STIFFNESS AND FAILURE MODELLING OF TEXTILE COMPOSITES

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SUMMARY: The ever increasing use of textile reinforced composite materials for structural applications makes the development of automated and computationally efficient design and analysis tools a must. The focus of this paper is on a very important, but often neglected, aspect of composites modelling: Geometric characterisation of 2D and 3D textile reinforcements for composites. Current work in this area, capabilities and limitations, are presented. Two mesomechanical methods for predicting the mechanical behaviour of textile reinforced composites are presented. The models consider the shape and type of the yarns, yarn interactions and crimp as well as the matrix distribution. Two FORTRAN software programmes called TEXCOMP and FLEXCOMP have been developed to automate calculation and turn both methods into practical design tools. These programmes compute stiffness, stress fields and failure. Results obtained are comparable to those obtained experimentally and from finite element modelling.

KEYWORDS: Textile reinforced composites, mesomechanical modelling, geometric characterisation, elastic properties, method of cells, complementary energy model, inclusion models.

INTRODUCTION

The anisotropic nature of textile reinforced composites makes it possible for designs to be tailored to specific loading conditions which in return results in significant gains in strength and stiffness to weight ratio. Despite these advantages their widespread use is hindered by a limited understanding of their mesomechanical behaviour. The development of mesomechanical models to predict the macroscopic behaviour of composites, with sufficient accuracy and efficiently, is therefore imperative.

Many different models exist for modelling textile composites. These can be grouped into two classes. The first one includes the laminate theory and fabric geometry models [1, 2, 3, 4, 5,

6]. These models are primarily used to predict the thermoelastic behaviour of the composite as well as to provide a rough estimate of internal stresses. Finite element models[7, 8, 9] form the second class. In addition to providing thermoelastic analysis they also provide predictions of the internal stress state and damage analysis. Unfortunately finite element models are not computationally efficient and are, in most cases, cumbersome to use.

New modelling approaches are therefore required that will provide accurate predictions of three dimensional stiffness and internal stresses in addition to being computationally efficient and user friendly. This paper presents briefly two such models and then focuses on one very important aspect of modelling: Accurate geometric description of different reinforcement architectures.

MECHANICAL MODELLING

The Complementary Energy Model

This modelling scheme consists of a multilevel automated geometric decomposition of a representative volume element (unit cell) into smaller elements (micro cells) containing yarn and matrix parts (see Fig. 1). This way, the problem of stress analysis for the whole unit cell is split into a number of subproblems at each level of the decomposition scheme. This decomposition of the unit cell is achieved automatically with only a limited amount of input data from the textile company and a few measured values. This top to bottom decomposition is followed by a bottom to top homogenisation scheme in which internal stresses (sub-unit cell level) are linked to external ones (unit cell level). The complementary variational principle[10] has been utilised to implement this [11, 12, 13]. This procedure results in the prediction of stiffness, internal stress fields and failure of the composite. Additionally the model is capable of predicting the onset of failure. This model has been implemented in the TEXCOMP package. Two and three dimensional woven fabric composites can be modelled at present.
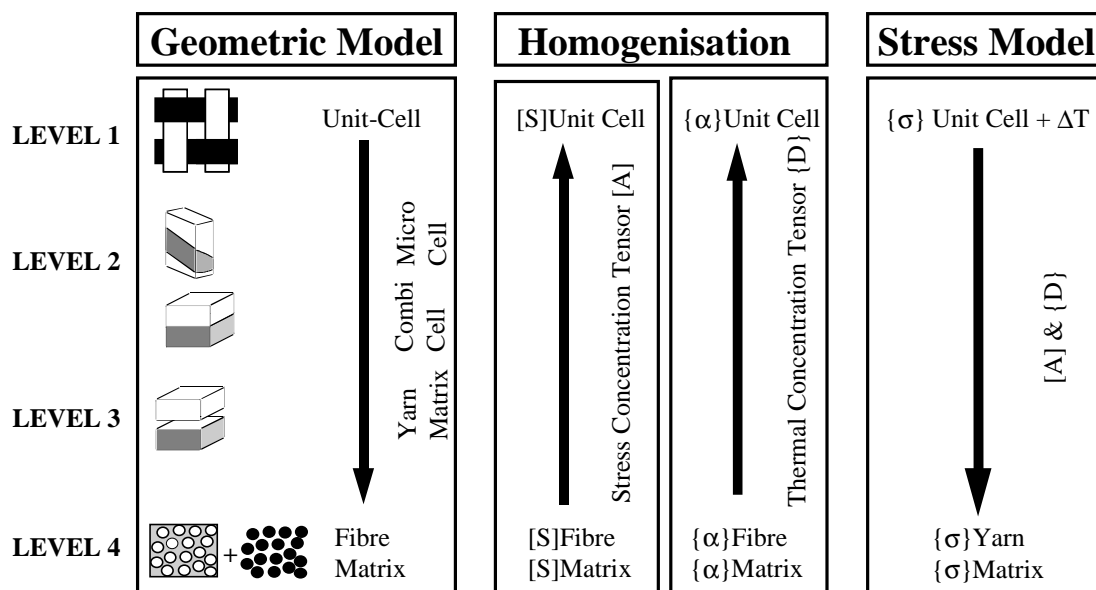

