



Micromechanics of wing crack propagation for different flaw properties

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ARTICLE INFO

Article history:

Received 1 June 2015

Received in revised form 27 November 2015

Accepted 29 December 2015

Available online 7 January 2016

Keywords:

Rock

Discrete Element Method

Mixed mode fracture

ABSTRACT

The Discrete Element Method is used to study crack propagation in intact rock from pre-existing flaws of different natures. Damage mechanisms occurring during open and closed cracks propagation are analyzed at the local scale using an innovative micromechanical investigation. Different micromechanisms are captured, due to the development of either tensile or deviatoric states of stress in the vicinity of the flaw, which are shown to be dependent on the flaw properties. In turn, crack propagation patterns, as strength, are greatly affected by the mechanical and geometrical characteristics of the initial flaw.

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1. Introduction

Rock failure occurs after little plastic deformation under unconfined conditions. Such brittle failure involves catastrophic crack propagation that results from stress concentration around flaws of different natures. These flaws may result from rock genesis, e.g. joints between rock minerals, or loading history, e.g. cracks. Among the numerous possible configurations leading to fracture generation and growth, the focus is set here on a classical configuration where a rock sample is submitted to an unconfined compressive loading in presence of a unique flaw (see Fig. 1). This corresponds to mode I+II loading, and pioneering experiments based on this configuration were undertaken mainly on model materials (gypsum, PMMA, glass, etc.) as presented in [1–3]. These authors observed what is now classically denoted as *wing* or *primary cracks* and *secondary cracks*.

Wing cracks are localized crack patterns propagating along the most compressive stress direction from the flaw tips. Secondary cracks are located near the flaw tips, forming after the wing cracks and extending in a more restrained and diffuse manner compared to the latters (see e.g. [2,4]). Generally, a tensile nature is associated to wing cracks, whereas secondary cracks, sometimes denoted as *shear cracks*, would arise from a shear mechanism [5,6,4]. However, some authors may state that these secondary cracks appear through the coalescence of local tensile cracks oriented along a different direction than the wing cracks [7,8].

Wing and secondary cracks have been observed with distinct shapes in model materials [1,3,9,4], fragile polymers [10–12] or marble [8]. Their occurrence might be less remarkable in other rock types such as e.g. granite [12]. Nonetheless, wing and secondary cracks are now commonly used by geomechanicians to describe crack propagation and coalescence in rocks [5,8,13].

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Nomenclature

DE	discrete element
DEM	Discrete Element Method
SJM	smooth joint model
UCS	uniaxial compressive strength
UTS	uniaxial tensile strength
c	cohesive strength parameter of the DE model
D_{AB}^0	initial distance between DEs A and B
D_{AB}	current distance between DEs A and B
D, D'	mean diameters of DE samples
E	energy released during bond failure within the DE model
K_n^j	normal stiffness parameter for DE interaction obeying the SJM
K_t^j	shear stiffness parameter for DE interaction obeying the SJM
P	tangential stiffness parameter of the DE model
\mathbf{s}^p	deviatoric part of the particle stress tensor
t	tensile strength parameter of the DE model
u	normal relative displacement across a discontinuity
u_n	relative normal displacement between DEs
Y	normal stiffness parameter of the DE model
α	damping coefficient of the DE model
γ	tangential relative displacement along a discontinuity
γ_{int}	near neighbor interaction parameter
ϕ	contact friction angle for DE interaction obeying the SJM
φ	contact friction angle for classical DE interaction
ψ	contact dilatancy angle for DE interaction obeying the SJM
σ	nominal stress during uniaxial compression
σ^p	particle stress tensor
σ_I^p	greatest eigenvalue of the particle stress tensor (most compressive stress)
σ_{III}^p	smallest eigenvalue of the particle stress tensor (most tensile stress)
θ	flaw inclination

Because of their consequence on the overall behavior of rock and other brittle materials, numerous models have been proposed to study crack propagation. Analytical derivations have been led, generally at the cost of elasticity hypothesis [14–16]. More complex mechanical behaviors can be handled more easily using continuous numerical modelings, such as in [17]. Nevertheless, propagating cracks are difficult to describe with continuous numerical modelings; though this can still be done using meshless methods such as XFEM [18].

On the other hand, discrete multi-scale models describe efficiently by nature both crack propagation and complex mechanical behavior. The inherent discrete structure of rock involving a cohesive assembly of minerals as in granite, or grains as in sandstone, is one reason to use such discrete models. Furthermore, the Discrete Element Method for instance (DEM, [19]) has proven to be an efficient modeling approach for crack propagation analysis in brittle materials [20–24], including rock [25]. For this reason, many recent works rely on the DEM to study damage in rock, in order to reproduce experimental results such as acoustic emissions [26,27] or constitutive behavior [28,29]. Crack propagation from an open flaw has been studied with DEM, mainly in 2D [30,12,31]. In the regular lattice model of [30], wing cracks could be generated, with a limited kink. The damage patterns obtained in [12,31] were less marked: this may arise from the heterogeneous strength parameters in these models, which might be related to the differences obtained experimentally for different materials.

One can note that less studies consider crack propagation from closed flaws. Experimentally, it is difficult to generate closed flaws with controlled properties [9], but some results suggest similar crack propagation patterns from open or closed flaws [9,6,4]. Closed flaws were simulated in DEM in 2D [32] and in 3D [33], with, however, contradictory conclusions regarding the numerical requirements for wing crack simulations. This will be discussed in Section 5.2, considering different approaches to model closed flaws. As it will be emphasized in the paper, modeling closed flaws with DEM may be biased due to the spherical shape of the discrete particles if the formulation is not upgraded.

Aiming to study crack propagation in rock with various flaw properties, our objective is twofold. First, we aim to propose an approach that is valid for either open or closed planar flaws. Second, we seek to get micro-mechanical insights on the damage mechanisms associated to wing and secondary cracks.

First, the DEM model used to simulate the rock matrix is presented in Section 2. The model relies on previous developments [29], and its limitations are discussed. The micro-mechanical tools are also introduced. Section 3 discusses how closed flaws are simulated in the DEM model. In Section 4, crack propagation is studied considering the case of open flaws,

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