3D TEXTILE COMPOSITE MECHANICAL PROPERTIES PREDICTION USING AUTOMATED FEA OF THE UNIT CELL

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Abstract

Finite element (FE) analysis of the repeating unit cell of textile composites has been a developing technology for a number of years. This paper describes recent work conducted at the University of Nottingham which removes the traditional requirement of user intervention during model creation, bringing a new stage of maturity to the technique. The computer aided engineering (CAE) methodology is described, together with the mechanical modelling methods employed. The techniques are applied to composites with 3D woven reinforcements and the results which are obtained are compared with those published in the literature.

1 Introduction

Textile reinforced composites offer good mechanical performance coupled with reduced labour costs for manufacture compared with unidirectional reinforcements. However, while computational tools for prediction of their mechanical behaviour are available (e.g. [1]-[4]), they are still limited in terms of their availability, the level of validation and, in some cases, their functionality. This is particularly true for 3D woven composites, although there is much interest in these due to their resistance to delamination, and because of the opportunities for net-shape woven preforms to reduce manufacturing costs and material wastage further. The purpose of this paper is to describe recent developments in finite element (FE) modelling of the repeating unit cell, and to give examples of the technique as applied to composites with 3D woven reinforcements.

2 Geometric and FE modelling

2.1 Geometric modelling using TexGen

Geometric modelling of textile reinforcements has received considerable attention in the literature, notably, but not exclusively, from Lomov et al. [5], and from authors at the University of Nottingham [6],[7]. The work presented in this paper complements the work on geometric modelling at Nottingham. An in-house package named TexGen has been developed over the past few years; TexGen uses a general vector path description for yarn centrelines and imposes an appropriate cross section to build the yarn volumes; this allows the geometric modelling of any textile which can be manufactured. Some routines to correct the geometry of overlapping yarns are also incorporated. The modelling approach of TexGen is purely geometric, requiring no information about mechanical behaviour of the yarns.

Recent development activities have resulted in a new version of TexGen [8] which is platform-independent and has an application programming interface (API) accessible through both the C++ and Python programming languages. This version has been released into the public domain as an open source project, under the terms of the GNU General Public Licence. Both the source code and compiled executables are available for free download and contributions to development are welcomed from sources outside the University of Nottingham. It is hoped that this step will facilitate the interchange of ideas and the advancement of textile modelling.

TexGen facilitates the export of textile composite geometric data and metadata in a number of formats; moreover, the provision of an API allows textile models to be built and interrogated ‘on-the-fly’ from within a range of environments, including commercial engineering software packages.

2.2 Feature based FE modelling

Many commercial FE packages incorporate a pre-processor capable of creating parametric geometry models, often driven by a scripting interface. This functionality is employed in current work to enable TexGen textile models to be reproduced within a mechanics modelling environment in an automated fashion, thus overcoming the traditional requirement for significant manual intervention during model creation. Although similar routes exist for the Gambit (Fluent pre-processor) and Ansys packages, this paper will explain the methodology used for model creation within Abaqus/CAE since this is the most fully integrated modelling route.

Since TexGen and Abaqus/CAE each have a Python scripting interface, a clear methodology for linking the two codes was identified. A Python script (program) is called from within Abaqus/CAE, which has access to TexGen library functions using the standard Python '`import`' keyword (equivalent to the C++ `#include` statement). This script contains code either to create a TexGen model, or to read in an existing textile which has been saved. Subsequently, the program loops over the textile hierarchy and retrieves the geometric data defining the outer surfaces of the yarns. These points are used for lofting solid yarn bodies within Abaqus/CAE. Subsequent operations are incorporated which perform Boolean subtraction to generate the complex matrix volume, and to define the materials and boundary conditions. Mesh generation operations, using quadratic tetrahedral elements, are also undertaken within the script.

