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Three-dimensional nonlinear micro/meso-mechanical response of the fibre-reinforced polymer composites

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ABSTRACT

A three-dimensional multi-scale computational homogenisation framework is developed for the prediction of nonlinear micro/meso-mechanical response of the fibre-reinforced polymer (FRP) composites. Two dominant damage mechanisms, i.e. matrix elasto-plastic response and fibre–matrix decohesion are considered and modelled using a non-associative pressure dependent paraboloidal yield criterion and cohesive interface elements respectively. A linear-elastic transversely isotropic material model is used to model yarns/fibres within the representative volume element (RVE). A unified approach is used to impose the RVE boundary conditions, which allows convenient switching between linear displacement, uniform traction and periodic boundary conditions. The computational model is implemented within the framework of the hierarchic finite element, which permits the use of arbitrary orders of approximation. Furthermore, the computational framework is designed to take advantage of distributed memory high-performance computing. The accuracy and performance of the computational framework are demonstrated with a variety of numerical examples, including unidirectional FRP composite, a composite comprising a multi-fibre and multi-layer RVE, with randomly generated fibres, and a single layered plain weave textile composite. Results are validated against the reference experimental/numerical results from the literature. The computational framework is also used to study the effect of matrix and fibre–matrix interfaces properties on the homogenised stress–strain responses.

1. Introduction

Compared to conventional materials, fibre-reinforced polymer (FRP) composites can offer exceptional physical and chemical properties (including high strength, low specific weight, fatigue and corrosion resistance, low thermal expansion and high dimension stability), making them ideal for a variety of engineering applications, including aerospace, marine, automotive industry, civil structures and prosthetics [1–3]. Phenomenological or macro-level models cannot accurately describe the complex behaviour of FRP composites due to their underlying complicated and heterogeneous microstructure. Furthermore, nonlinearities associated with the matrix elasto-plasticity and fibre–matrix decohesion make the computational modelling even more challenging. Multi-scale computational homogenisation (CH) provides an accurate modelling framework to simulate the behaviour of FRP composites and determine the macro-scale homogenised (or effective) response, based on the physics of an underlying, microscopically heterogeneous, representative volume element (RVE) [4–9,3]. The homogenised properties calculated from the multi-scale CH are subsequently used in the numerical analysis of the macro-level structures.

A variety of numerical techniques have been developed to model the nonlinear micro-mechanical response of unidirectional (UD) FRP composites, mostly based on finite element analysis. For UD glass/carbon (G/C) FRP composites, a computational model was developed in [10,11] within the framework of finite deformation. Both in-plane shear and compressive loading scenarios were considered. The Mohr–Coulomb yield criterion and cohesive interface elements were used to model the response of epoxy matrix and fibre–matrix interfacial decohesion respectively. Fibres were generated randomly within the RVEs using the algorithm presented in [12] and were modelled as a linear-elastic and isotopic material. A parametric study, including the effect of matrix and interface properties on the stress–strain response, was also conducted. The idea of [10] was extended further in [13] by incorporating thermal residual stresses (due to cooling of FRP composites after curing process, caused by the mismatch in thermal expansion coefficients of matrix and fibres) in the simulation,

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in addition to transverse tensile and cyclic loading for the CFRP composites. The nearest neighbour algorithm (NNA) [14] developed by the same authors, was used to randomly generate the fibres within the RVEs. Using the same constitutive models for matrix, fibres and fibre–matrix decohesion as in [10], a multi-layer multi-fibre (M^2) RVE was used in [15] for laminates. Each lamina was modelled as a cube with randomly distributed but axially aligned fibres, generated using a fibres randomisation algorithm in DIGIMAT FE [16]. Both cross $[0/90]_{ns}$ and angle $[\pm 45]_{ns}$ (where the subscript ns represents n layers with the same sequence and symmetric about the mid plane) GFRP composites were considered with in-plane shear loading and results of stress–strain behaviour were validated against the experimental results. A combined transverse compression and axial tension loading scenario was considered in [17] for UD GFRP composite. In addition to matrix plasticity and fibre–matrix decohesion, fibre breakage was also included in the FE simulation. The pressure dependent, Drucker-Prager yield criterion was used to model matrix plasticity and both fibre breakage and fibre–matrix interfacial decohesion were modelled with cohesive interface elements. A simple periodic, hexagonal fibre arrangement was assumed. In [18], a modified von Mises yield criterion was used to model the behaviour of the matrix material, while a maximum tensile stress criterion was used to model fibre breakage. Fibre–matrix decohesion was also included in the simulation and was modelled with cohesive interface elements. The random distribution of the fibres was also included within the RVE based on the optical microscopy of real composites. A variety of loading conditions was used subsequently to study the response of the UD FRP composite. The limitations of different plasticity models for modelling matrix materials, including Mohr–Coulomb and Drucker-Prager were argued in [19,20], especially in complex loading scenarios. Instead of the conventional plasticity models, a pressure dependent thermodynamically consistent plasticity model [21] was used. A statistically proven random distribution algorithm proposed by the same authors in [22] was used to randomly generate UD fibres within the RVEs. Similar to previous studies, fibres were modelled as linear-elastic and isotropic material and fibre–matrix decohesion was modelled with cohesive interface elements. A variety of RVE loading scenarios was considered including transverse tension and compression, transverse and longitudinal shear and combined transverse compression and transverse shear.

