

# Automated Finite Element Modelling of 3D Woven Textiles

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**Abstract.** The advance of 3D fabric technology allows tailored material structure in different directions for optimised performance. 3D fabrics open up increasing applications in automotive, medical, energy and many other areas. This paper explores highly automated techniques to simulate 3D fabric geometry and mechanical behaviour. The basis of the work starts from TexGen, an open source software package developed at the University of Nottingham. A complex variety of 3D fabrics can be defined as subclass functions from base functions for individual yarns, cross-sections and yarn paths. The 3D fabric geometry can be generated automatically in TexGen using a script given a number of parameters. From this geometrical model, an automated procedure is followed to create an input file for finite element analysis. Yarns are meshed with hexahedral and wedge elements. The input file contains the mesh, element orientations, material definitions, contact surfaces and definitions, periodic boundary conditions and loading steps. Once the FEA simulation is completed, the nodal displacement data are parsed into TexGen to build the deformed 3D fabric geometry. The deformed geometry model can then be used for further analyses, eg. to predict permeability or composite mechanical properties. An example for a complex three layer woven fabric is demonstrated.

**Keywords:** Finite element method, 3D textile, software interface and mechanical deformation

## 1. INTRODUCTION

3D textiles are being used in many applications both in dry form as well as composite reinforcement due to cost savings while retaining desirable performance compared to conventional laminate structures. The geometric complexity of textile internal structure is one major challenge for numerical modelling. Various approaches have been proposed to address this issue. Some researchers used homogenised formulation to model fabric as anisotropic continuum with preferred material directions [1]. Discretised textile structure by using beam and truss elements captured the limited interwoven structure and interaction [2-3]. However nonlinear effects of geometry, contact and friction are not explicitly interpretable from the simplified models. Increasingly research efforts shift to three dimensional finite element methods with meshing mesoscale geometry of textile [4-6]. The FEA approach offers advantages to describe precise textile geometry, assign appropriate material properties and material orientations, and predict full field stress and strain response in great detail. This paper describes the effort to generate and process FEA models for 3D textile simulation. An automated procedure is undertaken to integrate the interface between the geometric model and the finite element analysis.

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## 2. GEOMETRIC MODELLING

3D textiles exist in many forms by various manufacturing processes such as weaving, braiding, knitting and nonwovens [7]. In this study, the multilayer interlaced 3D woven fabric is presented. The multilayer woven fabrics are used for composites reinforcement, paper machine clothing [8] and other technical applications. One example is shown in Figure 1, where a three layer fabric consists of two separate woven fabrics and binder yarns running through top and bottom layers to prevent delamination.

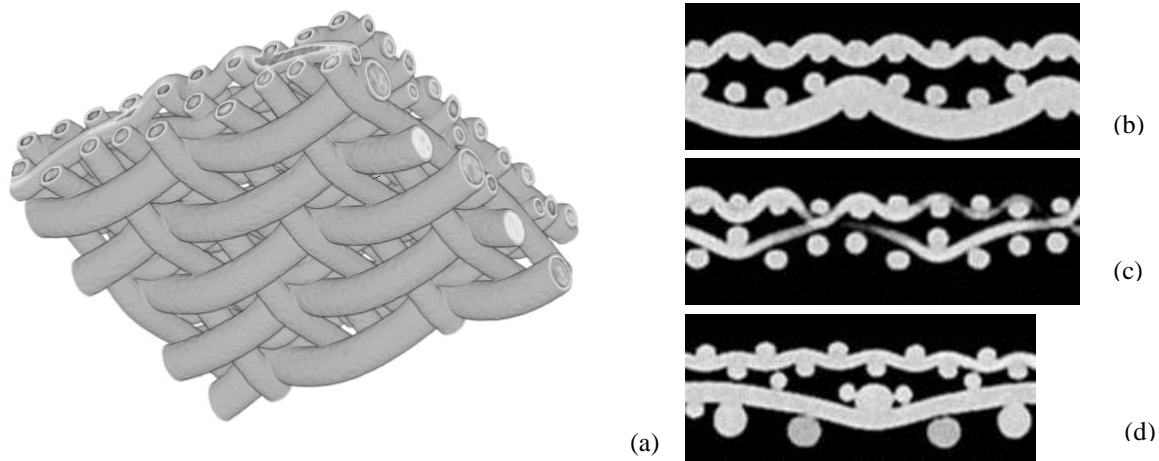


Fig. 1: Geometry of three layer fabric. (a) A screen shot of rendering micro-CT 3D image. (b-d) micro-CT image slices of internal structures respectively of weft yarns, binder yarns and warp yarns.

The geometric model for FEA is generated by using TexGen which is an open source software package for textile modelling [9]. It has been developed at the University of Nottingham. The modelling theory is described elsewhere [10]. The graphical user interface (GUI) provides access to major TexGen functions. Alternatively an application programming interface (API) allows to use the Python scripting language or to directly link TexGen libraries. The latter method is much more flexible and suitable to deal with structural diversity of 3D textiles. In addition, the Python interface can be used to create robust and functional GUI plug-in for TexGen. It is realised by using WxPython [11], an adapted wxWidgets C++ class library for Python programming language.

