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Numerical simulation of fracture of concrete at different loading rates by using the cohesive crack model

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ABSTRACT

This paper presents an implementation of the Cohesive Crack Model using the Strong Discontinuity Approach technique to simulate the fracture of the concrete and other quasi-brittle materials at different strain rates. Since one of the principal applications of this model is to simulate the fracture at high strain rates, it has been programmed as a user subroutine in the commercial explicit finite element solver LS-DYNA. For the validation of the model, in addition to studying the sensitivity to element size, it has been compared with a collection of experimental results, both in quasi-static and dynamic regimes. The results prove the ability of the model to accurately reproduce different parameters, such as load-displacement curves, crack trajectories or fracture mechanisms.

1. Introduction

Important efforts have been devoted in recent years to developing robust models capable of modeling the fracture of concrete and other quasi-brittle materials when subjected to loads of different strain rates. Among the different approaches for modeling the fracture of concrete, the Cohesive Zone Model or Cohesive Crack Model (CCM), initially proposed by the seminal works of Dugdale [1] and Barenblatt [2] and successfully introduced for concrete by Hillerborg and co-workers [3], is considered nowadays the most reliable methodology for addressing the simulation of fracture of concrete pieces [4]. Besides the simulation of fracture of plain concrete, its use has been also extended to several applications related with concrete, such as steel corrosion [5,6], splitting tests [7], and different materials, like fiber reinforced concrete [8,9], aluminum [10], rocks [11], gray cast iron [12] and even explosive propellants [13].

Up to the early 1990s, in spite of its capability for providing accurate predictions of the structural behavior of concrete specimens, some of the main drawbacks of the CCM were the need (i) to know the crack trajectory in advance for its implementation [14,15], (ii) to implement complex remeshing techniques in those cases where such crack trajectory was not known in advance [16,17] and (iii) to insert multiple interface elements in the element boundaries in order to allow the crack to propagate as a result of the calculation [18]. During the 1990s, different finite element techniques emerged to overcome this drawback, such as the generalized finite element method (GFEM) [19], the extended finite element method (XFEM) [20] and the strong discontinuity approach (SDA) [21]. These techniques, also known as embedded discontinuities, allow us to insert the crack through the finite elements, being the technique thoroughly described in [22–24]. The crack trajectory is obtained as a result of the simulation, thus making the use of the CCM possible in cases of nontrivial crack trajectories, even with relatively simple meshes.

But crack path prediction is not the only benefit of these techniques. Since the crack is inserted inside the elements, all parameters accessible at the element level are available for the crack. This fact allows for making the CCM influenced by many different variables if required, such as the stress triaxiality [12] or the strain rate, as in the case of the simulations presented in this work. Moreover, when the SDA is implemented by means of single integration points, the equilibrium equations can be solved at the material level [25,26], enhancing the possibilities of this technique even more since most commercial finite element codes allow the user to implement his own created material models. This makes it possible to combine the CCM with some of the features offered by commercial finite element codes, such as impact modelling, blast modelling, heat transfer, etc.

Given that the formulation of the CCM is based on the so-called *softening curve*, which relates stresses across the crack with crack opening displacements, the most consistent way to approach dynamic loading effects seems to be making the softening curve dependent on the crack opening velocity [27]. However, most experimental data about the effect of dynamic loadings on the different parameters of the

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Nomenclature

Acronyms

CCM	Cohesive Crack Model
DIF	Dynamic Increase Factor
FOI	Swedish Defence Agency
GFEM	generalized finite element method
SDA	strong discontinuity approach
XFEM	extended finite element method

Latin symbols

$\mathbf{1}$	unity second order tensor
A^+	part of the element that contains the solitary nodes
A^-	part of the element that does not contain the solitary nodes
$\mathbf{b}^+$	vector that defines the contribution of the crack opening vector to the strain field
$\mathbf{D}$	cauchy elastic moduli fourth order tensor
f( )	softening curve function
f_{ct}	concrete tensile strength
f_{td}	concrete tensile strength under high strain rates
f_{ts}	concrete tensile strength under static strain
G_F	specific fracture energy
$\mathbf{I}$	fourth order identity tensor
$\mathbf{N}$	normal vector to the fracture surface
$N_\alpha(\mathbf{x})$	shape function associated with node α
$\mathbf{T}$	traction vector between crack borders
$\mathbf{u}^+$	displacement field vector for A^+ region
$\mathbf{u}^-$	displacement field vector for A^- region
$\mathbf{u}_\alpha$	displacements vector of node α
$\mathbf{W}$	crack opening vector
$\widetilde{W}$	normalized crack opening parameter

