Automated geometric modelling of textile structures

Article Information
Volume: 82 issue: 16, page(s): 1689-1702
Article first published online: May 15, 2012;Issue published: October 1, 2012
DOI: https://doi.org/10.1177/0040517511418562
Hua Lin, Xiesheng Zeng, Martin Sherburn, Andrew C Long, Mike J Clifford
Corresponding Author: Hua Lin, Division of Materials, Mechanics & Structures, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK
Email: hua.lin@nottingham.ac.uk

Abstract

An automated approach (TexGen) for modeling the geometry of textile structures is presented. This model provides a generic approach to the description of yarn geometry and yarn interlacement for all types of weaving. One feature of this model is that 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 penetration of yarns. Another feature of this model is that it acts as a pre-processor for finite element simulations by generating a mesh, definition of contact, materials orientation and boundary conditions, thus providing an automatic procedure. This paper describes the modeling techniques, algorithms and concepts implemented in TexGen and examines the functionality of their implementation for a range of two-dimensional/three-dimensional commercial fabrics. Comparisons between the images of real fabrics and modeled fabric structures confirm that the software is capable of modeling sophisticated fabric architectures, including twisted yarns with varied yarn cross sections. Accurate input measurements of fabric geometry are critical for successful results. The paper also discusses directions for further development of the approach to overcome current limitations.

Keywords fabric geometry, modeling, simulation

Realistic fabric geometric description is essential for modeling of the mechanical and physical properties of textiles and textile composites. It determines the accuracy of modeling results and geometric non-linear response to external loadings. Attempts to model textile geometry were recorded as early as the1930s[1] and have continued up to the present time.[2] There are many challenging aspects of modeling fabric structures, for example, even the geometry of relatively simple plain-weave fabrics is complicated and requires careful modeling to obtain accurate results. There are two major obstacles: the complexity of the textile structure topology and the contact between yarns.[3] Indeed, yarns are highly flexible and their path and cross-sectional shape do not, in general, fit the usually assumed single geometrical form, for example, an elliptical cross section.

A traditional simplified approach is to use the idealized assumptions on yarn path and cross-sectional shapes in the fabric, such as Pierce’s model[1] and its derivatives.[4,5] This approach is only reasonably accurate when the yarns remain circular and are flexible enough for the free lengths between crossovers to be straight. This applies to plain weaves. Pierce’s model[1] cannot be used realistically to describe other fabrics. There are several studies on the use of analytical techniques to predict fabric geometry and mechanical behaviors for specific fabrics. While these techniques generally resolve issues of robustness and speed, different equations must be formulated for each fabric architecture.[6–8]

Apart from the analytical models, several commercial computational tools are available, such as TechText CAD, WeaveEngineer and ScotWeave. In TechText CAD, yarn paths are calculated based on Peirce's geometric model, and the program provides the basic facilities for setting up weaves and simple weft knits, defining yarn specifications and viewing the structures in three dimensions. The software has the ability to predict the uniaxial and biaxial stress–strain curves of fabrics for two-dimensional (2D) woven and weft-knitted fabrics based on an energy method using the yarn mechanical properties.[9] The Weave Engineer software[10] is dedicated to the design of three-dimensional (3D) woven textile structures, with both solid and hollow architectures and non-crimp composite reinforcements. It does not contain any features for predicting the mechanical properties of fabrics. The ScotWeave software is aimed primarily at industrial users. It contains a number of features that are valuable to weave designers, such as artwork designer, Dobby Designer and Jacquard Designer, rather than for research.[11] A relatively new product, the ScotWeave Technical Weaver, is aimed specifically at modeling technical textiles at the mesoscopic scale. Yarn cross-sectional shape and weave pattern can be specified to create a 3D geometrical model, but it does not contain any algorithms for calculating mechanical properties and it is limited to modeling orthogonal woven fabrics. In all these computational tools, yarn cross sections are considered as uniform, although the real yarns are normally uneven.

Lomov et al.[12] and Verpoest and Lomov[13] have developed a software package, WiseTex, that is capable of (i) modeling a variety of fabric structures incorporating physical properties of the yarns and (ii) modeling fabric physical properties, including resistance to tension, compression, shear and bending. However, in the current implementation of the model in WiseTex software, the cross sections of the yarns have symmetrical prescribed shape (elliptical, lenticular or rectangular). This leads to not-so-good definition of the yarn volumes when it comes to building of the finite element (FE) model of the fabric unit cell.[14]

TexGen is an open source software distributed under the General Public License. It has been used by researchers at the University of Nottingham and elsewhere as a modeling pre-processor for textiles simulation for a variety of applications in solid mechanics,[15,16] fluid dynamics[17] and thermodynamics. The objectives of this paper are (i) to demonstrate the modeling techniques, algorithms and concepts implemented in TexGen and (ii) to show the multi-functionality of the software when applied to commercial fabrics. For this purpose, the concepts and algorithms for the yarn path, cross section and unit cell modeling implemented in TexGen are described in the following section. The fundamental techniques and novel functionalities of the software are demonstrated by simulation of a variety of commercial fabric structures in the third section. Then FE implementation in TexGen is illustrated in the fourth section. An example application of TexGen geometric data to a mechanics modeling environment, Abaqus, to predict fabric mechanical properties is givenin the fifth section. In the final section, directionsfor further development of the software are proposed.

TexGen fabric geometry simulations

Yarns are the basic meaningful structural elements of interlaced fabrics. Fabric geometric structures are determined mainly by the central paths and cross-sectional shape of their constituent yarns. TexGen generates the geometry of any textile fabric in a generic way by specifying yarn path and yarn cross sections independently. In this approach, TexGen allows models to be generated easily for any 2D and 3D textile fabric structures, for example, woven, knitted, knotted or non-crimp.

Yarn path

In TexGen, the yarn path is represented by a spline *S(u)* (Bezier, natural or periodic cubic):

$$S(u)=S_0(u),u_0\le u<u_1 \quad S(u)=S_1(u),u_1\le u<u_2 \ldots\ldots S(u)=S_{k-2}(u) \quad u_{k-2}\le u\le u_{k-1}$$

$$S(u)=S0(u),u0\le u<u1S(u)=S1(u),u1\le u<u2\ldots\ldots S(u)=Sk\text{-}2(u)uk\text{-}2\le u\le uk\text{-}1$$

The given k points u_i are called knots or control nodes. The vector $u=(u_0,\ldots,,u_{k-1})$u=(u0,…,,uk-1) is called a knot vector for the spline, as shown in Figure 1. Yarn cross-sectional geometries will be defined locally at each control node.

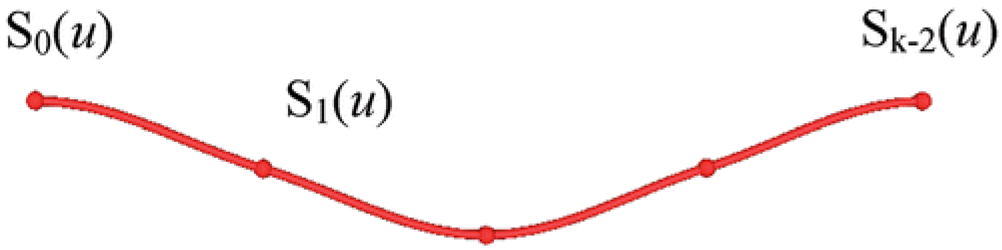

Figure 1. b-splines represent yarn centerlines.