Fig. 1. Schematic representation of the Complementary Energy Model (CEM). Note that the geometric model is independent of the mechanical model but is included in the figure for the sake of clarity.

The Inclusion Models

Two inclusion models [14] have been under development at KULeuven. As for the Complementary Energy Model they also work at the unit cell level. In principle this model can be applied to all kinds of reinforcement architectures. The hearline of the yarns in the unit cell is mathematically represented by cubic splines. The yarns are subdivided into small segments which are characterised by their orientation, local curvature and volume fraction (see Fig. 3). From these segments an equivalent model composite is derived by replacing them with straight ellipsoids (inclusions).

The elastic properties of the original composite can be computed by solving the equivalent composite using a mean field approach based on the equivalent inclusion theory. Two mean field schemes are under study: The Mori-Tanaka and the Self-Consistent methods. Since these models allow the prediction of internal stress distribution they can also be used for damage modelling. The FLEXCOMP software programme has been developed based on these schemes.
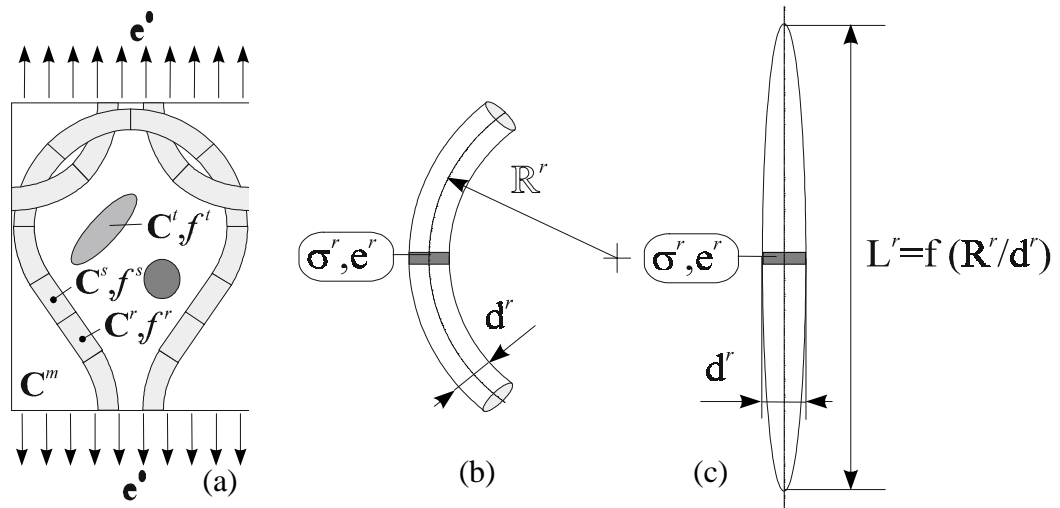

Fig. 2: A model composite unit cell (a), a yarn segment (b) and an equivalent inclusion (c) used to replace the curved segment.

