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Research Paper

Influence of stress induced microcracks on the tensile fracture behavior of rocks

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ABSTRACT

The study characterizes the influence of preferentially oriented microcracks on the tensile fracture behavior of rocks by means of a discrete modeling approach. A series of numerical experiments is performed so as to systematically evaluate the emergent properties of media containing microcracks swarms with predefined intensities and orientations. Emphasis is put on the apparent Young's modulus, tensile strength and fracture toughness. Microcracks swarms reduce the strength of materials, affect their overall brittleness and induce anisotropic behavior. They also directly influence the initiation and propagation of mode I fractures which can deviate from their expected path as a result of branching.

1. Introduction

Knowledge of the strength and deformability of fractured rocks is important for design, construction and stability evaluation of slopes, foundations and underground excavations in either civil, mining or petroleum engineering. At large scales, fractures control the strength and deformation properties of natural and engineering rock structures [1–3]. At a smaller scale, it is well known that microcracks affect both the hydraulic and mechanical properties of rocks [4–8] and thus have direct consequences on the stability of structures [9]. Due to their formation conditions and to the stress states they were submitted to, rocks generally exhibit microcracks. These microcracks are often preferentially oriented because they are related to the rock fabric itself as, for example, in sedimentary or metamorphic rocks, but also because they form as a result of stress perturbations related to either natural or anthropogenic processes as detailed exhaustively in [10–12] (Fig. 1).

Microcracks (also referred to as microfractures in the literature) generally form as mode I (opening) fractures in locations where the minimum principal stress exceeds the local tensile strength of the material and are thus preferentially oriented along the maximum principal stress direction. Microcracks hence provide critical information on the growth and development of fault zones, the evolution of regional stress fields as well as on the earthquake cycle [11]. Obviously, depending on their intensity, these microcracks may affect the propagation of fractures and might thus have non-negligible impacts on the fracturing processes developing in rock masses. Indeed, growth and propagation of tension and shear fractures in rocks result from the nucleation and coalescence of microcracks within the fracture process zone [14–16]. Fracture propagation occurs through branching mechanisms or "step-path" failure mechanisms taking place at the grain scale which, in the case of pre-cracked material, is most likely influenced by the amount as well as by the orientation of natural or mechanically induced microcracks.

Nonetheless, although the importance of microstructures on macroscopic behaviors has been recognized for decades now [17], relatively few experiments have systematically evaluated the influence of pre-existing preferentially oriented microcracks on the fracture behavior of rocks. For instance, Nasseri et al. [18] or Griffiths et al. [19] did characterize the role of thermally induced microcracking on both the strength and deformation properties of rock but only Nasseri et al. [20] actually highlighted the consequences of preferentially oriented microcracks on the propagation of fractures. Of course, numerous analytical works proposed to estimate effective properties of cracked or damaged materials [21,22,6,23]. However, despite the obvious elegance of analytical methods for calculating macroscopic properties, difficulties arise when it comes to the description of discrete mechanisms at stake, *e.g.*, in fracture propagation problems. In this context, numerical methods provide more flexibility as they can take into account more refined mechanical behaviors as well as rather complex geometric characteristics for the discontinuities. Numerous computational methods have been proposed to study the mechanical behavior of fractured media. On one side of the spectrum, continuum numerical

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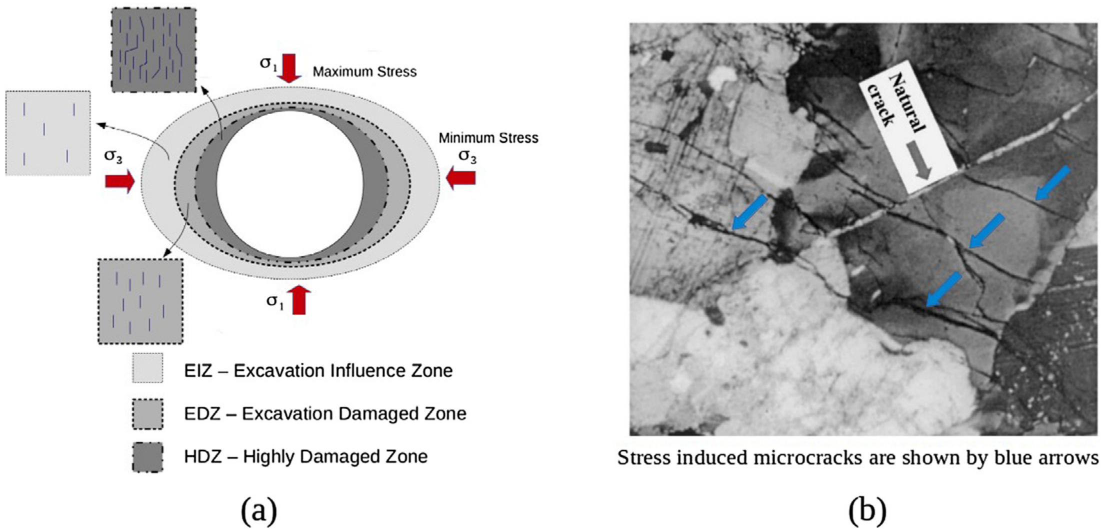