In TexGen geometry modeling, the yarn path is usually determined by other parameters, such as fabric structure, yarn cross section, yarn spacing and fabric thickness. It is not necessary to define the yarn mid-line based on direct experimental measurement. In practice, the yarns are initially modeled as a symmetrical and constant cross section with a well-defined central line. Then the yarn cross section is modified locally based on experimental images. The central line is retained as a convenience reference line.

Yarn cross section

The yarn cross section is defined as the 2D shape of the yarn when cut by a plane perpendicular to the yarn path tangent. In TexGen, yarns are treated as solid volumes and the cross section is approximated to be the smallest region that encompasses all of the fibers within the yarn (it will generally be convex). TexGen models a yarn as a series of individual sections defined at each control node along the yarn path, as shown in Figure 2. These sections are composed of separate upper and lower curves to improve conformance to the geometry. The outline of the cross sections is defined using 2D parametric equations. Standard formulae for various yarn shapes, such as the ellipse proposed by Peirce,[1] the power ellipse[4] and the lenticular proposed by Hearle and Shanahan,[5] have been implemented in TexGen, hence these cross-sectional shapes can be assigned to each section of yarns accurately and easily.

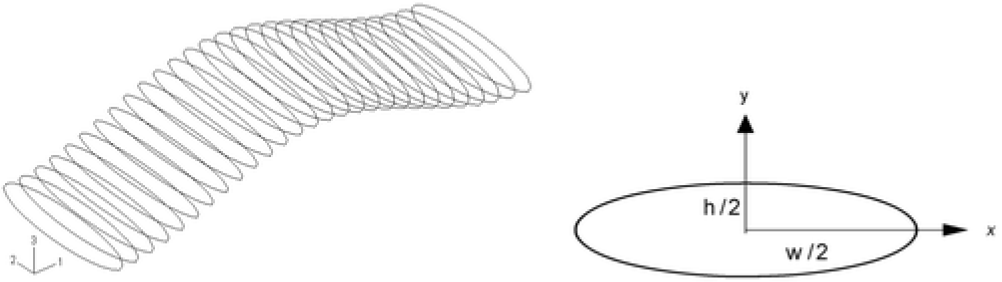

Figure 2. A series of sections for a yarn.

The yarn cross section is defined as the 2D parameter equation of the form *C(v)*. The ellipse form is described as

$$C(v)_x = \frac{w}{2}\cos(2\pi v) \quad 0 \le v \le 1$$

$$C(v)_y = \frac{h}{2}\sin(2\pi v) \quad 0 \le v \le 1$$

where w is the width of the yarn cross section and h is the height of the yarn cross section (Figure 2). The given k points v_i are called knots.

A power ellipse is defined by

$$C(v)_x = \frac{w}{2}(2\pi v) \quad 0 \le v \le 1$$

$$C(v)_y = \begin{cases} \frac{h}{2}\sin(2\pi v)^n & 0 \le v \le 0.5 \\ -\left(\frac{h}{2} - \sin(2\pi v)\right)^n & 0.5 \le v \le 1 \end{cases}$$

where n is power index (0,1,2….).

The lenticular cross sectional is defined as an intersection of two circles of radii r_1 and r_2 offset vertically by distances o_1 and o_2, respectively. The parameters r_1, r_2, o_1 and o_2 can be calculated from the desired width$w$, height h and distortion d of the lenticular section:

$$r_1 = \frac{w^2 + (h-2d)^2}{4(h-2d)}, \quad r_2 = \frac{w^2 + (h+2d)^2}{4(h+2d)}$$

$$o_1 = -r_1 + \frac{h}{2} \quad o_2 = r_1 - \frac{h}{2}$$

The lenticular section is given by

$$C(v)_x=\begin{cases} r_1\cos\theta+o_1 & 0\le v\le 0.5\\ -r_2\cos\theta+o_2 & 0.5\le v\le 1\end{cases}$$

$$C(v)_y=\begin{cases} r_1\cos\theta+o_1 & 0\le v\le 0.5\\ -r_2\cos\theta+o_2 & 0.5\le v\le 1\end{cases}$$

where

$$\theta=\begin{cases}(1-4v)\sin^{-1}\left(\frac{w}{2r_1}\right) & 0\le v\le 0.5\\ (-3+4v)\sin^{-1}\left(\frac{w}{2r_2}\right) & 0.5\le v\le 1\end{cases}$$

These basic shape functions are capable of representing many real fabric cross sections to a certain extent. For more realistic descriptions in the case of asymmetric cross sections, TexGen enables a hybrid shape function to assign cross-section segments to different basic shape functions. The hybrid shape is more accurate and versatile for shape approximation.

Yarn surface

After the yarn path and cross section are defined, the two are brought together using a parametric surface formed from the yarn path *S* and the cross-section *C*:

$$P(u,v)=S(u)+\left(C(u,v)_x\vec{X'}(u)+C(u,v)_y\vec{Y'}(u)\right)\qquad a\le u\le b\qquad 0\le v\le 1$$

where $\vec{X'}$ and $\vec{Y'}$ are the local coordinate axes of the yarn path.

Yarns are usually uneven. Hence, an appropriate geometrical model should be able to track changes in the size and shape of yarn cross sections. In TexGen, as stated previously, yarn cross sections are specified at discrete positions along the yarn path, which allows the shape and size of the cross sections to be defined locally. Suppose two cross-sections A (*v*) and B (*v*) are defined, which are to be interpolated. The interpolated cross-section C (*v*) is defined as

$$C(v,\mu)=A(v)+(B(v)-A(v))\mu\qquad 0\le v\le 1\quad 0\le\mu\le 1$$

where μ varies from 0 to 1 linearly with distance between cross-sections A (v) and B (v). This linear interpolation is the simplest approach to allow a smooth transition with continuity C^0between two different cross-sectional shapes.

Unit cell and weave pattern

The series of individual sections (Figure 2) are lofted by the TexGen geometry solver to create a solid yarn volume (Figure 3(a)). This is repeated for each yarn in the unit cell (Figure 3(b)). A domain representing the limits of the unit cell is created (Figure 3(c)). The yarns are duplicated so that they extend beyond the limits of the domain (Figure 3(d)). Yarns are trimmed to fit inside the domain (Figure 3(e)).

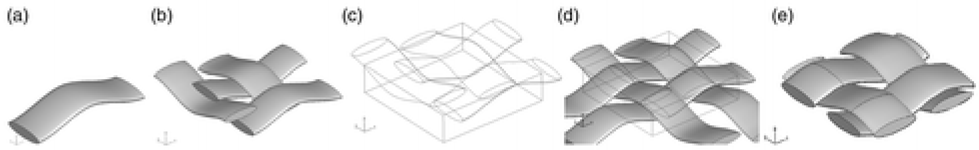

Figure 3. Generation of a unit cell.

A single-layer woven fabric is made from one set of warp and one set of weft yarns. By arranging interlacement between the warp and weft yarns, different types of woven patterns can be obtained. A 2D binary matrix is used to represent these patterns. Every interlacing is represented by an element in the 2D binary matrix, and elements in the array can only have one of the two values: 1 and 0. ‘1’ means that the warp yarn is over the weft yarn at the crossover and ‘0’ indicates the opposite situation. Figure 4 shows a binary array and the fabric structure for a 2/2 twill weave.