The primary definition of any textile in TexGen is to use a centreline describing yarn paths in 3D space with superimposed cross sections. The shape and size of cross section can be varied locally to represent more realistic fabric geometry and avoid yarn surface interpenetration. It is difficult to find a generic set of variables and functions to describe all 3D textiles. However for the specific three layer woven fabric, it is possible to have a closed formulation. The size and profile of yarn, the distance between yarns, and the crimp height are part of the required parameters. Although the top and bottom layers are constructed from different weave patterns from plain, twill and satin weave, the weave pattern can be described by four integral variables. The yarn path is described by a sine function which offers a good approximation, as compared with the laboratory measurement in Figure 2. A vector is used to control the relative position of the two layers. The binding pattern of each pair of binder yarns is described by five integral variables. The path of binder yarns is determined by considering the space constraint from both top and bottom layers. A list of 39 variables is fed in TexGen to allow a unit cell model of the three layer fabric to be automatically generated as demonstrated in Figure 3. The fabric comprises a plain weave layer, a five shed satin layer and one pair of binder yarns between adjacent weft yarns, a total of 40 yarns within the unit cell.

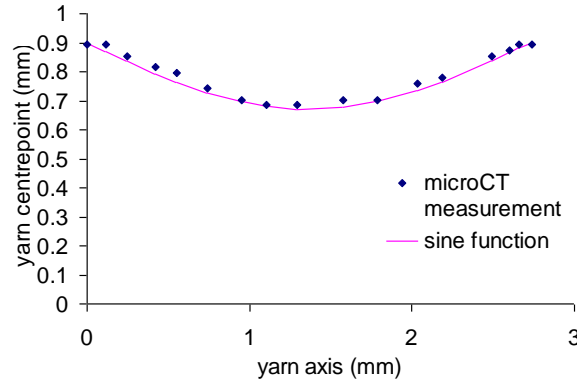


Fig. 2: Measured coordinates of yarn centreline compared with the sine function approximation

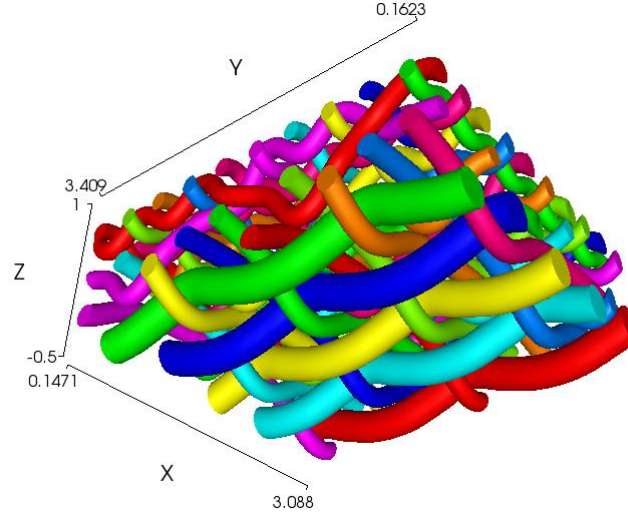


Fig. 3: Unit cell model of three layer fabric generated in TexGen

### 3. GENERATING A FINITE ELEMENT MODEL

A two-step meshing algorithm is applied to the yarn domain: the first is to generate 2D cross section meshes by a rectangular meshing technique; the next is simply to link the consistent cross section meshes together to form 6 noded wedge elements and 8 noded hexahedral elements, seen in Figure 4. In order to apply periodic boundary conditions to simulate an infinite size of fabric, the meshing algorithm ensures no overlapping and compatible mesh at the unit cell domain boundary. An ABAQUS input file .inp is then generated in TexGen. The nodes and elements are written to the input file along with an element set for each yarn. Element orientations are written to a file with the same base name but with .ori extension and referenced from the .inp file. Additional element data is saved to a file with extension .eld. The data is stored as ABAQUS depvars which are accessible from ABAQUS user materials. The data stored are yarn index, location, volume fraction and element distance from the surface of yarn.

Apart from the mesh data, the input file contains material definitions which can be UMAT or the ABAQUS standard materials. Different material properties can be assigned to different yarns. Each yarn has two sets of surfaces defined as upper and lower surfaces which allow a contact definition between the lower and upper surface of two yarns when they are directly above and below each other at a cross over. It reduces the unnecessary contact search between yarns. Periodic boundary conditions are applied on the unit cell based on the assumption that the fabric deformation is uniform at the mesoscale. The displacement field of the periodic structure is

$$\bar{u}^{j+} = \bar{u}^{j-} + \Delta\bar{R} \quad (1)$$

where  $\bar{u}^{j+}$  and  $\bar{u}^{j-}$  are the displacement vector of matching nodes  $j+$  and  $j-$  on the opposite sides of the unit cell, and  $\Delta\bar{R}$  is the deformation vector of the unit cell. The ABAQUS implementation of the periodic boundary conditions is to use an equation to represent the relative displacement of two node sets at opposite boundaries equal to the displacement of a dummy node. Thus the unit cell deformation is controlled by applying boundary conditions to the dummy node.

