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A coupled constitutive model for fracture in plain concrete based on continuum theory with non-local softening and eXtended Finite Element Method

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ABSTRACT

The paper presents a constitutive model for concrete which combines a continuous and discontinuous fracture description. In a continuum regime, two different constitutive laws were used. First, a plasticity model with a Rankine failure criterion and an associated flow rule was used. Second, a constitutive law based on isotropic damage mechanics was formulated. In order to capture the width of a localized zone and to obtain mesh-independent results, both models were equipped with a characteristic length of micro-structure by applying a non-local theory of an integral format. In order to describe a macro-crack as a displacement jump along/across a localized zone, the eXtended Finite Element Method (XFEM) was used. A transition algorithm between a non-local continuum model and XFEM was formulated. The implementation details of a coupled approach were given. The performance of two coupled models were numerically analysed based on several 2D benchmarks with a dominating mode-I (e.g. uniaxial tension and bending) and under mixed-mode conditions. The numerical results were compared with our experimental ones. The advantages of a continuous–discontinuous coupling in describing crack patterns were outlined.

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1. Introduction

Fracture is the salient feature of concrete-like materials. It is responsible for both strength and stiffness reductions and precedes the structure failure. At the beginning, a thin zone composed of diffused micro-cracks is formed, called a fracture process zone (FPZ) or a localized zone [1]. Later, during further deformation, a distinct discrete macro-crack emerges. An adequate description of fracture in numerical FE calculations (composed of localized zones and macro-cracks) is extremely important to obtain physically realistic outcomes [2].

Within continuum mechanics, there exist two main approaches to describe cracks. The first one describes them in a smeared sense as strain localized zones of micro-cracks with a certain finite width. The material behaviour may be described using e.g. enhanced elasto-plastic, damage mechanics or smeared crack and coupled constitutive laws [2]. These formulations include material softening and have to be equipped with a characteristic length of micro-structure to preserve the well-posedness of BVPs and the mesh-insensitivity of FE results and to properly capture the width, inclination and spacing of localized zones. A characteristic length can be included by means of e.g. non-local, gradient and micro-polar theories. As an alternative, displacement jumps (discontinuities) along cracks may be introduced while keeping the remaining region as a continuous one. The oldest solutions used interface elements which were defined along finite element edges. The modern ones allow for considering displacement jumps in the interior of finite elements using embedded discontinuities or XFEM (eXtended Finite Element Method) [3,4], the latter based on a concept of the partition of unity. A smeared approach is more appropriate when describing a micro-crack formation process while a discontinuous one allows for a more realistic simulation of a discrete macro-crack propagation. The application of a continuum description at the fracture onset provides automatically a algorithm to determine directions of the smeared crack growth. It also updates the set of dominant active cracks (e.g. their direction) if necessary. Such a modification usually cannot be achieved with XFEM. In contrast, the regularized continuum often fails to properly simulate the final deformation stage with almost zero stress conditions. Usually, one approach is solely used to simulate a fracture process in concrete during the entire deformation process [4]. A combination of a continuous and discontinuous approach makes it possible to realistically capture all stages of concrete fracture occurring in experiments [5].

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One of the first coupled continuous–discontinuous crack descriptions was formulated by Jirásek and Zimmerman [6]. They tried to remove the stress locking observed in simulations with both smeared and conventional embedded crack models. In order to avoid this pathological behaviour, a delayed embedded crack model (DEC) was used in which a transition from a smeared crack approach into an embedded displacement discontinuity formulation occurred at a certain degradation stage. As a regularization technique with respect to the load–displacement diagram, a crack band approach was used in a continuum regime. A softening curve in a discrete regime was tuned to ensure a smooth and energy conserving transition. Moreover, in order to eliminate the observed mesh-induced directional bias, they postulated a coupling of an isotropic damage model enhanced by integral non-local theory with embedded cracks. Wells et al. [7] combined the traction-free XFEM with a viscoplastic constitutive law with softening. The regularization of a boundary value problem at high loading velocities was assured by a visco-plastic constitutive model by Perzyna [8]. Simone et al. [9] proposed a numerical model with a transition from an implicit gradient-damage model into XFEM. The transition point was assumed at the fully damaged state, so again traction-free discontinuities were being inserted in a discrete regime. Comi et al. [10] formulated a constitutive law based on a coupling of an integral non-local damage model with XFEM using cohesive cracks. They analysed carefully the transition process and used their model to simulate mode-I problems. Cazes et al. [11] developed a thermodynamically motivated algorithm to construct a cohesive law equivalent to a differential non-local model. Seabra et al. [12] formulated a model for ductile fracture which a combined isotropic continuum damage law enhanced by a non-local integral formulation with macro-cracks defined by XFEM. These macro-cracks were inserted at the final failure stage, so solely traction-free discontinuities were considered. Cuvilliez et al. [13] used an implicit gradient model together with cohesive interface elements to simulate the behaviour of quasi-brittle materials. Recently, Tamayo-Mas and Rodriguez-Ferran [14] presented a coupling between a gradient enhanced model based on smoothed displacements and XFEM with cohesive tractions. All models described above assumed a transition process at the material point at a specified time moment. The second group of coupled formulations assumed a diffuse nature of this phenomenon. Moonen at el. [15] formulated a general continuous–discontinuous framework based on a 'time-continuity' concept introduced by Papoulia et al. [16]. It allowed for a gradual transition from a continuous to discrete crack description. Benvenuti et al. [17] formulated the REXFEM (the regularized XFEM) approach to simulate a transition point from a continuous to discontinuous displacement. They replaced a standard Heaviside jump function by a continuous regularized Heaviside function with a parameter called a regularization length. It allowed for simulating localized zones of a finite width. They also proposed a new integration technique when calculating the stiffness matrix of finite elements. REXFEM was later used by Benvenuti [18] and Benvenuti and Tralli [19] to capture a smooth transition from a local continuum damage model to cohesive discontinuous cracks.