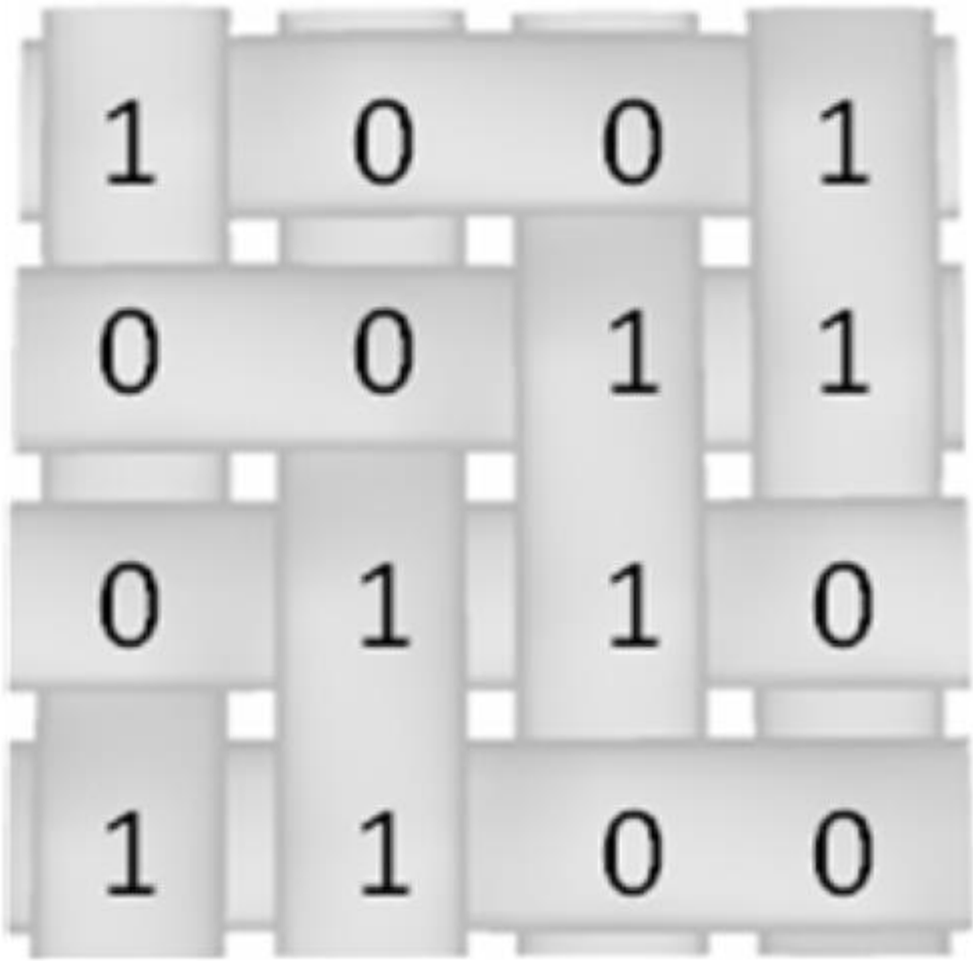

Figure 4. 2/2 twill weave.

For a wide range of 3D weave patterns, a single mathematical description, such as the matrix system, is not an efficient approach, since yarns interlace through multiple layers. The primary definition of any textile in TexGen is based on centerlines describing yarn paths in 3D space with superimposed cross sections. The control nodes along a yarn path are created around a yarn circumference at interlacing points. These nodes help avoid yarn intersections and capture local waviness. As illustrated in Figure 5, eight virtual control nodes with decimal indices are created on the weft yarn circumference at potential contact locations (i, j, k) with binder yarns. More nodes can be easily inserted for finer yarn path control. The nodes are now assigned by index to individual yarns. In this way, a yarn can be defined to take any possible path to form complex weaves. A complicated mathematical formulation for 3D weave patterns is avoided here. APython script is written as an automated generator for 3D weave in TexGen. The generator is mainly used for modeling orthogonal and angle inter-lock reinforcement structures. The set of input data required are yarn spacing, number of layers and cross sections of weft, warp and binder yarns. These data can be measured for real fabrics. Additional information to complete the geometric model is the control node list for binder yarns to describe various interlacing styles.

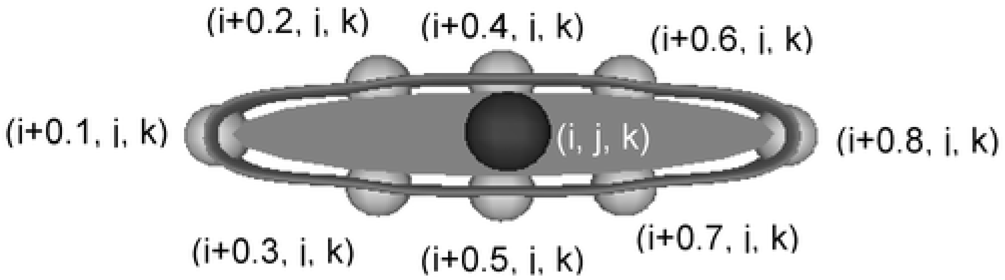

Figure 5. Index scheme for control nodes of binder yarn path.

Application of TexGen to simulate commercial fabrics

Geometric measurements

In this section, a variety of commercial fabrics provided by industrial partners are modeled and simulated with TexGen. The fabrics' specifications are given in Table 1. In order to model their internal structure, it is necessary to make a number of measurements on fabric samples. Based on the manufacturers' specifications (Table 1), all fabric structures are considered to be unbalanced, that is, the warp and weft have different geometric and material properties, and hence the two systems yarns are measured and modeled separately. The set of input data required for modeling fabrics in TexGen are yarn width, yarn heights (fabric thickness), yarn spacing and cross-sectional shape. The yarn cross sections were cut using a laser beam razor blade and the cross-section images were obtained with a scanning electron microscope (SEM) or light microscopy (LM). The images were imported to the software ImageJ[20] for further analyses. In ImageJ, the yarn cross-section images were fitted with an ellipse, lenticular section or with a power ellipse, and the shape closest to the real yarn cross sections was chosen. Figure 6 shows two typical cross sections and their elliptical approximations for weft yarns in fabric A. The larger axis (yarn width) and shorter axis (yarn height), as well as yarn cross-section area, were obtained in ImageJ. The yarn spacing was calculated from the yarn sett, which is very close to the measured average yarn spacing. The fabric thickness was measured using the Kawabata Evaluation

System for Fabrics (KES-F)[21] at a pressure of 0.05 KPa. The measured fabric geometric parameters to be used in the models are given in Table 2.

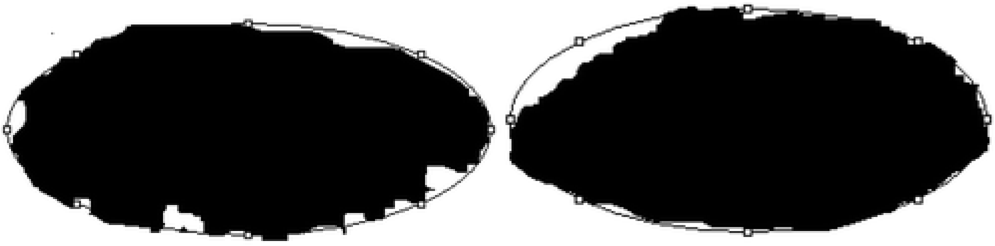

Figure 6. Elliptical approximation to weft yarn cross sections for fabric A.

