ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING 15 (2015) 1085–1097

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

Numerical study on failure behavior of brittle rock specimen containing pre-existing combined flaws under different confining pressure

S.Q. Yang[a,*], T. Xu[b], L. He[c], H.W. Jing[a], S. Wen[a], Q.L. Yu[b]

[a] *State Key Laboratory for Geomechanics and Deep Underground Engineering, School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, PR China*
[b] *Center for Rock Instability & Seismicity Research, Northeastern University, Shenyang 110819, PR China*
[c] *Department of Civil Engineering, Monash University, Melbourne, Victoria 3800, Australia*

ARTICLE INFO

Article history:
Received 6 April 2014
Accepted 26 March 2015
Available online 23 April 2015

Keywords:
Brittle rock
Combined flaws
Numerical simulation
Crack coalescence
AE

ABSTRACT

To understand deeply the fracture mechanism of brittle rock material, the rock specimen containing combined flaws (two square holes and one pre-existing fissure) with seven different fissure angles is carried out the numerical simulation by RFPA^{2D}. Numerically simulated results show a good agreement with the experimental results. The crack coalescence behavior of specimen containing combined flaws under uniaxial compression is summarized, which is closely dependent to fissure angle. The stable propagation of original cracks does not lead to a larger AE event, but the coalescence of new cracks causes a larger AE event. The peak strength of specimen containing combined flaws increases with the confining pressure. According to the linear Mohr–Coulomb criterion, the cohesion and internal friction angle of specimen containing combined flaws are obtained, which is found to take on a distinct nonlinear relation with the fissure angle. The accumulated AE events decreases as the confining pressure increases from 0 to 30 MPa, which results mainly from the restraining of higher confining pressures on the initiation and propagation of tensile cracks at the fissure tips and nearby double squares.

1. Introduction

Rock is a kind of natural geological material, which usually consists of unequal flaws with different shapes (such as holes, fissures, inclusions) [1–7]. With the development of numerical methods, many simulation softwares were adopted to analyze the crack coalescence process of brittle rock material, such as the code ''FROCK'' based on displacement discontinuous method (DDM), 2-D (two-dimensional) particle flow code (PFC), 2-D rock failure process analysis (RFPA^{2D}), boundary element method (BEM) [8–10], cellular automata (CA) [11,12], extended finite element method (X-FEM) [13–15], etc.

Mughieda and Omar [16] investigated the stress distribution of rock containing two fissures by using the finite element code with the name of SAP2000. The simulated results showed that tensile stress was mainly responsible for wing crack initiation while the shear stress was responsible for the

---

[*] *Corresponding author*. Tel.: +86 516 83995678.
E-mail address: yangsqi@hotmail.com (S.Q. Yang).

http://dx.doi.org/10.1016/j.acme.2015.03.005

secondary crack initiation. Vásárhelyi and Bobet [17] adopted FROCK code to model experimental observations on pre-cracked specimens of gypsum. They analyzed mainly the crack initiation stress, the direction and propagation of the new cracks, and type of coalescence in the gypsum containing two open and close fissures. Using PFC^{2D} based on the DEM (Discrete Element Method), Lee and Jeon [18] made a numerical simulation for the crack coalescence characteristics in Hwangdeung granite containing a horizontal fissure and an inclined fissure. Yang et al. [19] carried out a discrete element modeling for the fracture coalescence behavior of red sandstone specimens containing two unparallel fissures under uniaxial compression, which shows a good agreement with the experiment results.

On basis of the maximum tensile stress failure criterion, Chen et al. [10] developed a new BEM procedure to predict the crack initiation direction and the crack propagation path in anisotropic rock discs under mixed mode loading, which found a good agreement between crack initiation angles and propagation paths predicted with the BEM and experimental observations reported by previous researchers on isotropic materials. Using a modified G-criterion and DDM, Shen [8] carried out a numerical simulation for the coalescence observed in the tests, which showed that the numerically predicted path and critical load of coalescence were in good agreement with the experimental results. Feng et al. [12] and Pan et al. [11] developed a numerical elasto-plastic cellular automation (EPCA) 2D and 3D code, which can be used to simulate the initiation, propagation and coalescence of cracks in the failure processes of rock material.

