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Research Paper

Influence of crack surface friction on crack initiation and propagation: A numerical investigation based on extended finite element method

Yousheng Xie *, Ping Cao, Jie Liu, Liwei Dong

School of Resources and Safety Engineering, Central South University, Changsha 410083, China

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ABSTRACT

Rock strengths are directly influenced by the open or closed flaws widely distributed in rock masses. Extensive studies have been conducted on the propagations of open flaws in rocks. However, few concerns are paid on the propagation of closed flaws, the influence of the surface friction on the initiation and propagation of closed flaws should be investigated systematically. In present article, the crack initiation and propagation in rock like material subjected to compressive loads have been investigated. The effects of crack surface friction on crack initiation and propagation have been quantified with the help from extended finite element method which is efficient and accurate. Based on the analysis on stress distribution and propagation patterns, following results are obtained: Firstly, minor effects are exerted by crack surface friction on the stress distribution around the flaws when the flaws inclination angle is 30° and 45°. However, as the inclination angle increases to 60°, the effects are much more significant. Secondly, as the inclination angle ranges from 30° to 60°, the most favorable angle for crack propagation is 45°. Thirdly, the initiation location and angle of the wing cracks will not be influenced by the frictions. However, the propagation length will be greatly influenced by the friction and the inclination angle.

1. Introduction

The mechanical characteristics of the rocks containing joints, faults and micro fissures are hard to be investigated by applying mechanical analysis based on continuum solid mechanics [1]. However, the accurate recognition of the rock fracture of fissured rocks is significant to mining and underground space engineering. Extensive experimental and numerical studies have been conducted to investigate the initiation and propagation of pre-existing flaws in rock-like materials subjected to compressive loads [2–14].

In previous studies, two kinds of cracks named wing cracks and secondary cracks (quasi-coplanar secondary crack and oblique secondary crack) are proposed (Fig. 1) [4,7–9,16,15]. Wing cracks which are resulted from tensile stresses emanate from the tips of the flaw, and propagate along a curvilinear path that eventually aligns with the loading direction. Secondary cracks which are resulted from shear stress emanate from the tips of the flaw and propagate along parallel or perpendicular to the flaw, while the propagation patterns of secondary cracks are frequently observed. The mixed fracture mode (mode I tensile and mode II shear) is considered in previous studies, however, most of pre-existing flaws are open in above studies, the effects of the friction between crack surfaces are not investigated. As everyone knows, the rock mass contains not only the open flaws, but also the open flaws (Fig. 2). The close and contact of the crack surfaces are widely distributed in rock mass, so, it appears to be more reasonable to take the effects of static and sliding friction into consideration when investigating the propagation of these closed cracks.

In the past 2 decades, innovative, effective and accurate numerical methods for rock facture mechanics have been developed, and extensive achievements have been obtained. The typical numerical methods are the displacement discontinuity method (DDM) [17–19], the numerical manifold method (NMM) [20–28], the discontinuous deformation analysis (DDA) [29–31], the mesh free methods(EFG, SHP) [32], the discrete element method (DEM) [33–35] and the general particle dynamics (GPD) [14]. The results obtained from above methods agree well with the results from experimental studies, however, few concerns are paid on the contacting relations between closed crack surfaces. To investigate the propagation process of the closed cracks precisely, the closed flaws with surface friction should be adopted.

Analytical studies on the influence of crack surface friction on crack initiation and propagation have also been conducted by Steif [36], Horii and Nemat-Nasser [37], Ashby and Hallam [38] and

* Corresponding author. Tel.: +86 15074990272.
E-mail address: yousheng_xie@163.com (Y. Xie).

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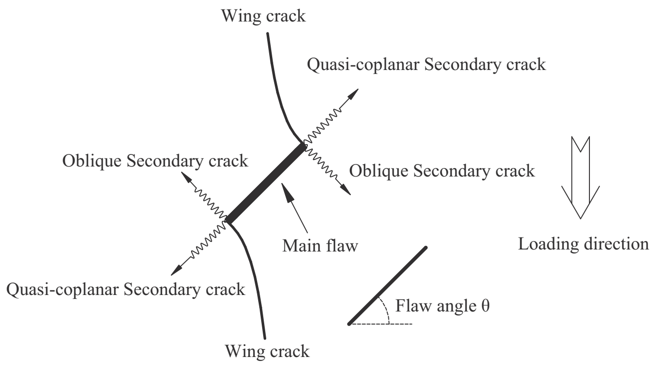

Fig. 1. Crack types observed in pre-cracked specimens of rock materials under compression [4].