Click to view table

Table 1. Fabric specifications

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Fabric code	Composition	Structure	Yarn sett (warp/weft per inch)	Yarn linear density(warp/weft)	Yarn type
A	65/35 polyester/cotton	Plain	135/72	13/13tex	Combed ring spun
B	100% nylon	Plain	22.3/19.6	47 tex f136[a]	Multifilament
C	100% polyester	Plain	172.8/79.1	9.5/18.7tex	Multifilament
D	67/33 polyester/cotton	2/1 twill	82/52	42 tex	Ring spun
E	100% carbon	3D angle inter-lock	5/7	2 × 800/800 tex 400 tex (binder)	Multifilament
F	100% carbon	3D orthogonal	11.4/9.5	800/2 × 400 tex 67 tex (binder)	Multifilament

[a]There are 136 filaments within a yarn.
3D: three-dimensional

a

There are 136 filaments within a yarn.

3D: three-dimensional

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Table 2. Input data for unit cell geometry simulation in TexGen (mm)

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Fabric code	Yarn width (warp/weft/binder)	Yarn height (warp/weft/binder)	Yarn spacing (warp/weft/binder)	Yarn cross-section shape (warp/weft/binder)	Fabric thickness
A	0.16/0.20/-	0.11/0.10/-	0.19/0.35/-	Lenticular/ellipse	0.21
B	(0.44–0.48)/0.39/-	0.18/0.18/-	0.45/0.51/-	Power ellipse (n = 1.3)	0.36
C	(0.17–0.20)/0.16/-	0.08/0.11/-	0.17/0.32/-	Power ellipse (n = 0.75)/circular	0.21
D	0.30/0.30/-	(0.16–0.28)/-	0.31/0.488/-	Hybrid of ellipse and lenticular	0.54
E	4.01/3.16/1.0	0.41/0.38/0.37	4.98/3.65/5.01	Ellipse and power ellipse	2
F	1.94/2.29/0.31	0.43/0.41/0.3	2.23/2.68/2.12	Power ellipse and hybrid	6.32

View larger version

Geometric modeling

The LM image and TexGen model of fabric A is shown in Figure 7. From yarn cross-section image analysis, lenticular and elliptical cross sections were assigned to the warp yarn and weft yarn, respectively, along the yarn length. The yarn width and height are modeled as constant.

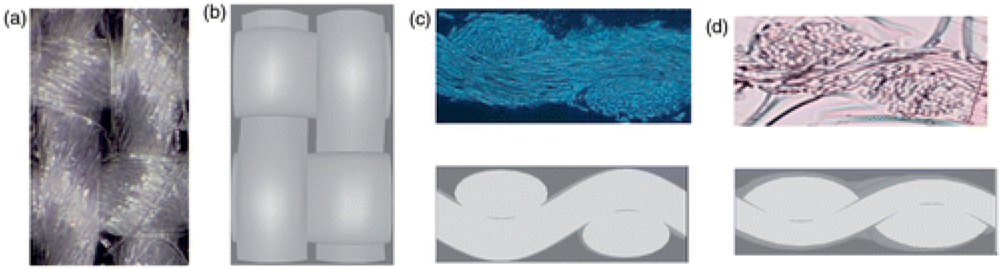

Figure 7. Fabric A, unit cell geometry, light microscopy (LM) image (a), modeled unit cell (b), elliptical cross section for weft yarn (c)and lenticular cross section for warp yarns (d) (top: LM image, bottom: TexGen model).

Fabric B, a tightly packed nylon filament fabric for vehicle airbags, is presented in Figure 8(b). The challenge of modeling this fabric is that the warp yarns are overlapped and their cross sections are uneven. To start with, the paths of the yarns are described by specifying discrete points (control nodes) and a Bezier interpolation function was used (Figure 8(a)) as described in the *Yarn path* section. More nodes can be easily inserted for finer yarn path control. An initial model was created with the warp yarn defined as a power ellipse (n = 1.3), with constant width and height corresponding to the average width and height as measured from the experimental images. A more realistic model was then developed by inserting extra nodes along the yarn path with different elliptical geometries (widths 0.44–0.48 mm) asobserved in the images. The result is shown in Figure 8(a). The modeled fabric shows excellent correlation with SEM images (Figures 8(b–c)). It is worth noting that the modeled contacts between yarns are realistic and interference free (Figure 8(d)) for such a tight fabric, which is essential for mechanical analysis.

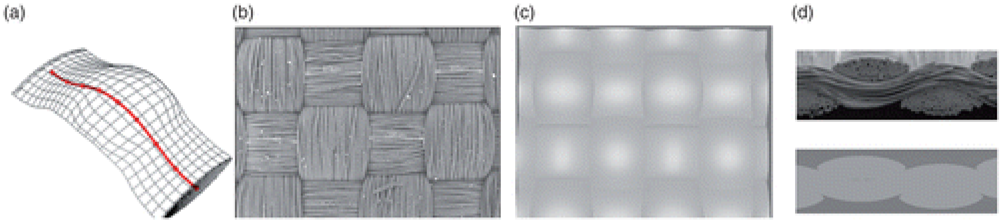

Figure 8. Fabric B, b-splines represent yarn centre-lines and modelled warp yarn surface with varied cross sections (a), SEM image (b), TexGen model with uneven yarn cross-sections (c), lenticular cross-section for warp yarns (d) (top: SEM image, bottom: TexGen model).

Interesting features can be observed from fabric C (Figure 9(a)): warp yarns are crimped and their cross sections are uneven; weft yarns are straight and their cross sections are almost uniform. Based on image analysis, the warp yarn cross sections were modeled as power ellipses (n = 0.75) and yarn width varied from 0.17 to 0.20 mm using the interpolation algorithm (Figures 9(b–c)). Weft yarns were modeled as straight with circular constant cross sections (Figure 9(d)).

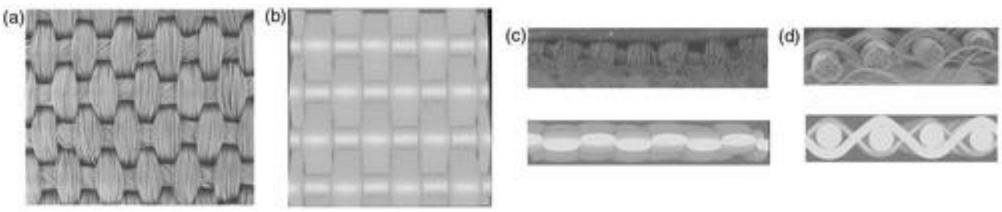

Figure 9. Fabric C, scanning electron microscope (SEM) image of the highly unbalanced fabric (a), TexGen model of fabric C (b), SEM image of warp yarn cross section ((c), top), simulated warp yarn cross section as power ellipse with varied yarn cross sections ((c),bottom), SEM image ((d), top) and modeled circular weft yarn cross section ((d), bottom).