Greek symbols

$\dot{\varepsilon}$	strain rate
$\dot{\varepsilon}_0$	threshold of static strain rate
$\varepsilon^{\mathbf{a}}$	apparent strain tensor
$\varepsilon^{\mathbf{c}}$	continuum strain tensor
λ	Lamé elastic constants
μ	Lamé elastic constants

softening curve, such as the tensile strength or the specific fracture energy, characterize the loading velocity through the strain rate in the continuum [28] and not through the crack opening velocity (since this latter parameter is extremely difficult to measure). For this reason and as already discussed in the previous paragraph, CCM implementations based on the SDA like the one used in this paper are especially well suited for implementing dynamic effects via the strain rate calculated in the continuum.

Focusing on the strain rate effect on the mechanical properties of concrete, most studies that can be found in the literature are based on the measurement of the *Dynamic Increase Factor* (DIF) as a function of the strain rate. The DIF is the ratio between a given material property under high strain rate and under static conditions. Several studies can be found in the literature about the DIF at different strain rates for the compressive strength and for the tensile strength. An extent compilation of DIFs for concrete can be found in [28]. However, the number of references that address the characterization of the DIF for the specific fracture energy is considerably lower.

This paper presents a constitutive model for modeling the fracture of concrete and other quasi-brittle materials under both static and dynamic loadings. When compared with other publications with similar approach, the main contributions of this paper are: (i) 3D simulations with hexahedral single-integration-point elements are used (in contrast with Sancho et al. [25,26]), (ii) simulation of existing quasi-static experimental results and (iii) an increased number of highly dynamic experimental results simulated, finding a good match in both terms of cracking pattern and failure mode.

The constitutive model presented is based on the combination of the CCM with the SDA, so it is possible to take into account the strain rate effect on the softening curve of concrete in an easy manner. The model has been programmed in a commercial finite element code [29] as a material user subroutine.

The remainder of the paper is organized as follows. The second section is devoted to summarizing the basis of fracture mechanics of concrete from the perspective of the CCM, as well as the effect of the strain rates in the mechanical properties of concrete. In the third section, the constitutive model is presented, along with the main details about its implementation. In the fourth section, the model is validated, first by discarding possible mesh dependency and then, by confronting the numerical predictions achieved by the model with a series of quasi-static and dynamic tests taken from the literature. Finally, the fifth section presents a summary and conclusions from this research.

2. Fracture behavior of concrete under tensile stresses

2.1. The cohesive crack model

The response of concrete under tension can be roughly considered as linear elastic under pure tension loading (mode I) until it reaches its tensile strength. When this occurs, damage appears in the material and the stresses that it can withstand are progressively reduced, as depicted in Fig. 1a. This phenomenon can be simulated through the CCM [3], according to which damage is assumed to concentrate in a discontinuity surface (crack) that is governed by the so-called softening curve

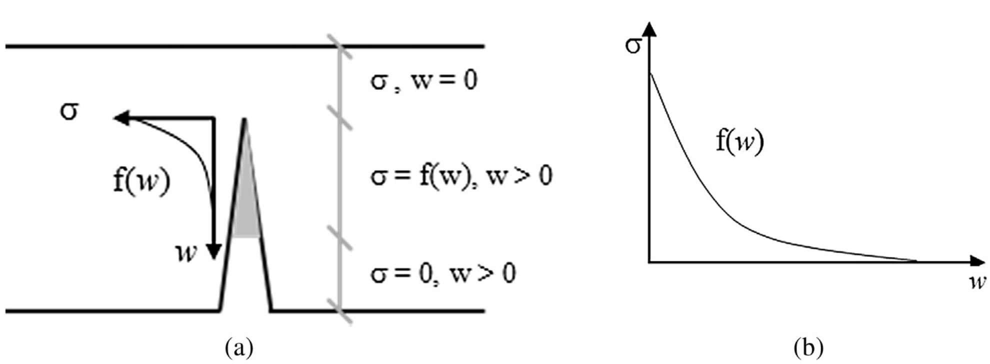

Fig. 1. (a) Fracture of concrete under tensile stresses. (b) Softening curve.