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

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Abstract

A multiscale numerical approach is presented in this paper to model the tensile behaviour of engineered cementitious composites. A unit cell model with a random realisation of the matrix cracking strength distribution and fibre volume fraction distribution is employed. Cracks are adaptively introduced within cracked elements by means of extended finite element method along with a cohesive law which defines the relationship between the stress and the crack opening displacement. The developed numerical method is used to predict the tensile properties of an ECC, and good agreement between the numerical results and experimental results from direct tension tests validate the developed numerical method.

Keywords: Engineered cementitious composites (ECC), Tensile behaviour, Multiple cracking, Multiscale numerical modelling, Unit cell model

Introduction

High performance fibre reinforced cementitious composites (HPFRCC) are a special family of fibre-reinforced cement-based composites, and they distinguish from the conventional quasi-brittle fibre reinforced concrete (FRC) by macroscopic pseudo strain-hardening behaviour in tension with multiple cracking developed up to relatively high strain levels. The associated enhanced ductility, energy absorption capacity and toughness compared with FRC are expected to significantly enhance the serviceability and sustainability of cementitious materials. Engineered cementitious composites (ECC) are a unique member of HPFRCC, featuring extraordinary tensile ductility with a low to moderate fibre content. For example, ECC materials reinforced with polyethylene fibre or the polyvinyl alcohol (PVA) fibre with a fibre volume fraction no greater than 2 % exhibited a tensile strain capacity of 3 – 6 % [Li (1998)].

The tensile behaviour of ECC has been most often characterized by results of direct tension or flexure tests. Although some numerical models have been developed over the past few years [Spagnoli (2009); Kabele (2010)] to model the tensile strain-hardening behaviour of ECC, these models could only qualitatively assess the tensile strain capacity of an ECC in comparison to that of conventional FRC. In this paper a multiscale numerical approach based on the unit cell (UC) model is developed to predict the tensile behaviour of ECC. The bridging behaviour of individual fibres is regarded as the composite characteristics at microscale. The formation and opening of one single crack is regarded as a representation of the material behaviour at mesoscale, and it is derived by superimposing the bridging responses of all fibres involved in the crack-bridging action. The effect of crack bridging provided by matrix and fibres is considered for the individual crack through a cohesive law that relates the bridging stress to the crack opening displacement. Finally, the overall microscopic tensile stress-strain relationship for ECC is determined from the joint response of sequentially emerged individual cracks and the contribution of the uncrack matrix. The UC should be able to accommodate a random number of cracks under the tensile loading. Various micromechanics crack bridging model are available to derive the cohesive law based on the material constituent parameters and fibre/matrix interface parameters. As a result, the presented multiscale approach has the great advantage to link the material parameters at microscale with composite properties at macroscale. The multiscale modelling framework for HPFRCC was first proposed by Kabele [Kabele (2007)] and an analytical method was employed to derive the overall tensile stress-strain relationship of the proposed model. However, in this work the overall tensile stress-strain relationship of the UC model is obtained numerically by means of the extended finite element method (XFEM).

A cohesive law

It is assumed that cracks can occur at any material point during the loading where the maximum principle stress attains the local matrix cracking strength σ_{ck}. After crack occurs, the crack response is governed by the cohesive law utilizing the cohesive crack concept, which corresponds to a characteristic material response at the mesoscale. In this study, the contributions to the crack bridging effect from both matrix and fibres are taken into account, and therefore, the cohesive law is the superposition of the crack bridging law of plain matrix and the crack bridging law due to fibres [Wang (2005)]. Especially, the fibre bridging law is computed by summing up the force contributions of all fibres bridging the crack. A representative cohesive law of the ECC is shown in Fig. 1 schematically. It should be noted that the cohesive law of ECC possesses a hardening branch prior to the softening, i. e. the ultimate bridging strength σ_{pb} exceeds the matrix cracking strength such that more cracks can be triggered, and this essentially differentiates ECC from conventional quasi-brittle FRCs.

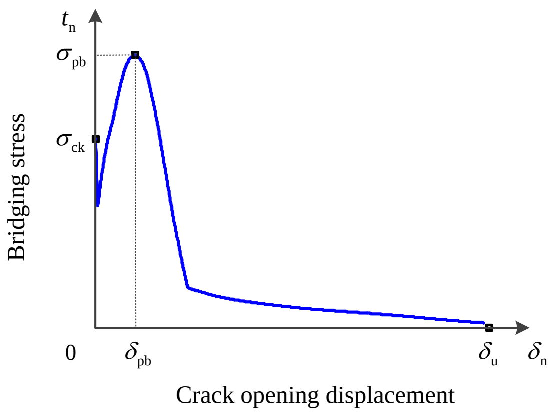

Figure 1. The cohesive law of ECC

In Fig. 1, δ_{pb} is crack opening displacement corresponding to the peak bridging stress and δ_u is the ultimate cracking opening displacement.