It is clear that the twill weave structure is much less uniform than the plain weave. The principal difficulty with modeling twill weave is that yarns deflect due to side crimp forces.[22] Figure 10(a) (top) shows a side view of the unit cell SEM image of fabric D; the non-symmetrical structure of the twill weave gives bending and contact forces causing the yarns to rotate and deflect. To reflect this feature, the unit cell geometry is modeled by rotating the yarns to a certain angle in the

TexGenmodeler, as show in Figure 10(a) (bottom). This rotation enables the yarn path to be fairly smooth without penetrating the adjacent/neighboring yarns. In addition, the yarn cross sections are defined locally along the yarn length and hybrid ellipse andlenticular sections are assigned to the yarns, as observed inthe LM images. In this example, this results in a variable yarn height along the length of the yarn, as seen in Figure 10(b). Figure 10(c) shows a comparison of the unit cell model with the actual textile.

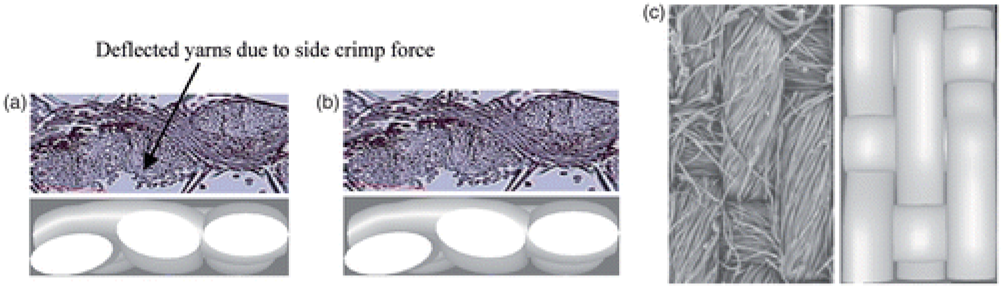

Figure 10. Fabric D, LM image of yarn cross-sections (a, top); TexGen model with deflected yarns (a, bottom); Yarn cross-section varies along yarn length (b, upper: LM image; bottom: TexGen model); 2/1 twill weave unit cell (e, left: SEM images, right: TexGen model).

Figures 11 and 12 show two 3D woven carbon fiber structures used as composite reinforcement. The TexGen model for the angle inter-lock Fabric E is based on averaged microscopic measurement of cross sections from a composite panel. Elliptical and power elliptical shapes are used to approximate the cross sections for weft and warp yarns. As clearly shown in Figure 11, binder yarns push surface weft yarns through the thickness direction to form flat top and bottom planes. This local crimping feature is captured in the TexGen model by adjusting the coordinates of local nodes. For fabric F, the TexGen model is based on micro-computed tomography (μCT) measurement of dry fabric without compaction, as shown in Figure 12. The orthogonal weave has distinctive cross sections of surface layer weft yarns. Hybrid cross sections in TexGen were used to represent the semi-ellipse shape of these yarns. The parameter *n* for the power ellipse (Equation (5)) was determined by curve fitting the measured shape from μCT images. As demonstrated in Figures 11 and 12, TexGen is capable ofdescribing these different binder paths closely compared with fabric cross-section images.

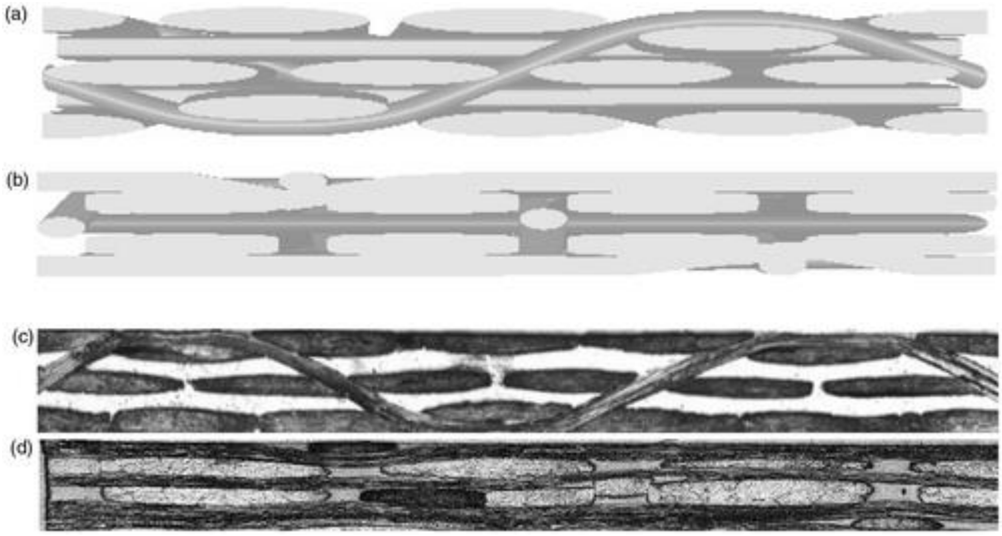

Figure 11. Fabric E angle inter-lock carbon fiber. (a), (b) Weft and warp views of the TexGen model. (c), (d) Microscopic images of weft and warp cross sections.

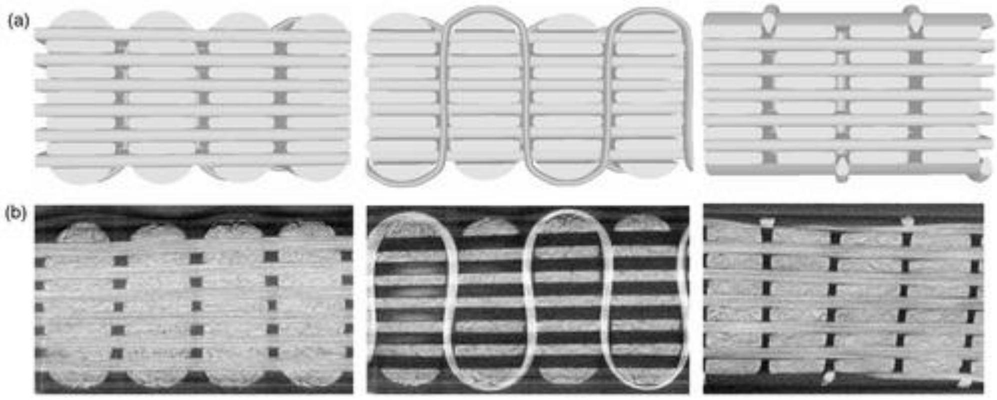

Figure 12. Fabric F orthogonal three-dimensional carbon fiber. (a) Weft and warp views of the TexGen model. (b) Micro-computed tomography images of corresponding weft and warp cross sections.

Finite element implementation in TexGen

Mesh generation

A simple mesh generator has been implemented in TexGen to discretize yarns.[16] TexGen meshes yarns in two steps. The first is to mesh the cross sections in two dimensions, ensuring that the cross-section meshes are compatible. It is then simply necessary to link adjacent cross-section meshes together to form 3D elements.

Figure 13(a) shows an elliptical cross section meshed using this technique. Note that the four corners of thegrid contain triangular elements rather than quadrilateral elements. This is to avoid having highly distorted elements, which are undesirable in numerical simulations.

