$is the position vector of the corner p in the initial configuration and $\boldsymbol{I}$ is the second identity order tensor. The Eqs. (1) and (2) can be implemented in ABAQUS by using the linear equation constraint, in which the value of the last two terms of the right hand side will be imposed as displacements of the control points. Moreover, to impose the shear deformation to the RUC, control point 2 is rotated clockwise around control point 1, while control point 3 is rotated clockwise around control point 1. It is assumed that the fabric yarns are not stretched and only fabric shear happens during the deformation in the picture frame test. Therefore, the distances between the control points are kept constant during the course of the rotation.

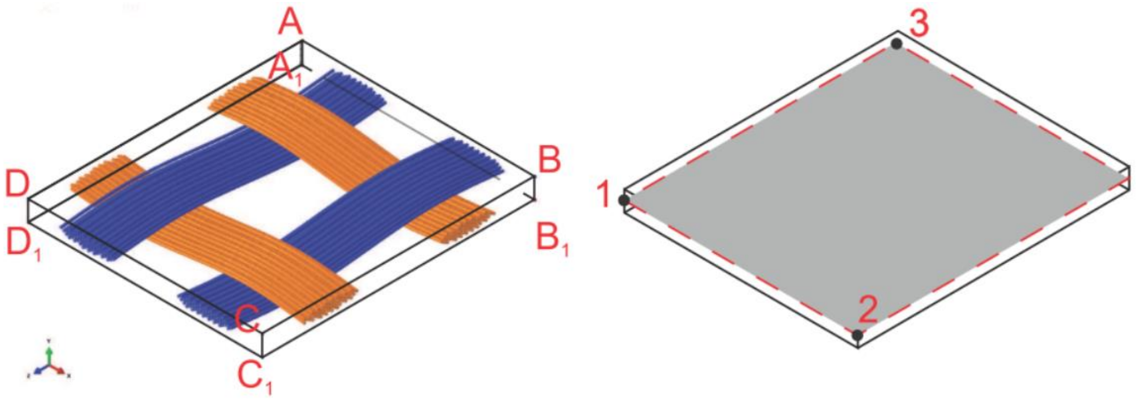

Figure 1: A repeated unit cell of the Chomarat 150 and the position of the reference points, which are used to impose the boundary conditions.

2.2 Numerical homogenization method for woven fabric materials within the finite deformation framework

The averaged RUC stress tensor can be calculated from the stress field $\boldsymbol{\sigma}(\boldsymbol{x})$ in the RUC as follows:

$$\overline{\boldsymbol{\sigma}} = \frac{1}{v_{RUC}} \int \boldsymbol{\sigma}(\boldsymbol{x}) dv \,, \tag{4}$$

where v_{RUC} is the deformed volume of the RUC. This integration can be done numerically with respect to the used element type and element geometry. However, this approach is not numerically efficient. Indeed, by using the divergence theorem and exploiting the equilibrium condition, the Eq. (4) can be expressed as:

$$\overline{\sigma}_{ij} = \frac{1}{v_{RUC}} \int f_j x_i da \,, \tag{5}$$

where $\boldsymbol{f}$ and $\boldsymbol{x}$ are respectively the traction and position vectors of material points in the surface of the RUC. This equation can be further simplified as follows [8]:

$$\overline{\sigma}_{ij} = \frac{1}{v_{RUC}} \int f_j x_i da = \sum_{p=1}^{3} f_j^p x_i^p \,, \tag{6}$$

where $\boldsymbol{f}^p$ and $\boldsymbol{x}^p$ are respectively the traction and position vectors of the control points (cf. Fig. 1).

3. SIMULATION OF FABRIC SHEAR USING THE DIGITAL ELEMENT METHOD

In this section, the digital element method is used to simulate the shear behaviour of dry woven fabric. The Chomarat 150 is chosen as a case study because the geometrical data of its unit cell and mechanical properties of the fabric fibre are available. Moreover, the experimental data of the shear behaviour of this fabric obtained from a picture frame test is also available and can be found in [9].

It has been revealed that regardless of the fibre type and weaving type the obtained shear-angle load is always a J-shaped curve. This curve can be divided into three stages. In the first stage, the initial shear stiffness is low and governed by friction among yarns. In the second stage, adjacent yarns come into contact, the shear stiffness is thus gradually increased. Eventually, in the last stage, the yarn lock-up happens. As a result, the shear stiffness increases exponentially. It has been mentioned in [9] that there are four fundamental deformation mechanisms during shear, viz., inter-yarn trellising, intra-yarn slipping, rotation at crossovers, and lateral compression.