A number of numerical modelling approaches have been used to simulate the behaviour of textile composites subjected to different loading scenarios. A comprehensive review of these methods can be found in [23]. Continuum damage mechanics (CDM) was used in [24] to model both matrix and yarns for glass and carbon plain weave textile composites. Dissipated energy density was used as damage parameter and both material and geometric nonlinearities were included in the simulation. Further use of CDM in the simulation of textile composites can also be found in [25–27]. Moreover, a three-dimensional CDM based approach was used to simulate the progressive damage in laminated FRP composites in [28,29]. A variety of failure mode, including matrix tensile and compressive cracking, fibre tensile and compressive failure, fibre–matrix shearing and delimitation between the layers were included in the simulations. For a twill weave textile CFRP subjected to in-plane loading, a meso-mechanical analysis was performed in [30]. The matrix was modelled as elasto-plastic material with the same plasticity model as in [19–21], while yarns were modelled as linear-elastic and transversely isotropic material. Results of the RVE strain fields and homogenised stress–strain response were validated against the experimental results and found in a good agreement.

These numerical simulations, described above, of FRP composite behaviour are limited to specific RVE type (2D or 3D, UD or woven/textile) or loading scenarios (normal or shear). In contrast, this paper develops a fully generalised three-dimensional micro/meso-mechanical framework, which is subsequently implemented in the authors' open source FE software, MOFEM [31]. The dominant damage mechanisms (observed experimentally [10]), i.e. matrix elasto-plasticity and fibre–matrix decohesion, are included in the computational framework. Matrix material is modelled using a pressure dependent paraboloidal yield criterion [19,20,30,21] with an exponential hardening law. Fibre–matrix decohesion is modelled with zero thickness cohesive interface elements. Yarns are modelled as linear-elastic and transversely isotropic materials. Rather than simplified fibre arrangements for UD FRP composites, e.g. in [32,33,17,34], which are not the actual representation of the real FRP composites and can lead to erroneous results. this study adopts a statistically proven random distribution algorithm proposed in [22] to generate fibre arrangements within the RVE. The RVE boundary conditions are imposed in a unified manner which allows convenient switching between displacement, traction and periodic boundary conditions [35]. Hierarchic finite elements are adopted, which permits the use of arbitrary order of approximation, leading to accurate results for relatively coarse meshes. The computational framework is designed to take advantage of distributed memory high-performance computing. Moreover, CUBIT [36] and ParaView [37] are used as pre- and post-processor respectively.

This paper is organised as follows. The computational framework is fully described in Section 2. The material models are given in Section 2.1, consisting of material model for matrix (Section 2.1.1), yarns/fibres (Section 2.1.2) and fibre–matrix interfaces (Section 2.1.3). The nonlinear multi-scale CH with corresponding RVE boundary conditions are explained in Section 2.2. Calibration and validation of the matrix plasticity model is given in Section 3. Three numerical examples are given in Section 4, including UD GFRP composites (Section 4.1), M^2RVE (Section 4.2) and plain weave textile composites (Section 4.3). Finally, the concluding remarks are given in Section 5.

2. Computational framework

The computational framework developed for FRP composites consists of a set of constitutive models for individual components including matrix, yarns/fibres and fibre–matrix interface and implemented within the formulation of first-order multi-scale CH.

2.1. Material constitutive models

Typical RVEs in the case of UD FRP and textile composites are shown in Fig. 1(a) and 1(b) respectively, consisting of yarns/fibres embedded within a polymer matrix. The constitutive model for FRP composites is a combination of constitutive models for these individual components, together with fibre–matrix interface decohesion. In the following, each of these constitutive model is explained in detail.

2.1.1. Matrix

The polymer matrix is modelled as an elasto-plastic material using a non-associative pressure dependent paraboloidal yield criterion [21,19,20,30,9]. This plasticity model can incorporate different yield strengths in tension and compression and is shown Fig. 2 (a) in the principal stress space. The yield function is written as

$$f(\boldsymbol{\sigma}, \sigma_c, \sigma_t) = 6J_2 + 2I_1(\sigma_c - \sigma_t) - 2\sigma_c\sigma_t, \quad (1)$$

where $\boldsymbol{\sigma}$ is Cauchy stress tensor, $I_1 = \mathrm{tr}(\boldsymbol{\sigma})$ is the first invariant of Cauchy stress tensor, $J_2 = \frac{1}{2}\boldsymbol{\eta} : \boldsymbol{\eta}$ is the second invariant of deviatoric stress $\boldsymbol{\eta} = \boldsymbol{\sigma} - \frac{1}{3}I_1$ and σ_t and σ_c are yield strengths in tension and