Once a mesh has been generated, the coordinates of the centroids of those elements within the yarns are calculated. These coordinates are passed to a TexGen function which returns the fibre orientation vector at each point. In models where fibre volume fraction (V_f) is not constant (i.e. those where yarn cross sections are variable, and those where there is a fibre distribution imposed such as that observed by Koissin et al. [9]) the V_f is also returned by this function. These data are incorporated into the FE analysis. For further investigation of the effects of variable fibre fractions on mechanical behaviour, the reader is referred to [10]. The script creates a job which is submitted for analysis, whereupon post-processing operations may also be performed automatically if required.

Whilst the method described above can be used for any type of textile composite, the focus of this paper is on those with 3D woven reinforcements. One of the principal challenges of such materials is the size of the repeating unit cell, which has significant implications on the computational facilities required for model solution. The models presented in this paper were run on a 64 bit Linux system having 24Gb of RAM.

2.3 Elastic modelling

A glass/vinyl ester composite with orthogonal 3D woven reinforcement was modelled, the geometric architecture of which was measured and reported by Rudov-Clark et al.[11]. A TexGen model was created using a simple Python script. Fibre volume fractions within the yarns were calculated from the yarn weights. Input data to the model and measured and predicted physical data are provided in Table 1. Data predicted by Rudov-Clark et al. using the WiseTex software are also included for comparison. The TexGen geometric model of the yarns is illustrated in Figure 1.

The fabric architecture was simplified, assuming that warp and weft yarns remained straight and that cross sections remained constant along the yarn length. Because of these assumptions the geometric model had a greater thickness than the real material, resulting in a slightly lower overall V_f. This was due to the fact that, in the real fabric, the binder yarn compresses the outer weft yarns such that it does not contribute to the fabric thickness. However, in the model this was not the case because of the assumption of straight yarns, and the thickness was increased by 2 x (binder height + gaps between weft yarns, binder yarns and mould) ≈ 0.25. Further thickness increase was caused by the requirement to retain a clearance between crossing yarns in order to facilitate mesh generation. This is a clear limitation of analysis techniques using a conformal mesh, and one which is receiving considerable attention, both at Nottingham and elsewhere. It is anticipated that more realistic geometric assumptions for 3D weaves will be developed and validated from experimental observations in the near future, as they have been for 2D woven reinforcements [7].

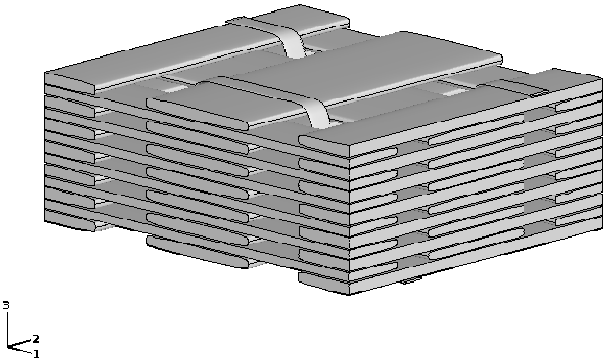

Figure 1 Internal geometry of the orthogonal weave

Table 1 Selected geometric input data and predicted physical data.

	Measured	WiseTex	TexGen
Warp yarn pitch (mm)	4.878	-	-
Weft yarn pitch (mm)	5.618	-	-
Warp density (Tex)	1800	-	-
Weft density (Tex)	2400	-	-
Binder density (Tex)	68	-	-
Unit cell dimensions (x,y,z) (mm)	(9.9, 11.24, 3.74)	(9.8, not stated, 4.14)	(9.76, 11.24, 4.36)
Fabric weight (gm^{-2})	5020	5235	5225
Overall V_f	0.524	0.498	0.462

Mechanical properties of the constituent materials, also taken from [11], are given in Table 2. Properties of the yarns were calculated using the micromechanics equations proposed by Chamis [12].

Table 2 Constituent material mechanical properties.

	E-Glass	Dow Derakane 411-C50 Vinyl ester
E (GPa)	69	3.38
ν	0.22	0.14

2.4 Fatigue modelling

Fatigue modelling of a second 3D woven composite has also been performed using a two-scale approach. This was undertaken using the Ansys FE package.

