COMPLIANCE MODELLING OF 3D WEAVES

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Abstract

This paper presents preliminary work on modelling the deformation behaviour of 3D woven textile preforms. Idealised geometrical models have been developed using TexGen software, based on the nominal weave specifications. Dry textiles deform considerably even under modest loading applied during composites processing. Two different approaches have been presented here: analytical energy minimisation scheme and FE analysis. Kawabata Evaluation system (KES) has been used for evaluating the constitutive tow properties and the load-deformation behaviour of 3D weaves. The cross-section and the path of an individual tow depend on the thread-line tensions in 3D weave. In this work, an attempt has been made to measure the thread-line tensions using Raman spectroscopy.

1 Introduction

Three-dimensional woven and braided fabrics have been around for at least three decades; the US space programme has mainly driven the initial developments in 3D preforming. Lately, military (JSF) and civilian aircraft programmes have been taking a fresh look at 3D weaves in order to reduce ply count and hence save labour costs, and to improve the through-thickness properties. While there has been a large volume of literature on processing and process modelling of 2D textiles [1], information on 3D weaves is scant. WiseTex [2] and TexGen [3] software are capable of creating geometric models for 3D weaves (figure 1). These models tend to be somewhat idealised. In reality, path and cross-sectional geometry of individual tows is far more complex than represented in figure 1. One of the objectives of the work reported here is to evaluate the influence of geometric idealisations on the predicted compliance.

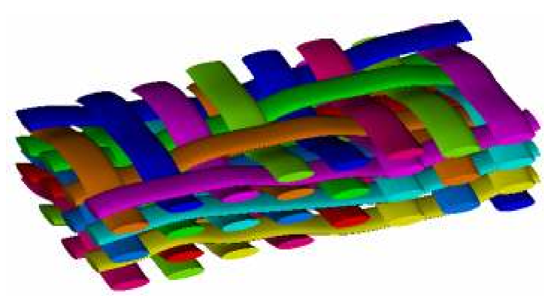


Fig.1. 3D weave generated by TexGen [3]

2 Energy minimisation scheme

Sagar *etal*[4] presented an energy minimisation scheme for computing the load-deformation behaviour of 2D fabrics. This procedure assumes a trial function to represent the deformed configuration, similar to Raleigh-Ritz method. The trial function may be based on simple circular (Peirce) geometry or represented by a set of polynomial functions.

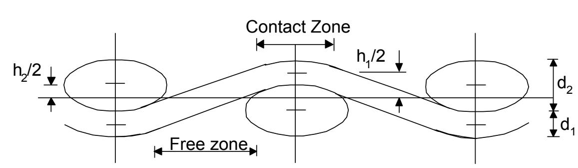


Fig.2. Woven fabric geometry

Total energy of a unit cell under a biaxial load is given by,

$$V = -F_1(x_1 - X_1) - F_2(x_2 - X_2) + U_e + U_b + U_c \quad (1)$$

The first two terms represent the potential energy of external loads, U_e the extension energy, U_b bending energy and U_c the transverse compressional energy of the yarns. The energy function is minimised to satisfy the geometric constraint,

$$h_1 + h_2 = d_1 + d_2 \qquad (2)$$

Equation: 2 ensures that the interlacing yarns are in contact with each other during each step of the deformation process. Additional equations are used to ensure that the yarn cross-sections do not overlap with each other.

2.1. Compaction of 3D weaves

A simple 3D weave is presented in figure 3. It has two interconnected woven layers. From the modelling point of view, the weave has been subdivided into smaller units; each unit is somewhat similar to a plain weave.

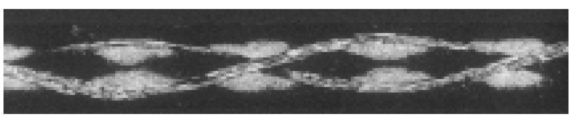


Fig. 3: Interconnected double layer fabric

Bending and compressional properties of the yarns are required for computing the individual energy terms. Non-linear bending and transverse compression curves of the yarns were measured using Kawabata Evaluation System [5]; similar approach was adopted by Lomov *etal* [6]. Figure 4 shows the predicted thickness *vs* pressure curve of the fabric shown in figure 3. It can be seen that the initial part of the curve is dominated by bending energy and the final part by the compression energy. Ignoring the yarn bending stiffness (often done in compaction models) would underestimate the pressure generated during the compression up to about 2 kPa.

