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Cracking behaviour of fibre-reinforced cementitious composites: A comparison between a continuous and a discrete computational approach

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ABSTRACT

In the present paper, the mechanical behaviour of fibre-reinforced brittle-matrix composites, with emphasis to cementitious composites, is examined by adopting both a discontinuous-like FE approach and a lattice model. The main phenomena involved, such as crack formation and propagation, crack fibre bridging, fibre debonding, fibre breaking, are taken into account. The basic assumptions and theoretical background of such approaches are outlined, and some experimental data related to plain and fibre-reinforced concrete specimens under Mode I and Mode I + II loading are analysed. The comparison of the numerical simulation results shows that the lattice model allows us a very detailed description of the fracture pattern, whereas the discontinuous FE approach mainly gives us only global information in terms of both crack path and stress–strain response curve. Nevertheless, the FE approach is computationally convenient and a useful tool for studying problems which do not require a detailed description of the fracture process.

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1. Introduction

As is well-known, brittle or quasi-brittle materials suffer from several drawbacks, such as low tensile strength and low fracture and fatigue resistance, and poor wear resistance and durability under repeated loading. Since ancient ages, it has been observed that the above shortcomings can be reduced by adding fibres to the (matrix) material so as to obtain the desired mechanical properties of the fibre-reinforced composite (FRC) materials which are often economical and competitive in comparison to more technologically advanced materials. The above advantages have produced an increasing interest in the computational simulation of such a class of materials when designing composite structures.

Since FRC materials are multiphase in nature, the mechanical characteristics of the different phases as well as their interactions must be taken into account in order to correctly describe their effective behaviour. Phenomena such as matrix cracking, fibre crack bridging effects on the matrix material, fibre debonding, and fibre breaking have to be modelled. For design purposes, the knowledge of the macroscopic mechanical behaviour of FRC materials generally allows us to assess the in-service safety level of structural components. In order to examine such materials, various approaches can be used, such as micromechanical models (physically-based approach [1–3]), and homogenisation models (mathematically-based approach [4,5]).

Due to low fracture toughness of brittle materials, crack propagation up to failure can easily occur even if the fibre phase has a beneficial effect in limiting such a phenomenon. From a mathematical point of view, cracking corresponds to a severe strain localisation phenomenon which is not easily represented by numerical models: computational instabilities, divergence or non-uniqueness of the solution due to the discontinuous displacement field, which develops in narrow highly

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strained zones, can take place. Several models to solve this class of mechanical problems can be found in the literature: classical smeared crack approaches (which are affected by a strong mesh-dependence [6]), specific strategies based on the description of the evolving cracked geometry, such as remeshing or mesh adaptivity [7,8], finite element enrichment approaches [9–12], interface element approaches [13,14], meshless methods [15,16], and discontinuous formulations [17–24]. Discrete models, such as the well-known lattice model [25–27], can also be employed to solve such problems.

When the fracture process occurs in a fibre-reinforced material, the description of the phase-interaction behaviour as well as bridging effects produced by the reinforcing phase must be taken into account. As a matter of fact, even if each component behaves in a linear elastic manner, the composite material can show a non-linear mechanical behaviour due to the imperfect bonds between the constituents, leading to fibre debonding or breaking.

In the present paper, two different mechanical models are compared:

(i) a continuous model based both on a fracture energy approach for the brittle matrix [28] that simulates the cohesive crack behaviour through an appropriate stress field relaxation and on a micromechanical approach to examine the macroscopic fibre-reinforcing effects (for both random and unidirectional fibre distribution) [29];
(ii) a micromechanical discrete lattice model [27,30] that can be used to simulate heterogeneous materials and multiphase composites such as fibre-reinforced ones.

The basic assumptions and theoretical background of such approaches are firstly outlined and discussed and, finally, experimental data related to both plain and fibre-reinforced cementitious composites under Mode I or Mode I + II monotonic loading are analysed. The results provided by the two approaches are compared and some conclusions are drawn.

2. Fracture simulation in brittle or quasi-brittle materials

In this Section, the main features of the two theoretical models being compared are reviewed. Details of such models can be found in Refs. [28] and [27,30] for the continuous model and the discrete lattice model, respectively.

2.1. Continuum approach to fracture: a plasticity-like FE model

A crack process zone in a continuum material can mathematically be represented as a high strain localisation occurring in a very narrow region. Let us assume the existence of a discontinuity of the displacement field along the line S, contained in a solid which occupies the region Ω (Fig. 1).

The discontinuous displacement field can be expressed as follows [24]:

$$\boldsymbol{\delta}(\mathbf{x}) = \bar{\boldsymbol{\delta}}(\mathbf{x}) + H(\mathbf{x}) \cdot [[\boldsymbol{\delta}(\mathbf{x})]] = \bar{\boldsymbol{\delta}}(\mathbf{x}) + \underbrace{H(\mathbf{x}) \cdot \mathbf{w}(\mathbf{x})}_{\boldsymbol{\delta}_d(\mathbf{x})} \tag{1}$$

that is, $\boldsymbol{\delta}(\mathbf{x})$ is the sum of its continuous part, $\bar{\boldsymbol{\delta}}(\mathbf{x})$, and the discontinuous one, $\boldsymbol{\delta}_d(\mathbf{x}) = H(\mathbf{x}) \cdot [[\boldsymbol{\delta}(\mathbf{x})]] = H(\mathbf{x}) \cdot \mathbf{w}(\mathbf{x})$, with $H(\mathbf{x})$ being the Heaviside jump function placed across the crack line, i.e. $H(\mathbf{x}) = 0$ if $\mathbf{x} \in \Omega^-$, $H(\mathbf{x}) = 1$ if $\mathbf{x} \in \Omega^+$.

The displacement jump vector across the line S, $[[\boldsymbol{\delta}(\mathbf{x})]]$, coincides with the displacement discontinuity vector $\mathbf{w}(\mathbf{x})$, i.e. $[[\boldsymbol{\delta}(\mathbf{x})]] = \mathbf{w}(\mathbf{x})$, and such a vector can be written as follows: $\mathbf{w}(\mathbf{x}) = \mathbf{u}(\mathbf{x}) + \mathbf{v}(\mathbf{x}) = \mathbf{i}u(\mathbf{x}) + \mathbf{j}v(\mathbf{x})$, where the versors $\mathbf{i}$ and $\mathbf{j}$ identify the normal and tangential jump displacement components, respectively (Fig. 2).

In the following the above relationships are considered referred to a FE by using the subscript c for the related quantities.

The mechanical behaviour of a cracked body can conveniently be described by a cohesive-friction law for the cracked zone and by an elastic or an elastic–plastic law for the uncracked (continuous) region. According to the cohesive crack model [31], the crack faces are assumed to transmit a non-zero stress whose value $\sigma_c(u_c)$ can be represented by a decreasing function of the relative displacement, u_c, normal to the crack face. In particular, such a stress is here assumed to be described by a decreasing exponential continuous law [28]:

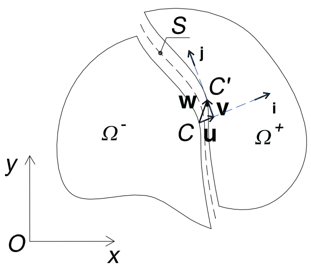

Fig. 1. Discontinuous displacement field along the line S in a 2-D solid. Definition of the versors **i** and **j** at point C on S.

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