To characterize the dry fabric shear a picture frame test can be used. The frame is made by assembling four rods that are pinned together at the ends. In the test, a square fabric is placed in the frame in such a way that the warp and fill yarns are respectively parallel to the frame sides. A tensile force is applied at the corner of the frame, which is referred to as a crosshead, while the opposite corner is fixed. As a consequence, the square configuration transforms into a rhombus. During the test, the force applied to the crosshead and the displacement of the crosshead are recorded. Based on these data, the shear force and shear angle are derived. Moreover, because the picture frame test has not been standardized and the frame size varies for different research groups, thus the normalization based on the energy method proposed in [10]. Following this method, the shear force will be normalized by the length of the frame. This method was also used in [9], from which the experimental data used in this section are extracted.

The homogenized stresses of the RUC can be calculated by using the Eq. (6) and the obtained stresses are indeed represented in the global coordinate. To compare with the normalized shear stress from the experiment, the homogenized stresses have to be transformed from the global coordinate $x_1 - x_3$ to local coordinate $\eta - \xi$ (cf. Fig. 2) by using the following equation:

$$\tau_{\eta\xi} = -\frac{\left(\sigma_{x_1} - \sigma_{x_3}\right)}{2} sin\gamma + \tau_{x_1 x_3} cos\gamma \tag{7}$$

As mentioned earlier, when using the digital element method, we do not have to use the same number of fibres of the considered fabric in the numerical model. In the work of Miao et al. [6] and Mahadik and Hallet [11], it has been reported that a model that has 19 fibres per yarn was sufficient to predict 3D braided fabric micro-geometries. In our case, the fibres are distributed hexagonally in the yarns, thus there is a coupling between the number of fibres in the thickness and the width directions of the yarn. As a consequence, the exact number of fibres per yarn cannot be assigned. Instead of using 19 fibres per yarns as the aforementioned works, the present authors consider four cases in which the numbers of fibres per yarn are respectively equal to 11, 21, 44 and 61. While the number of fibres per yarn varies, the cross-section of each fibre is also adjusted such that the yarn volume fraction can be preserved.

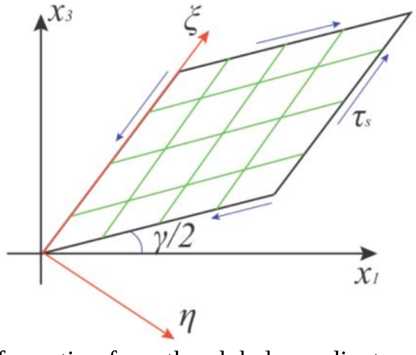

Figure 2: Stress transformation from the global coordinate system to the local one.

Moreover, when a fabric specimen is fixed onto the frame, it is possible that the fabric is tensioned. To apply this pretension, a linear temperature drop is applied to the fibres. This temperature drop does not only impose the prestress in the fibres but also causes reducing the crimp height of the fibres as well as changing the shape of the fabric yarn. Noteworthily, the aforementioned fabric pretension can affect the shear behaviour of the fabric, especially in the low-strain regime. However, this datum was missing in [9], from which the experimental data are used in this work. Nevertheless, by testing with different values of the thermal drop, the one that is equivalent to applying the strain of -0.15% in the fabric fibres is chosen.

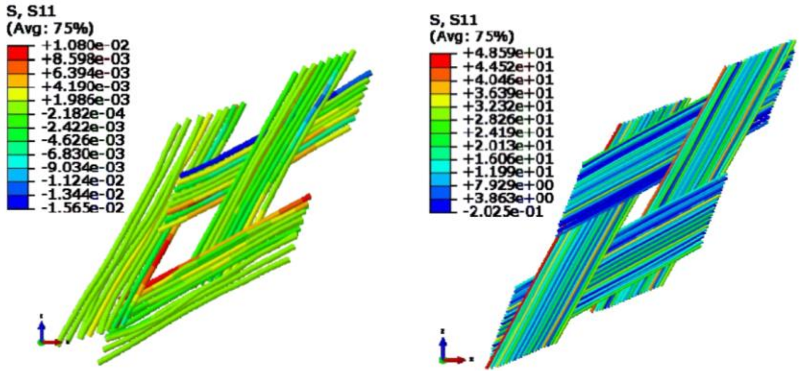

Figure 3: The deformed configuration of the 11-fibre-per-yarn and the 61-fibre-per-yarn fabric model.

The deformed configurations of the fabric when 11 fibres and 61 fibres are respectively used to model the fabric yarn are shown in Fig. 3. The comparison of the homogenized shear behaviour of the fabric with different numbers of fibres per yarn is plotted in Fig. 4. The experimental data, as well as the numerical simulation by Lin et al. [9], are also shown in this graph. It is clear from the obtained results that the number of fibres per yarn plays a crucial role and has a profound effect on the homogenized results. When the number of fibres per yarn is too low, the contact among the fibres cannot be properly described. As a result, the fibres are dispersed and the fabric is unwoven (cf. Fig. 3). This phenomenon can also be observed in the homogenized shear behaviour shown in Fig. 4. The result obtained from the model with 11 fibres per yarn is almost zero during the deformation. When the contact among fibres is modelled properly, the typical J-shaped curve can be reproduced. The obtained result from the model with 21 fibres per yarn can bring a rough approximation for the shear behaviour of the fabric. Moreover, it is evident that further refinement of the number of fibre per yarn can capture better not only the inter-yarn deformation but also the intra-yarn deformation. These phenomena manifest themselves in the stiffer shear behaviour that is obtained in the small shear angle regime, where the inter-yarn deformation is dominant, and at the larger locking angle, where the intra-yarn deformation is dominant. Compared to the numerical simulation presented in [9], the result obtained from the model with 61-fibre-per-yarn is identical in the large shear angle regime, while in the small angle regime there is a clear improvement.

