EFFECTS OF VARIABLE FIBRE DENSITY ON MECHANICAL PROPERTIES OF A PLAIN WEAVE GLASS REINFORCED POLYESTER

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Abstract

The results obtained from meso-scale mechanics models of textile composites have been shown to be strongly dependent on the micromechanics models and fibre distribution assumptions used to describe bundle behaviour. In this paper the effects of the yarns' internal fibre distribution on composite mechanical properties are explored. Studies on woven carbon based composites by Lomov et al have shown that the internal fibre volume fraction of a yarn can vary significantly, for that class of composites this generally resulted in lower fibre volume fraction (V_f) towards the side of the tow. Experiments undertaken at Nottingham confirm this finding for glass based composites, although the phenomenon appears to be less pronounced.

This study is written mainly as a first step in quantifying how such factors can be expected to affect the overall mechanical behaviour of the material. Parametric studies are conducted using Finite Element (FE) models in conjunction with Adaptive Mesh Refinement (AMR) driven by the TexGen geometric modeller.

1 Introduction

The mechanical analysis of textile composites is generally regarded to be a hierarchical problem comprising three length scales, commonly named the micro-, meso- and macro level. The micro-level describes the interaction of single filaments with surrounding matrix material. The meso-level analyses the interaction between yarns or bundles and resin “pockets”. The macro level is generally where structural loads are taken into account, the composite material is homogenised at this level, such that it can be used as a set of (orthotropic) elastic constants.

In this paper only the meso-scale is dealt with explicitly, the micro-scale is present as a set of closed form material relations (see [1]) and the macro-scale is in effect eliminated by testing specimens of roughly the same size as the meso-scale domain. A more extensive survey of the field is given in Lomov's paper on the topic [2,3], where also the issue of in-tow V_f variation is dealt with for carbon-epoxy composites.

2 Methodology

2.1 Geometric modelling

Geometric modelling of the textile is done using the TexGen geometric modelling package. This package internally uses B-splines to represent the yarn path and polylines to represent the yarn cross section at any point along the line. The package has been described more extensively in previous publications [4] and can be downloaded with source code (see [5]). The additional feature used in this work provides the capability to maintain consistent yarn parameters throughout the model. This means that cross sections of the yarn can vary according to their position but the fibre area in each cross section is constant, resulting in local changes of Vf. The distribution of fibres also remains consistent. The current focus is on a combination of the following geometric phenomena:

- Nesting, when undulations in multiple stacked layers of textile are out of sync (phase shift between the layers) a stack of n layers of fabric of thickness t becomes thinner than n*t.
- Yarn flattening, the fact that yarn cross sections have flat sides where they meet solid moulds.
- Interference correction, general term used to describe the correction of cross sections such that boundaries of crossing yarns don't intersect. It is generally found that it is impossible to obtain models with realistically high V_f without using some form of interference correction. In the present study the

correction algorithm is based on geometric considerations (non-mechanical) and operates on the tow cross-section (the yarn path remains the same).

2.2 FEM modelling

2.2.1. Adaptive mesh refinement

Finite Element models of the textile are generated using Adaptive Mesh Refinement (AMR) as opposed to using a mesh generator, a method resulting in similar grids was devised by Kim and Swan [6]. The rationale behind developing such a method is to circumvent the difficulties that arise when trying to mesh realistic textile geometries. The touching yarns tend to generate high aspect ratio geometries which are either unmeshable or generate such fine grids that they are impossible to solve on current hardware. The procedure in the current method is as follows:

1. Generate coarse grid (of hexahedral elements)
2. Solve
3. Estimate error for all cells
4. Refine cells with highest error
5. Back to 1 for refined grid

The error estimator used is a so-called Kelly error estimator [7] which uses the sum of discontinuities in computed strain over element boundaries as a measure for the discretisation error. Without modification this results in refinement around stiffness jumps, as are introduced by the multiphase character of the composite (see Fig. 1).
Note that this method requires a textile

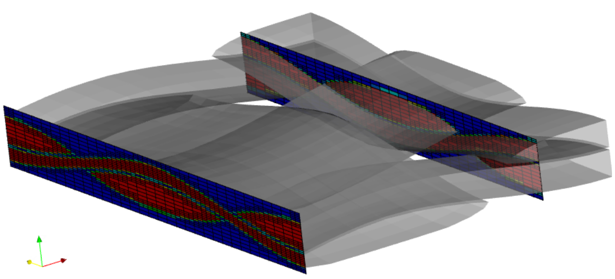


Fig. 1. Grid refinement around tow edges

representation that can be queried in different stages of refinement. This is implemented by linking to the TexGen library.