TEXTILE GEOMETRY

Characterisation of Reinforcement Architectures

An accurate description of the reinforcing medium in a textile composite is of the utmost importance in obtaining good elastic properties and predicting failure in any modelling effort. The CEM and the Inclusion models have been shown to be quite accurate in predicting the stiffness properties for a variety of textile composites. Even though the mechanical models in the form of the TEXCOMP and FLEXCOMP software packages can deal with a wide range of reinforcement geometries, the necessary geometric input is not easy to obtain. A major effort is currently underway to develop accurate geometric models for 3D weaves, 2D braids and stitched materials. A first version of a programme (CETKA-KUL) to generate geometric input for 2- and 3D woven fabrics is currently being tested (Fig 3).

Let us take a closer look at braids. A variety of geometric models for braids do exist but they describe the geometry in terms of the centrelines of the yarns. In doing so, these models exclude some very important information which results in them not providing a realistic description of the yarn architecture. Questions like the following need to be answered: What is the yarn cross-sectional shape and path due to interlacing and processing? Does yarn interlacing at angles other than 90° result in yarn twisting? What is the effect of stacking up multiple layers of a braid on the two points mentioned previously? All of these parameters are important in determining accurately engineering constants and failure. To this end, computer tomography is being utilised to provide 3D images of the internal structure of braid reinforced composites (see Fig. 4).
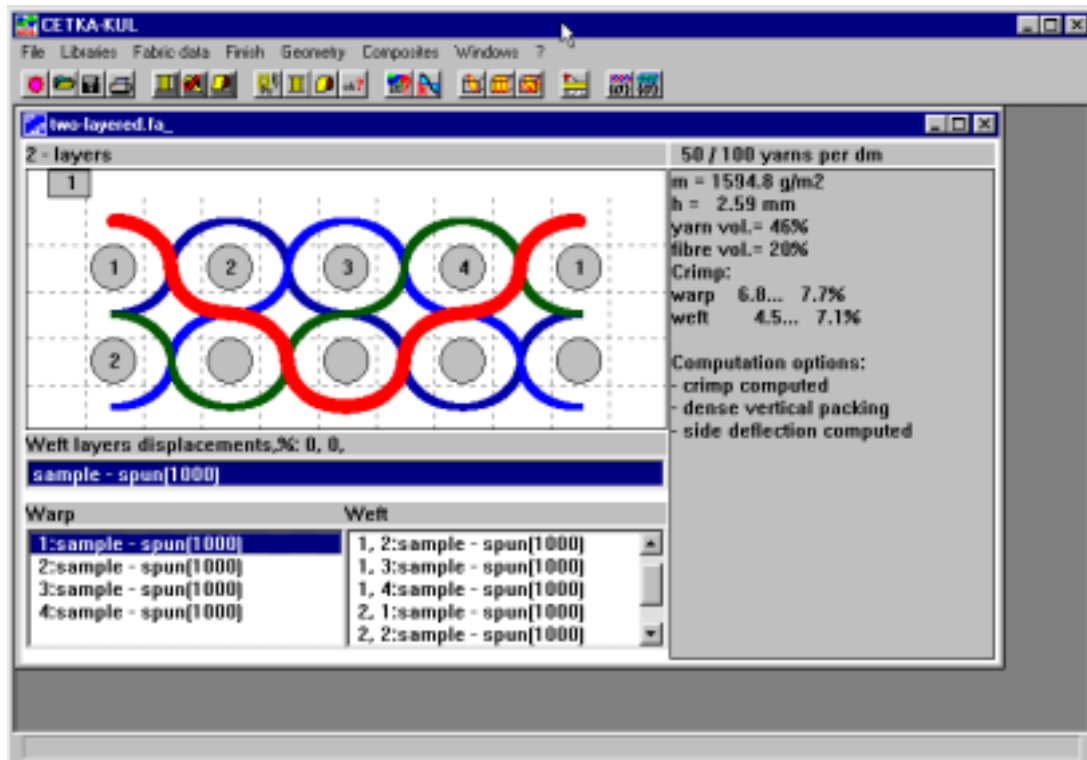

