PREDICTION AND CHARACTERISATION OF THE SHEAR BEHAVIOUR OF VISCOUS WOVEN TEXTILE COMPOSITES

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ABSTRACT: The objective of this study is to develop a predictive model of the shear behaviour of textile composites to replace time-consuming material characterisation tests. This paper describes an energy minimisation method (EMM) to reduce experimental inputs for a predictive model developed in previous studies. The algorithm of the EMM is to minimise the summation of the in-plane shear energy dissipated at different regions of the composite sheet. A series of in-plane shear characterisation tests, Picture Frame (PF) tests, were performed. In order to validate the test results, some essential experimental conditions, such as boundary conditions, the direction of the shearing deformation, tow-meander and variability, were investigated. Comparisons between predictions and PF test results show that the implementation of the EMM is promising.

KEYWORDS: predictive modelling, shear behaviour, tow kinematics, Picture Frame test.

INTRODUCTION

Predictive modelling of the shear behaviour of viscous woven textile composites is of interest to many manufacturers as this can potentially decrease the time required to characterise materials and may also facilitate pre-manufacture material optimisation. Both these factors may produce significant reductions in processing costs. The overriding motivation is thus to make viscous textile composite materials more competitive in terms of both cost and functionality.

Multi-Scale Energy Model (MSEM) that predicts the shear behaviour of viscous woven textile composites was developed [1]. In the originally published versions of the MSEM [1, 2], certain experimentally determined input were required in the model. Most of these inputs, such as matrix rheology and fibre volume fraction of the composite are easily obtained. However, a more difficult to determine experimental input is the so-called ‘tow kinematics’ [3]. A tow is a fibre bundle. This term ‘tow kinematics’ refers to the kinematics that reflects different deformations between the tow and the overall material. The tow kinematics had to be obtained from experimental samples, and used as input for the MSEM before predictions could be made [1]. In the current work an energy minimisation algorithm is implemented that predicts the tow kinematics by minimising the energy contributions from tow crossovers, tow regions and inter-tow regions. Hence the inclusion of the energy minimisation method means that the MSEM requires less experimental input.

Fundamental to the development and evaluation of the MSEM are material characterisation experiments. One of the most popular methods of characterising the in-plane shear behaviour of woven textile composites is the Picture Frame (PF) test [4]. Certain experimental conditions involved in these experiments are analysed. Finally, the MSEM based on the energy minimisation algorithm is evaluated by comparing with PF test results.

PREDICTIVE MODELLING

The role of the MSEM is to predict the shear force – shear angle – shear rate behaviour of viscous textile composites using parameters supplied readily by material manufacturers, such as fibre volume fraction, weave architecture and matrix rheology. The model has been described in detail previously [2] and so only a brief description is given here.

The meso-scale kinematics observed in many types of viscous textile composites have motivated the use of a novel two-phase material model structure to analyse the energy dissipation within viscous textile composites. These kinematics have important consequences for the deformation occurring during shear, both within tow and inter-tow regions, and also between tow crossovers. Namely, the rate of deformation tensor must be derived separately for both the tow and inter-tow regions and a further dissipative energy term must be derived to account for viscous energy loss at the tow crossovers.

The stress-power in the tow region can be calculated using the constitutive equation for a uniaxial ideal fibre reinforced fluid [5]. Within this model appear terms describing the longitudinal and transverse viscosities of the tows. These terms describe the dynamic interaction occurring between fibres and matrix on a micro-scale. Using micro-mechanical modelling principals [6, 7] reasonable predictions for both these viscosity terms can be made from the matrix viscosity and fibre volume fraction within the tows. The stress-power in the inter-tow region and also between crossovers can be calculated using the matrix viscosity. Thus, given the rate of deformation and stress tensor for the tow and inter-tow regions, the stress power generated by these regions can be determined.

The velocity field between crossovers is calculated by analysing the in-plane kinematics of tow deformation during shear. Using the velocity field and matrix film thickness the shear strain rate in the matrix film separating tows at crossovers can be estimated. From these calculations an estimate of the rate of energy dissipation can be determined due to shear between tow crossovers. By combining the energy contributions from both tow and inter-tow shear together with crossover shear, the total rate of energy dissipation during shear of the textile composite can be estimated and from this the resistance to shear deformation can be determined.