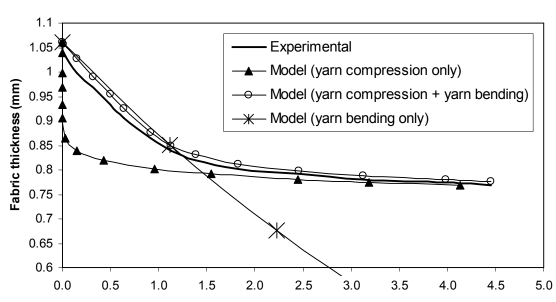


Fig4: Comparison with experimental results [7]

3 Kevlar 3D woven Fabric

A 3D woven fabric has been developed consisting of 3 warp layers (stuffers), 4 weft layers(stuffers) and a set of binder yarns to hold the fabric together in an orthogonal weave (figure 5).

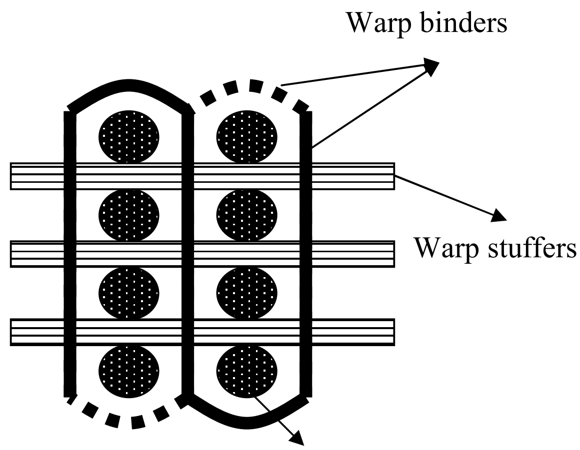


Fig.5. Orthogonal Weave

Fabric constructed with 1580 dTex Kevlar yarn has the following specifications: warp stuffers = 6/cm, weft stuffers = 4.66/cm, binders=6/cm (divided into two groups). The reason for using Kevlar fibers is that these fibers can be used as strain gauges using Raman spectroscopy.

3.1 Kawabata tests on yarns

Kawabata Evaluation System has been used for measuring the bending and compression properties of Kevlar yarn. Due to inter-fibre friction, these properties are nonlinear. In the present work, average modulii are used as a first approximation.

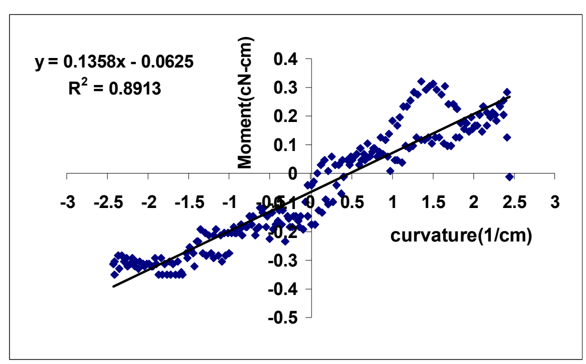


Fig.6. Moment-curvature relation of a yarn

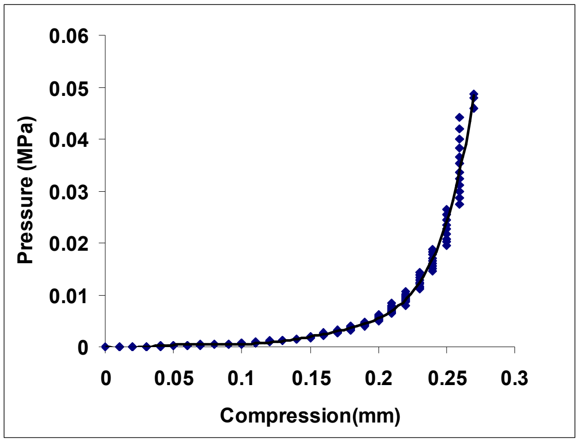


Fig. 7. Yarn compression curve

Bending stiffness of the yarn has been found to be 0.14 cN.cm^2. Average linearised compression modulus has been found to be about 0.12 MPa.

4. Geometric and FE Modelling

The unit cell fabric geometry was generated using the TexGen textile schema [3] based on measured fabric geometric parameters. The yarn cross-section was modelled as elliptical. The generated fabric geometry was transferred to ABAQUS through a Python script for FE analysis.

A unit cell compression model was created using the commercial software package Abaqus Standard 6.6. The yarns were modelled using a linear elastic orthotropic material model, with material axes defined automatically to track the yarn direction for each element. Axial yarn modulus (E_1) was calculated directly from the fibre modulus (84 GPa), whilst the transverse compression moduli (E_2, E_3) were estimated from experimental data (0.12 MPa). Two rigid bodies were generated to represent the compaction platens. Periodic boundary conditions were applied to replicate the repeating nature of the fabric, and displacement control was used to define the maximum displacement of the upper platen (indenter). One challenge of 3D fabric modelling is the multiple contacts between yarns; this was solved using a surface to surface contact algorithm. The friction coefficient between yarns was defined as 0.3, allowing yarns to slide over each other.

