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Numerical modelling of mechanical behaviour of engineered cementitious composites under axial tension

Ting Huang, Y.X. Zhang *

School of Engineering and Information Technology, University of New South Wales, Canberra, Australian Defence Force Academy, ACT 2600, Australia

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ABSTRACT

In this paper, an extended finite element model is developed for accurate and effective modelling of the tensile strain-hardening and multiple-cracking behaviour of engineered cementitious composites (ECC) under uniaxial tension. The crack is modelled using the cohesive zone model with a simplified cohesive constitutive model accounting for the matrix and fibre bridging effect, and multiple cohesive zones are adaptively embedded within the model upon the occurrence of sequential cracking based on the extended finite element method (XFEM). The extended finite element model is implemented in the ABAQUS via the user element subroutine (UEL) for the numerical analysis of the tensile behaviour of ECC. Material randomness including random matrix flaws and random fibre distribution, which can significantly affect the tensile behaviour of ECC, has been accounted for in the proposed model. Three ECC mixes are modelled and good agreement between the computed and experimental results demonstrates the effectiveness of the proposed method for modelling the tensile behaviour of ECC. It is also shown that the two aspects of material randomness should be considered simultaneously in the model.

1. Introduction

High performance fibre reinforced cementitious composites (HPFRCC) are a relatively new class of fibre reinforced cement-based materials emerged in recent decades, featuring macroscopic pseudo strain-hardening behaviour in tension. Unlike conventional fibre reinforced concrete (FRC), which undergoes tension softening immediately after first cracking, HPFRCCs are of the capability to carry further load with sequential development of multiple cracks up to relatively high strain levels. Due to their excellent ductility, enhanced energy absorption capacity and fracture toughness, the research and application of HPFRCCs have attracted increasing interests. Engineered cementitious composites (ECC) are a unique group of HPFRCCs distinguished by extraordinary tensile ductility with moderate fibre content, which have been achieved through rigorous micromechanics-based design [1–3]. ECC reinforced by polyethylene (PE) fibre or polyvinyl alcohol (PVA) fibre possess a tensile strain capacity up to 3–6% with a fibre volume fraction of about 2% [4,5]. Besides, the crack width in ECC is self-controlled typically below 100 μm [6]. ECC exhibits considerably low water permeability even in the cracked state with the tiny cracks, which can noticeably decelerate the deterioration process caused by the ingress of water [4]. The strain-hardening and microcracking characteristics of ECC can significantly benefit the structural strength and ductility, damage tolerance and repairability, making ECC a superior construction material with excellent serviceability and durability.

Although the tensile properties of ECC are closely dependent on the multiple-cracking behaviour, the insightful relation between the unique multiple-cracking behaviour and the extraordinary tensile strain-hardening capability of ECC has not been well understood so far. Several analytical models were developed to analyse the tensile behaviour of ECC over the years. Kanda et al. [7] proposed a bilinear tensile stress–strain model based on two states, namely the first crack state and the ultimate state corresponding to the initiation and termination of multiple cracking, and theoretically predicted the two states by means of fracture mechanics and micromechanics. Specifically, the ultimate tensile strain was determined as the cracking strain by smearing the crack opening at the peak bridging stress over the ultimate crack spacing, assuming a uniform crack opening and spacing for the multiple cracks. A similar model was adopted by Kabele [8], whereas the nonuniform crack spacing was considered with an average cracking strain obtained by smearing the total crack opening of all cracks over the gauge length. In addition, the overall tensile strain was determined by summing up the cracking strain and the elastic tensile strain in the continuous materials between the cracks. In