In all above papers isotropic damage constitutive laws were used only (elasto-plastic laws were not employed). Specimens under tensile dominated (mode I) loading were solely simulated under 2D conditions (uniaxial tension, three-point bending or wedge splitting test). Thus the mixed-mode failure modes were not investigated. No convergence analyses and detailed numerical performances of algorithms used have been carried out which are particularly important when switching from a smeared description to discontinuity for large tractions (far from a traction-free state).

The main aim of our research group is to formulate a reliable coupled constitutive model for concrete under monotonic and cyclic loading which links a continuous and discontinuous fracture description defined within continuum mechanics. In a continuous phase, an elasto-plastic-damage constitutive model with non-local softening will be used [20,21]. In turn, a discontinuous displacement jump will be described by XFEM [4]. This paper presents a coupled quasi-static constitutive model for numerical simulations of two-dimensional (2D) plain concrete under quasi-static monotonic loading (thus the stiffness recovery was not needed to be taken into account). Tensile dominated loading was considered only. Branching and crossing of cracks were not taken into account. In the continuous phase, two different constitutive laws were assumed: the elasto-plastic model with a Rankine criterion or isotropic damage model with non-local softening. In the discontinuous phase, XFEM was used. The proposed model was implemented into the commercial FE code Abaqus/Standard [22]. Several benchmark simulations were performed under a dominated mode-I (e.g. uniaxial tension and bending) and mixed-mode conditions (shear-tension) in order to assess the numerical robustness and physical validity of the model. Attention was laid on a smooth transition from plasticity/damage with non-local softening to XFEM with respect to oscillations emerging on load–displacement and stress–strain curves. The transition point between a non-local model and XFEM was determined with the help of the Digital Image Correlation (DIC) technique during three-point bending experiments on notched concrete beams [21].

As compared to other coupled models, the innovative points are: a) numerical analyses of mixed-failure modes for concrete (in the literature mainly the mode I was studied), b) a comparison of numerical results with experiments on concrete beams with respect to displacement and strain evolutions in a fractured zone, c) an improved transition algorithm with respect to existing ones dealing with a continuous–discontinuous transition in order to avoid unwanted oscillations on load–displacement curves and d) a careful study of transition algorithms for 2 different continuum laws (elasto-plastic and damage) with non-local softening and XFEM.

The paper is organized as follows. In Section 2, two continuum constitutive laws enriched by an integral non-local theory are presented. The general information about the Extended Finite Element Method (XFEM) with a description of a discrete cohesive law and a crack propagation algorithm is given in Section 3. The formulation of a transition phase from a continuous to discontinuous approach is described in Section 4. Section 5 includes the details of the implementation and other numerical issues. The results of numerical tests are analysed in detail in Section 6. The final conclusions are listed in Section 7.

2. Smeared crack constitutive laws

2.1. Elasto-plasticity

An elasto-plastic model was defined within a standard plasticity theory. In a tensile regime the classical Rankine criterion was used [2,23,24]. The yield function f was:

$$F = f - \sigma_t(\kappa) = \max\{\sigma_1, \sigma_2, \sigma_3\} - \sigma_t(\kappa), \tag{1}$$

where σ_1, σ_2 and σ_3 are the principal stresses, σ_t is the tensile yield stress and κ is the hardening/softening parameter (equal to the maximum principal plastic strain ε_1^p in uniaxial cases). An associated flow rule $f=g$ was assumed. A linear or an exponential curve was chosen to describe softening under tension:

$$\sigma_t(\kappa) = \max\left\{0, f_t\left(1 - \frac{\kappa}{\kappa_u}\right)\right\} \text{ or } \sigma_t(\kappa) = f_t \exp\left(-\frac{\kappa}{\kappa_u}\right), \tag{2}$$

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