ON THE EFFECT OF FIBRE SHAPE IN FIBRE REINFORCED POLYMERS: STRENGTH AND TOUGHNESS

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Abstract

Computational micromechanics of composites is an emerging tool required for virtual materials design (VMD) in order to address the effect of the involved variables before materials are manufactured. This strategy will avoid unnecessary costs reducing trial-and-error campaigns leading to fast material developments for tailored properties. In this work, the effect of the fibre cross section on the transverse behavior of unidirectional fibre composites has been evaluated by means of computational micromechanics. A parametric analysis of fibres cross section shape on transverse strength has been carried out through the computational micromechanics approach. A numerical algorithm to generate microstructures of non-circular (lobular, polygonal and elliptical) randomly distributed fibres has been developed. Prediction of the strength under transverse tension and compression was achieved by means of computational micromechanics applied on representative volume elements of fibre-reinforced polymer.

1. Introduction

Since the discover of high-performance carbon fibres, the composite production process has been optimized to maximize their intrinsic mechanical, thermal and electrical properties. Despite these efforts, the morphology of the reinforcing fibres has barely evolved since its discovery and most developments in this field were kept at a basic research level due to major manufacturing difficulties. Pitch-based carbon fibres with different non-circular cross section have been extensively studied by Edie and Dunham [1]. This research group determined the main manufacturing parameters as the mesophase pitch viscosity, winding speed and temperature controlling the fibre properties using a lab scale set-up. Trilobal and octolobal fibres were obtained from the extrusion of the filaments from different cross section spinnerets [2,3]. From a mechanical point of view, trilobal and round fibres respond differently to increasing process temperatures (i.e. carbonization). Trilobal fibres exhibited a higher longitudinal elastic modulus and tensile strength than standard circular ones (744GPa and 2.72GPa, respectively being 1900°C the carbonization temperature). Comparing to the radial fibre texture, typical of carbon fibres spun from mesophase pitch, the microstructure of trilobal carbon fibres does not emanate radially from a center point, but instead grows up from three lines extending from the tip of each lobe. Ribbon-shaped mesophase-pitch fibres have also been produced, obtaining a linear line-origin transversal texture which enhances their transport properties [3]. Recent studies demonstrated the possibility to manufacture X-type fibres which theoretically can increase 3-8 times the fracture energy of cementitious composites when compared to standard circular fibres [4].

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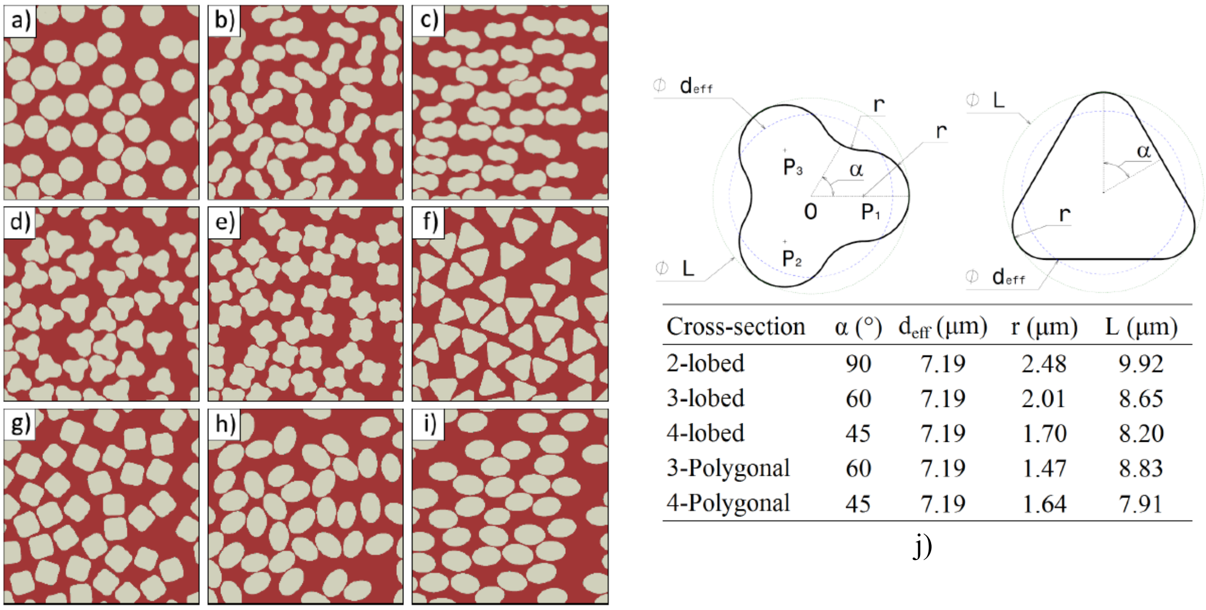
2.1. Computational micromechanics