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

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Nomenclature

$\mathbf{a}_i$, $\Delta\mathbf{a}_i$	standard degrees of freedom (DOFs) at node i and their increment
a	superscript denoting quantities associated with standard DOFs
$\mathbf{b}_{j,k}$, $\Delta\mathbf{b}_{j,k}$	enriched DOFs at node j for the k-th discontinuity and their increment
b_k	superscript denoting quantities associated with enriched DOFs
$\mathbf{C}$	elastic tangent stiffness matrix
c	radius of matrix flaw
c_{mc}	critical flaw size separating inert and active flaws
c_0	scale parameter of Weibull distribution of matrix flaw size
d_f	fibre diameter
E_c	composite Young's modulus
E_f	fibre Young's modulus
$\mathbf{f}_{ext}$	external force vector
$\mathbf{f}_{int}$	internal force vector
$\mathbf{f}^{mat}$, $\mathbf{f}^{coh}$	contribution of continuous material and cohesive effect over cracks to $\mathbf{f}_{int}$
F	cumulative distribution function (CDF) of the initial flaw size
F_n	CFD of the representative flaw size in finite element model
f	fibre snubbing coefficient
G_f	fibre shear modulus
H_k	step function related to k-th discontinuity
$\mathbf{K}_T$	overall tangent stiffness of the structure
$\mathbf{K}^{mat}$, $\mathbf{K}^{coh}$	contribution of continuous material and cohesive effect over cracks to $\mathbf{K}_T$
K_m	matrix fracture toughness
L_f	fibre length
m	shape parameter of Weibull distribution of matrix flaw size
$\mathbf{n}_t$	outward normal vector of external boundary with prescribed traction
$\mathbf{n}_{d,k}$	outward normal vector of internal boundary at k-th discontinuity
$\mathbf{R}_k$	rotational matrix related to k-th discontinuity
s	standard deviation of Gaussian distribution of local fibre volume fraction
s_1, s_2	coefficients defining the relation between flaw size and correction factor
$\mathbf{T}$	tangent stiffness matrix of the cohesive law
$\bar{\mathbf{t}}$	prescribed traction on external boundary
$\bar{\mathbf{t}}_k$, $\mathbf{t}_k$, $\dot{\mathbf{t}}_k$	global, local and incremental cohesive traction vector at k-th discontinuity
t_n, t_s	normal and tangential traction
$\mathbf{u}$	displacement field
$\hat{\mathbf{u}}$, $\tilde{\mathbf{u}}_k$	continuous displacement field and k-th discontinuous displacement field
$\bar{\mathbf{u}}$	prescribed displacement on external boundary
$\Delta\mathbf{u}$	incremental vector containing unknowns of $\Delta\mathbf{a}_i$ and $\Delta\mathbf{b}_{j,k}$ of all nodes
$\mathbf{v}_k$	displacement jump at k-th discontinuity in global coordinates
V_f	fibre volume fraction
$V_{f\,min}$	fibre volume fraction at the weakest fibre bridging plane
V_{f0}	mean of Gaussian distribution of local fibre volume fraction
$\mathbf{x}$	coordinate vector
x_d	minimum crack spacing
χ	correction factor of the flaw size for calculating matrix cracking strength
$\boldsymbol{\delta}_k$	displacement jump at k-th discontinuity in local coordinates
δ_n, δ_s	crack opening displacement (COD) and crack sliding displacement
δ_{ck}, δ_{pb}	COD at cracking stress and ultimate bridging stress in the cohesive model
δ_{nf}	COD at the kink point of the softening branch in the cohesive model
δ_u	ultimate COD in the cohesive model
$\boldsymbol{\varepsilon}$	Cauchy strain
Γ	boundary
Γ_t, Γ_u	external boundary with prescribed traction and displacement
$\Gamma_{d,k}$	internal boundary at k-th discontinuity
κ	correction factor accounting for the snubbing effect when calculation x_d
λ	dimensionless scaling factor in F_n
$\boldsymbol{\sigma}$	Cauchy stress
σ_{ck}	matrix cracking strength
σ_{pb}	ultimate crack bridging strength
σ_{nf}	cohesive stress at kink point of the softening branch in the cohesive model
Ω	domain
Ω_k^+, Ω_k^-	two domains divided by the k-th discontinuity
$\mathfrak{I}$	set of all nodes in the mesh
$\aleph_k$	set of the nodes from the elements intersected by the k-th discontinuity

contrast to the bilinear model where the tensile stress–strain relationship between the first crack state and the ultimate state was approximated using interpolation, Kabele [9] derived the overall tensile stress–strain relationship of ECC with the consecutive states of multiple cracking considered. During the multiple-cracking process, the crack spacing evolves with an increasing crack density till reaching the ultimate crack spacing at the ultimate state. And an instant load drop followed by a gradual stress recovery accompanies each cracking as the crack occurs and opens. Kabele's model can capture the sequential crack formation and load fluctuations that are characteristic of the multiple-cracking process. Cai [10] developed a statistical tensile stress–strain model of multiple cracking by considering the cracks, which originate from matrix flaws with a size distribution, to be activated at different stress levels.

Numerical methods, such as the finite element method, have been widely employed to analyse the mechanical behaviour of materials and have been demonstrated to be efficient approaches. However, very few numerical studies were conducted to clarify the tensile behaviour of ECC, and this might be due to the numerical difficulties in modelling the crack in cementitious materials [11]. Spagnoli [12] analysed the tensile behaviour of ECC by finite element method using a two-dimensional triangular lattice model. The cracking behaviour was incorporated in the material model, which was assumed to be perfectly elastic up to a first cracking stress followed by the post-cracking behaviour governed by the matrix bridging and fibre bridging. Kabele [13] simulated the tensile behaviour of ECC by means of stochastic finite element method with spatial variation of material properties. The individual cracks were modelled using the crack band approach, and the