Modelling of mechanical behaviour for woven fabrics under combined loading

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ABSTRACT: This paper presents a modelling approach for mechanical behaviour of textile reinforcements, based on Nottingham's TexGen textile modelling schema. TexGen allows models to be generated easily for any textile reinforcement, and has automated functions to discretise the model, assign material orientations and properties to elements, and export the model to external analysis software. In this study Abaqus FE software is used, incorporating a transversely isotropic material law with non-linear transverse mechanical properties determined from experimental characterisation of yarn compression. This is validated firstly for discrete load-cases, including compaction and in-plane shear. The approach is then applied to simulate combinations of these loadings to represent important interactions that can occur during fabric forming. For example, compaction combined with shear is modelled to represent the effect of tool normal force on deformation. Combined tension and shear, which can arise due to the use of a blank-holder during forming, can also be analysed. It is hoped that results will assist in understanding of experimental data that is beginning to be generated on combined loadings.

Key words: Composite forming, textile modelling, compaction, in-plane shear and combined deformation

1 INTRODUCTION

Most engineered fabrics are not manufactured in the shape of the final component and must be formed or draped to the component shape. A textile sheet is deformed into a complex part with double curvature primarily by in-plane trellis shearing [1]. However during forming the sheet is subjected to a combination of loads, including compaction and tension due to the normal tool contact force and, in some cases, blank-holder force. The force varies over the sheet due to anisotropy of the material properties. Whilst several studies have demonstrated the use of finite element analysis to model textile composite forming [eg. 2], such studies generally utilise materials characterisation data for individual mechanisms. So far there is very little understanding of the effects of combined deformations.

Finite element modelling of textile deformation under a variety of loadings may allow one to understand the mechanisms associated with complex deformations, allowing the draping process to be modelled accurately. However, while computational tools for prediction of textile mechanical behaviour are available [3-5], they are still limited in terms of their availability, the level of validation and, in some cases, functionality. The purpose of this paper is to describe recent developments in finite element modelling of the mechanical behaviour of woven fabrics at Nottingham University, providing a fundamental understanding of textile deformation during forming.

2 TEXTILE GEOMETRIC MODELLING

In this study, geometric modelling of the engineered fabric is undertaken using the TexGen software [6]. The basis of TexGen is the description of yarns using a centreline and superimposed cross section. The shape and size of the cross sections may change locally; this is exploited in the functions for interference correction, which modify the textile according to geometric considerations to avoid inter-penetration of yarns. When cross-sections change, the fibre volume fraction (V_f) within the yarn is recalculated based on the updated cross-section, i.e. the total amount of fibres within the textile remains consistent. TexGen includes automated routines to discretise the model, assign material orientations and properties to elements.

For the purposes of the present study, Chomarat 150TB plain woven E-glass fabric is considered. The material model and geometric and mechanical data have been given in reference [7]. The fabric unit cell of the plain weave and the corresponding TexGen model are shown in Fig.1.

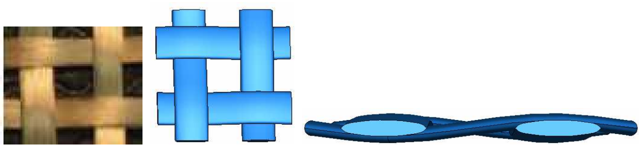

Fig.1.Chomarat 150TB (left), modelled unit cell (middle and right)

3 TEXTILE MATERIAL MODELLING

At present it is not feasible to simulate each fibre in an FEM application. In this study the yarns are considered as orthotropic solid bodies. The orthotropic behaviour of the yarn is described using a 3D stiffness matrix containing nine independent constants, incorporating a transversely isotropic material law with non-linear transverse mechanical properties determined from experimental characterisation of yarn compression [8].

$$E_{33}(\varepsilon_{33}) = \frac{\sigma_{33}}{\varepsilon_{33}} = \frac{-a\left(\frac{V_{f0}}{e^{\varepsilon_{33}}}\right)^b + a(V_{f0})^b}{\varepsilon_{33}} \qquad (1)$$

$$G_{23} = \frac{E_{33}}{2(1+\nu_{23})} \qquad (2)$$

where E_{33} is transverse Young's Modulus; G_{12} is transverse-longitudinal shear modulus; V_{f0} is initial fibre volume fraction; a and b are experimentally determined parameters. Average frictional coefficients (0.3) and (0.5) were chosen for contacts between yarns and yarns with compression platens, respectively. The yarn transverse-longitudinal shear behaviour is governed mainly by the sliding of fibres relative to each other. As such this cannot accurately be represented by an elastic modulus G_{13} alone. There are no experimental data available for yarn transverse-longitudinal shear modulus. Boisse et al. [3] used a small value for the property but they did not specify the value used in plain weave glass fabric tensile FE modelling. A Poisson's ratio of 0.2 for both transverse and longitudinal directions of the yarns was selected from the literature [9]. The input data for compression and shear modelling are given in Table1.

