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Numerical study on static and dynamic fracture evolution around rock cavities

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In this paper, a numerical code, RFPA^{2D} (rock failure process analysis), was used to simulate the initiation and propagation of fractures around a pre-existing single cavity and multiple cavities in brittle rocks. Both static and dynamic loads were applied to the rock specimens to investigate the mechanism of fracture evolution around the cavities for different lateral pressure coefficients. In addition, characteristics of acoustic emission (AE) associated with fracture evolution were simulated. Finally, the evolution and interaction of fractures between multiple cavities were investigated with consideration of stress redistribution and transference in compressive and tensile stress fields. The numerically simulated results reproduced primary tensile, remote, and shear crack fractures, which are in agreement with the experimental results. Moreover, numerical results suggested that both compressive and tensile waves could influence the propagation of tensile cracks; in particular, the reflected tensile wave accelerated the propagation of tensile cracks.

1. Introduction

The stability of cavities in the presence of static and dynamic loads has long been the subject of intensive studies in mining and civil engineering. Extensive examinations of fracture evolution around a single pre-existing cavity have been completed (Gay, 1976; Hoek and Brown, 1980; Ewy and Cook, 1990; Carter et al., 1991; Carter, 1992; Ingraffea, 1997). The fracture patterns under increasing uniaxial compression generally consist of primary fractures (T_1), remote fractures (T_2) as well as shear fractures (NS) (see Fig. 1). Primary fractures form at the center of the crown and invert due to the high local tension. Remote cracks form at a remote position from the cavity, while shear fractures develop where high compressive stresses exist (Lajtai and Lajtai, 1975).

Under static or dynamic loads, fractures can initiate from cavities and propagate. Meanwhile, new cracks may be initiated. The damage caused by micro-cracking is the main dissipation process associated with inelastic behavior and failure in brittle rock. In this case, rock failure occurs due to a progressive material degradation, micro-cracks initiate and propagate on a small scale, and then coalesce to form large-scale macroscopic fractures and faults (Souley et al., 2001). To describe this mechanism of crack evolution around cavities, micromechanical fracture models have been proposed based on experimental studies.

Based on continuum damage mechanics, many damage models have been developed to study the dynamic damage evolution of brittle materials with micro-flaws and cavities (Grady and Kipp, 1979; Suaris and Shah, 1985; Taylor et al., 1986; Fahrenthold, 1991; Yang et al., 1996; Yazdchi et al., 1996; Liu and Katsabanis, 1997; Li et al., 2001; Huang et al., 2002). Most of these models were developed by combining the theory of fracture mechanics with a statistic treatment to account for the random distribution of micro-cracks.

Although many numerical methods, including finite element, boundary element, finite difference and discrete element methods do well in simulating the nonlinear behaviors of rock deformation, most of them do not consider the effects of strain rate on the rock strength, and they cannot demonstrate progressive failure due to

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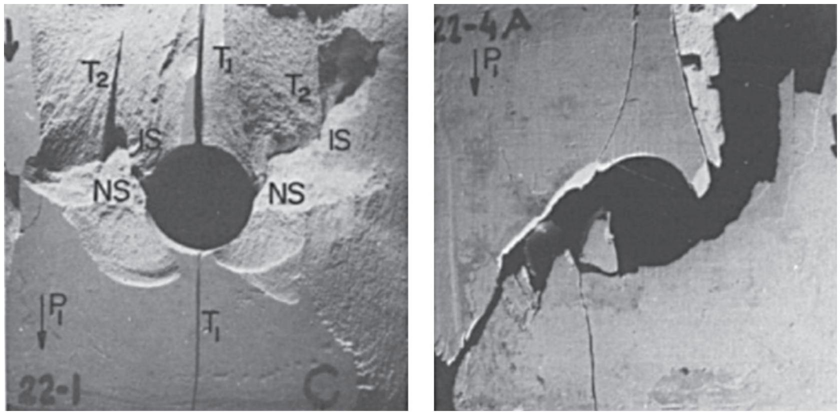

Fig. 1. Fracture pattern of plaster samples (Lajtai and Lajtai, 1975).

rock heterogeneity, which is the primary cause of nonlinear behavior. Therefore, a more reasonable numerical code RFPA^{2D} (rock failure process analysis) was developed (Tang et al., 1993, 2000; Tang, 1997; Tang and Kou, 1998). This code, which considers the effects of strain rate on rock strength, has been successfully applied to studying the dynamic failure process of rock (Chau et al., 2004; Zhu and Tang, 2006; Wang et al., 2011).