The meso-scale kinematics were obtained by measurements in the previous papers [1, 2]. In order for the MSEM to require less experimental input, an energy minimisation method has been attempted to predict the meso-scale kinematics and is described in the following section.

Energy Minimisation Method (EMM)

The actual tow kinematics are determined by minimising the energy generated due to in-plane tow shear, in-plane inter-tow shear and crossover shear. For example, a low degree of in-plane tow shear generates a relatively small amount of energy due to in-plane shearing of tows but a relatively large energy contribution due to in-plane inter-tow shear and crossover shear. Alternatively, a high degree of in-plane tow shear generates a relatively large amount of energy due to in-plane shearing of tows but a relatively small energy contribution due to in-plane inter-tow shear and crossover shear. The amount of energy dissipated by the in-plane tow shear, Eqn (1), is directly related to the longitudinal viscosity of the tows, η_L. The amount of energy dissipated by inter-tow regions, Eqn (2), and crossovers, Eqn (3), is directly related to the matrix viscosity, η_m. The tow angular shear rate, $\dot{\chi}_t$, determines the in-plane shear rate of the tow and inter-tow regions as well as the crossover shear rate. Thus, by increasing $\dot{\chi}_t$ from 0 to $\dot{\theta}$ (material angular shear rate) the minimum energy dissipation during any small angular increment can be determined. In this way the tow angular shear rate corresponding to minimum energy can be determined. The process is demonstrated in Fig. 1. Calculations were made for automotive prepreg (4x4 twill weave, carbon/epoxy) using the following experimental parameters: temperature = 23°C, θ =30°, material shear angular velocity $\dot{\theta}$=0.0026 rad/s, the tow shear angle for this step χ_t = 3°.

$$E_{tow} = \frac{a w_o T \eta_L \dot{\gamma}_t}{2\dot{\theta}\cos\theta} \tag{1}$$

where a is the distance increment of tow regions at small increment of θ, w_o is the initial width of tow regions, T is the thickness of the composite sheet and $\dot{\gamma}_t$ is the simple shear rate in the tow region.

$$E_{\text{int}\,er-tow} = bq\eta_m \dot{\gamma}_m T / \cos\theta \tag{2}$$

where b is the distance increment of inter-tow regions at small increment of θ, q is a factor accounting for weave architecture, $\dot{\gamma}_m$ is the simple shear rate in the inter-tow region and η_m is the matrix viscosity (a function of $\dot{\gamma}_m$).

$$E_{crossover} = \sum c A_e \eta_m^* \dot{\gamma}_f \tag{3}$$

where c is the distance increment of a small element at crossovers at small increment of θ, A_e is the area of the small element, $\dot{\gamma}_f$ is the simple shear rate at this small element at crossovers and η_m^* is the matrix viscosity (a function of $\dot{\gamma}_f$).

