FPCM-9 (2008)
The 9th International Conference on Flow Processes in Composite Materials
Montréal (Québec), Canada
8 - 10 July 2008

FINITE ELEMENT MODELLING OF COMPACTION FOR TEXTILE REINFORCEMENTS USING AUTOMATICALLY GENERATED UNIT CELL MODELS

Andrew Long [1, 2], Hua Lin [1], Dhiren Modi [1], Andreas Endruweit [1], and Mike Clifford [1]

[1] *School of Mechanical, Materials and Manufacturing Engineering,*
University of Nottingham, Nottingham, NG7 2RD, UK
[2] *Corresponding author's Email: Andrew.Long@nottingham.ac.uk*

SUMMARY: This paper describes finite element analysis of compaction for dry textiles during preform manufacture. The models are generated using procedures encompassed in our TexGen textile modeling schema. Meshing and material property allocations are performed automatically, including definition of material orientations for each of the elements. Tow elements are modeled using a transverse isotropic model, incorporating a non-linear transverse stiffness based on measured tow compaction data. The approach is validated for both two-dimensional textiles and is demonstrated for three-dimensional (orthogonal) textiles. In addition to comparison of predicted and measured compaction pressure relationships, the study includes detailed analyses of the evolution in textile architecture during the compaction process. Results provide insights into the effects of textile structure on compaction behaviour, and the ability to study effects of compaction on further properties such as permeability and composite mechanical behaviour.

KEYWORDS: compaction, textile modeling, finite element analysis, textile mechanics.

INTRODUCTION

Most engineered fabrics are not manufactured in the shape of the final component and must be formed and compacted to the component shape. Analysis of this problem requires an understanding of textile mechanics, and to this end a number of experimental and modeling approaches have been applied in the past [1]. Finite element modelling of textile deformation under a variety of loadings may allow one to understand the mechanisms associated with complex deformations, allowing compaction and forming to be modelled accurately. However, while computational tools for prediction of textile mechanical behaviour are available [2-4], 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. Our approach is based on automatic model generation from a textile modeling schema, thus allowing models to be generated and analysed efficiently for any textile reinforcement of interest.

MODELLING APPROACH

Textile Modelling

In this study, geometric modelling of the engineered fabric is undertaken using the TexGen software [5, 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 yarn remains consistent. TexGen includes automated routines to discretise the model, assign material orientations and properties to elements.

For validation purposes in the present study, two E-glass fabrics from Chomarat were considered - 150TB plain weave and 800S4-F1 satin weave. The material model and geometric and mechanical data have been given in [7]. The fabric unit cell of the plain weave and the corresponding TexGen model are shown in Fig.1.

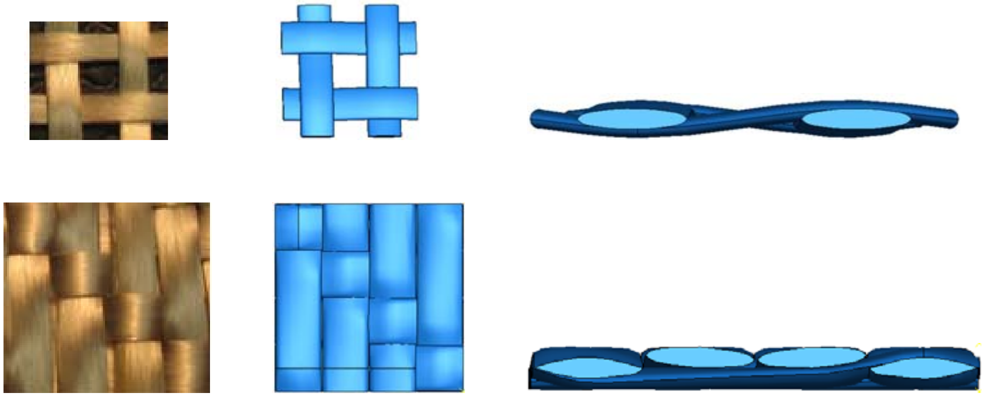

Fig.1 Fabric models - Chomarat 150TB (top) and 800S4-F1 (bottom). Each figure shows actual fabric (left) and TexGen model (centre and right).