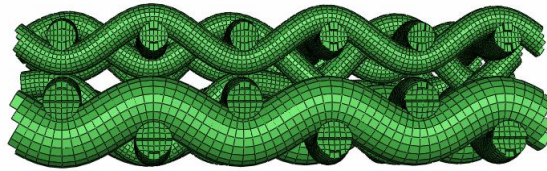


Fig. 4: Volume mesh of three layer fabric

Since the complex geometry and contact gives rise to highly nonlinear behaviour of the structure, the static stress analysis procedure in ABAQUS/Standard has difficulty to convergence. Instead, ABAQUS/Explicit is chosen with adding appropriate damping parameters to damp out the inertia effects for a quasi-static solution. The launch of ABAQUS job is automated after completing the .inp file.

#### 4. DEFORMING GEOMETRY MODEL

Once the ABAQUS simulation completes, a procedure is used to rebuild a deformed TexGen geometry model by using a volume mesh with nodal displacements predicted by ABAQUS. The purpose is to move on to further analysis and design based on the mechanically predicted geometry under certain loading conditions. It is achieved by adjusting the yarn centreline and then the yarn cross section. A tetrahedral mesh is obtained by splitting the existing hex and wedge element mesh to simplify interpolation. The deformed centreline is a spline calculated from a series of sample points whose displacements are interpolated from the host tetrahedron's nodal displacements. Similarly the cross section is treated as a spline with sample points. The displacements associated with these sample points are calculated in the same manner for the centreline. The cross section may vary along the length of the yarn. The repeat vectors and domain of the unit cell are updated to match up the deformed structure. Figure 5 illustrates a TexGen model of three layer fabric after stretching in Y direction with a nominal strain 15% over the unit cell, for comparing the undeformed structure as shown in Figure 3. The fabric is made of polyester monofilaments with Young's modulus 3GPa and Poisson's ratio 0.3. The force strain history calculated in ABAQUS is also plotted aside.

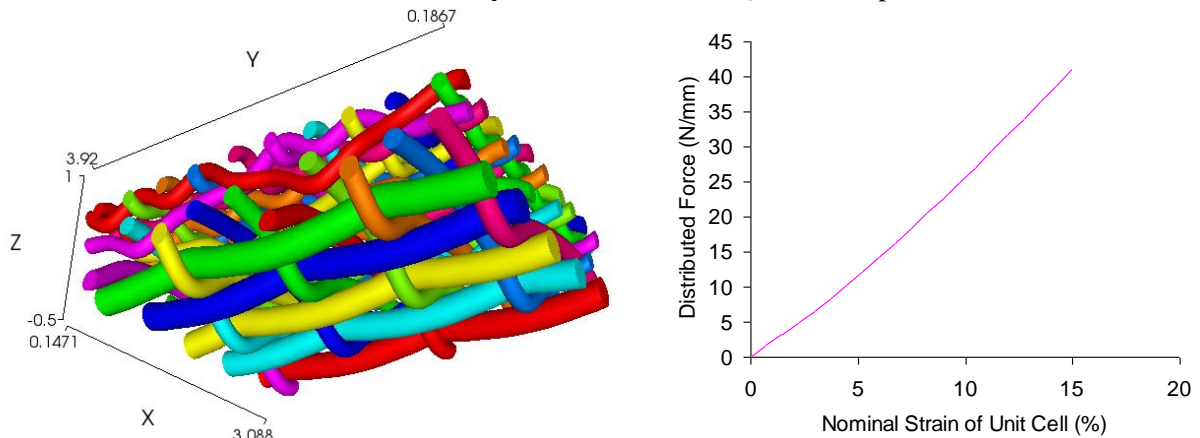


Fig. 5: (a) TexGen model after deforming the three layer fabric shown in Figure 3; (b) The corresponding stretch force vs nominal strain predicted from FEA.

#### 5. SUMMARY

An automated method is implemented to undertake a finite element simulation of mechanical loading for a 3D textile. The complex geometry of 3D fabric is generated through TexGen API Python scripting. A range of geometry parameters are required as input. The geometry is then meshed and ABAQUS input file is created with definitions of elements, nodes, materials, contact, boundary condition and loading step. After the finite element analysis, the data of predicted deformation was used to rebuild a TexGen geometry model for further analysis and design. The whole process was automated with minimum user intervention. This modelling procedure is highly desirable for material optimisation and design. By bridging the design variables with mechanical performance assessment, it is possible for a further implementation of multi-objective material optimisation.

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