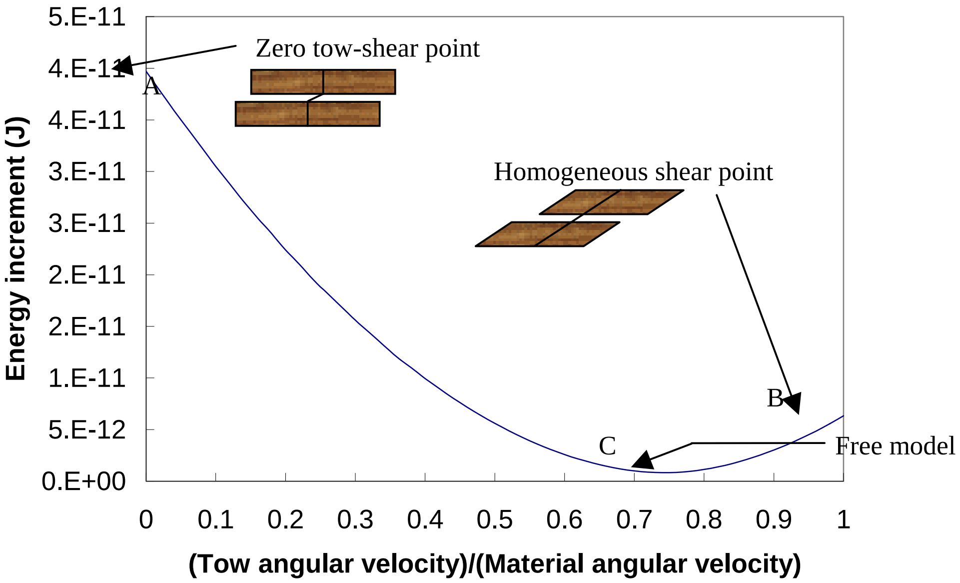

Fig. 1 Schematic of energy minimisation method to predict the tow kinematics.

From Fig. 1, $\dot{\chi}_t$ can be predicted by minimising the total energy increment, which is at point C. Then χ_t can be calculated analytically. By increasing the material shear angle (θ), the corresponding $\dot{\chi}_t$ and χ_t can be determined, which induces a form of χ_t versus θ, i.e. predicted tow kinematics.

CHARACTERISATION TESTS

Material

The material used in this study is a 4x4 twill weave, carbon/epoxy automotive prepreg, provided by Hexcel Composites in the UK, and its material code is ‘M47N/42%/280T4X4/CHS-3K/1000mm’. Specimens were cut into a shape with the tows parallel or perpendicular to the outer edges. The thickness of the un-tested sheet is 0.36 mm.

Test Procedure

Picture frame test apparatus comprises of four-bar linkage loaded by a Hounsfield Universal Testing machine through a load cell connected to the crosshead. Four bars are jointed such that the initially square frame becomes a rhombus.

An environmental chamber was used to test materials at elevated temperatures. To minimise heat-up time the picture frame rig and clamps are heated to the required temperature in the chamber prior to mounting the sample. Once samples are clamped within the frame, heat-up times must be sufficiently short to avoid epoxy resin cure during testing.

During the test, a constant displacement rate is applied to the crosshead and the axial picture frame force (F_{pf}) and the displacement (d_{pf}) of the crosshead are measured. If data of shear force versus shear angle is required, then F_{pf} and d_{pf} need to be converted through Eqns (4) and (5).

$$F_s = \frac{F_{pf}}{2\cos\Phi} \tag{4}$$

where Φ is the frame angle, and can be related to the shear angle (θ) through $\theta = \pi/2 - 2\Phi$.

$$\theta = \frac{\pi}{2} - 2\cos^{-1}\left[\frac{1}{\sqrt{2}} + \frac{d_{pf}}{2L}\right] \tag{5}$$

where L is the side length of the picture frame.

Results and Discussions

Effect of boundary conditions

As the test boundary condition is a critical factor in obtaining reliable data [8, 9], two boundary conditions were investigated, clamped (four edges of PF are clamped) and pinned (three pins at each clamping edge provide shear force to material sheet during testing). It had been found that the pinned case is more suitable for Twintex (a 2x2 twill weave, glass/polypropylene thermoplastic composite) [4]. Three tests for each case were performed. Slight wrinkling occurred in only one test for the clamped case, whereas serious wrinkling happened at the start of all tests for the pinned case. This suggests that the clamped case should be used in the PF tests for the automotive prepreg used.

Influence of direction of the shearing deformation

There are two directions of shear deformation, positive and negative. A positive shearing deformation is defined with the warp fibre directions at an angle of + 45^o with the axis of loading, as viewed from the front of the PF apparatus. PF test results for a 1/7 satin weave (glass fibre reinforced Nylon 12) showed that the force required to shear the composite sheet in positive shear was nearly double the corresponding force in negative shear [10]. A theory developed in [11, 12] gives predictions consistent with the results of this test. To investigate its influence, three tests for each case were performed. The results suggest that the direction of shearing deformation for this prepreg has a negligible effect on the PF results, compared to variability of PF tests (see the following analysis).