When fibres on one of the cracks have exhausted their load carrying capacity and became unable to carry increasing load, softening starts on this plane. Consequently, only this crack continues to open while others undergo unloading, which triggers fracture localization. For cracks that undergo unloading, it is assumed that the protruding fibres elastically contract [Kabele (2007)].

A unit cell (UC) model

The most common UC approach assumes that the microstructure of composite tends to spatially repeat itself at macroscale, i. e. the whole macroscopic specimen consists of periodically arranged unit cells. Therefore the UC approach is based on describing the microstructure of material in a unit cell, which can statistically represent the macroscopic material point, and periodic boundary conditions are imposed on the boundaries of the UC to capture the effect of the surrounding medium. A UC model as shown in Fig. 2 under uniaxial tension loading is adopted. The UC is meshed by a one-dimensional array of quadrilateral strips along the loading direction, and the matrix strength as well as the fibre volume fraction of each element is randomly generated based on a probability distribution function calibrated from experimental observations. Element size is determined by referring to the minimum spacing x_{d} of the cracks, which can be theoretically estimated for the randomly distributed short fibre composites based on the fibre parameters and interface parameters [Wu and Li (1992)]. Consequently, only one crack can occur in an element in one simulation. A crack initiates when the axial stress reaches the matrix strength at an element, and it is introduced directly within the element through the entire middle cross-section perpendicular to the loading direction by means of the XFEM. While the behaviour of uncracked matrix is considered to be linear-elastic, the crack behaves according to the non-linear cohesive law.

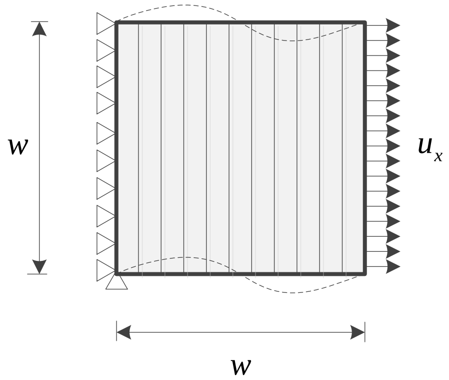

Figure 2. A unit cell model (UC) with boundary conditions for uniaxial tension and the periodic boundary conditions on the top and bottom boundaries (dash lines)

The macroscopic material properties are then obtained as the volume average of their microscopic counterparts at the UC level as given by [Nguyen et al. (2011)]:

$$\sigma_{xx}^{\mathrm{M}} = \frac{1}{w} f_{\mathrm{R}\ x}^{\mathrm{m}} \tag{1}$$

$$\varepsilon_{xx}^{\mathrm{M}} = \frac{1}{w} u_x \tag{2}$$

where σ_{xx}^{M} and $\varepsilon_{xx}^{\mathrm{M}}$ are macroscopic stress and strain in the x direction; $f_{\mathrm{R}\ x}^{\mathrm{m}}$ stands for the sum of internal x-forces at all nodes along the right boundary of the UC on which an prescribed displacement u_x has been imposed.

Numerical validation and discussion

In this research, the experimental results obtained from the selected mix design named as Mix-3 in literature [Wang (2005)] is used to validate the proposed numerical model. In the test, the interface parameters, the macroscopic tensile stress-strain relationship as well as the matrix flaw size distribution were measured. The direct tension tests were conducted on specimens with a gage length of 180 mm. Here, a UC of a dimension nearly two-thirds of this characteristic length, which can be discretized into 60 elements, is used. The computational macroscopic material properties including the ultimate tensile strength and tensile strain capacity, as well as the experimental results are summarized in Table 1.

Table 1. Summary of computational and experimental tensile properties

	Ultimate tensile strength (MPa)	Tensile strain capacity (%)
Prediction	5.04	1.79
Experiment [Wang (2005)]	4.84	1.86

While the measured ultimate tensile strength is 4.84 MPa and the tensile strain capacity is 1.86 %, the computational tensile properties of the ECC are 5.04 MPa and 1.79 % respectively, which are in reasonably good agreement. This demonstrates the effectiveness of the proposed numerical multiscale approach in predicting the tensile properties of ECC.

Conclusions

In this study, a multiscale numerical approach is developed for modelling of the multiple-cracking fracture behaviour of ECC under direct tension. The macroscopic material properties including the ultimate tensile strength and tensile strain capacity are obtained based on the homogenized response of a UC under uniaxial tension proposed in the work. The UC is able to accommodate a number of cracks accompanying the strain hardening, which is one of the distinct features of ECC. These cracks are adaptively introduced within cracked elements by means of the XFEM, with the effect of crack bridging provided by matrix and fibres implemented through a cohesive law.

The approach was verified by comparison of the predicted tensile properties of an ECC with experimental results obtained from the uniaxial tension tests.

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