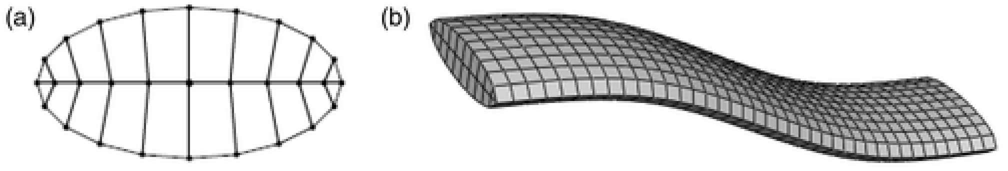

Figure 13. Cross section meshed with simple mesh generation technique (a). Meshed yarn in TexGen using hexahedral elements (continuum three-dimensional eight-node brick elements) for the yarn main body and wedge elements (continuum three-dimensional six-node tetrahedral elements) for the edges (b).

A number of equi-spaced meshed cross sections arecreated along the length of the yarn path and the number of columns and rows are the same for each cross section along the length of the yarn. Consecutive cross sections are linked together to form 3D volume elements. In order to link two cross sections together, the meshes must be compatible, that is, each element from one cross section must map to an element on theother cross section. In this way, pairs of triangles can be linked together to form six-noded wedge elements and pairs of quadrilaterals can be linked together to formeight-noded hexahedral elements, as shown in Figure 13(b).

The advantage of the unit cell mesh generated by TexGen is that it ensures that the degrees of freedom of each node lying on the boundary of the unit cell are linked to the degrees of freedom of a corresponding node on the opposite side of the unit cell. In essence these pairs of nodes represent identical positions in theunit cell and as such cannot have different displacements or slope. This is important for the application of periodic boundary conditions to the unit cell in order to represent the repeating nature of fabrics.

Material orientation

Since yarns are highly anisotropic, an important point is to ensure the stress and strain components will be defined in the local orientation. A local (Gauss-point level) orthogonal coordinate system is defined for material properties. TexGen defines material orientation for each element, as shown in Figure 14. In this manner, the mechanical constitutive behavior of yarns is fully defined at each element. Hence all stresses, strains andstate variables are defined with respect to local material axes and these axes rotate with material deformation.

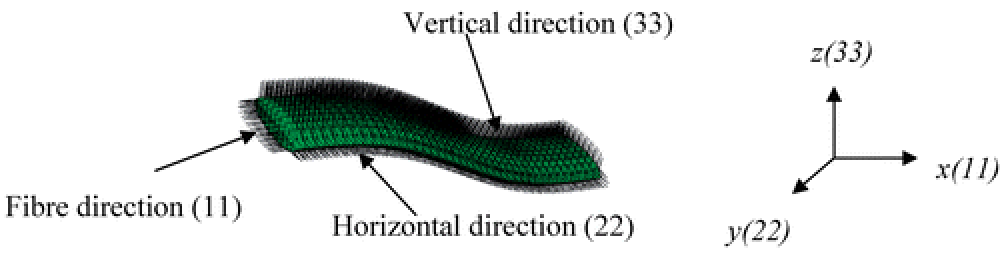

Figure 14. TexGen orientation vectors.

Contact algorithm

TexGen creates an upper and lower surface for eachyarn and defines contacts between the lower and upper surface of two yarns when they are directly or potentially in touch with each other using master and slave contact techniques for FE analysis (Figure 15).

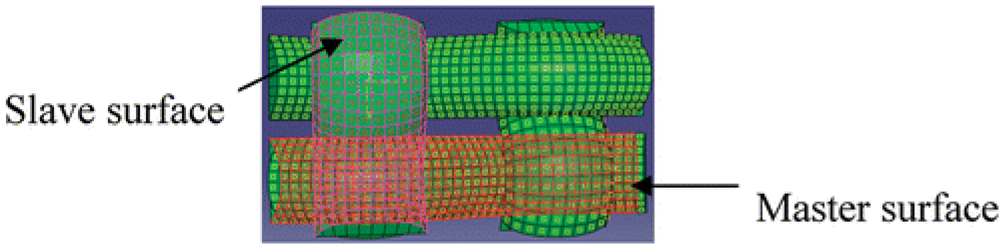

Figure 15. An upper and lower surface was created for each yarn. Corresponding upper and lower surfaces at crossover regions define a contact pair of surfaces using master and slave contact techniques for finite element analysis.

Periodic boundary conditions

Fabric unit cell modeling is based on the assumption that fabric deformation is uniform at the macro scale. Periodic boundary conditions are applied to replicate its repeating nature.

In order to ensure the individual unit cells can beassembled as a continuous physical body, the displacements in the neighboring cells must be continuous.

TexGen applies the following nodal displacement-difference constraint equations for the boundary conditions to meet this requirement:

$$U_1 = x_B - x_A$$

$$U_2 = y_B - y_A$$

U_1 and U_2 are displacement differences between two opposite node sets A and B (Figure 16). x_A and x_B are displacements in the x direction for node sets A and B, respectively; y_A and y_B are displacements in the y direction for the two node sets.

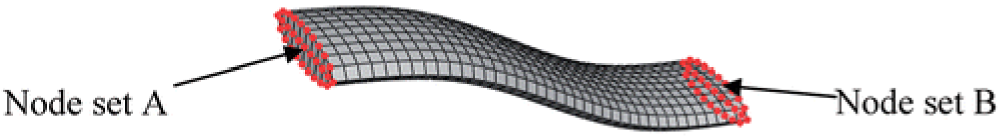

Figure 16. Nodal displacement periodic boundary constraints.

Application of TexGen to commercial fabric mechanical modeling

In this section, fabric A was selected as an example of using TexGen geometrical models as inputs to the standard FE analysis package Abaqus, implicit to predict its mechanical properties.

Mechanical model of the yarns

Yarns were modeled as continuum orthotropic solid bodies. The longitudinal direction is defined by the subscript 11, which is parallel to fibers; the transverse plane is described by the directions 22 and 33, which arecharacterized by a plane of isotropy at every point in the material.

The orthotropic behavior of the yarn is described using a 3D stiffness matrix containing nine independent constants:

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{23} \\ \varepsilon_{13} \\ \varepsilon_{12} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_{11}} & -\frac{\nu_{12}}{E_{11}} & -\frac{\nu_{13}}{E_{11}} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & -\frac{\nu_{23}}{E_{22}} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_{11}} & -\frac{\nu_{23}}{E_{22}} & \frac{1}{E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix}$$

where E_{11}, E_{22}, E_{33}, v_{12}, v_{13}, v_{23}, G_{12}, G_{13} and G_{23} are Young's moduli, Poisson's ratios and the shear moduli ofthe yarn material, respectively. ε_{ij} and σ_{ij} are the microscopic strain and stress field solutions within the yarns.

The yarn is transversely isotropic, hence:

$$E_{22}=E_{33}, \nu_{12}=\nu_{13}, G_{12}=G_{13}$$

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

A Poisson's ratio of 0.4 for both longitudinal (v_{12}) and transverse (v_{23}) directions of the yarns was selected based on measured data.[23]

The yarn transverse-longitudinal shear behavior, G_{12}, is governed mainly by the sliding of fibers relative to each other. A constant value $G_{12}=30$ MPa, obtained from the measured initial yarn tensile stress–strain curve, was used in this study.