It is noted that, although there are some limitations, the laboratory experimental and numerical tests on small scales still have their own advantages. For example, it is easy to control the loading/boundary conditions, and also can monitor more data during the failure process of specimen. In this paper, RFPA^{2D} was used to simulate the evolution of static and dynamic fracture initiation and propagation around pre-existing cavities in brittle rock. Moreover, the characteristics of acoustic emission (AE) associated with the fracture evolution were simulated. Finally, the evolution and interaction of fractures between multiple cavities were investigated by stress redistribution and transference in compressive and tensile stress fields.

2. Brief description of RFPA^{2D}

RFPA^{2D} (Tang, 1997) is a two-dimensional finite element code that simulates fracture and failure processes of quasi-brittle materials such as rocks. To model the failure of rock material (or rock mass), rock medium is assumed to be composed of many mesoscopic rectangle elements of the same size. The material properties of these elements are different and can be specified according to a Weibull distribution. These elements are considered as four-node isoparametric elements in a finite element analysis. Elastic damage mechanics is used to describe the constitutive laws of the meso-scale elements, and the maximum tensile strain criterion and the Mohr–Coulomb criterion are utilized as damage thresholds (Zhu and Tang, 2004).

2.1. Elastic damage constitutive law

The damage mechanics approach is employed to model the mechanical behavior of meso-scale elements. For each element, the material is assumed to be linearly elastic, isotropic and damage-free before loading. Its elastic properties are defined by the elastic modulus and Poisson's ratio. Based on elastic damage mechanics, the strength and stiffness of the element are assumed to degrade gradually as damage progresses. The elastic modulus of the damaged material is given by

$$E = (1-\omega)E_0 \tag{1}$$

where ω represents the damage variable; E and E_0 are the elastic moduli of damaged and undamaged materials, respectively.

The damage variable of the mesoscopic element under uniaxial tension is expressed as (Zhu and Tang, 2004; Wang et al., 2011):

$$\omega = \begin{cases} 0 & (\varepsilon > \varepsilon_{t0}) \\ 1 - \dfrac{f_{tr}}{E_0 \varepsilon} & (\varepsilon_{tu} < \varepsilon \le \varepsilon_{t0}) \\ 1 & (\varepsilon \le \varepsilon_{tu}) \end{cases} \tag{2}$$

where E_0 is the elastic modulus of undamaged material; f_{tr} is the residual tensile strength, which is given as $f_{tr} = \lambda f_{t0} = \lambda E_0 \varepsilon_{t0}$, f_{t0} and λ are the uniaxial tensile strength and residual strength coefficient, respectively; ε_{t0} is the strain at the elastic limit, which can be called the threshold strain; and ε_{tu} is the ultimate tensile strain at which the element is completely damaged. The ultimate tensile strain is defined as $\varepsilon_{tu} = \eta \varepsilon_{t0}$, where η is the ultimate strain coefficient (Zhu and Tang, 2004, 2006). Eq. (2) can be written as (Zhu and Tang, 2004; Wang et al., 2011):

$$\omega = \begin{cases} 0 & (\varepsilon > \varepsilon_{t0}) \\ 1 - \dfrac{\lambda \varepsilon_{t0}}{\varepsilon} & (\varepsilon_{tu} < \varepsilon \le \varepsilon_{t0}) \\ 1 & (\varepsilon \le \varepsilon_{tu}) \end{cases} \tag{3}$$

In addition, it is assumed that damage to mesoscopic elements in multi-axial stress states is also isotropic and elastic (Tang, 1998). The damage to the elements occurs in the tensile mode whenever the equivalent major tensile strain, $\bar{\varepsilon}$, is greater than the threshold strain, ε_{t0}. The equivalent principal strain, $\bar{\varepsilon}$, is defined as follows (Wang et al., 2011):

$$\bar{\varepsilon} = -\sqrt{\langle -\varepsilon_1 \rangle^2 + \langle -\varepsilon_2 \rangle^2 + \langle -\varepsilon_3 \rangle^2} \tag{4}$$

where ε_1, ε_2 andε_3 are three principal strains; and $\langle\cdot\rangle$ is a function defined as follows (Zhu and Tang, 2004):

$$\langle x \rangle = \begin{cases} x & (x \ge 0) \\ 0 & (x < 0) \end{cases} \tag{5}$$

The constitutive law of the element subjected to multi-axial stresses can be easily obtained by substituting the equivalent strain,