While elastic properties for unidirectional composites can be calculated using simple analytical models, to develop an understanding of fatigue behaviour requires a more rigorous treatment. Unidirectional composites were modelled at the micro-scale (fibres and matrix) using standard numerical homogenisation techniques, assuming hexagonal fibre packing and full periodicity, in order to obtain mechanical property data for the yarns in the meso-scale (textile unit cell) model.

The approach was based on the S-N data of fibres and resin. A carbon/epoxy material system (AS/3501-5A) was modelled, for which the S-N data of the constituents were taken from the literature [13]. The elastic properties of the constituents are provided in Table 3, while fatigue data are given in Table 4.

Table 3 Elastic properties of carbon fibre and epoxy resin.

	Fibre	Resin
E_1 (GPa)	194.3	3.45
E_2 (GPa)	15.4	3.45
ν_{12}	0.275	0.35
G_{13} (GPa)	18.1	1.28

Table 4 Fatigue properties of carbon fibre and epoxy resin.

Cycle number	Fibre strength (MPa)	Resin strength (MPa)
10^3	1880	26.4
10^4	1780	24.8
10^5	1683	23.2
10^6	1586	21.8

The fatigue strength properties were evaluated at the micro scale using the hexagonal arrangement of fibres illustrated in Figure 2. A fibre volume fraction of 0.70 was selected in order to permit comparison with experimental data. Cyclic loading was applied to the unit cell with periodic boundary conditions. The properties used represented those of the fatigue-degraded constituents for a given stage in the fatigue life from Table 4 and the simulation examined the damage shakedown at each stage of life. A maximum principal stress criterion was used for damage initiation and propagation. A continuum damage mechanics approach was applied, degrading the stiffness of the elements where the principal stress exceeded the failure strength of the corresponding constituent.

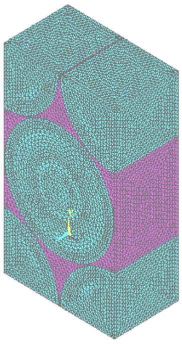

Figure 2 FE mesh of unit cell for micro-scale fatigue analysis

The fatigue data predicted at the micro-scale were used as input for the fatigue strength of the impregnated yarns in the meso-scale analysis of a 3D woven composite unit cell. Since there were no fatigue data available for a 3D woven composite comprised of the constituents for which fatigue behaviour was known, the same textile geometry detailed above was reconstructed in Ansys. Using the results of the micro-scale analyses as input for the yarn behaviour (giving an overall V_f=0.44). A single load case was considered for illustrative purposes. Cyclic loading was applied to the 3D woven composite unit cell model and the fatigue behaviour was obtained using the same procedure employed in the micro-scale analysis.

3 Results and discussion

3.1 Elastic predictions

Uniaxial elastic load cases were analysed to obtain the three normal Young's moduli and the Poisson's ratios of the composite reinforced with the glass fabric. The stress distribution on a section through the composite is shown in Figure 3. This Figure also illustrates the nature of the tetrahedral meshing technique employed, where the mesh was fine near the yarn/matrix interface where stress gradients were expected to be high, but relatively coarse in the centre of large isotropic matrix regions. This led to some considerable computational saving, although the model was still large, having approximately 4.1 million degrees of freedom.

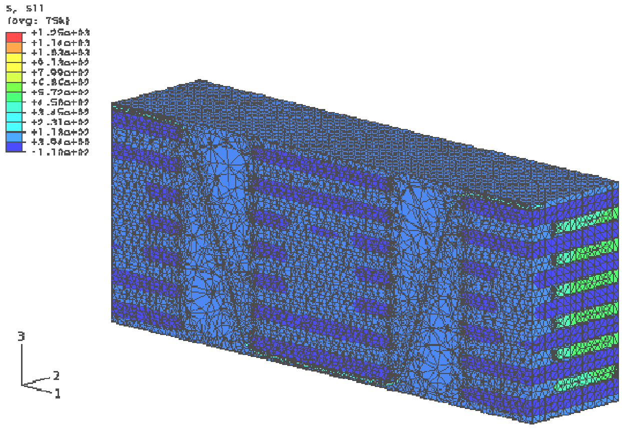

Figure 3 Stress distribution on a section through the 3D woven composite subjected to loading in the warp direction. Stress measure plotted is stress in the fibre direction of the yarns and stress in the global 1-direction (warp) in the matrix.