The longitudinal stiffness, E_{11}, is a function of strain ϵ_{11}, and the transverse stiffness, E_{33}, is a function of strain ϵ_{33}, due to yarn tensile and compression non-linear mechanical response. The non-linear elastic constitutive relationships E_{11} and ϵ_{11}, E_{33} and ϵ_{33} are taken from physically measured yarn tensile and compression data.

Figure 17 presents the experimentally determined stress and strain relationship in the longitudinal direction for warp and weft yarns. Initially, warp and weftyarns have identical properties before weaving (Table 1). After weaving, the warp yarns have a smaller cross-section area and higher fiber volume fraction dueto their smaller yarn spacing and higher tension during the weaving process. As a result, the constitutive behaviors are different for the warp and the weft yarns, as shown in Figure 17.

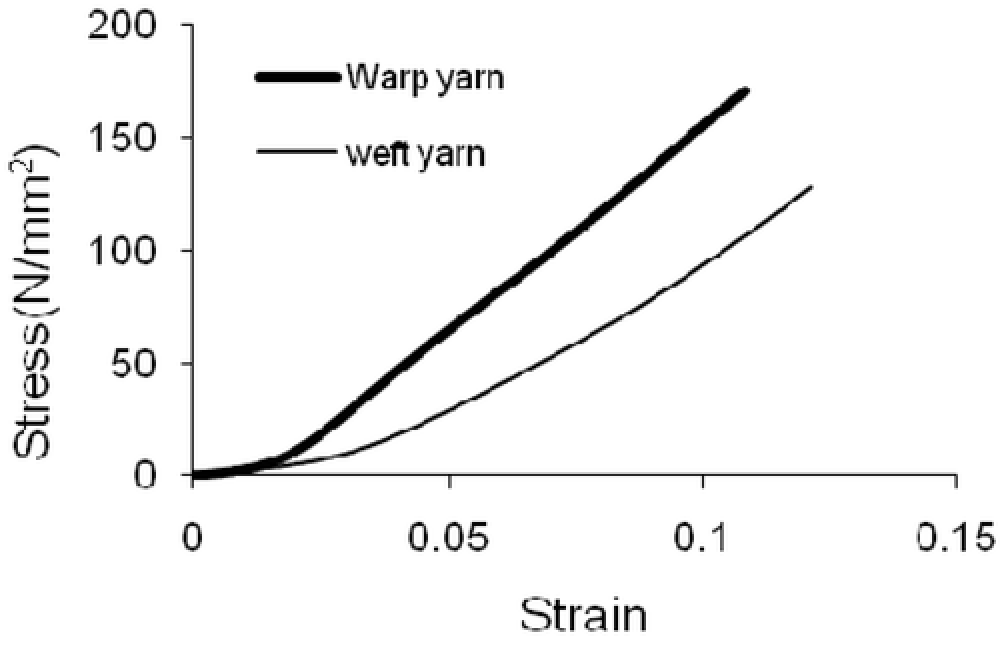

Figure 17. Measured yarn tensile behavior.

The constitutive behavior of yarn in the transverse direction is characterized using Equation (14).[16] The parameters, *a* and *b*, in Equation (14), are determined by curve fitting experimental data for warp/weft yarn compressions using a power law, Equation (15).[24] The compression measurements were carried out using theKES-F on single yarns:

$$E_{33}(\varepsilon_{33})=\sigma_{33}\varepsilon_{33}=-a[V_{f0}e^{\varepsilon_{33}}]^{b}+a(V_{f0})^{b}\varepsilon_{33}$$

$$p=aV_{f}^{b}$$

where V_{f0} is the initial fiber volume fraction for yarns. The values of V_{f0} are 57.7% and 45.0% for the warp and the weft yarns, respectively. From least squares curve fitting of the experimental yarn compression data, *a* = 0.0416, 0.0654 and *b* = 13.08, 9.3607 were obtained for the warp and the weft yarns, respectively, as shown in Figure 18.

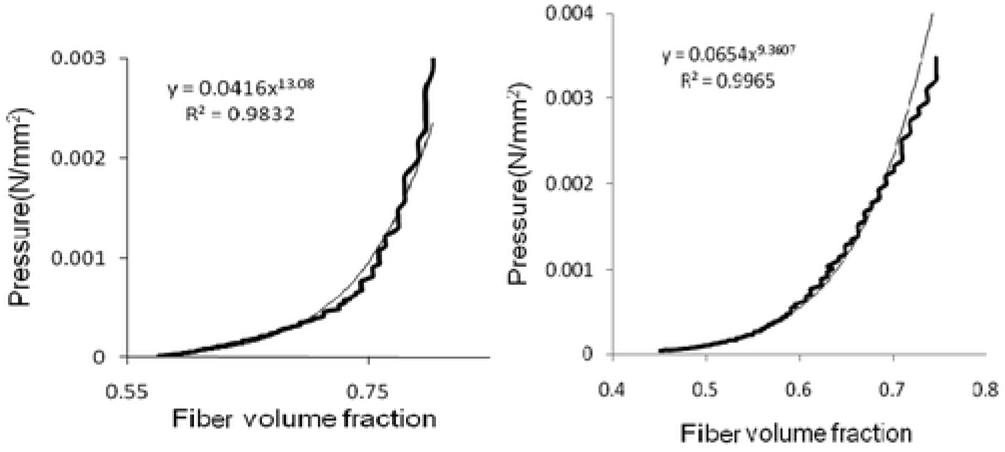

Figure 18. Measured warp yarn (a) and weft yarn (b) compression behavior (bold lines) and power law fit (faint lines).

The mechanical constitutive yarn models are programmed as a user-defined material subroutine (UMAT) in ABAQUS/Standard, an implicit FE code. The curves in Figure 17 are approximated in a piecewise linear manner to provide input data into theUMAT.

The geometric model of the fabric unit cell and theconstitutive material model for yarns are both interfaced with a mechanics modeling environment, ABAQUS, through a Python script. The details of the modeling techniques can be found in Lin et al.[17,18] Anaverage experimentally measured friction coefficient of 0.5 is used to define yarn sliding relative to one another. The material non-linearity and contact non-linearity, as well as geometric non-linearities, which are the characteristic features of fabric mechanics problems, are taken into account in the model.

Simulation set up

Simulations were carried out on this fabric to mimic theuse of standard equipment for textile testing, the KES-F testing principle.[21] In compression modeling, two compression platens were created using rigid elements with steel properties (E = 200 GPa and Poisson's ratio = 0.3).The unit cell was placed between the two platens. The lower platen was fully constrained. Compression was applied at a constant displacement rate of the upper platen. Node sets were generated at the ends of each yarn. Tie constraints were applied to the node sets using a master–slave surface approach to implement periodic boundary conditions. In tensile modeling, the same displacments were applied to the opposite boundaries of the unit cell, ensuring the individual unit cells can be assembled as a continuous physical body. In the KES-F bending test, the fabric is subjected to pure bending under uniform curvature. Simulation was performed by setting the central line of the unit cell on a fixed support and two ends of the unitcell were subjected to the same displacement in the vertical direction. In essence, yarns are considered to be elastic beams deflected under uniform curvature. In the KES shear tester, a rectangular piece of fabric is clamped along two opposite edges and is free on the other two edges. On this specimen, a tension is imposed along the clamped sides of the fabric in the horizontal direction.