Baud et al. [39]. Wong and Chau [5] investigated the pattern of crack coalescence and strength of a sandstone-like material containing two parallel inclined frictional cracks under uniaxial compression. Two sets of laboratory tests on specimens containing open or closed flaws show that the propagation patterns are close in specimens with open or closed flaws, however, higher initiation and propagation stresses are observed in specimens containing closed flaws, since part of the stresses are counteracted by surface frictions in latter specimens [8,9]. Similar conclusions are obtained by Sharafisafa and Nazem [16] investigations based on the extended finite element methods and discrete element methods. Results mentioned above are significant. However, the friction between crack surfaces which is not quantified needs more detailed investigations.

In present article, based on the effective and accurate extended finite element method and the introduced crack initiation conditions and damage criterion, a numerical model has been established to investigate the propagation of closed cracks. Detailed analysis has been conducted to investigate the effects of frictions between crack surfaces on the initiation and propagation of the pre-existing flaws in rock-like material under compression.

2. Brief introduction to extended finite element method (X-FEM)

The first effort for developing X-FEM can be traced back to 1999 when Belytschko and Black [40] presented a minimal remeshing finite element method for crack propagation. They added discontinuous enrichment functions based on a local partition of unit (PUM) to the finite element approximation to account for the presence of the crack. The displacement approximation of the method is composed of continuous and discontinuous displacement approaching [41,42]. The continuous displacements are derived from the traditional FEM, while the discontinuous ones are obtained from the specific enrichment functions.

2.1. Displacement method

As shown in Fig. 3 that a pre-crack is observed in the rock-like material, Ω. The displacement which is composed of continuous and discontinuous displacements can be written as:

$$u = u_{\mathrm{cont}} + u_{\mathrm{disc}} \tag{1}$$

where u_{cont} and u_{disc} are the continuous and discontinuous displacements respectively; Γ_c denotes the crack boundary.

Based on traditional FEM, u_{cont} can be written as:

$$u_{\mathrm{cont}} = \sum_{i \in N^s} N_i u_i \tag{2}$$

where N^s are the Gauss integral point in the computation area, N_i are shape functions of the nodes, and u_i are the displacements of the nodes.

The discontinuous displacement can be written as:

$$u_{\mathrm{disc}} = \sum_{i \in N^*} M_i a_i \tag{3}$$

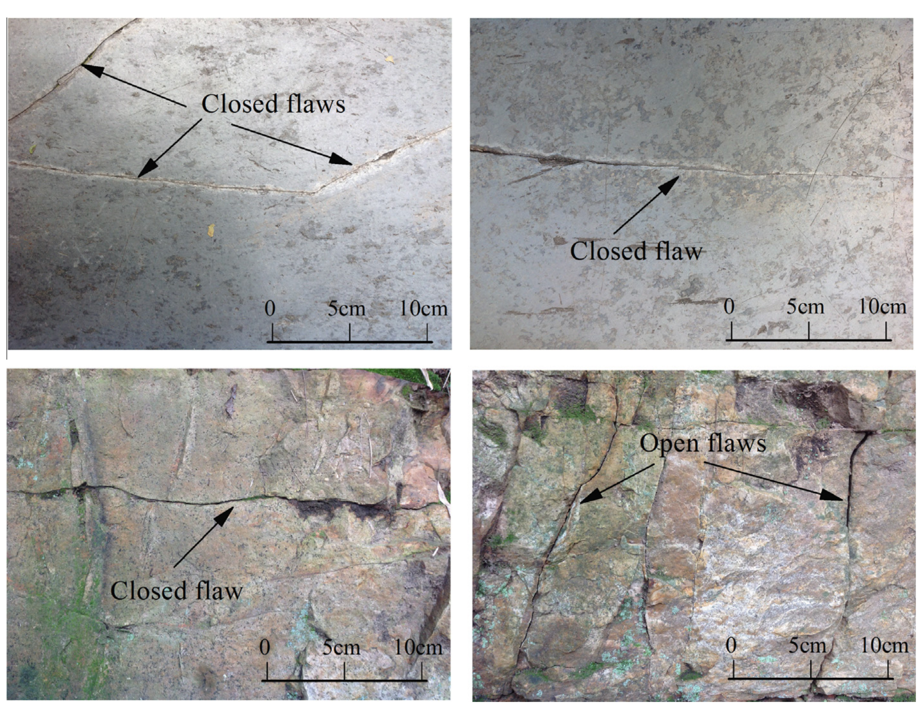

Fig. 2. Open flaws and closed flaws in rock masses.