Fig. 3: Screen shot from the package CETKA-KUL used to generate input for the TEXCOMP mechanical modelling software. The particular example is for a multilayered woven fabric.
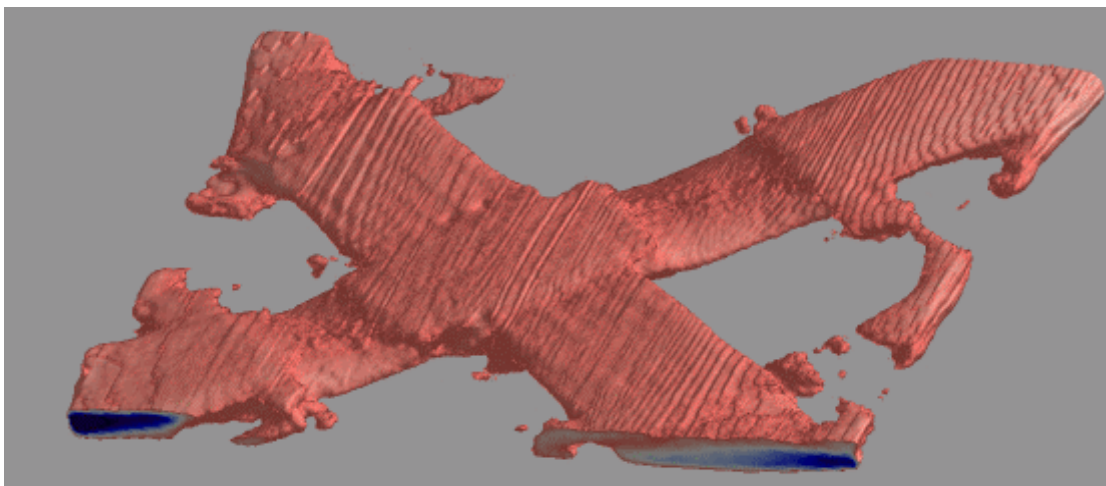

Fig. 4: Tomographic image of 2 braider yarns of a 2D braid.

The particular example in Fig. 4 is of a textile with a braiding angle of 55°. Significant yarn flattening due to processing was observed. Surprisingly no yarn twist at the cross over point was observed. Stereomicroscopy (see Fig. 5) is also used to acquire 2D exterior surface information like yarn spacing. Fig. 6 shows the top surface of a multilayered stitched material. Considering geometric information obtained from only microscopic data one could consider that the yarns move in a straight path inside the material. Computer tomography reveals the true path yarns, which are not straight, inside the fabric (Fig. 7).
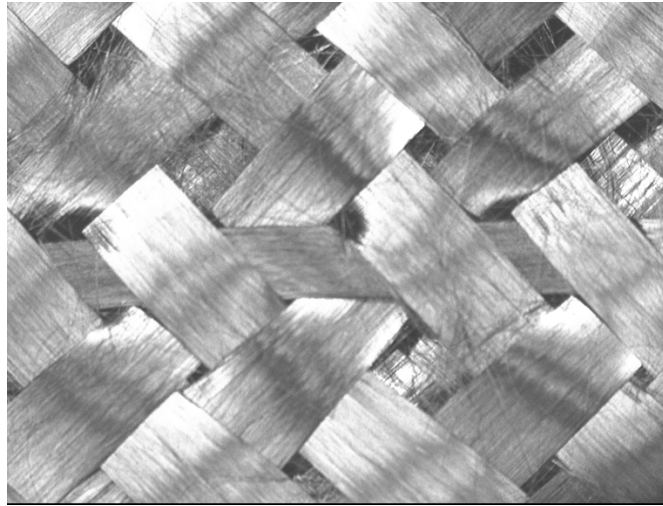
Fig. 5: Image of a 2D carbon braid with inlays (obtained using a stereomicroscope).