In Table 5, the stiffness predictions are compared with experimental data and with predictions obtained by Rudov-Clark et al. [11] using a Mori-Tanaka technique. As stated previously, the thickness dimension of the textile unit cell was larger in the model than that measured experimentally. The last column in Table 5 shows data calculated with a revised thickness, t:

$$t = t_0 \frac{Vf_{measured}}{Vf_{modelled}} \qquad (1)$$

These data were calculated for comparative purposes. This new thickness affects the cross-sectional area terms used when calculating the nominal applied stress on the unit cell, in turn adjusting the stiffness. It was verified that, numerically, the effect is almost the same as scaling the moduli directly in accordance with the ratio of fibre volume fractions; however, to adjust the effective thickness is a more rigorous treatment of the problem.

Table 5 Measured and predicted elastic properties of 3D woven glass/vinyl ester composite (V_f≈0.5). Coordinate system: 1 – warp, 2 – weft, 3 – through-thickness.

	Measured (V_f=0.524)	Mori-Tanaka (V_f=0.498)	FEM (Vf=0.462)	FEM (normalised)
E_1 (GPa)	23.2 ± 3.2	26.6	21.0	23.7
E_2 (GPa)		26.3	24.7	28.0
E_3 (GPa)		6.85	8.25	
ν_{12}		0.122	0.095	
ν_{13}		0.199	0.174	
ν_{23}		0.053	0.062	

3.2 Fatigue strength predictions

The predicted fatigue strength data for unidirectional carbon/epoxy composites (V_f=0.7) under transverse and longitudinal uniaxial loads are shown in Figure 4. Experimental measurements of the fatigue behaviour were reported in [13], and these data are also plotted. It can be seen that agreement between the experimental and predicted values is excellent for the longitudinal load case, but that this is not the case for transverse loading.

These predicted fatigue strengths were used, as described previously, for evaluation of the fatigue behaviour of a 3D woven composite. Results are shown in Figure 5. Due to a shortage of complete sets of published experimental data, it was not possible to validate these meso-scale predictions, although it is hoped that a suitable route for validation will be identified in due course.

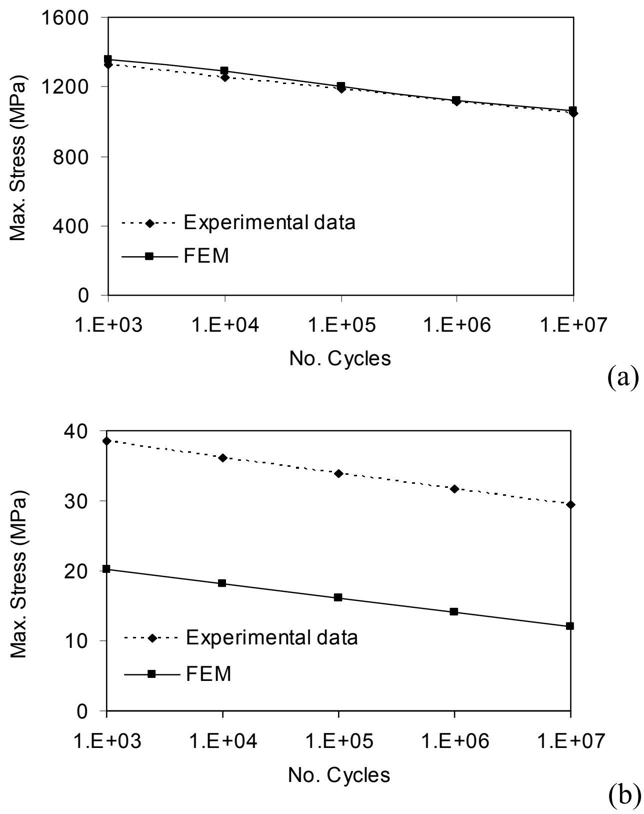

Figure 4 Predicted fatigue strengths of unidirectional carbon/epoxy composites (V_f = 0.7) under (a) longitudinal and (b) transverse cyclic loading conditions.