Material Modeling

At present it is not considered 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 characterization of yarn compression [6]:

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

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

where E_{33} is transverse Young's Modulus; V_{f0} is initial fibre volume fraction; and 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.* [2] 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 [8]. 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}	v_{12}	v_{13}	v_{23}
40150	Eq (1)	5	Eq (2)	0.2	0.2	0.2

FE Implementation

The plain weave and satin weave unit cells were discretized using 8818 and 32384 4-noded tetrahedral three dimensional continuum elements, respectively. The predictions were practically insensitive to further refinement in mesh density. Compression platens were created using rigid elements. The unit cell was placed between the two platens as shown in Fig. 2. The lower platen was fully constrained and compression was applied at a constant displacement rate via the upper platen. Due to geometrical nonlinearities, the model is analysed according to large strain theory i.e., the non-linear geometry option was used. Multiple contacts were defined between yarns and the unit cell surfaces with the platens using the surface-surface approach.

An automated modelling approach has been employed in this study. A Python scripting interface was created to enable TexGen textile models to be reproduced within a mechanics modelling environment in an automatic way. This incorporates all of the steps required to undertake the simulation: geometric definition, mesh generation, material property assignment and boundary conditions.

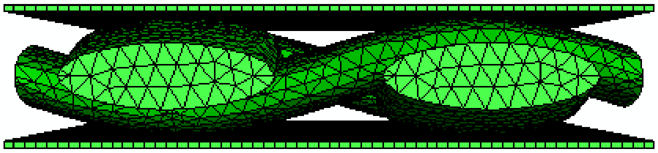

Fig. 2 Simulation set-up for plain weave unit cell compression.

RESULTS AND VALIDATION

Validation for 2D Weaves

In this section, predicted compaction behaviour for 2D fabrics is compared to experimental measurements. Compression tests on the plain weave and satin weave were carried out on standard testing equipment (Hounsfield). Fabrics were compressed between two parallel plates, with force measured using a load cell and displacement measured using a displacement transducer (LVDT).

Comparisons between predicted and measured pressure vs strain curves are shown in Fig. 3 and 4. Generally these figures illustrate that the modeling approach is able to predict the mechanical response during compaction reasonably well. It should be noted that no curve fitting was required to obtain this level of agreement. All properties were taken from Table 1, with yarn compression behaviour (eqn. 1) based on previously published yarn compaction data.

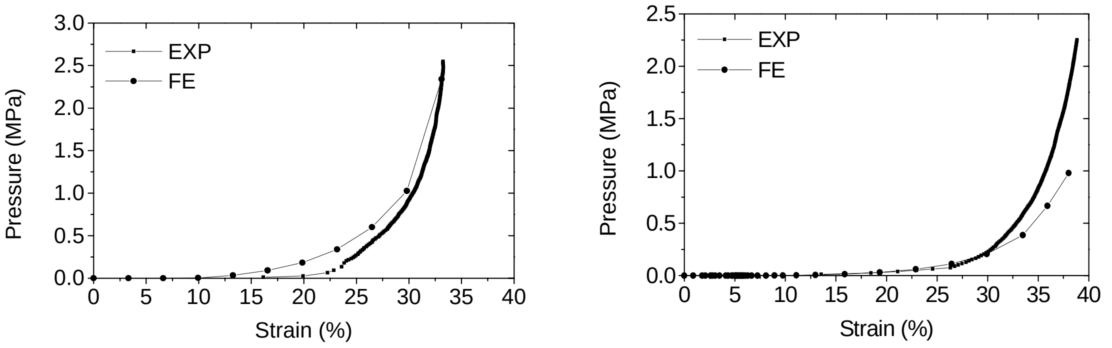

Fig. 3 Comparison between experimental data and FE analysis for the plain weave (a) and the satin weave.

