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A constitutive model for self-reinforced ductile polymer composites

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ABSTRACT

Self-reinforced polymer composites are gaining increasing interest due to their higher ductility compared to traditional glass and carbon fibre composites. Here we consider a class of PET composites comprising woven PET fibres in a PET matrix. While there is a significant literature on the development of these materials and their mechanical properties, little progress has been reported on constitutive models for these composites. Here we report the development of an anisotropic visco-plastic constitutive model for PET composites that captures the measured anisotropy, tension/compression asymmetry and ductility. This model is implemented in a commercial finite element package and shown to capture the measured response of PET composite plates and beams in different orientations to a high degree of accuracy.
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1. Introduction

A drawback with traditional fibre reinforced plastics (FRP) such carbon fibre reinforced plastics (CFRP) and glass fibre reinforced plastics (GFRP) is their low tensile failure strain for loading in fibre direction. Under tensile loading, the failure of these composites is usually catastrophic with little damage prior to ultimate failure. As a consequence, designs with these materials have high safety margins and also require costly structural health monitoring systems to be employed when such composites are used in safety critical applications.

There has been considerable recent interest in designing FRPs with higher ductilities. One approach is the use of a relatively new class of composites called single polymer composites (or self-reinforced composite) made from polymers such as polyethylene terephthalate (PET) and polypropylene (PP) [1–3]. These composites have been shown to have significantly higher ductilities compared to traditional CFRP and GFRP composites. As an example, the tensile failure strain of self-reinforced PET composites is >10% which is an order of magnitude higher than the failure strain of e.g. GFRP (1.4%) [4]. Most of the work reported to-date in these self-reinforced composites has focused on development of materials/manufacturing methods [5,6] and the characterisation of the mechanical properties for various single polymer materials [7–9]. Another important aspect with these group of materials is that the final mechanical properties of the material is highly dependent on manufacturing parameters such as consolidation temperature and pressure. The effect of manufacturing parameters on the mechanical properties of single polymer PP has e.g. been investigated by Alcock et al. [10,11] and Hine et al. [12].

There has only been limited research on the modelling of the mechanical properties and behaviour of single polymer composites. Previous work has mainly focused on modelling the homogenised stiffness properties of the material by using a rule-of-mixture approach [13,14]. However, the application of single polymer composites in semi-structural and structural settings (e.g. such as the lattice sandwich cores developed by Schneider et al. [15]) requires the availability of design tools that includes more complete material constitutive models for performing structural calculations using finite element codes. Constitutive models such as the Hashin model [16], the Matzenmiller model [17] and the LaRC model [18] developed for CFRP and GFRP are unsuitable for the ductile self-reinforced composites because they: (i) are designed for elastic–brittle materials; (ii) cannot account for a rate sensitive plastic response and (iii) typically only model the in-plane response of composites.

In this study we will develop an anisotropic visco-plastic material model to capture the complex behaviour of ductile self-reinforced composites as described above. The outline of the paper is as follows. First we describe the PET composite material investigated in this study and report measurements of material properties in tension, compression and shear in different directions to fully

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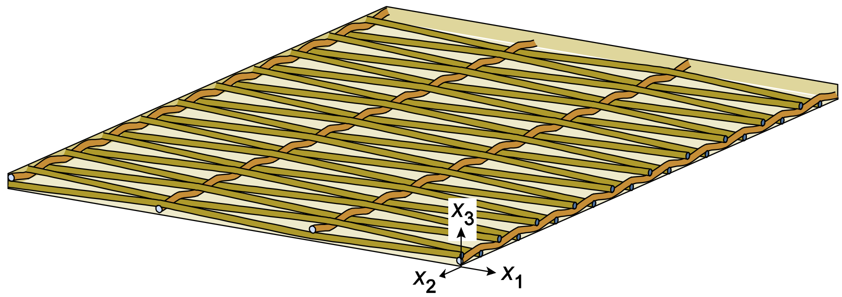

Fig. 1. Sketch of the micro-structure of the fabric comprising comingled PET yarns. The definition of the material axes x_i is included and the sketch shows that 80% of the PET yarns lie in the x_1 direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

characterise the orthotropic properties of these composites. Next, we describe an anisotropic visco-plastic model that is capable of capturing the measured anisotropic properties including tension/compression asymmetry and material rate dependence. The model is based on the homogenised properties of the composite material post consolidation and does therefore not require information on the material constituents (e.g. fibres/tape and matrix) properties prior to the consolidation process (these properties can change depending on processing conditions as discussed previously). Finally, structural tests on beams and plates of the composite in different orientations are reported. These measurements are compared with finite element predictions using the proposed constitutive model to demonstrate the fidelity of the constitutive model in capturing the complex structural behaviour of PET composites.