Influence of tow-meander

Ideally, the tows of specimens in the weft direction are straight and perpendicular to those in the warp direction. However, in practice, the tows are not exactly straight and perpendicular to each other, as shown in Fig. 2(a). In order to investigate the influence of tow-meander, three tests were performed with samples taken directly off-the-roll. From Fig. 2(b), the results for off-the-roll specimens are much higher than those for the case of straightened specimens (i.e. where the material was straightened to improve tow alignment), and show poor repeatability. This suggests that test specimens should be straightened prior to testing in order to reduce the influence of tow-meander on test data.

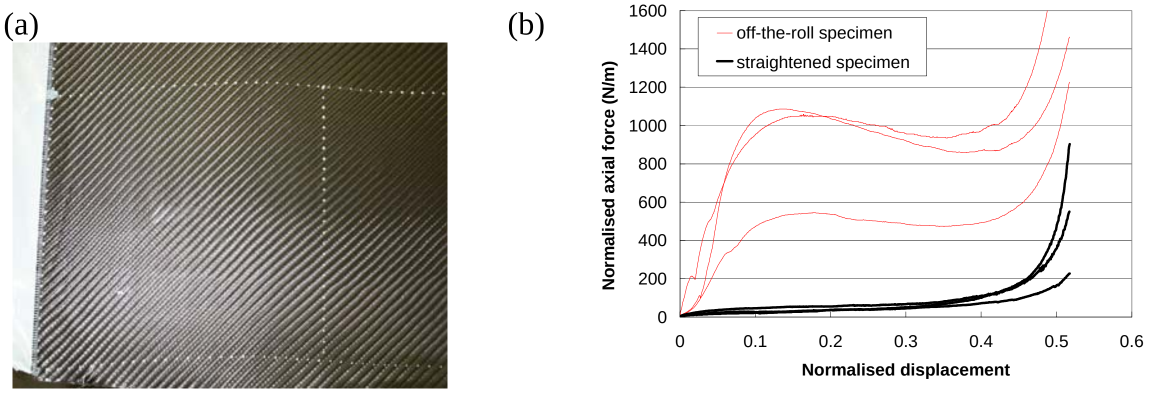

Fig. 2 (a) The profile of tows in the warp and weft direction in the material roll. (b) PF results with the cases of tow-meander and straightened specimens. Note that PF results are normalised by the side length of the picture frame [4], e.g. the normalised displacement equals to the recorded displacement divided by the side length.

Variability of Picture Frame tests

The repeatability of tests can be used to measure the accuracy of the test. The experimental errors involved during the tests may be due to misalignment due to cutting material sheets from the material roll, aligning sheets, clamping of the material, sample misalignment etc. Some PF tests were discarded due to premature wrinkling. Fig. 3 shows the PF results at three normalised crosshead speeds.

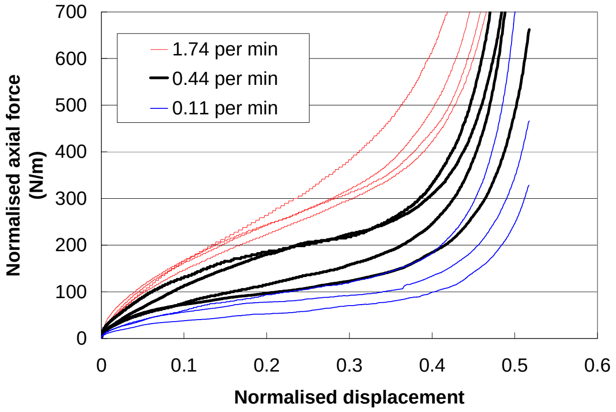

Fig. 3 PF test results at different normalised crosshead speeds to investigate the variability of experiments.

COMPARISONS BETWEEN PREDICTIONS AND CHARACTERISATION

Predictions from the MSEM using the EMM were made to compare with PF results. Within experimental variability, a good agreement between force predictions and experimental results is found (Fig. 4(a)), although the shape of predicted curve of the tow kinematics does not conform to the measurements (Fig. 5). MSEM predictions at a higher rate, 1.74 min^{-1}, were also made to compare with PF test results, shown in Fig. 4(b). The magnitude of force predictions increases rapidly as the rate increases, but the shape remains similar. The discrepancies between predictions and measurements are thought to be mainly due to the accuracy of longitudinal/transverse viscosities used in the MSEM. An suggestion on the improvement of these two viscosities was given by [13]. These problems will be addressed future work.