The simulated deformed unit cells for the plain weave and the satin weave are shown in Fig. 4. In the case of fabric compression, the stress is localized in a small area in contact with the upper platen. First a flat region is developed on a yarn cross section in two component yarns, and as a result the cross-section deforms and the yarn is compacted. The yarn fibre volume fraction will vary spatially, with V_f increased in the contact area but not at the yarn edges. The compressive force is not evenly distributed between regions of warp-weft contacts (Fig. 5). Compressive force acting on yarns is distributed over a small area of warp-weft contacts, while the area of the contact region is dependent on the geometry and mechanical properties of the yarns, as well as the loading condition.

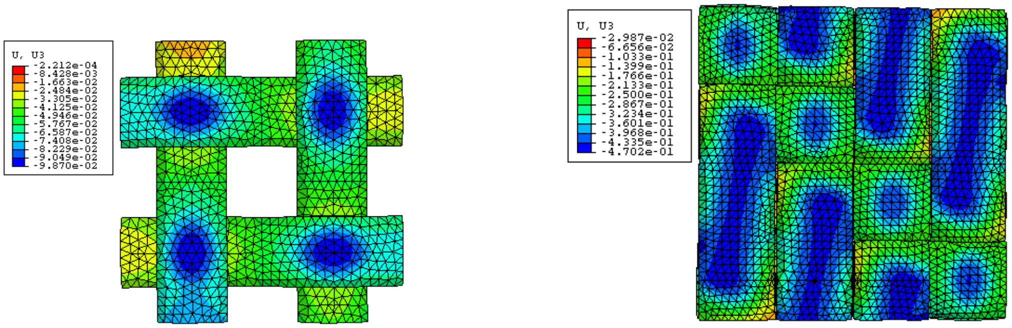

Fig. 4 Predicted displacement distribution in the unit cells (a) plain weave, (b) satin weave.

These simulations confirm that during compaction, not all the sections of a yarn carry the same load simultaneously, and only those at yarn crossovers carry the external load. Change of fabric thickness arises from yarn compression and changes in yarn crimp. The external load is equivalent to the internal forces acting on the yarns, due primarily to yarn compaction and yarn bending. Sensitivity studies based on the finite element (FE) approach [7] have indicated that yarn compression behaviour has most influence on the mechanical response during compaction, with transverse-longitudinal shear modulus (related to yarn bending) also having a noticeable effect. In contrast results are insensitive to changes in axial yarn stiffness.

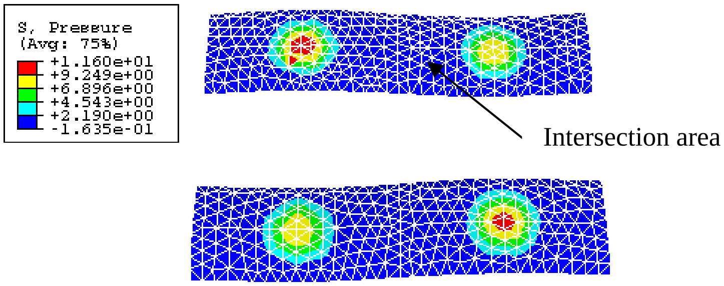

Fig.5 Predicted pressure (MPa) distribution in yarn contact regions for the plain weave.