4. CONCLUSIONS

In this article, the fabric shear modelling of Chomarat 150, which is a dry woven fabric, is conducted using the digital element method-based multiscale modelling technique. The obtained results have a significant improvement compared to the one available in the literature both in the small and large shear angle regimes. As such, the model can be utilized not only for composite materials, where the material behaviour in the large shear angle regime is of interest but also in apparel textiles, where the material behaviour in the small shear angle is important. Moreover, it has been shown that the intra-yarn shear, which can be accounted for by our enhanced PBCs, plays a crucial role in capturing the shear behaviour of the woven dry fabrics at the small shear angle regime.

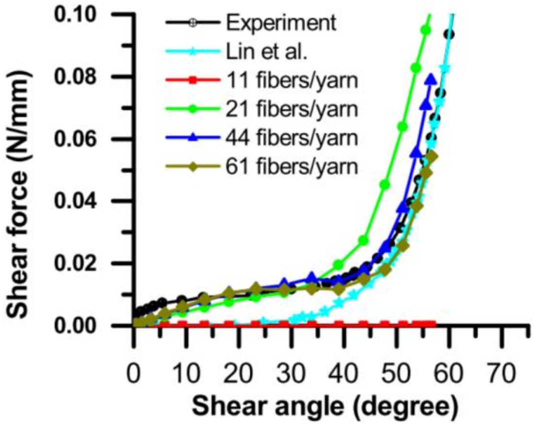

Figure 4: The shear behaviour of Chomarat 150 obtained from the picture frame test and numerical simulations.

REFERENCES

[1] D. Durville, “Simulation of the mechanical behaviour of woven fabrics at the scale of fibers,” *Int. J. Mater. Form.*, vol. 3, no. 2, pp. 1241–1251, Sep. 2010.

[2] A. Charmetant, J. G. Orliac, E. Vidal-Sallé, and P. Boisse, “Hyperelastic model for large deformation analyses of 3D interlock composite preforms,” *Compos. Sci. Technol.*, vol. 72, no. 12, pp. 1352–1360, Jul. 2012.

[3] A. Charmetant, E. Vidal-Sallé, and P. Boisse, “Hyperelastic modelling for mesoscopic analyses of composite reinforcements,” *Compos. Sci. Technol.*, vol. 71, no. 14, pp. 1623–1631, Sep. 2011.

[4] Y. Wang and X. Sun, “Digital-element simulation of textile processes,” *Compos. Sci. Technol.*, vol. 61, no. 2, pp. 311–319, Feb. 2001.

[5] L. Huang, Y. Wang, Y. Miao, D. Swenson, Y. Ma, and C.-F. Yen, “Dynamic relaxation approach with periodic boundary conditions in determining the 3-D woven textile micro-geometry,” *Compos. Struct.*, vol. 106, pp. 417–425, Dec. 2013.

[6] Y. Miao, E. Zhou, Y. Wang, and B. A. Cheeseman, “Mechanics of textile composites: Micro-geometry,” *Compos. Sci. Technol.*, vol. 68, no. 7–8, pp. 1671–1678, Jun. 2008.

[7] O. Döbrich, T. Gereke, and C. Cherif, “Modeling the mechanical properties of textile-reinforced composites with a near micro-scale approach,” *Compos. Struct.*, vol. 135, pp. 1–7, Jan. 2016.

[8] M. G. D. Geers, V. G. Kouznetsova, and W. a. M. Brekelmans, “Computational homogenization,” in *Multiscale Modelling of Plasticity and Fracture by Means of Dislocation Mechanics*, R. Pippan and P. Gumbsch, Eds. Springer Vienna, 2010, pp. 327–394.

[9] H. Lin, M. J. Clifford, A. C. Long, and M. Sherburn, “Finite element modelling of fabric shear,” *Model. Simul. Mater. Sci. Eng.*, vol. 17, no. 1, p. 015008, Jan. 2009.

[10] P. Harrison, M. J. Clifford, and A. C. Long, “Shear characterisation of viscous woven textile composites: a comparison between picture frame and bias extension experiments,” *Compos. Sci. Technol.*, vol. 64, no. 10–11, pp. 1453–1465, Aug. 2004.

[11] Y. Mahadik and S. R. Hallett, “Finite element modelling of tow geometry in 3D woven fabrics,” *Compos. Part Appl. Sci. Manuf.*, vol. 41, no. 9, pp. 1192–1200, Sep. 2010.