Modeling results

Figure 19 gives the modeled deformed unit cell under the four principal loadings: tension, compression, shear and bending. Comparison between the predicted mechanical properties and experimental data shows that the model is able to represent the fabric mechanical behavior, as seen in Figure 20. The model provides an excellent fit for the warp direction in tension; the tensile forces are slightly underestimated for the weft direction (Figure 20(a)). The predicted compression pressures are slightly greater than the experimental data (Figure 20(b)). The predicted shear forces are slightly different from the experimental data (Figure 20(c)). Small errors in sample configuration during experiments, such as yarn misalignments and local yarn bending at the clamped edges, could be possible reasons for this. Thediscrepancy between the predicted bending behavior and measured data can be explained by the fact that the yarns are modeled as solid bodies, which cannot characterize fiber slipping within the yarns during bending deformation (Figure 20(d)). Accurate geometric modeling, physically measured yarn mechanical data used as inputs to constitutive material models and correct FE implementation are key requirements to achieve this level of accuracy in predicted mechanical behavior.

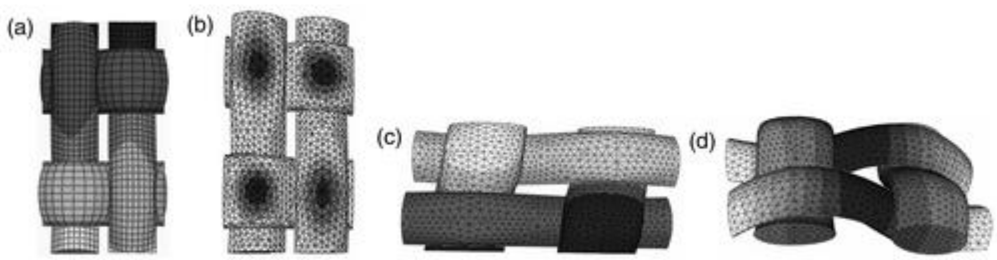

Figure 19. Modeled deformed plain weave unit cell in tension (a), compression (b), shear(c) and bending (d).

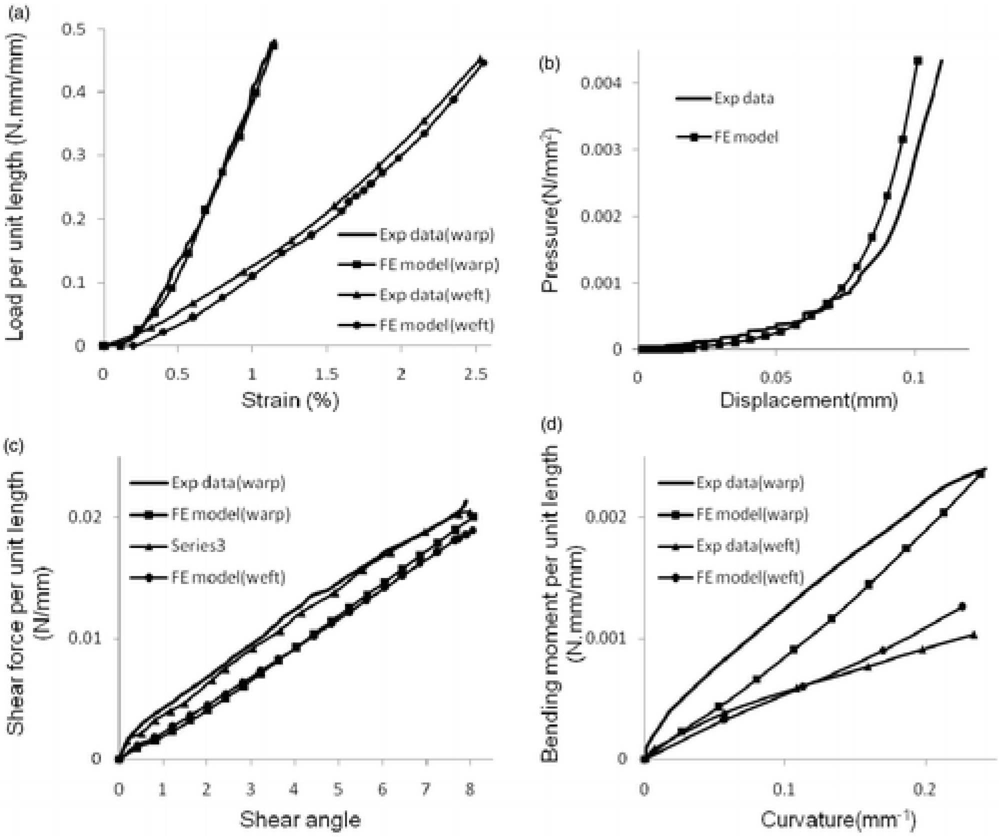

Figure 20. Experimental data versus finite element (FE) predictions for tension (a), compression (b), shear (c) and bending (d).

Discussion and conclusions

In this paper we have presented the fundamental techniques for creating geometric models for 2D and 3D fabrics in TexGen. One particular feature of this software is that it is able to model varied and hybrid yarn cross sections and it ensures a realistic contact surface between yarns without interpenetration for all types of weaving. In addition, TexGen has automated functions to discretize the model, assign material orientations andproperties to elements, define periodic boundary conditions and export the model to external analysis software in several data formats. All of this functionality provides a solid foundation for a priori prediction of physical properties of textiles and textile composites. The example of the pre-processed fabric geometrical model in TexGen as inputs to the standard FE analysis package Abaqus to predict fabric mechanical properties shows that

TexGen geometry modeling in conjunction with Abaqus mechanical prediction can be a powerful tool for engineers and designers. By using these modeling techniques, they could efficiently design new materials and new fabric structures to accelerate the fabric development process and foster innovation.

However, the software is still in development. There are two potential routes for improving the capabilities of the model.

The TexGen geometric solver computes a spatial placement of all yarns in a fabric repeat based on measured fabric geometry data for a given weave structure. Ideally, it should be possible to predict the geometry of any fabric without knowing the yarn path and cross-sectional shape, given information about the yarn mechanics and the manufacturing process for a given weave structure. The geometry of a woven structure in the relaxed state is determined by the equilibrium of forces of the warp and weft interaction, caused by the necessity to accommodate the topology of contacts between yarns in a weave. The bending of yarns necessary to maintain this topology creates transversal forces in yarn intersections. The latter leads to yarn compression and flattening and, in the case of non-symmetry of contact conditions (twill weaves), to local deflection (resisted by friction between yarns) of yarns from ideal straight directions prediscribed by tension of the warp and weft on a loom. Therefore, a realistic fabric geometric model can be achieved by minimizing the total strain energy from yarn bending, compression and tensile deformations. A new feature within TexGen is under development, which describes a realistic topology and position of yarns by applying an energy minimization technique based on a simplified yarn mechanical model.[25]

Alternatively, it should be able to read the 2D digital images of fabric structures and convert the 2D images to 3D fabric structures.

Acknowledgements

The authors would like to thank the Technology Strategy Board and Engineering and Physical Science Research Council 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 Workwear Ltd, Moxon Ltd, Airbags International, Technitex Faraday Ltd.

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