Application to 3D Weaves

The automated modelling techniques described above can easily be extended to high-performance 3D textiles. The material analysed was a 3D woven Kevlar orthogonal weave, with 3 warp layers (6 yarns/cm), 4 weft layers (4.66 yarns/cm), and warp binder yarns (6 yarns/cm, divided into two groups) that hold the fabric together. The details of the fabric can be found in Potluri *et al*. [9]. The FE model (Fig. 6-A) for this textile was prepared using the same methodology as outlined earlier. The axial yarn modulus (E_1) was calculated from the fibre modulus (84 GPa), while the transverse compression moduli (E_2, E_3) were estimated from experimental data (0.12 MPa). Fig. 6-B shows the deformed FE mesh depicting the textile compaction due to the downward movement of the top platen, while Fig. 6-C shows the textile geometry at the end of the compaction. It is clear that the crimp of the through-thickness yarn undergoes significant change. Fig. 7 shows the compaction of the textile as a function of compaction pressure, clearly capturing the expected non-linear compaction behaviour of the textile during initial loading.

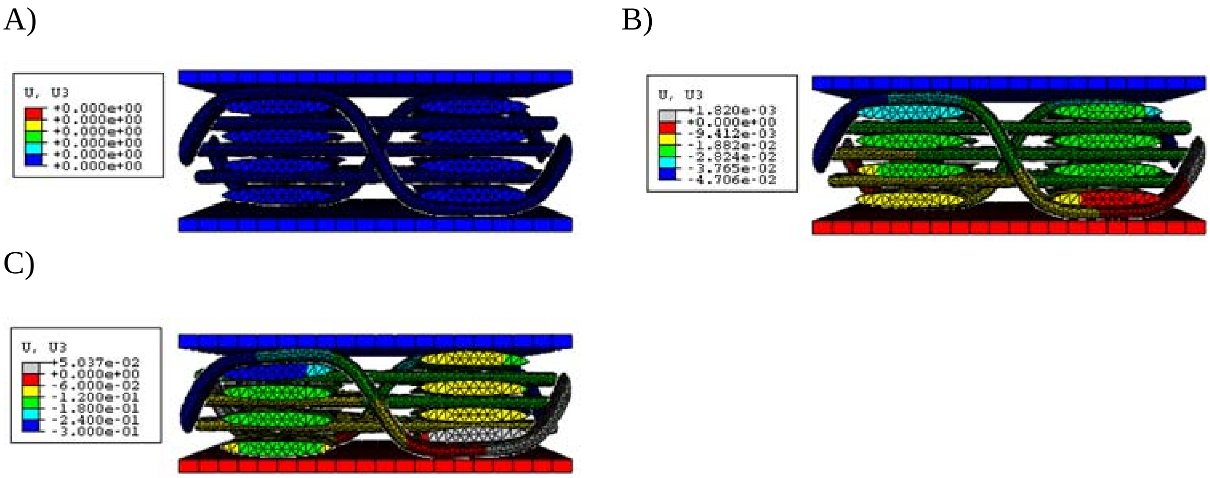

Fig. 6 Simulation of the 3D woven (orthogonal) Kevlar fabric, (A) before compaction, (B) during compaction, and (C) at the end of compaction.

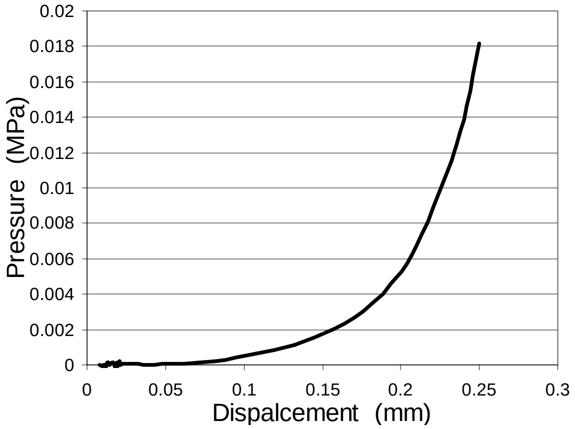

Fig. 7 Predicted compaction pressure vs. textile compaction using FE analysis.

