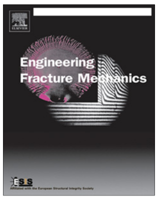
Engineering Fracture Mechanics 160 (2016) 52–66

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech



Multiscale modelling of multiple-cracking tensile fracture behaviour of engineered cementitious composites

Ting Huang [a], Y.X. Zhang [a,*], Chunhui Yang [b]

[a] School of Engineering and Information Technology, University of New South Wales, Canberra, Australian Defence Force Academy, ACT 2600, Australia
[b] School of Computing, Engineering and Mathematics, University of Western Sydney, Penrith, NSW 2751, Australia

ARTICLE INFO

Article history:
Received 10 August 2015
Received in revised form 4 April 2016
Accepted 4 April 2016
Available online 8 April 2016

Keywords:
Engineered cementitious composites (ECC)
Extended finite element method (XFEM)
Multiscale modelling
Representative volume element (RVE)
Multiple cracks

ABSTRACT

In this paper a hierarchical multiscale modelling method is proposed to analyse the strain-hardening and multiple-cracking tensile fracture behaviour of engineered cementitious composites. A simplified multi-linear crack bridging relationship is proposed at a lower mesoscale based on analytical crack bridging analysis for a single crack. A representative volume element model is developed at an upper mesoscale accounting for random fluctuations of internal material properties and sequentially occurred cracking, and it is analysed using the extended finite element method. The multiscale modelling method is validated, and the effect of fibre distribution uniformity on the tensile behaviour of ECC is investigated.

1. Introduction

As a special class of high performance fibre reinforced cementitious composites emerged in recent decades, engineered cementitious composites (ECC) (also known as ductile fibre reinforced cementitious composites DFRCC, or strain-hardening cement-based composites SHCC) have attracted increasing research interests. In addition to the macroscopic pseudo strain-hardening behaviour in tension, ECC is characterised by the multiple micro-cracking behaviour and extraordinary tensile ductility with a moderate volume of short random fibres, which have been achieved through rigorous design based on the micromechanics of material and fracture principles [1–3]. ECC reinforced by polyethylene (PE) fibre or polyvinyl alcohol (PVA) fibre with a fibre volume fraction no greater than 2% exhibits a tensile strain capacity up to 3–6% and the crack width is self-controlled normally below 100 μm [4,5]. ECC possesses significantly enhanced ductility and damage tolerance which can greatly benefit the strength, ductility, damage tolerance and repairability of the structure [4], making ECC a promising construction material, and these superior performance are eventually attributable to the high tensile strain capacity and multiple micro-cracking behaviour of ECC.

The tensile behaviour of ECC has been most often characterised by results of direct tension tests. The phenomenological tensile stress–strain models of ECC have been developed based on the general response of ECC under uniaxial tension [6]. These models are consisted of an initial linear-elastic stage followed by a linear strain-hardening branch up to the ultimate tensile stress and strain, showing improved ultimate tensile strength and strain capacity compared to that of concrete and fibre reinforced concrete. Some analytical models have been proposed based on the micromechanics [7,8]. These models can describe the crack width and crack spacing of ECC in addition to the pseudo strain-hardening behaviour in terms of the

---

* Corresponding author. Tel.: +61 (2) 6268 8169; fax: +61 (2) 6 268 8581.
E-mail address: y.zhang@adfa.edu.au (Y.X. Zhang).

http://dx.doi.org/10.1016/j.engfracmech.2016.04.006
0013-7944/

constitutive properties of the fibre, matrix and fibre-matrix interface. These models can also be used to tailor the composites to meet specific structural requirements with the link between the micromechanical properties of the constituents and the macroscopic mechanical properties of ECC. However, the effect of the fibre distribution randomness on the tensile behaviour of ECC has not been accounted for in these analytical models.

Due to microstructural imperfections including initial matrix flaws and nonuniform fibre distribution, the tensile properties of ECC especially the tensile strain capacity can vary significantly [9–11]. It seems imperative to account for the microstructural variations in the tensile stress–strain model of ECC. With an ever-growing computational capability, mesoscale numerical modelling technique has been increasingly employed to study the mechanical behaviour of composite materials, including concrete and fibre reinforced cementitious composites [12–15], based on a properly devised mesoscale model with discretised internal material structure. The mesoscale modelling has the advantage that a substantial portion of material randomness is naturally included during the construction of the mesoscale model, such as the randomness of the constituents in terms of the material and geometric properties, spatial locations and distribution. The mesoscale modelling of ECC has also been performed with the internal material structure represented by mortar matrix and randomly entrapped air voids [16], or by mortar matrix and randomly distributed short fibres [17].