This study does not include 3D braids and knitted materials; this is because it is very difficult, if not impossible to obtain an accurate geometric description for the unit cells of these materials. In some cases it is also very difficult to identify a unit cell. Particularly in the case of 3D braids the unit cell may have the size of the whole structure which would not be efficient to analyse using the models presented in this paper.
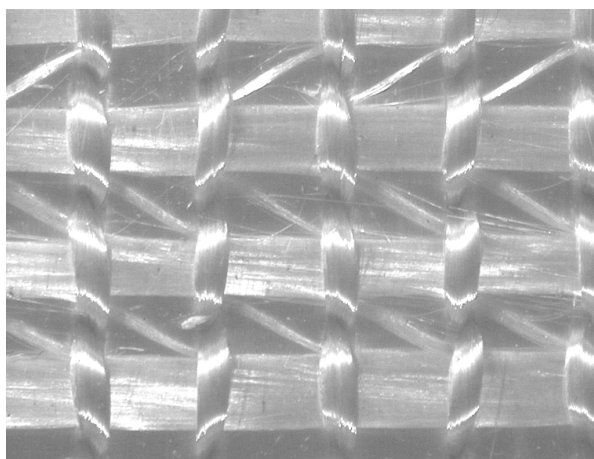
Fig. 6: A surface view of multilayered stitched material (dry textile) obtained using stereomicroscopy.
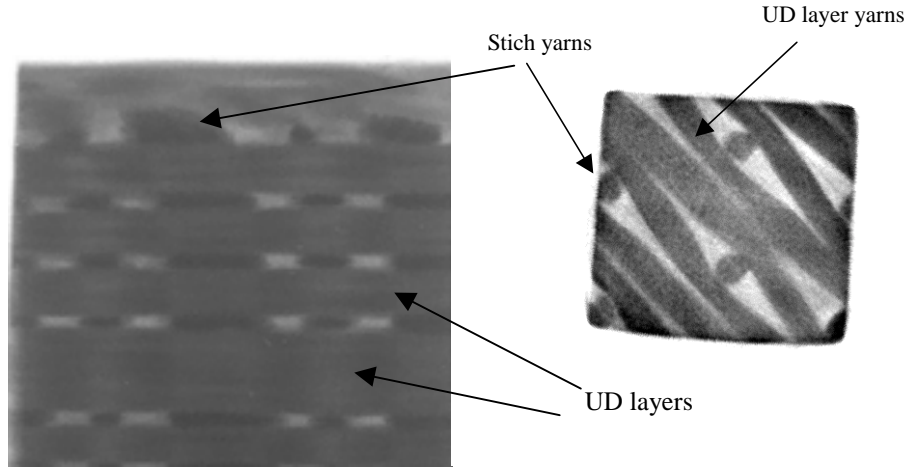
Fig.7: Internal views (tomographic images) of the stitched material (composite) of Fig. 8. Notice the curved yarn paths which are not evident using simple light microscopy.