The FE model before and after compression is illustrated in Fig. 8. Figure.9 shows the model is able to predict fabric geometry non- linearity and contact non–linearity, even using a linear elastic material model.

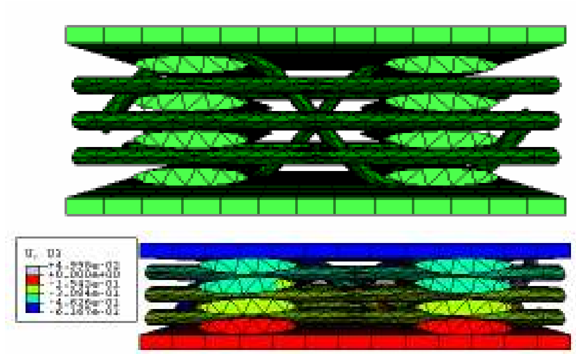


Fig.8. Finite element mesh of platens and fabric – before (top) and after (bottom) compaction

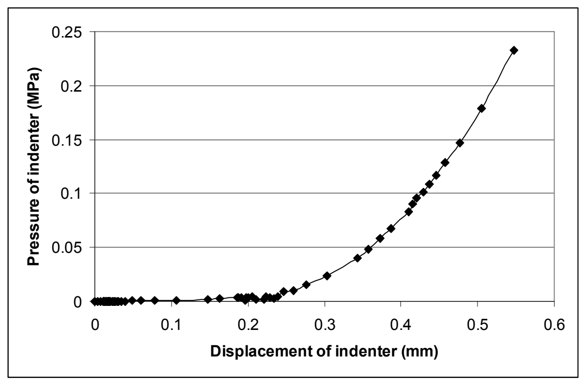


Fig.9. Predicted pressure vs displacement using FEA

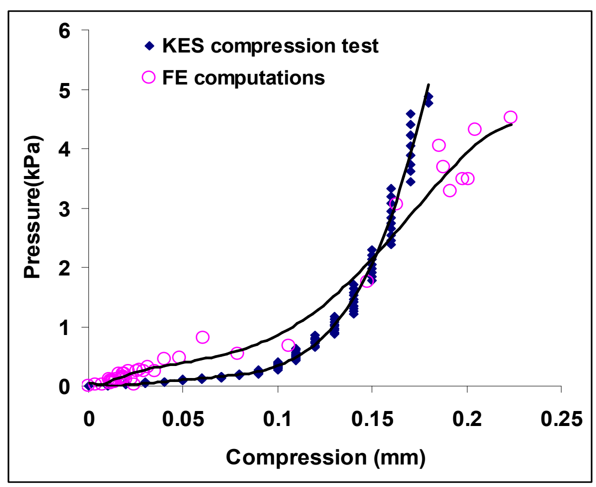


Fig.10. Comparison with KES data up to 5kPa

Difference between the predicted and experimental curves(fig.10) is due to the assumption of a linear yarn compression model. A bi-linear model would have improved the predictions.

5. Compliance under in-plane tension

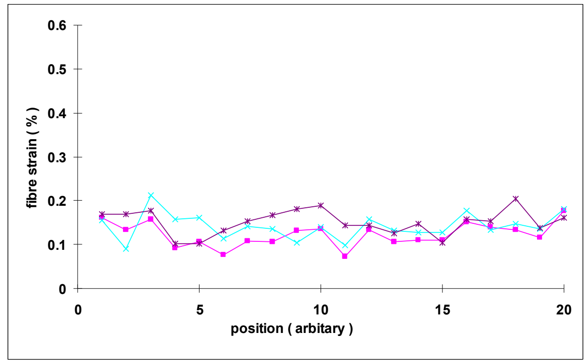
Fabric compliance under tension is very sensitive to yarn crimp. In a 2D fabric, all the yarns in the loading direction have similar crimp values. In the case of 3D fabrics, binder yarns have significantly higher crimp, and stuffer yarns have very small crimp. Kawabata tensile test gives fabric extension value of 0.95% under a tensile load of 5N/cm. In an idealised geometry, as shown in figures 5&8, stuffer yarns are assumed to be straight. If we were to model such a system using FE, entire tensile loading is supported by the warp stuffers and the binder would experience little or no load. It can be shown that the theoretical fabric extension would be of the order of 0.003% under a tensile load of 5N/cm, where as the experimental value is around 0.95%.

