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A micromechanical lattice model to describe the fracture behaviour of engineered cementitious composites

Andrea Spagnoli *

Department of Civil-Environmental Engineering and Architecture, University of Parma, Viale Usberti 181/A, 43100 Parma, Italy

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ABSTRACT

Engineered cementitious composites (also called pseudo-ductile cementitious composites or strain-hardening cement-based composites), a special class of high performance fiber-reinforced cementitious composites, exhibit a tensile strain-hardening response with a superior ductility (which is the result of the development of multiple stable micro-cracks bridged by fibers) in comparison to normal concrete or other fiber-reinforced concretes. In the present paper, the fracture propagation in engineered cementitious composites (ECC) under tensile loading is analysed using a two-dimensional lattice model. A regular triangular lattice model (formed by pin-joined truss elements) accounting for the actual multiphase structure (at the meso-scale level) of the material is developed, and an automatic image processing procedure for phase detection is adopted. The trusses are assumed to have a linear elastic behavior in compression, whereas in tension a linear elastic behavior up to a first cracking stress is followed by a linear piecewise post-cracking curve with softening branches. Some numerical results related to ECC tensile specimens are presented along with those of a standard fiber-reinforced cementitious composite and of a plain concrete for comparison.

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1. Introduction

Engineered cementitious composites (ECC), a special class of high performance fiber-reinforced cementitious composites, have been developed to achieve specific composite performances which can be designed on the basis of the micromechanics of the material [1,2]. Under tensile loading, in contrast to normal concrete where a single unstable crack develops, an important characteristic of ECC is the development of multiple stable micro-cracks bridged by fibers. Consequently, tensile stress–strain curves of ECC exhibit a strain-hardening response with a superior ductility (ultimate strain up to 8%, with a certain degree of scattering), which is several hundred times that of normal concrete [3] (see Fig. 1). It has experimentally been observed that the tensile ductility of ECC is influenced by the number of stable micro-cracks developing before failure. A maximum ductility is reached for a so-called saturated cracking of the material (crack spacing in the saturated condition is directly correlated with fiber length, and crack width is of the order of a hundredth of a millimeter). Due to their peculiar tensile behaviour, ECC are also named pseudo-ductile cementitious composites (e.g. see Ref. [4]) or strain-hardening cement-based composites (e.g. see Ref. [5]).

The multiple micro-cracking behavior of ECC is strongly dependent on the fiber crack bridging law, in relation to the so-called steady-state condition for crack propagation [6], and on the degree of heterogeneity in the material, in relation to the condition for crack initiation. Typically, crack initiation sites in ECC material are at material flaws, which are in the majority of cases voids (bubbles of entrapped air). Consequently, crack initiation behavior is influenced by the size and spatial distribution (which are both random in nature) of voids in the material [7,8].

Under a given remote stress σ, the steady-state (SS) crack opening displacement w (note that SS cracks are characterized by a flat profile [6]) obtained from the adopted $\sigma-w$ crack bridging curve due to fibers. The condition for SS cracking is [6]

$$\sigma w - \int_0^w \sigma(w)\mathrm{d}w = G_f \qquad (1)$$

where G_f is the fracture energy of the matrix. Since the left hand side of Eq. (1) attains a maximum when $\sigma = \sigma_0$ (σ_0 = peak stress of the fiber crack bridging law) and $w = w_0$ (w_0 = crack opening displacement at the peak stress of the fiber crack bridging law), the condition for SS cracking is guaranteed when the left hand side of Eq. (1) written for $\sigma = \sigma_0$ and $w = w_0$ is greater than G_f.

* Fax: +39 0521 905924.
E-mail address: spagnoli@unipr.it.

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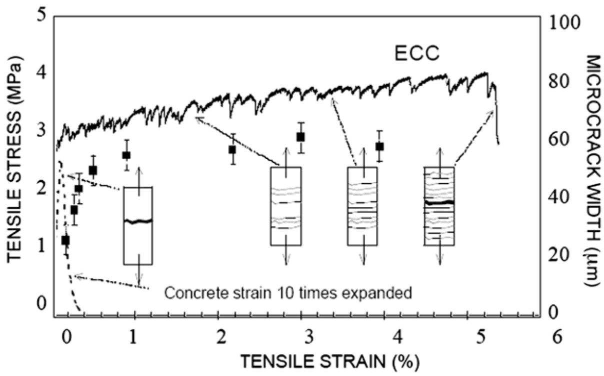

Fig. 1. A typical tensile stress–strain curve of ECC [2].

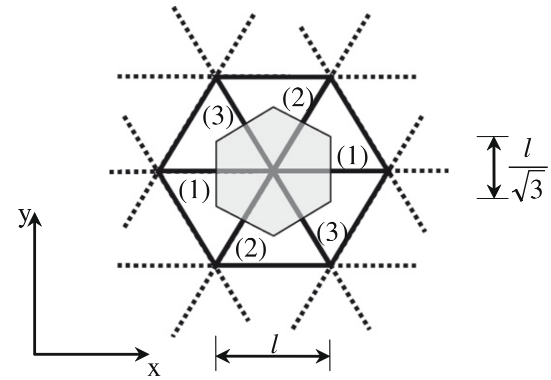

Fig. 2. The unit cell of a regular triangular lattice.