Four different families of fibre section geometries were considered in this work as represented in Figure 1 including standard circular, lobular (2, 3 and 4-lobed), polygonal (3 and 4 edges) with smoothed vertex, and elliptical with 0.75 of eccentricity ratio. The equivalent diameter of non-circular fibres was keep constant and equal to the standard circular fibres (≈7.19μm for AS4 carbon fibre) for comparison purposes [5]. A new set of distributions with 2-lobed and elliptical fibres aligned in a fixed direction is presented to study the effect of cross section orientation on the overall transversal behaviour of the composite material. The detailed geometry definition of the lobular and polygonal fibres is presented in Figure 1j), with the corresponding dimensions used in the simulations (fillet radii, vertex, etc).



Cross-section	α (°)	d_{eff} (μm)	r (μm)	L (μm)
2-lobed	90	7.19	2.48	9.92
3-lobed	60	7.19	2.01	8.65
4-lobed	45	7.19	1.70	8.20
3-Polygonal	60	7.19	1.47	8.83
4-Polygonal	45	7.19	1.64	7.91

j)

Figure 1 Representative volume element example of each microstructure configuration: (a) circular, (b) 2-lobed, (c) 2-lobed aligned, (d) 3-lobed, (e) 4-lobed, (f) 3-polygonal, (g) 4- polygonal, (h) elliptical and (i) elliptical aligned, Definition of the geometry of lobular and smooth polygonal fibers (j).

Periodic RVE's containing 50% volume fraction of fibre reinforcement were generated [6]. Periodicity is guaranteed through the application of periodic boundary conditions (PBC). PBC are applied between opposite faces of the RVE to ensure the continuity with the virtually neighbouring RVEs. Tension and compressive stress states are applied to the RVE's to determine the transverse-to-the-fibres strength in tension and compression. At least five randomly generated microstructures were employed to determine the averaged tensile (Y_t) and compressive strength (Y_c) for each configuration. An homogeneous thermal step is applied prior to the application of the external loading to simulate the cooling down process from the curing temperature to the service temperature (ΔT=160ºC). This thermal step induces a residual stresses at the microlevel resulting from the thermo-elastic mismatch between fibres and matrix.

Carbon fibres are modelled as thermo-elastic transversely isotropic material. The interface behaviour is captured by means of the cohesive crack approach using cohesive elements (COH3D8 in Abaqus Standard) inserted at the fiber/matrix interface. Cohesive elements response is governed by a traction-separation law. The damage initiation is controlled by quadratic interaction criterion between normal and shear stresses acting at the interface while damage evolution is governed by the mixed mode Benzeggagh-Kenane propagation criterion.

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The polymer matrix behaviour is modeled using the Lubliner damaged/plasticity model included in Abaqus Standard. This constitutive equation allows the material to behave as quasi-brittle when subjected to dominant tensile stress while it shows elasto-plastic behaviour under pressure confinement and compressive loads. The matrix is modelled with 8-node fully integrated brick isoparametric elements (C3D8 in Abaqus Standard), while the fibres are meshed with 6-node fully integrated wedge isoparametric elements (C3D6).