The Effect of Geometry on Simulation Results

The elastic properties of a number of different textiles (2D woven fabrics) are compared in Fig. 8. Results shown were obtained using the FLEXCOMP package (Mori-Tanaka model). One clearly sees that the models developed at KULeuven and the FGM model provide comparable performance for in-plane properties of textile composites. In the case of the two steel fabrics the FGM fails completely. Fig. 9 presents the results of a parametric study (again on 2D woven fabrics) in which both the material properties and the fibre volume fraction were varied.
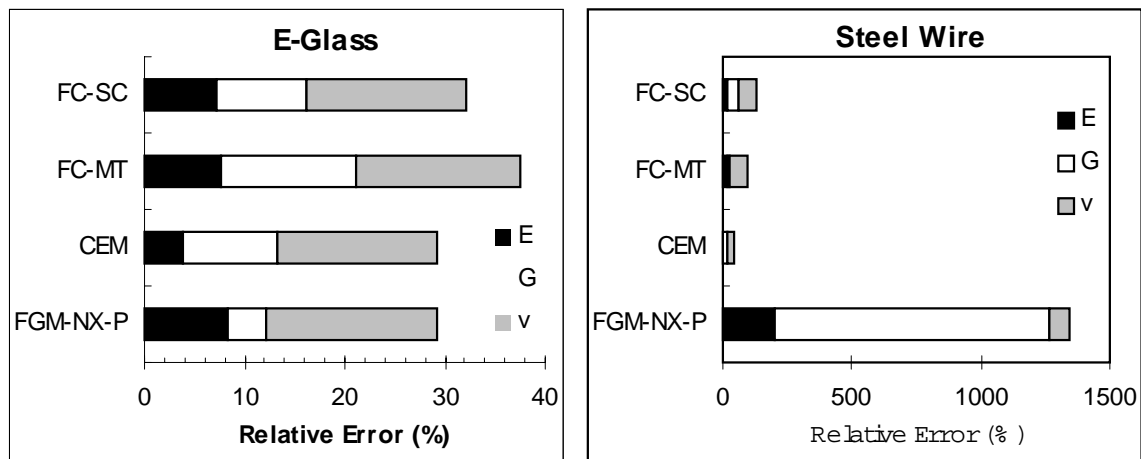

Fig. 8: Performance of the elastic models for the prediction of in-plane properties: (a) E-glass/epoxy fabrics – (b) Steel monofilament fabrics. FC-SC and FC-MT are the Self-Consistent and the Mori-Tanaka schemes respectively. CEM is the Complementary Energy Model and FGM is an iso-strain Fabric Geometry Model.
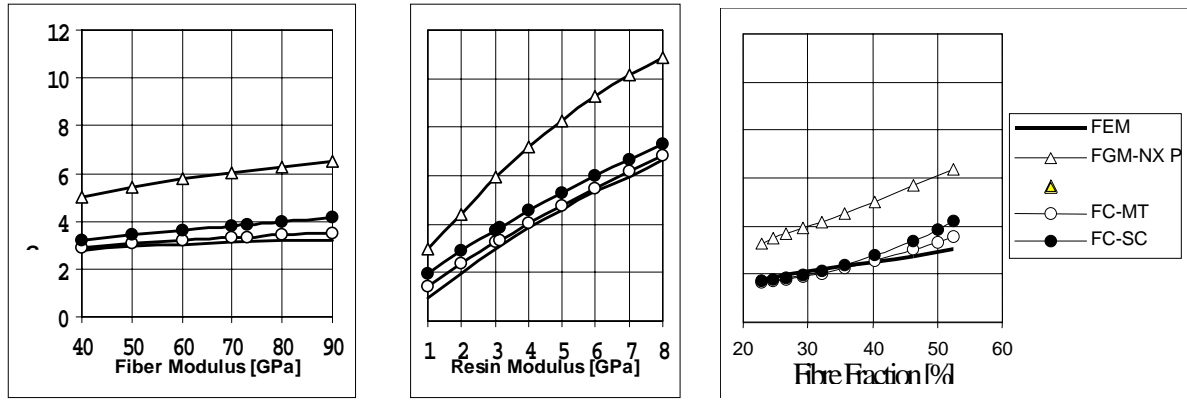
Fig. 9: - Out-of-plane shear moduli predictions: FEM, FGM-NX-P (iso-strain, non-mixed model), Mori-Tanaka (FC-MT) and Self-Consistent (FC-SC) models.