Table 1 Input data for the plain weave unit cell modelling (moduli in MPa)

E_{11}	E_{33}=E_{22}	G_{12}=G_{13}	G_{23}	ν_{12}	ν_{13}	ν_{23}
40150	Eq (1)	5	Eq (2)	0.2	0.2	0.2

4 MODELLING APPROACH AND BOUNDARY CONDITIONS

Implicit static simulations were carried out using an automated modelling approach. The details of FE implementations are given in reference [7]. For unit cell compression modelling, the unit cell was placed between two platens. The lower platen was fully constrained. Compression was applied at a constant displacement rate of the upper platen. For in-plane shear modelling, the boundary condition for the unit cell were based on picture frame testing (pure shear). The two boundary conditions were combined to product a combination of shear and compression modelling.

5 RESULTS AND DISCUSSION

Simulated unit cells under the compressive loading and the shear loading are shown in Fig.2. It is seen that stress concentration appears in the intersection regions between warp and weft yarns for unit cell compression (Fig.2 left). During shear, yarns are subject to the lateral compression, which generates pressure inside yarns (Fig.2 right).

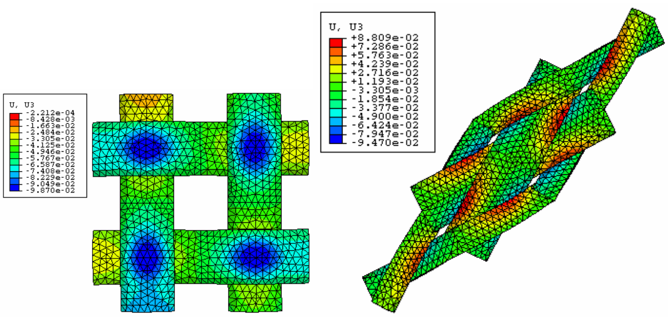

Fig.2 Predicted displacement distribution through unit cell thickness: (left) under compressive loading, (right) under pure shear loading

Figs.3-4 illustrate the effects of using different initial fibre volume fractions (V_{f0}) in Eq. 1. These show that the transverse Young's Modulus, E_{33}, dominates both the compressive and shear behaviour of the fabric. This is due to the fact of that the elastic stiffness and the transverse-longitudinal shear rigidity of the yarns is proportional to fibre volume fraction (Eqs. 1-2).

The influence of transverse-longitudinal shear modulus (G_{12}) on the compression behaviour is illustrated in Fig.5. In the case of unit cell compression, although only global normal strains are applied, the global shear stress is not zero because there exists a normal-shear stress coupling due to yarn undulations. This Figure also illustrates that the predicted unit cell compression behaviour is closer to experimental data for the lower transverse-longitudinal shear rigidity.

Fig.6 illustrates the effect of G_{12} on in-plane shear. The unit cell shear behaviour depends on transverse-longitudinal shear rigidity. Again there is good comparison between the predicted and experimental data for the lower shear rigidity.

In this study, as a consequence of the pure shear deformation condition, yarns were rotated as shown in Fig.2 (right); the results are consistent with Badel et al's work [4]. Shear force is due to friction at crossovers, and yarns are in contact with neighbouring yarns and laterally compressed. However, experimental study shows that intra-tow deformation (tow shearing) also occurs during picture frame testing [10]. From comparison between experiment data and FE predictions (Fig.6), and previous research [4], we can conclude that yarn shear is not dominating the deformation mechanisms in fabric shear for picture frame testing, at least for large shear angles. This is probably due to the fact yarn transverse-longitudinal rigidity is very low. Work is in progress to analyse the relative contributions of different mechanisms to the total shear resistance by isolating the yarn shear and rotation deformations in the simulation based on the analysis of the details of picture frame kinematics.

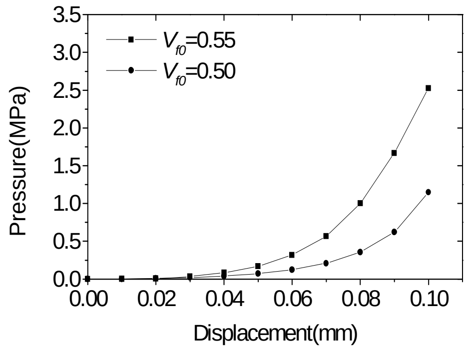

Fig.3. Effect of initial fibre volume fraction on compression

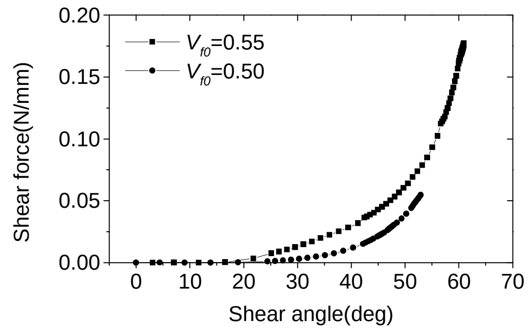

Fig.4. Effect of initial fibre volume fraction on shear

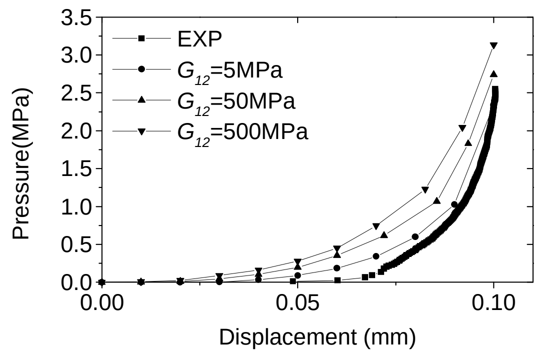

Fig.5 Comparison between experimental compaction results and FE predictions for different G_{12}