DISCUSSION AND CONCLUSIONS

A FE unit cell compression model has been developed for woven textiles, based on an automatically generated textile modeling approach. One major advantage of this approach is the ability to capture the most important characteristics of the material under compressive loading, including non-linear geometric material behaviours. Comparisons with experimental results for 2D weaves indicate that the approach has a reasonable predictive capability, capturing the non-linear compaction curve reasonably well. Sensitivity studies suggest that compression behaviour is controlled by transverse yarn stiffness, with transverse-longitudinal shear behaviour also of importance. Yarn longitudinal stiffness has essentially no influence. An application of this approach to 3D weaves demonstrates the capability of the approach, in particular in the ability to predict the evolution of the internal fabric structure. Future studies will concentrate on validation for 3D weaves. In addition the effects of fabric compaction on preform permeability and composite mechanical behaviour will be analysed, using the compacted textile geometry as the basis for appropriate unit cell simulations.

Although the model presented here is able to capture the most important responses of a textile to compressive loading, a fundamental issue is that the yarn is modelled as a continuum solid body which is unable to accurately capture real yarn deformation mechanisms. A yarn is a bundle of fibres, and the meso-bending and shearing behaviour and cross-section compaction behaviour are very complex. The internal fibre strains cannot be correctly represented by traditional continuum elements. Development of a finite element which can capture the internal fibre strains is hence desirable. Another hurdle is in obtaining yarn mechanical behaviour, in particular compressive and transverse-longitudinal shear behaviour. This indicates a requirement for fundamental modelling of yarn behaviour. The authors are currently studying this problem as part of collaborative research.

ACKNOWLEDGEMENTS

The work reported in this publication was carried out under the Technology Strategy Board's collaborative research and development programme, through Project No: TP/5/MAT/6/I/H0558C 'Multi-Scale Integrated Modelling for High Performance Flexible Materials'. The authors would like to thank Technology Strategy Board for financial support, and acknowledge the participation of the industrial and academic partners involved in this project: Unilever UK Central Resources, OCF PLC, Croda Chemicals Europe Ltd, University of Manchester, Heriot-Watt University, ScotCad Textiles Ltd, Carrington Career and Work wear Ltd, Moxon Ltd, Airbags international, Technitex Faraday Ltd.

REFERENCES

1. F. Robitaille and R.Gauvin, “Compaction of Textile Reinforcements for Composites Manufacturing. I: Review of Experimental Results”, *Polymer Composites*, Volume 19, Issue 2, pages 198-216 (1998).

2. P. Boisse, A. Gasser and G. Hivet, “Analysis of Fabric Tensile Behaviour: Determine of the Biaxial Tension-Strain Surfaces and Their Use in Forming Simulations”, *Composite Part A* Volume 32, Issue 10, pages 1395-1414 (2001).

3. P. Badel, E. Vidal-Salle and P. Boisse, “Computational Determination of In-Plane Shear Mechanical Behaviour of Textile Composite Reinforcements”, *Computational Material Science*, Volume 40, pages 439-448 (2007).

4. S.V. Lomov and I. Verpoest, “Compression of Woven Reinforcements: a Mathematical Model”, *Journal of Reinforced Plastic and Composites*, Volume 19, Issue 16, pages 1329-1350 (2000).

5. M. Sherburn M, “Texgen Open Source Project”, online at http://texgen.sourceforge.net/

6. M. Sherburn, “Geometric and Mechanical Modelling of Textiles”, *PhD thesis*, University of Nottingham, 2007.

7. H. Lin, M. Sherburn, J. Crookston, A.C. Long, M.J. Clifford and I.A. Jones, “Finite Element Modelling of Fabric Compression”, *Modelling and Simulations in Material Science and Technology*, Volume 16, 16 pp (2008).

8. F. Sadykova, “The Poisson Ratio of Textile Fibres and Yarns”, *Fibre Chemistry*, Volume 3, Issue 2, pages 45-48 (1972).

9. P. Potluri, A. Long, R. Young, H. Lin, Y. Shyng, A. Manan, “Compliance Modelling of 3D Weaves”, *Proc. of 16th International Conference on Composite Materials: (ICCM-16),* Kyoto (Japan), 2007.