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Numerical study of failure behaviour of pre-cracked rock specimens under conventional triaxial compression

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ABSTRACT

Macroscopic pre-existing flaws play an important role in evaluating the strength and the failure modes of a heterogeneous rock mass. Crack initiation, propagation and coalescence from macroscopic pre-existing flaws are considered in a 3-D numerical model (RFPA3D) to investigate their effects on the underlying failure modes of rock. A feature of the code RFPA3D is that it can numerically simulate the evolution of cracks in three-dimensional space, as well as the heterogeneity of the rock mass. Three types of flaw geometries were evaluated numerically against experimental results: Type A for intact specimen, and Types B and C for flawed cylindrical specimens with different macroscopic pre-existing flaws, respectively. The effect of confining pressure on the fracture evolution was also considered. Numerical results showed that both the ligament angle and the flaw angle of two pre-existing cracks can affect the uniaxial compressive strength of the specimen and the mechanism of fracture evolution. In addition, both the uniaxial compressive strength and the accumulated acoustic emission increase with increasing heterogeneity.

1. Introduction

Rock is a heterogeneous geo-material, with many pre-existing fractures varying from microscopic cracks to macroscopic joints and even to continental faults. When rock mass is subjected to different types of loading, fractures can initiate and propagate from these pre-existing cracks or pores, and then coalescence into macro-failure of rock. Usually, in uniaxial compression, three basic kinds of failure modes of rock can be observed. They are splitting, spalling, and oblique failure (Germanovich et al., 1994). Splitting and spalling are actually tensile failure, whereas oblique failure appears like shear failure. Certainly, all these failure modes can be observed at the macro scale. However, at the micro scale, the three macro failure modes are the results of interaction between micro-cracks (Griffith, 1924). Micro-cracks can be tensile cracks or shear cracks, depending on the local stress distribution within the rock specimen. In addition, for biaxial loading, the confining pressure can hamper the growth of tensile cracks and thus cause the growth of smaller and more densely distributed pre-existing cracks. This can result in localization and shear fractures in the brittle regime. The interaction of these localised shear fractures can initiate macro-failure of the rock specimen. Healy et al. (2006a, 2006b) provided a micromechanical model to explain how brittle shear fractures can form obliquely to all three remote principal stresses.

Many researchers have studied the mechanism of two-dimensional fracture evolution from pre-existing flaw(s) (Brace and Bombolakis, 1963; Hoek and Bieniawski, 1965; Horii and Nemat-Nasser, 1985, 1986; Ashby and Hallam, 1986; Bobet, 1997, 2000; Bobet and Einstein, 1998; Zhu et al., 1998; Wong and Chau, 1998; Vasarhelyi and Bobet, 2000). Basically, two secondary tensile cracks initiate from both ends of the inclined flaw(s), and propagate in a stable manner towards the major axis of compression. Wong et al. (2001) studied the mechanism of crack interaction in specimens with three parallel flaws, and results showed that the arrangement of the flaws played an important role in the coalescence of cracks. However, most studies on mechanisms of brittle rock fracturing in compression have been limited to cracks in two dimensions. For three-dimensional specimens, tensile cracks or shear cracks occur on 3-D faces, makes the evolution mechanism much more complicated (Yang et al., 2012a,b).

Huang and Wong (2007) carried out a series of uniaxial compressive tests on polymethly methacrylate (PMMA) with pre-existing 3D flaws. Their experimental results showed that

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interaction of distinct cracks could either promote or restrain the evolution of cracks in 3D space. Yang et al. (2008) conducted a series of experimental tests on cylindrical marble specimens with two macroscopic pre-existing flaws. They observed three failure types: a tensile mode, a shear mode, and a mixed mode (which is a combination of the tensile and shear modes). These failure modes depend on the heterogeneity of the marble, the arrangement of macroscopic pre-existing flaws, and the confining pressure. Usually, the confining pressure can restrain the development of shear cracks. However, for laboratory tests, it is difficult to determine the heterogeneity of intact rock in specimens. Due to this inherent heterogeneity and the end-boundary conditions, the resulting stresses within a cylindrical sample are inevitably non-uniform on the micro-scale. As it is difficult to know the stress distribution within a specimen during the loading process, it is not possible to predict the orientation of the initiation of cracks *a priori*.

Numerical models can be used to determine the stress distribution within laboratory specimens, and hence predict and simulate the evolution of cracks. Based on experimental creep tests, a phenomenological model was presented by Kaiser and Morgenstern (1981) to investigate the time-dependent deformation and failure mechanisms of rock masses. Schlangen and Van Mier (1992) were the first to apply lattice models for simulating progressive failure in concrete. Place and Mora (1999) developed a particle-based lattice model to study the physics of rocks and the nonlinear dynamics of earthquake. Shen and Stephansson (1993) developed the displacement discontinuity method, using a modified G-criterion, to numerically simulate the crack propagation and coalescence between two open/closed macroscopic pre-existing flaws. Fanella and Krajcinovic (1988) proposed a micromechanical damage model for concrete subject to compression. The overall non-linear response of the material is attributed solely to the growth of the randomly oriented microcracks which are located on the aggregate-cement paste interfaces. The results generated from this model were in good agreement with the experimentally observed trends, even though a few assumptions were introduced to make the calculation less complex. Blair and Cook (1998) developed a statistical model, which is called non-linear rule-based model, and coupled it with the boundary element method. The effect of microscale heterogeneity on macroscopic deformation was researched using the model. Vasarhelyi and Bobet (2000) reported the displacement discontinuity method, FROCK, and numerically simulated the initiation, propagation and coalescence of cracks between two macroscopic pre-existing flaws under uniaxial compression. Their numerical predictions were in good agreement with their experimental results.