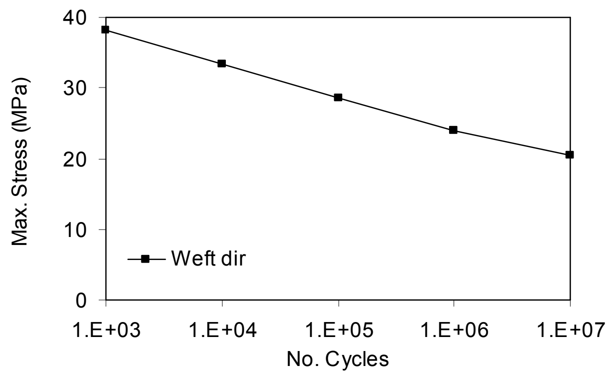

Figure 5 Predicted fatigue strength of 3D woven carbon/epoxy composites (V_f = 0.5).

3.3 Discussion and conclusions

This paper presents an automated approach to mechanical modelling of textile reinforced composites. This method permits the whole modelling process from building the textile model to mesh generation, solution and data reduction to be undertaken using an integrated scripting approach, without real-time intervention from the user. Predictions of both linear elastic behaviour and fatigue strength have been presented; these compare very well with the limited experimental data available.

Notwithstanding the deviation in thickness of the fabric due to the simplified geometric assumptions employed, the stiffness predictions showed reasonable agreement with the results of the Mori-Tanaka method published in [11]. Furthermore, when the in-plane stiffnesses are normalised according to the thickness deviation, good agreement with experimental data is also observed.

It may be noted that the ratio of E_1 to E_2 (stiffness along warp and weft directions, respectively) are not consistent between the Mori-Tanaka and FEM results. Since the axial stiffness is fibre dominated, since the warp and weft yarns are straight, and since the binder yarn content is much smaller than the warp yarn, it can be assumed that relationship in Equation 2 holds:

$$\frac{E_1}{E_2} \approx \frac{m_{warp}}{l_{weft}} \Bigg/ \frac{m_{weft}}{l_{warp}} \qquad (2)$$

where m_{warp} and m_{weft} represent the total mass of reinforcement in the respective yarns, while l_{warp} and l_{weft} represent the x and y dimensions of the unit cell respectively.

In the glass fabric, the right hand side of Equation 2 was calculated from the parameters in Table 1 to be 0.853, while the left hand side, from the FEM data presented in Table 5 (prior to rounding) was 0.848. The ratio of stiffnesses predicted by the Mori-Tanaka method was 1.01. This suggests that, within the scope of the validation data considered to date, there is a high level of confidence in the automated FEM technique for stiffness prediction. This is an essential pre-requisite for more elaborate damage modelling.

With respect to the fatigue data presented, it was shown that the technique agreed well with the experimental results for longitudinal loading, but that transverse loading conditions did not exhibit such agreement.

The reason for this discrepancy may be due to neglecting the residual stresses arising during material processing. If residual stresses are considered, the tensile strength may increase, as was observed by Zhao et al. [14]. Additionally, the resin is assumed to exhibit linear elastic material behaviour. Whilst in the longitudinal direction, the strength of the composite is fibre dominated and shows good agreement between experiments and predictions, the non-linear behaviour of the matrix may be a significant factor in transverse fatigue prediction.

Nonetheless, it was demonstrated that a two-scale technique could be practically employed such that fatigue behaviour of a 3D woven composite could be predicted simply from a knowledge of the yarn architecture and the properties of the fibre and matrix materials. This is thought to be a significant achievement and one which will be of great value should further validation continue to support the findings to date.

Although the methods presented are able to handle a wide range of textile architectures, one of the most significant hurdles is in finding comprehensive mechanical data for matrix materials, particularly in fatigue and in multiaxial stress states. Additionally, as the geometric description of the weave becomes more accurate, so the unit cell geometry becomes more complex, in turn requiring a higher level of mesh refinement. Due to the large unit cell sizes of 3D weaves this may cause the models to approach the limits of currently available computing hardware.

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