Fig. 1. Preferentially oriented microcracks in rocks: (a) at the engineering scale in an excavation damaged zone (EDZ), (b) at the grain scale in a granite (from [13]).

methods such as the finite element method (FEM), the extended finite element method (XFEM) or the boundary element method (BEM) use criterion generally based on the stress intensity factors (SIF) to simulate fracture initiation and propagation. On the other side of the spectrum, discontinuum methods like bonded particle models (BPMs) or lattice based methods (LMs) propagate cracks as a result of interparticle or element breakages according to the definition of their strength (*e.g.*, their tensile strength). In such models, the propagation of fracture results from the nucleation, interaction and coalescence of microcracks and does not require specific numerical treatments contrary to most continuum approaches. Furthermore, discrete models such as BPMs are appealing since they constitute pertinent analogs to rock materials which present inherent discrete microstructures and provide an explicit framework to test hypotheses about how the microstructure affects the macroscopic behavior of material as proposed, for instance, by Schöpfer et al. [24] or Hamdi et al. [25].

The focus of this work being toward understanding how stress induced microcracks affect the mechanical properties of rocks, a comprehensive study is proposed based on a series of simulations performed on synthetic rock samples containing pre-existing microcracks. In Section 2, we provide a brief description of the BPM utilized for the study and describe the strategy used to include microcracks swarms of different intensities and orientations in the numerical specimens. In Section 3, the uniaxial tensile behavior of both intact and microcracked media is assessed and discussed. In Section 4, the initiation and propagation of mode I fracture is investigated considering, here again, both intact and microcracked media. Finally, conclusions are given in Section 5.

2. Methodology

To investigate the influence of microcracks on the tensile fracture behavior of rocks we utilized the BPM implemented in the open source software YADE Open DEM [26]. As for any classical DEM, the numerical algorithm consists of two steps. In the first step, the interaction forces taking place between the particles constituting the medium are calculated following pre-defined force-displacement laws. In the second step, the acceleration of each particle is computed by applying Newton's second law of motion and their position updated by an explicit time domain integration scheme. This process is repeated iteratively until the end of the simulation.

The formulation of the BPM used in the present study is introduced in Section 2.1. In Section 2.2, we describe the strategy proposed to introduce pre-existing microcracks swarms into the numerical medium.

2.1. Model formulation

The rock material is simulated as an assembly of bonded spherical particles. Even though the model is substantially similar to other BPM (e.g. [27] or [28]), a major difference lies in the consideration of near neighbor interactions through a controlled interaction range. This specific feature provides the possibility to adjust the degree of interlocking of the constitutive particles forming the numerical medium and to reproduce characteristic features of rock like materials [29]. In particular, by increasing the number of bonds per particle, high values of the compressive to tensile strength ratio as well as non linear failure envelopes can be simulated. Practically, the definition of an interaction range coefficient enables to define bonds between particles that are not in strict geometric contact with one another but still in the neighboring zone. Given a previously generated particle assembly, interparticle bonds are formed between pairs of particles for which the following equation is fullfilled:

$$D_{AB}^0 \leqslant \gamma_{int}(R_A + R_B) \tag{1}$$

with R_A and R_B the radii of the two particles A and B, D_{AB}^0 the initial distance between the two centroids of A and B, and $\gamma_{int} \geqslant 1$ the interaction range coefficient. Following such concept, first proposed in [30], the average number of bonds per particle, N_b, can be increased by increasing γ_{int}. The approach provides a relatively simple yet effective alternative to the use of non spherical particles [31] or dedicated formulations proposed for instance by [32] or [33] to enhance particle interlocking.

In addition to this microstructural feature, the behavior of the system is defined through the normal and shear forces developing between each pair of interacting particles. D_{AB} being the current value of the distance between the two centroids, the normal force F_n is computed from the normal relative displacement $u_n = D_{AB}^0 - D_{AB}$ (u_n increases when spheres get closer to each other) such as:

$$F_n = k_n u_n \tag{2}$$

with k_n computed as:

$$k_n = 2Y\frac{R_A R_B}{R_A + R_B} \tag{3}$$

where R_A and R_B are the radii of the particles and Y is an equivalent elastic modulus (in Pa).

In compression, F_n is not restricted and can increase indefinitely. In tension, F_n can increase up to a threshold value F_n^{max} defined as:

$$F_n^{max} = tA_{int} \tag{4}$$