Some theoretical models are available in the literature to describe the tensile behaviour of ECC (e.g. see [9–11]). However, the detail links between material microstructure and composite performance requires further clarification. In Ref. [11] for instance, a simple micromechanical model is proposed to predict the overall tensile stress–strain curves of ECC. The material is treated as a chain of reference volume elements where each element contains a material flaw. Conditions for crack initiation at the flaw surface and for steady-state crack propagation within the reference volume element are defined. The model takes into account the randomness in size and in spatial distribution of material flaws.

Following the early so-called framework method of Hrennikoff [12] to simulate elasticity problems, the lattice models have been developed to analyse concrete fracture [13–15]. Accordingly the continuum model of the material is substituted by an array of discrete elements forming a truss or a frame structure; the multiphase characteristic of the material is simulated by assigning different mechanical properties to the truss/beam elements of the lattice model.

In the present paper, the fracture propagation in ECC under tensile loading is analysed using a two-dimensional lattice model (in Ref. [16], a similar version of such a model was used to investigate fatigue damage in concrete). A regular triangular lattice model (formed by pin-joined truss elements) accounting for the actual multiphase structure (at the meso-scale level) of the material is developed, and an automatic image processing procedure for phase detection is adopted. The trusses are assumed to have a linear elastic behavior in compression, whereas in tension a linear elastic behavior up to a first cracking stress is followed by a linear piecewise post-cracking curve with softening branches. Some numerical results related to ECC tensile specimens are presented along with those of a standard fiber-reinforced cementitious composite (FRCC) and of a plain concrete (PC) for comparison.

2. Description of the lattice model

2.1. General features

A two-dimensional lattice is adopted to discretize the continuum model of the material. A regular triangular lattice (having hexagonal unit cells) with truss (spring) elements is used. The length l of the truss elements dictates the level of the discretization (Fig. 2).

For the modeling of material heterogeneities (at the desired micro-/meso-scale level), different mechanical properties are assigned to the lattice elements to describe the different components (e.g. coarse aggregate, sand, mortar matrix, air bubble) of the material (which in general can be treated as an n-phased composite material). This requires to identify the regions occupied by these components (see the procedure below). Note that in the present case of a regular lattice, the randomness in the mechanical properties of the components can be described in principle by adopting, for each component, appropriate probability distributions for the mechanical properties of the lattice elements. However, we should bear in mind that, in contrast with a lattice model having a random geometry, some influence of the regular lattice on the resulting crack patterns has been observed [6].

The proposed model is run through the finite element code ABAQUS using the UMAT subroutine for implementing the stress–strain curve of the truss elements. Tensile load is applied under displacement control following a step-by-step procedure.

2.2. Elastic behavior

The Young modulus of the truss elements in the lattice model determines the stiffness of the continuum discretized with the lattice. The relationship between the Young modulus of the truss ($\bar{E}$) and that of the continuum (E) can be obtained by equating the elastic strain energy of the continuum occupying an hexagonal unit cell (having unit thickness) with that of the lattice occupying the same region (Fig. 2) [17], namely

$$\bar{E} = \frac{\sqrt{3}l}{2A}\, E \tag{2}$$

where A is the cross-sectional area of the truss elements. From now onwards we adopt the following notation: a bar above the symbol means that the quantity is related to truss elements of the lattice model, whereas the plain symbol means that the quantity is related to the continuum model. The adopted lattice of truss elements, in contrast with that of beam elements, is computationally less expensive (2 degrees of freedom per node instead of 3 are present), but we underline that it has the limitation of enforcing a Poisson ratio of the continuum equal to 1/3 [13]. Note that a regular triangular lattice with spatially homogeneous properties produces an overall isotropic behavior.

To switch from continuum to lattice, and hence to be able, for instance, to describe the stress–strain curve of the truss elements on the basis of that of the continuum (see below), a transformation rule for stresses has to be adopted. We consider here a plane stress field acting in the continuum (having the 3 components σ_x, σ_y, τ_{xy} in the xy frame). Assuming that the lattice unit cell is small enough by size to be regarded as embedded in a uniform strain field, we can write in a compact form (using Einstein summation rule) [17]

$$\bar{\sigma}^{(t)} = \bar{E}\; n_i^{(t)}\; n_j^{(t)}\; \varepsilon_{ij} \tag{3}$$

where the index t = 1,2,3 identifies the truss orientation with respect to the xy frame (Fig. 2), the indexes i,j = 1,2 identify the coordinate axes (1 is for x-axis, 2 for y-axis) so that $\varepsilon_{11} = \varepsilon_x$, $\varepsilon_{22} = \varepsilon_y$,

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