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Original Research Article

Mechanical behavior of an opening in a jointed rock-like specimen under uniaxial loading: Experimental studies and particle mechanics approach

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ABSTRACT

Generally, in many cases of rock engineering, the openings often constructed in rock-mass containing non-persistent joints. However, comparing with the previous works, few studies investigate the failure or damage due to the crack propagation and coalescence around an opening. Based on the uniaxial compression tests and particle flow code (PFC) the interaction effect of opening and joints on the crack coalescence behavior around an opening are investigated in this study. From the view of experimental and numerical results, strength parameters are mainly effected by joints (inclination and distance). Specifically, the uniaxial compressive strength of jointed specimen (UCS_J) and elastic modulus of jointed specimen (E_J) of specimens decrease for $0^\circ \leq \alpha \leq 45^\circ$ and increase for $\alpha > 45^\circ$. UCS_J and E_J increases with increasing joint distance (d) for all joint inclination angel (α) values, with the highest and lowest strengths obtained for d = 50 mm and d = 20 mm, respectively. The opening has a great influence on the failure mode of jointed specimen. Unlike previous results, in this study, jointed specimens present four new kinds of failure modes: Mode-I (horizontally symmetrical splitting failure); Mode-II (stepped failure at opening sides); Mode-III (failure through a plane); Mode-IV (mixed failure). The strength parameters and failure modes in the numerically simulated and experimental results are in good agreement, and the results are expected to be useful in predicting the stability of an opening in a non-persistently jointed mass.

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1. Introduction

Rock-mass are typically heterogeneous materials containing defects such as cracks, joints, and pores. The nonlinear deformation behavior of a rock-mass is induced by the propagation and coalescence of cracks and joints under external loads, hence, the mechanical characteristics and failure patterns of the rock-mass are difficult to predict. The

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mechanical behavior of jointed rock-mass is extremely interesting for engineers and scientists. Over the past decades, the failure behaviors of rock or rock-like materials have been extensively investigated and discussed. Previous works have promoted the understanding of the failure characteristics obtained from specimens contain fissures or joints. Substantial experiments have focused on the study of crack initiation and propagation under compressive tests for the specimen with single joint. And the results show that two types of cracks will initiate from the pre-existing fissure, namely, wing and secondary cracks [1–7].

Apart from the single joint or crack, the coalescence mode between parallel or un-parallel cracks has been investigated through experiment or numerical simulation as well [8–12]. Meanwhile, for the parallel cracks, based on the experiment of gypsum specimens, Shen [8] observed three types of linkage between two flaws: tensile coalescence, shear coalescence, and mixed coalescence, and the inclination angle of rock-bridge significantly influenced the coalescence pattern. Bobet and Einstein [9] produced gypsum specimens with two parallel flaws and identified five types of failure pattern. Sagong and Bobet [10] carried out uniaxial compression tests on rock-like specimens with three and 16 flaws, hence, nine types of coalescence mode are observed. The flaw geometry defined by the flaw inclination angle and the ligament angle has an extensive effect on coalescence mode. Furthermore, for the un-parallel cracks, Lee and Jeon [11] investigated the penetration mode between two un-parallel fissures, where the coalescence occurred mainly through the tensile cracks or tensile and shear cracks. Based on parallel bonded-particle models, Zhang et al. [12] studied the crack coalescence between two non-parallel flaws and observed five types of linkage between two flaws: tensile crack linkage, tensile crack linkage with shear coalescence at the tip, shear crack linkage, mixed linkage, and indirect crack linkage.

Moreover, compared with the in situ test and laboratory test, the numerical simulation is an economical and practical method to simulate the failure process of jointed rock-masses. In recent years, many numerical methods have been used to simulate the crack initiation and coalescence in brittle materials. These include the finite element method (FEM) or extended finite element method (XFEM) [13–15], smoothed particle hydrodynamics [16,17], displacement discontinuity analysis (DDA) [18,19], particle flow code (PFC) [20–24]. In the framework of FEM, Tang [13] developed a new numerical code – RFPA2D, which can be used to simulate the failure processes of rock material in geo-mechanical problems. Moes and Belyschko [14] analyzed the growth of arbitrary cohesive cracks by using extended finite element method, and the results show that the proposed approach avoids the evaluation of stresses at the mathematical tip of the crack. In the framework of SPH, Pramanik and Deb [16] developed an efficient methodology to model the behavior of pre-existing multiple intersecting discontinuities in rock material. Based on the DDA, Ning et al. [19] proposed a new methodology to simulate the opening and sliding along pre-existing discontinuities and can also reproduce the major failure mechanisms observed in footwall slope collapses. For the PFC, most of scholars used it to model the failure behavior of jointed specimens, such as un-parallel joints [22], multi-fissures specimens [21,23,24] and ubiquitous-joint brittle rock-like specimens [20]. Overall, the numerical results show good agreement with experimental results.

The previous works have promoted the understanding of crack propagation, coalescence, and failure modes of brittle materials with fissures. Rock-mass are heterogeneous materials containing defects including cracks and pores, especially for the jointed rock-mass around tunnel or underground space. Generally, in many cases of rock engineering, the construction of opening is not suitable in rock mass with fully persistent joints [26]. Instead, the openings often constructed in rock-mass containing non-persistent joints [27]. However, comparing with the previous works, few studies investigate the failure or damage due to the crack propagation and coalescence around an opening. In the loading process, the initiation or development of fractures may be caused by the change of joint geometry (inclination and distance) or the stress around the opening. Pre-existing joints and opening will influence each other. The interaction effect increases the complexity and unpredictability of the mechanical properties. As a consequence, the fracture process and failure characteristics of a jointed rock-mass around an opening will be different from those of a multiple jointed rock-mass. The existence of joints alters the stress distribution pattern around underground openings. This may result in different failure modes of rock-mass around the opening compared with the modes observed in previous studies. In this paper, we combine experiments using rock-like material and PFC2D to investigate the mechanical parameters, rock fracture behaviors around an opening in a rock-mass having many non-persistent joints.

2. Specimen preparation and testing

2.1. *Specimen preparation and test*

Previous works have used numerous kinds of materials to produce rock-like specimens. These include glass [3], gypsum [8–10,27,28], white cement and sand [10,12,20,21,29–31], and Columbia Resin [32]. Given that white cement and sand can produce brittle specimen and that sand can provide the frictional behavior of the modeling material, cement mortar is chosen as the rock-like material for our experiment.

Rock-like specimens are made of white cement, water, and sand. The volume proportions for all the specimens are shown as: V (water):V (white cement):V (silica sand) = 3:3:2. The dimensions (height × width × thickness) of specimens are 200 mm × 150 mm × 30 mm. Pre-existing fissures are created by inserting the mica sheets (0.6-mm thick, 20-mm long) into the fresh cement mortar paste at the location of the fissures. All specimens are kept inside the standard curing box for a fixed number of days (28 days) before being subjected to mechanical testing.

Previous works investigated the influence of joint orientation [1–13,20–33], joint persistence [23,24,29,33] and joint distance [20,23,29,33] on mechanical behavior of jointed rock mass. However, in this study, we focus on the interaction effect of opening and joints and the crack coalescence behavior around an opening. Thus, among the many

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