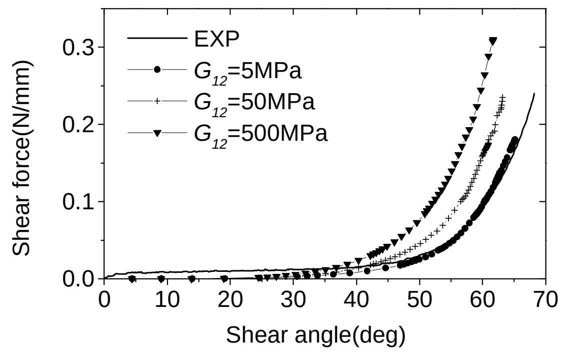

Fig.6 Comparison between experimental shear results and FE predictions for different G_{12}

The interaction between shear and compression is illustrated in Fig.7. It can be seen that when shear is combined with compression, as expected higher deformation loads are needed to shear the unit cell. Firstly, compression will introduce greater friction constrains acting at the yarn crossovers, and secondly, the elastic stiffness of the yarns will increase as a result of the fibre volume fraction being increased (Eq.1). The overall effect is to require higher shearing forces for the same degree of fabric deformation.

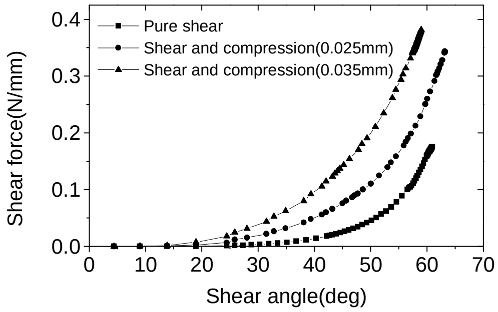

Fig.7 Interaction between compression and shear (in compression, the unit cell was compacted to 0.025mm and 0.035mm, respectively)

4 CONCLUSIONS

A combination of TexGen and Abaqus FE software has been used to model the behaviour of textiles under both isolated and combined loading. The Abaqus FE software incorporates a transversely isotropic material law with non-linear transverse mechanical properties determined from experimental characterisation of yarn compression. The complex deformation mechanisms that can occur during the forming of textile sheets have been illustrated using an example of glass fibre plain weave fabric in compression and shear. The simulation results show that the transverse Young's Modulus, E_{33}, a function of fibre volume fraction, dominates the compressive and shear behaviour of the fabric. Even a single load case can cause complicated stress fields in the material due to its unique architecture; combined afdsf loading brings more complexity to the material model and behaviour.

The accuracy of the model is essentially determined by the accuracy of the input parameters. It is important to remember that the shear strain of the continuum element does not accurately represent the strains applied to individual fibres. Therefore, no mater how accurately fibre sliding is modelled the internal stress of the fibres can never be modelled accurately. We anticipate that this work will lead to a greater understanding of the behaviour of materials forced to conform to complicated contours during forming.

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REFERENCES

1 Long AC, Rudd CD, Blagdon M, Smith P. Characterising the processing and performance of aligned reinforcements during preform manufacture. *Composites Part A*, **27** (1996), 247-253.

2 Lin H, Wang J, Long A.C, Clifford M.J and Harrison P, Predictive modelling for optimization of textile composite forming. *Composites Science and Technology*, **67** (2007)3242-3252.

3 Boisse P., Gasser A. and Hivet G., Analysis of fabric tensile behaviour: determine of the biaxial tension-strain surfaces and their use in forming simulations. *Composite Part A:* 32(10) 1395-1414, 2001.

4 Badel P, Vidal-Salle E and Boisse P, Computational determination of in-plane shear mechanical behaviour of textile composite reinforcements, *Computational Material Science*, **40** (2007), 439-448,.

5 Lomov S.V. and Verpoest I., Compression of woven reinforcements: A mathematical model, *Journal of Reinforced Plastic and Composites*, **19**(16) (2000),1329-1350.

6 Sherburn M., TexGen open source project, online at http://texgen.sourceforge.net/

7 Lin H, Sherburn M, Crookston J, Long A C., Clifford M J. and Jones I. A., Finite Element Modelling of Fabric Compression, submitted to *Modelling and Simulations in Material Science and Technology*, Dec.2007.

8 Sherburn M., *Geometric and mechanical modelling of textiles*. PhD thesis, Nottingham University, 2007.

9 Sadykova F. Kh., The Poisson ratio of textile fibres and yarns, *Fibre Chemistry*, **3**(2) 45-48, 1972.

10 Harrison P., Clifford M.J and Long A.C., A constituent-based predictive approach to modelling the rheology of viscous textile composites, *Composites Part A*, **35** (2004), 915-931.