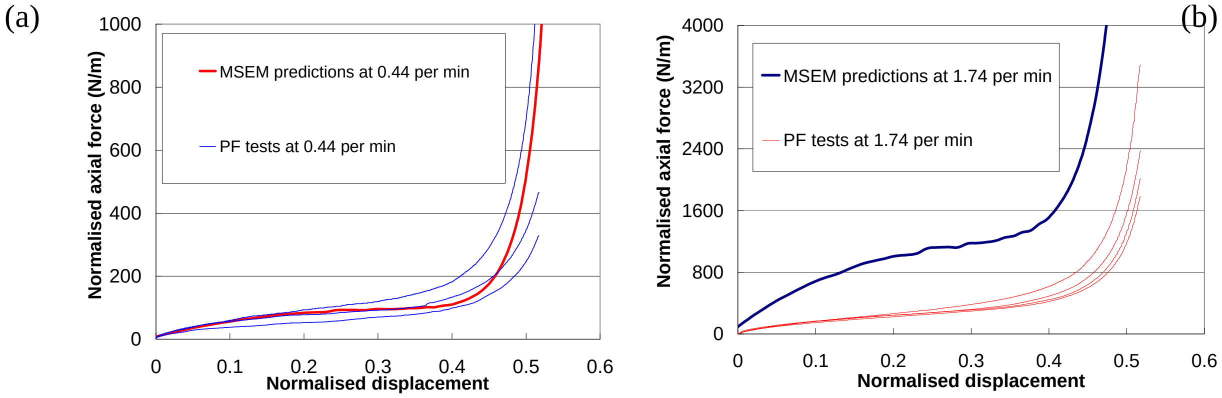

Fig. 4 Comparisons between force measurements from Picture Frame tests and force predictions based on the EMM for automotive prepreg sheet at different normalised displacement rates of (a) 0.11 min^{-1} (b) 1.74 min^{-1}

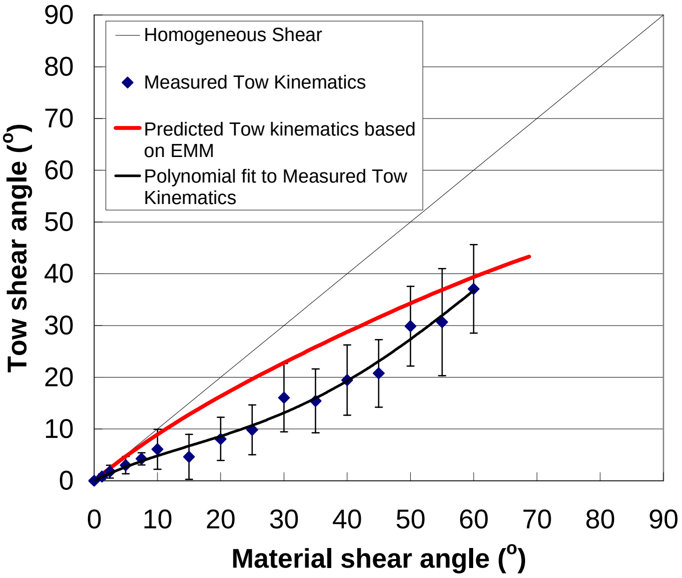

Fig. 5 Comparisons between measurements and predictions of tow kinematics based on the EMM at a normalised displacement rate of 0.11 min^{-1} for automotive prepreg sheet. Measurements were obtained from formed hemispheres. The error bars indicate the standard deviation.

CONCLUSIONS

A predictive model with less experimental input, based on the uniaxial continuum theory for ideal fibre-reinforced fluids but applied to woven textile composites, has been developed. The meso-scale kinematics for tow deformation that in the original MSEM had to be obtained from experimental measurements, such as formed hemisphere, can be predicted by an energy minimisation algorithm.

PF tests have been performed and suggest that the clamped boundary condition should be used for this particular prepreg, and the effect of direction of the shearing deformation for this prepreg can be neglected. The influence of tow-meander is significant, which suggests that test specimens should be straightened prior to testing.

A reasonable agreement between MSEM predictions and PF test results encourages the development of the energy minimisation method.

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