3. Results

The response of the unidirectional plies under transverse tension was linear and elastic up to the onset of damage which takes place at moderate transverse strains of approximate 1%. The behaviour is essentially brittle and formed by localization of fibre/matrix interface cracks at the poles of the fibres in a given section of the material. After the onset of interface debonding, the matrix ligaments between adjacent fibres are subjected to tearing until the RVE is completely damaged. RVE's subjected to transverse compression failed after significant non-linear deformation by the development of matrix shear bands where severe plastic deformation and fibre/matrix interface decohesion occurs. The final failure is produced by an inclined crack of ≈56° with respect to the plane perpendicular to the loading axis in the case of standard carbon/epoxy composites [5].

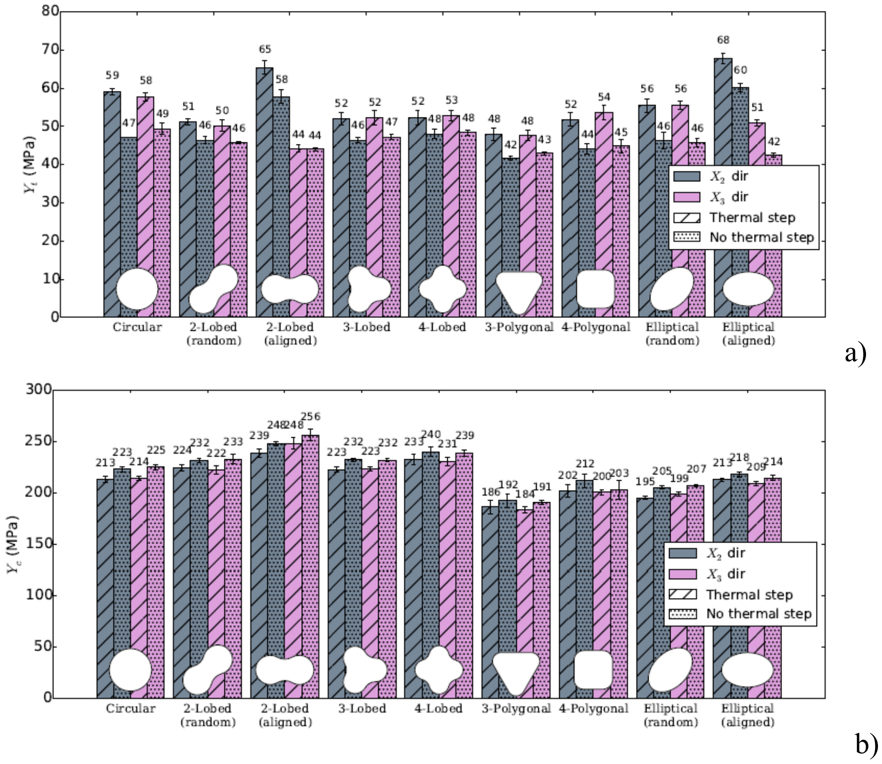

Figure 2 Effect of residual stresses on the transverse strength of non circular fibres RVE's: a) Tensile strength, b) Compressive strength.

The results shown in Figure 2a) represent the transverse tensile strength Y_t for the RVE's analyzed. Circular fibres showed the best balanced tensile strength in both directions for all the cross sections analyzed. This effect can be endorsed to the lower stress concentration created by the circular fibres when compared with polygonal or lobular.

Simulations were repeated without the initial thermal step in order to determine the effect of residual stress on the transversal strength of the fibre distributions. Average values and standard deviations corresponding to all the fibre realizations in the two directions were depicted in Figure 2a including the results with and without thermal temperature drop. In all the cases, the transverse tensile strength

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decreased in the absence of the thermal residual stress indicating a strong shielding effect due to their compressive nature. The results in terms of transverse yield strength Y_c for all the fibre geometries analyzed are represented in Figure 2b). The results showed that lobular fibres unidirectional plies presented the best transverse compressive performance and this effect can be endorsed to the pre-tensile residual stress induced in the lobular fibres microstructures (Figure 4) increasing the response under compression. After the onset of damage, the influence of the residual stress state was limited as they were partially relieved due to the plastic behaviour of the polymer matrix under confined stress states.

Acknowledgments

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