2.2.2. Damage modelling

Since the use of brittle material models as used by Blacketter et al. [8] has proved unsuccessful for materials that fail in a non-brittle fashion (such as polyester), a phenomenological stiffness degradation law is used to describe the local stiffness. This relation stems from the need to allow for failure mechanisms such as crazing and yielding which make the material macroscopically non-brittle (see [9]).
The following relation (Equation 1) is used for the stiffness of the matrix material and for the transverse stiffnesses of the yarn material. The constants are c1=8, c2=13 such that single element behaviour fits experimental data on the neat resin material:

$$E_d = E\left(1 - 1/\exp\left(-c1 * D + c2\right)\right) \qquad (1)$$

In this case the damage parameter D is the measure in which the relevant stress criterion is violated, for the matrix behaviour this is the Bauwens criterion (see [10]) operating on non-local stresses, for the transverse yarn behaviour these are the nonlocal transverse principal stresses. Damage in the fibre direction in the bundle is brittle degradation (see Equation 2) based on the nonlocal fibre direction stress.

$$E_d = E * 0.0001 \qquad (2)$$

2.2.3. Boundary conditions

In the current paper simple displacement boundary conditions are applied. Other authors have gone to great lengths to apply periodic boundary conditions, see [2]. The reasons for not pursuing this are twofold, firstly periodic boundary conditions only make sense in very limited textile geometries (in randomly nested stackings periodic boundary conditions are hard to define), secondly the modelling approach is verified with specimens of roughly the size of the model, meaning that any edge effects are present in both the experiment and the model.

2.3 Parametric modelling

The aim of setting up the current modelling methodology is to obtain a robust analysis tool that can deal with challenging textile geometries without manual intervention. This is demonstrated by doing the analysis of the range of textile composites described parametrically in Table 1.

	Single layer	Nested	Unnested
length (mm)	8	8	8
xshift (length)	[0]	[0,0.25]	[0,0.25]
yshift (length)	[0]	[0,0.25]	[0,0.25]
zoffset	-	0.85	1
nlayer	1	2	2
vgap (mm)	0.02	0.02	0.02
hgap (mm)	{0.2,0.8}	{0.2,0.8}	{0.2,0.8}
height (mm)	0.5	0.5	0.5
fibre area (mm^2)	0.4	0.4	0.4
V_f dropoff (-)	{0.75,1}	{0.75,1}	{0.75,1}
flat value (mm)	0.1	0.1	0.1
layer rotation (PI rad)	[0]	[0,0]	[0,0]

Table 1. Geometric variables for textile parametric study [] indicates values per layer, {} values per textile.

Where length is the wavelength of the yarn undulation, xshift and yshift indicate the phase shifting of the layer in x- and y-direction respectively. Zoffset indicates the elevation between two layers, if z<1 the textile is nested (this is only possible for layers that have a phase shift).
The fibre- and bias direction loaded model geometries are given in Table 2.

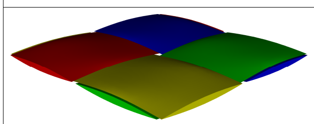
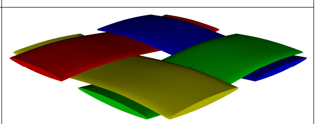
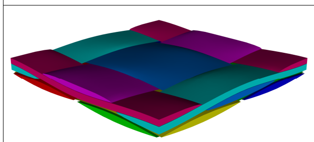
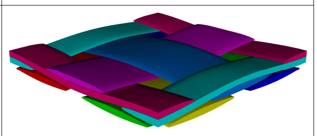
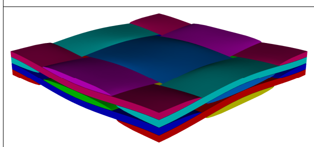
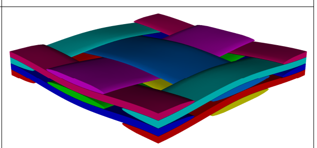
h gap = 0.2	h gap = 0.8
 Single layer	
 Nested 2 layer	
 Unnested 2 layer	

Table 2. Parametric textile models in case of full nesting

The effect of enforcing a larger horizontal gap between tows (hgap parameter) on the internal Vf of the yarns is shown in Fig 2 and Fig 3.