Though the mesoscale modelling techniques are capable of modelling the structural randomness and the damage evolution within the material, they generally tend to be computationally intensive. A multiscale modelling method, which obtains the composite macroscopic constitutive relationship using multiple models that describe the material behaviour on different length scales and thus reduces the calculation effort at a particular scale level, has received increasing attention. The multiscale modelling framework for ECC was first proposed by Kabele [18]. At a microscale level, the bridging behaviour of individual fibres is considered. The formation and opening of one single crack with a number of fibres bridging across is accounted for at a lower-mesoscale level. At an upper-mesoscale level, the joint response of the uncracked matrix and the multiple cracks is considered in a representative volume element (RVE) model, and the macroscopic properties of ECC is evaluated based on the volume average of the structural response of the RVE. The multiscale analysis of ECC has been conducted so far in a purely analytical way [18,19].

In this paper, a hierarchical multiscale modelling method is developed for accurate and effective modelling of the multiple-cracking tensile fracture behaviour of ECC materials. A semi-numerical approach is proposed for efficient implementation of the hierarchical multiscale modelling. At a lower mesoscale, the crack bridging behaviour is analysed analytically. A wide variety of micromechanics-based crack bridging models accounting for different fibre-matrix interface properties and fibre failure modes [3,20–24] are available to derive the fibre bridging stress-crack opening relationship in terms of the material constituent properties and interface properties. It is superimposed to the crack bridging law of the matrix, and the consequent composite bridging stress-crack opening relationship is further simplified by a piecewise linearisation. The simplified multi-linear crack bridging relationship is then integrated into an upper mesoscale and used as a cohesive constitutive model by the multiple cracks based on the cohesive crack concept. A RVE model, which is capable of accommodating a number of cracks and describing the characteristic material behaviour of ECC at the upper mesoscale, is developed and it is analysed using finite element method. The RVE model is discretised by bulk elements only, but once cracking is detected, a cohesive zone in the form of a strong discontinuity is adaptively embedded within the prospective element by means of extended finite element method (XFEM). Material randomness including matrix flaw randomness and fibre distribution randomness are also considered with spatial fluctuations of the matrix cracking strength and fibre volume fraction introduced into the RVE model. The tensile properties of ECC is determined based on the structural response of the RVE model using a homogenisation technique. The effect of the fibre distribution uniformity on the tensile properties of ECC is investigated.

The paper is structured as follows. The simplified multi-linear cohesive constitutive model is presented in Section 2. The construction and implementation of the RVE model as well as the homogenisation techniques is presented in Section 3. A polyvinyl alcohol fibre reinforced ECC (PVA-ECC) is modelled using the proposed method and the computed results are compared with experimental results in Section 4. The effects of the size of the RVE model and the uniformity of fibre distribution on the tensile behaviour of ECC are also studied in Section 4. Finally, the conclusion remarks are given in Section 5.

2. Lower-mesoscale modelling: a simplified multi-linear cohesive law

According to the micromechanics-based crack bridging models [3,20–24], the bridging behaviour of a single fibre with an arbitrary orientation angle and centroid distance (embedment length) relative to the crack plane can be determined in terms of the physical properties of the matrix, fibre and fibre-matrix interface as illustrated in Fig. 1. The fibre bridging stress-crack opening relationship is then obtained by summing the force contributions from the individual bridging fibres, which have a random orientation angle and centroid distance with respect to the crack plane as shown in Fig. 1. Uniform distribution of the orientation angle and centroid distance have been generally assumed in the crack bridging models. In addition, if the single-fibre bridging stress exceeds the fibre tensile strength, the fibre fails by rupture and ceases to bridging the crack. Fibres which are already completely pulled out also make no contributions to the crack bridging. The ruptured fibres and fully pullout fibres should be excluded when calculating the crack bridging stress due to the fibres.

A schematic fibre bridging stress-crack opening relationship is shown by the dash line in Fig. 2(a). A bilinear softening bridging law as shown by the dotted line in Fig. 2(a) is extensively used for the cementitious matrix [25]. The composite