5.1 Measurement of thread-line tensions

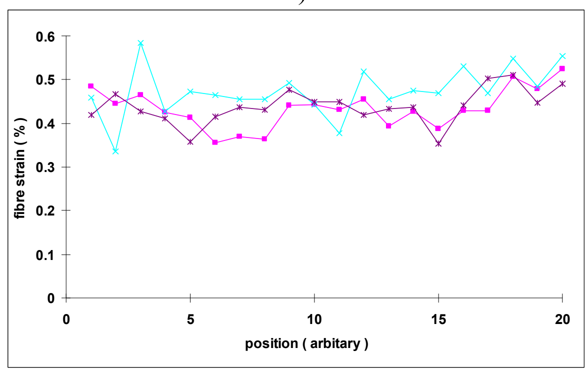
Measurement of thread-line tensions would be useful in verifying the validity of geometric idealisations used in FE modelling. In this work, Raman spectroscopy has been used to measure fibre stress/strain under applied in-plane tension. Kevlar fibres exhibit well defined Raman band shifts.

Fig.11. Tensile loading of the sample

The loading frame shown in figure 11 is used for applying tension to the fabric sample. Fibre strains have been mapped in the stuffer and binder yarns in the loading (warp) direction.

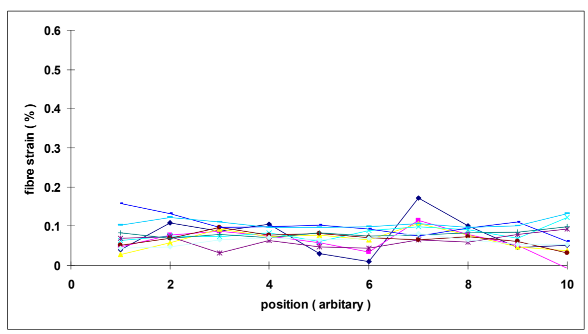


a)



b)

Fig.12. Fibre strain in the binder yarn at two loading positions



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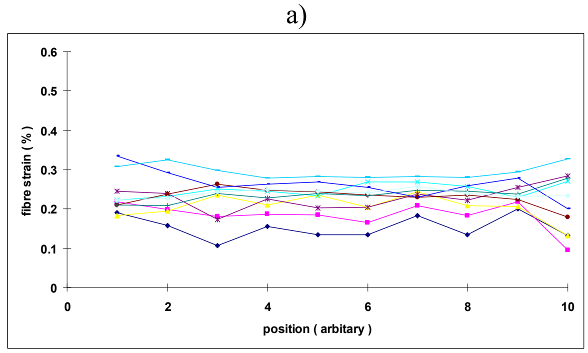

b)

Fig.13. Fibre strain in the stuffer yarn at two loading positions

Interesting observations can be made from figure 12 and 13. Figure 12a and 13a represent the first loading; where as figure 12b and 13b represent the second loading (actual applied loads have not been measured as the loading frame is not equipped with a suitable load cell). In the dry Kevlar fabric, the fibre strain is fairly constant along the length of each yarn segment –binder yarn with a considerable off-axis angle has also exhibited constant strains. This is entirely expected, however, was not verified by any previous experiments. Previous work on fibre strain measurement was on composite laminates where fibres strains increase with the off-axis angles [8].

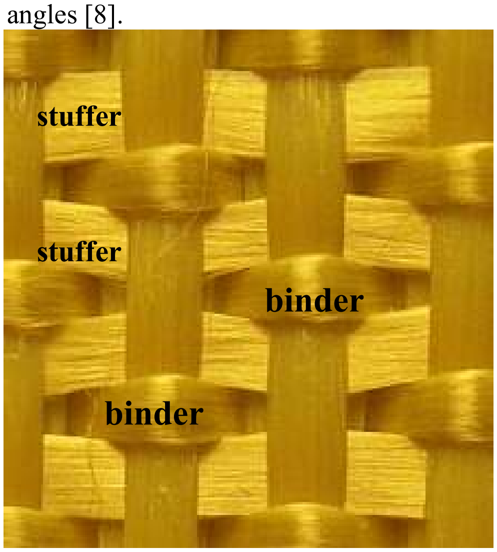

Fig.14. stuffer and binder yarn

Another interesting observation was that the stuffer yarns exhibit higher strains in comparison to binder yarns. Under the first loading, binder yarns experience an average strain of 0.15% and in the stuffers it was 0.07%. Under the second loading, strain in the binders was 0.45% and in the stuffers it was 0.23%. Strain in the binders is roughly half of that of stuffers - this cannot be predicted using a geometrical model in which stuffers are assumed to be straight. Figure 14 shows that the stuffers do have some in-plane waviness, and this delays the loading of stuffer fibres. On the other hand, binders are under pretension due to weaving forces, and are readily loaded when a tensile force is applied.

6. Conclusion

Raman spectroscopy studies point out the limitation of simplified fabric geometric models; subtle tow undulations, especially of stuffer yarns, cannot be ignored in predicting the compliance of 3D weaves.

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