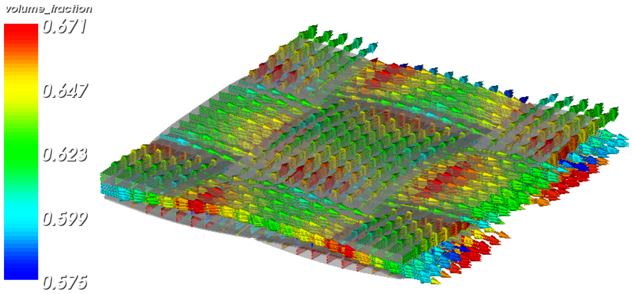


Fig 2. Fibre V_f distribution in yarn (hgap = 0.2)

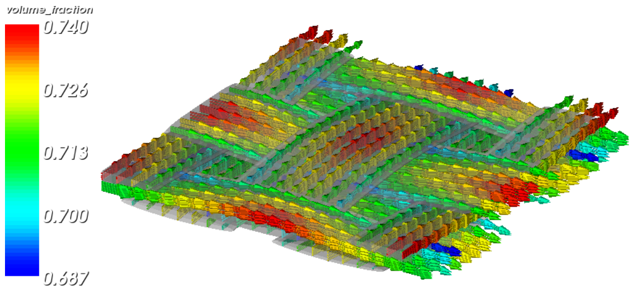


Fig 3. Fibre Vf distribution in yarn (hgap = 0.8)

3 Results

3.1 Microscopy

Microscopy has been used to validate the cross sectional parameters of the textile. The cross sections that were analysed to arrive at the average geometry of the yarns were obtained from the waste material of the same plaques as the tensile specimens. A stack of laminate cutouts was analysed and the outlines of the yarns were indicated using polylines (see Fig 4). The averaged cross section

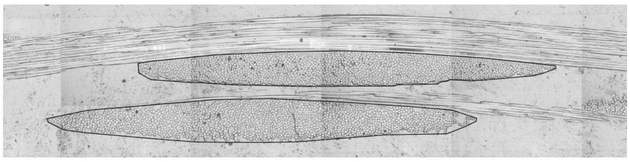


Fig 4. Stitched micrographs of yarns in a 2-layer plaque with polyline outline

resulting from this is given in Fig 5, it can be seen here that the shape is closer to lenticular than it is to elliptical. The height-width ratio of the binary image is roughly 1-10, the aspect ratio in the samples was in the range [1-8, 1-15].

Fig 5. Sum of 80 outlined yarn cross sections for a 2 layer plaque made with Vetrotex RT600 in grayscale and binary.

It is noted here that whilst this method provides some key variables that can be easily correlated to the modelled textile, it does not provide the mechanisms that underlie the shape, for instance, it is not known whether a certain (flat) cross section is caused by flatter sections where the textile is in contact with the tool or whether it is due to a flat shape of the base tow.

3.2 Mechanical testing: tensile loading

Tests have been conducted on dogbone specimens of 2-layer RT600 reinforced polyester. The specimens were made using both outlet vacuum and inlet pressure to ensure minimal void content. Stress strain data for the tensile tests is presented in Fig 6 along with modelling results for single layer models. As a reference the initial stiffness predicted by the rule of mixtures (ROM) is given as well (using the micromechanics data and V_f that are used in the FE analysis and a 90% reinforcement efficiency to account for crimp).

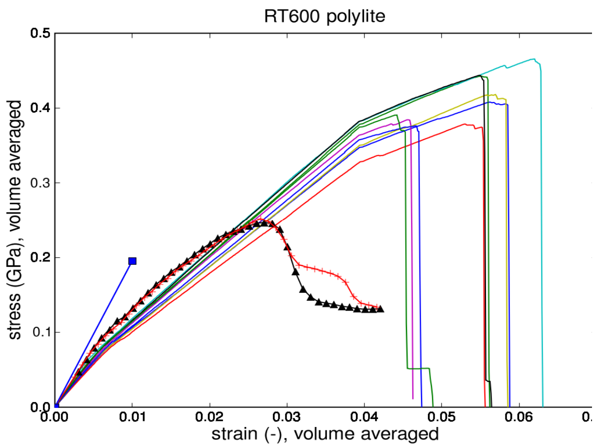


Fig 6. Experiments (-), modelling (+,▲) and ROM (■) showing the stress strain behaviour of the single layer model for hgap=0.2 and hgap=0.8

Fig 8 shows that the multilayer models overestimate stiffness of the composite in the damaged domain, more so than the single layer model does, however, the UTS value is better predicted with the multilayer model.

The effects of nesting and especially the

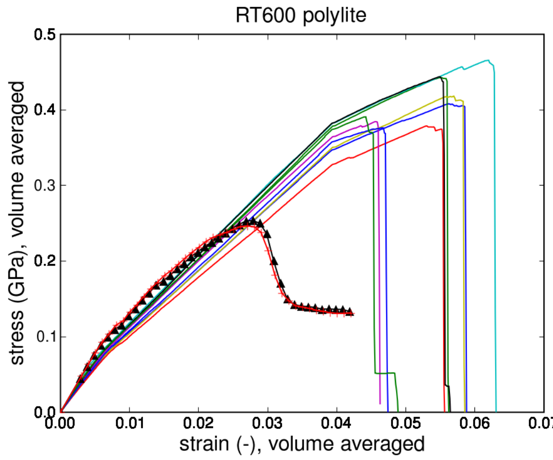


Fig 7. Modelling results for hgap=0.2 but V_f dropoff=1 (▲) and $V_f$dropoff=0.75 (+), it can be seen here that the stress strain behaviour more or less coincides. The initial damage stress is 5% higher in the case of the lesser dropoff, which is explained through the fact that the V_f in the region of initial damage is higher in that case.