RFPA^{2D} was developed by Northeastern University, China [20,21], which can reproduce many conventional phenomena of rock mechanics in the laboratory [22–24]. Wong et al. [25,26] analyzed the crack growth in brittle rocks containing a single, triple and multiple fissures under uniaxial compression by using RFPA^{2D}, which found that the fissure length, fissure location and stress interaction between the nearby fissures are important factors affecting the crack initiation, propagation and coalescence behaviors. Tang and Kou [24] conducted numerical simulation on rock-like specimens containing three fissures to investigate the failure mechanism and crack coalescence patterns by RFPA^{2D}. The numerical results replicated most of the phenomena observed in actual experiments, such as initiation and growth of wing and secondary cracks, crack coalescence, and the macro-failure of the specimen. The results obtained in the simulations are in good agreement with experiments [23]. Wang et al. [27] simulated a loading-type failure process and acoustic activities around an underground excavation (model tunnel) in brittle rock by RFPA^{2D}, which was in very in very good agreement with the experimental results.

However, in real rock engineering practice, some flaws (such as circular hole, square hole or elliptical hole) all existed, which was very possible to coalesce with the pre-existing fissures under complex stress states. Once the coalescence occurs between the holes and the fissures, rock mass will be able to occur the unstable failure. In the previous studies, the fracture coalescence behaviors of some rock material containing the holes or the fissures have been made some numerical investigations. But less simulations are carried out for real rock specimen containing combined flaws (i.e. the combination of two square holes and one pre-existing fissure), and the fracture coalescence mechanism of rock material containing combined flaws has not almost been understood. Therefore, the main aim of this research is to analyze the strength and deformation behavior of brittle rock specimen containing combined flaws, and to investigate its fracture coalescence process. Moreover, the influence of confining pressure on strength and deformation failure behavior of rock specimen containing combined flaws is also investigated.

2. Numerical model and micro-parameters

Before the numerical simulation is discussed, the numerical model and micro-parameters for brittle rock material will be illustrated in this section. RFPA^{2D} is chosen to simulate the fracture coalescence of brittle rock specimens containing pre-existing combined flaws. The essential features of RFPA^{2D} are described as follows [20–24]. The RFPA^{2D} code can be used to perform the stress analysis for each element by FEM. Using tensorial notation, the mechanical equilibrium equation for the solid is expressed as

$$-\sigma_{ij,j} = F_i, \quad i, j = 1, 2, 3, \tag{1}$$

where σ_{ij} is the stress tensor (Pa) in the solid and F_i the component of the body force (N/m^3). The constitutive equation defines the relation between the total bulk stress components (Pa), σ_{ij} and strain components, ε_{ij}. The stress–strain law is given by

$$\sigma_{ij} = D_{ijkl}\varepsilon_{ij} \quad i, j = 1, 2, 3, \tag{2}$$

where D_{ijkl} is the elasticity tensor (Pa), and is related to the Young's modulus E and Poisson's ratio υ for isotropic elastic media, which is regarded with damage initiation and development. $\varepsilon_{ij} = (U_{i,j} + U_{j,i})/2$ and U_i represents the displacement vector of the solid.

In RFPA^{2D}, the model is discretized into a large number of small elements. Taking into account the heterogeneity of real rock material, element local mechanical microscopic parameters are assumed to follow a Weibull distribution [28], i.e. Eq. (3):

$$P(\theta) = \frac{m}{\theta_0}\left(\frac{\theta}{\theta_0}\right)^{m-1} \exp\left[-\left(\frac{\theta}{\theta_0}\right)^{m}\right] \tag{3}$$

where θ is a random variable, representing strength, elastic modulus, etc. θ_0 is the mean value of element parameters for the whole specimen and m is the shape parameter of distribution function which is referred to as homogeneity index. Fig. 1 shows the influence of the shape parameter m on the distribution function, which indicates that a smaller m means a more heterogeneous rock material and vice versa. However for the same m, the Weibull's randomness indicated that the numerical simulated results of different rock specimens are very approximate, but not identical [29].

An elastic constitutive model with linear behavior is employed for all elements, which have been assigned different strength and elastic modulus according to the heterogeneity of rock material. The elastic constitutive relation for an element under uniaxial compressive stress and tensile stress is