The superiority of the Inclusion models in predicting out-of-plane properties is clearly evident. CEM results which are not shown are very close to the FEM ones. The FGM model always predicts higher out-of-plane shear moduli which is not the case for the other models.

As mentioned earlier, the formulation of the inclusion models is such that it allows them to be applied to virtually all kinds of textiles (in principle) as long as a unit cell can be identified. An overview of Mori-Tanaka model predictions on a variety of textiles is shown in table 1. All materials have an epoxy matrix. In general it can be said that the agreement between experimental and modelling results is good and in some cases extremely good. It is again evident that good elastic results are a function of proper geometric modelling. The more accurate the description of the reinforcement the better the predictions.

Material	Description	Vf (%)	Ex (GPa)	Ez (GPa)	Gxy (GPa)
Multilayered	glass (stitched)	46.5	18.3 (17.7)	9.7 (10)	9.4 (6.7)
Multilayered	glass (stitched)	53.5	22.0 (20.5)	10.3 (11)	11.4 (7.8)
Multilayered	glass (stitched)	54.5	23.4 (21.5)	13.5 (12)	10.9 (8.1)
Multilayered	carbon (stitched)	48.5	35.7 (35.5)	13.8 (13)	20.1 (13.2)
Multilayered	carbon (stitched)	50	35.3 (35.5)	14.4 (13)	20.3 (13.2)
Multilayered	carbon (stitched)	51.0	35.2 (35)	16.3 (11)	20.6 (13.2)
Tubular Braid	carbon – 0% inlays	60	30.7 (30.5)	7.3	5.2
Tubular Braid	carbon – 10% inlays	56.0	22.8 (21)	6.9	4.2
Tubular Braid	carbon – 50% inlays	54.0	49.8 (49)	7.1	16.6
Non-crimp	glass – (knitted)	51.0	18.1 (17)	9.0	8.5
Non-crimp	carbon – (knitted)	52.5	45.5 (43)	8.3	23.4
Modified non-crimp	glass – polyester stitch	45.0	17.2 (16.5)	7.3	9.1
Modified non-crimp	carbon – polyester stitch	41.0	35.3 (34)	6.6	16.0
Knit 1	glass – weft knit	30.7	14.8 (10.9)	12.7	2.4 (3.1)
Knit 2	glass – weft knit	30.8	10.5 (8.1)	9.3	3.9 (2.5)
Knit 3	glass – weft knit	35.7	13.2 (7.2)	14.7	4.9 (2.4)

Table 1: Mori-Tanaka predictions of elastic constants for different textile reinforcement architectures. Experimental data (where available) is indicated in brackets.

It should be noted that G_{xy} was measured indirectly [15] which could have some effect on the accuracy. Readers' attention is also drawn to the last three knits in table 1. Those materials exhibit the worst prediction accuracy. This is due to two factors: First, the complex yarn architecture made it very difficult to obtain good geometric descriptions. Second, geometric parameters were determined on the dry textile before the reinforcement architecture was modified due to processing. One more point that shows the significance of geometric description are the results for the shear modulus. This modulus depends on geometrical details, like yarn flattening, so the more accurate the geometric model the better the accuracy of mechanical modelling results.