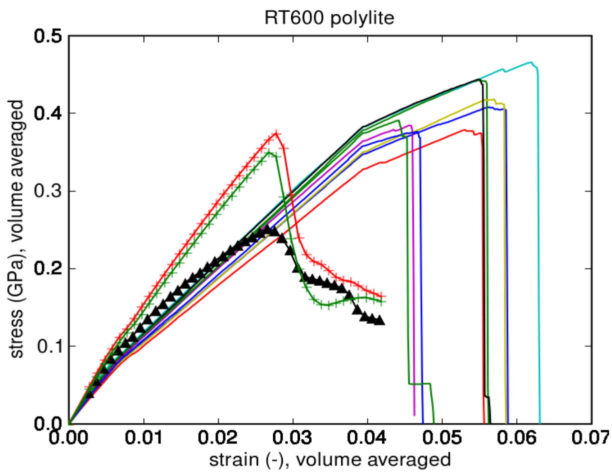


Fig 8. Experiments and modelling in fibre bundle direction for 2-layer RT600 polylite composite (+,+ nested and unnested 2 layer models, ▲single layer model, - experimental data)

presence of multiple layers are stronger than the effect of different V_f dropoff schemes (see Fig 7) for the material under consideration. However, when considering the initial damage stress a significant difference is found between hgap=0.2 and hgap=0.8, hgap=0.2 having a higher initial failure stress by 18%, due to the tows being less compacted (the initial failure mode is transverse tow damage).

The interaction between layers can also be seen qualitatively in Fig 9 and Fig 10 where the matrix damage parameter is plotted.

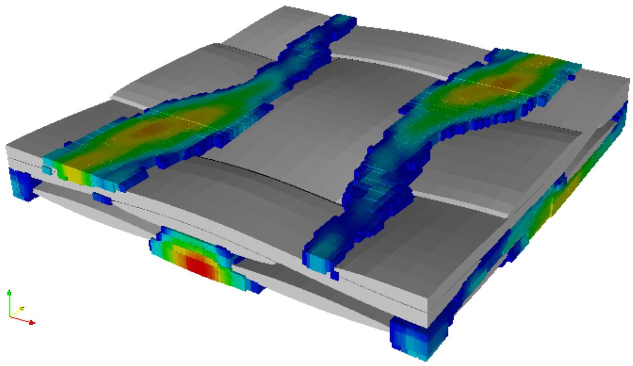


Fig 9: Matrix damage plot for a two layer nested textile composite with hgap=0.2, taken at ε=0.01

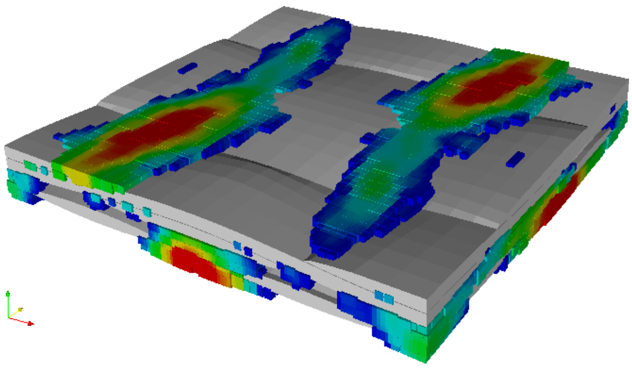


Fig 10. Matrix damage variable for the same composite with hgap=0.8, at ε=0.01, both clearly show the interaction between layers (the top layer would have had a plane symmetric damage pattern when loaded on its own).

4 Conclusions

The use of adaptive mesh refinement to obtain grids for the analysis of textile composites has been shown to be a particularly robust analysis method, making it suitable for parametric analysis. Whether or not it is efficient beyond mesh generation is a focal point of current research, requiring the analysis of a range of textile composites using both conformal and adaptive meshing.

The damage plots show that the damage distribution can change significantly with different in-tow volume fraction distribution. However, this is not reflected strongly in the stress-strain curve using the current material model. The effects of V_f distribution variation and even yarn width are overshadowed by interaction between layers (i.e. the multilayer model giving much higher UTS than the single layer model of equal V_f).

Results presented by Lomov et al [2] showed that the V_f effects are important when using brittle material models, which is also seen here in the damage initiation stresses for the different textile models.

Correlation of the modelling results with the experimental data is fairly poor (for ROM results more so than for FE results), which is most probably due to unknowns in the material data.

Ongoing research includes investigating the validity of the current methodology for carbon fibre reinforced plastics.

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