In addition, the discrete fibre-bundle model was provided by Turcotte et al. (2003) to study the brittle failure of a solid. This discrete, microscopic fibre-bundle model can give exactly the same solution for material failure by continuum, macroscopic damage model. A pore crack model was developed by Sammis and Ashby (1986) to investigate the interaction of growing cracks with a spherical pore. This approach to crack-pore interaction is in agreement with observations. Feng et al. (2006) simulated the failure process of heterogeneous rocks successfully by using elastoplastic cellular automata. Based on static fatigue laws, Amitrano and Helmstetter (2006) proposed a numerical model to study the time-dependent damage and deformation of rocks under creep. Using a different approach, RFPA2D was developed to investigate the failure process of rock mass (Tang, 1997; Tang and Kou, 1998; Tang et al., 2001; Wang et al., 2006, 2009, 2011a,b, 2012a,b; Xu et al., 2012; Li et al., 2012a,b,c). In this code, the Weibull distribution function was introduced to describe the heterogeneity of rock mass. This code can be used to simulate the non-linear deformation, stress distribution, initiation and growth of cracks and fractures in heterogeneous materials (Tang and Kou, 1998; Tang et al., 2001; Wang et al., 2012a). Brantut et al. (2013) provided a good review and summary of existing typical models for time-dependent cracking and brittle creep in crustal rocks in details. However, most of these numerical models were limited to 2-D situations and the evolution of cracks in the specimen was not well captured.

In this study, the code RFPA3D, which is an extension of RFPA2D, is applied to investigate the 3D fracturing processes of cylindrical rock specimens with two macroscopic pre-existing flaws. First, the numerical method, RFPA3D, is introduced briefly. Three types of flaw geometries, i.e. Type A for an intact specimen, and Types B and C for flawed cylindrical specimens with different macroscopic pre-existing flaws, are simulated numerically and the results are evaluated against experimental observations. The study also investigates the effect of the confining pressure on the fracture evolution, as well as the effects of both the ligament angle and the flaw angle of pre-existing cracks on the uniaxial compressive strength of a specimen. Finally, the influence of both the heterogeneity index (m) on the uniaxial compressive strength, and the accumulated acoustic emission (AE) on the crack evolution patterns, are considered.

2. Brief description of RFPA3D

In RFPA3D, it is assumed that the domain consists of elements with the same shape and size and that there is no geometric priority in any orientation (Tang, 1997; Wang et al., 2006). The statistical distribution of the elemental mechanical parameters is described by the Weibull distribution function (Weibull, 1951). These elemental mechanical parameters include the uniaxial compressive strength, the elastic modulus and Poisson's ratio. The Weibull distribution function is as follows (Weibull, 1951):

$$W(x) = \frac{m}{x_0}\left(\frac{x}{x_0}\right)^{m-1} \exp\left[-\left(\frac{x}{x_0}\right)^{m}\right] \tag{1}$$

where x is a given mechanical property (such as the strength or elastic modulus); x_0 is a scale parameter; and m is a parameter that defines the shape of the distribution function. In the present study, the parameter m defines the degree of material homogeneity and is thus referred to as the homogeneity index (Tang, 1997). As the homogeneity index increases, the material becomes more homogeneous.

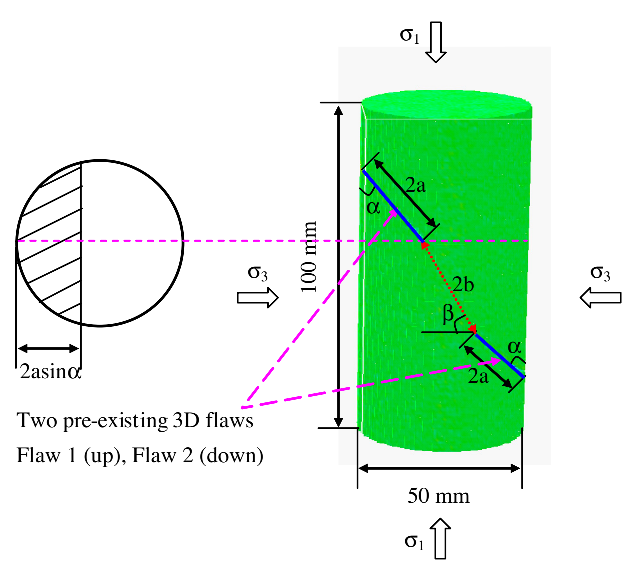

Fig. 1. Numerical model with two pre-existing 3D flaws.