2. Materials and manufacture

The PET composites are made from commingled yarns comprising of 50% high tenacity PET fibre (HTPET) with a melting temperature of 260 °C and 50% PET fibres (LPET) with a lower melting temperature of 170 °C that will subsequently be melted to form the matrix in the composite. These comingled yarns are then woven into a fabric with 80% of the yarns in the x_1 direction and only 20% in the x_2 direction as sketched in Fig. 1. This woven fabric was supplied by Comfil®APS[1] and is labelled by the supplier as unidirectional since the majority of the fibres lies in the x_1 direction. This fabric is then layered, with all layers stacked in the same direction, and consolidated into panels of the desired thickness in the x_3 direction under a pressure of 1.5 bar for 20 min at 220 °C (i.e. a temperature that melts the LPET fibres to form the matrix but does not affect the HTPET fibres). Schneider et al. [4] gives a more detailed description of the manufacturing process and the individual properties of the HTPET fibres (E = 15.2 GPa) and LPET matrix (E = 3.0 GPa). For the sake of brevity these pressed composite panels shall be referred to as PET composites.

3. Characterisation of mechanical properties

The PET composites are highly anisotropic and here we report measurements to characterise the anisotropic elastic and inelastic properties. Three types of measurements are performed: (i) uniaxial tension in the x_1 and x_2 directions; (ii) uniaxial compression in the x_1, x_2 and x_3 directions and (iii) three-point bending of short and thick beams to measure shear responses in the x_1–x_2, x_1–x_3 and x_2–x_3 planes. For the shear tests, only a single repeat was performed to measure the qualitative response (the stiffness measurement is however confirmed to be the same in all 3 shear tests) while in all other tests at least 3 repeat tests were conducted to confirm the reproducibility of the results.

3.1. Measurement protocol

3.1.1. Tensile tests

Tensile tests were performed in the in-plane x_1 and x_2 directions using the dog bone shaped specimen sketched in Fig. 2a. The PET composites are highly anisotropic with a high tensile strength in the fibre directions but a relatively low shear strength. Hence the use of a test standard (such as that defined by ASTM D3039) results in failure by fibre pull-out at the grips and hence the specimen sketched in Fig. 2a developed by Russell et al. [19] for the highly anisotropic polyethylene fibre composites was employed here. The applied tensile stress was defined using the load measured from the load cell of the test machine while the tensile strains were measured via a clip gauge on a central 12.5 mm gauge section of the specimen. In addition, in the initial elastic regime, the strains on the surface of the gauge section were recorded using the commercial digital image correlation (DIC) package GOM Aramis[2] and used to calculate the Poisson's ratio ν_{21}, ν_{13} and ν_{23}. All tests were conducted at an applied strain rate of $10^{-4}\,s^{-1}$ and unloading–reloading was also performed in order to measure the elastic moduli. No tensile tests were performed in the x_3-direction (thickness direction) as PET composites of sufficient thickness could not be manufactured in order to make tensile specimens of the appropriate shapes.

3.1.2. Compression tests

Two types of compression tests were conducted: (a) quasi-static tests at an applied strain rate of $10^{-4}\,s^{-1}$ and (b) high rate compression tests using a direct impact Kolsky bar at applied strain rates in the range $100\,s^{-1} \leqslant \dot{\varepsilon} \leqslant 2000\,s^{-1}$. All tests were conducted on cubes of specimens of side H = 13 mm (Fig. 2b). The quasi-static tests were conducted by compressing the cubes between lubricated rigid platens of a screw driven test machine in the x_1, x_2 and x_3 directions. Load measured from the machine load cell was used to define the applied stress and a laser gauge used to measure the platen displacement from which the applied strain is inferred. Unloading–reloading was also performed in order to measure the elastic moduli. The high strain rate Kolsky bar measurements were performed by compression tests in x_1 direction. Details of the Kolsky bar technique are given in [20]: briefly the compressive nominal stress is determined from strain measurements on the transmitter Kolsky bar and nominal strain for the imposed strain rate v_0/H defined as $v_0 t/H$ where v_0 is the velocity of the projectile that impact the specimens and time $t = 0$ corresponds to the instant the projectile impacts the specimen. High speed photography was used to confirm the accuracy of the above definitions of strain rate and strain.

[1] Karolinelundsvej 2 – DK- 8883 Gjern, Denmark.

[2] GOM Gmbh. User Manual: Aramis v6.3.0, Braunschweig, Germany, http://www.gom.com.

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