Table 2 shows some preliminary strength results (X, Y, Z) for some of the fabrics of table 1. Since both kinds of models can compute internal stress distributions in the unit cell they can be used to predict failure. Stress strain curves like the ones in Fig.10 can be produced and from them one can extract a value for the strength. Table 2 indicates some differences between model and experimental results. Failure is a function of the geometry, the failure criteria and the stiffness degradation scheme used. As a result not only an accurate geometric model is needed but also appropriate failure models for textiles. Additionally, during loading the geometry of the reinforcement architecture changes, so constitutive models describing this change are necessary. The values in table 2 were obtained using the Mori-Tanaka scheme that is more accurate at low fibre volume fractions. It is a good model to get a quick first estimate of the strength but for a more accurate calculation (especially at high fibre volume fractions) one should use the Self-Consistent method. This model provides for better stress redistribution after each degradation step but it is computationally much more intensive and thus requires significantly more time for simulations to be carried out.
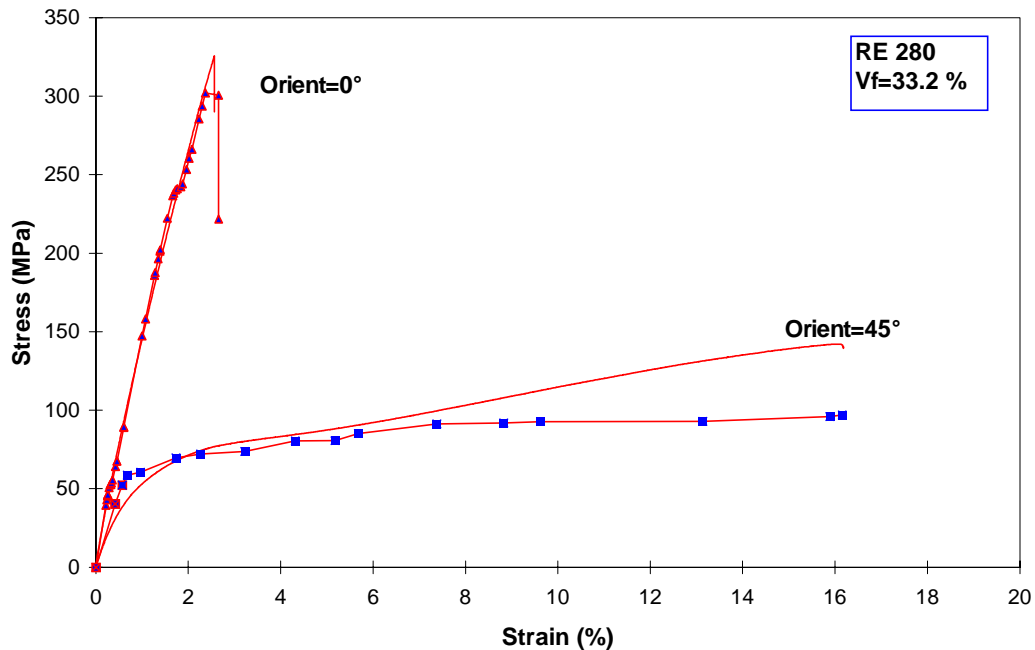

Fig. 10: Stress strain curve for a 2D woven fabric composite (glass) Obtained using the Complementary Energy Model.

Material	Description	Vf (%)	X (MPa)	Y (MPa)	Z (MPa)
Tubular Braid	carbon 50% inlays	54.0	858.7 (650-750)	1314.9	72.2
Non-crimp	carbon (knitted)	52.5	613 (530-590)	624.3	51.2

Table. 2: Strength calculation results for some of the textiles of table 1 (computed using the Mori-Tanaka model). Experimental values (where available) are given in parentheses.

CONCLUSIONS

A lot of work remains to be done before accurate and efficient design tools become a reality. This paper has focused on the geometric characterisation of textile composites and the importance of good geometric models in accurate prediction of the engineering properties of textile reinforced composites. Simulation results using the inclusion models and the Complementary Energy Model (implemented in the FLEXCOMP and TEXCOMP programmes) were used to demonstrate in practice the importance of an accurate geometric description of textile reinforcements.

Results can be summarised as follows. The more accurate the description of the reinforcement architecture the more accurate the stiffness results. Regarding failure modelling an accurate geometric model is not enough. This is for the simple reason that other factors such as changes in geometry during loading and choice of failure criteria come into play. Work is ongoing in both stiffness and failure modelling with the aim of developing accurate and efficient simulation tools.

ACKNOWLEDGEMENTS

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