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Numerical Approach to Investigating Pre-existed Cracks in Rocks

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Abstract. Rock failure analysis is an important research in investigating the behavior of rocks, especially its failure process. And a rock sample, which contains pre-existing cracks, is a typical sample to investigate the rock failure behavior which under tension or compression, because almost all the natural materials exist micro-flaws more or less. This mode is closed to the natural material character. By using Rock Failure Process Analysis code, RFPA2D, we present a numerical simulation and similar materials experiment on rock samples with two pre-existing cracks in uniaxial compression were conducted to investigate the initiation, propagation, coalescence of cracks and failure mechanism of rock. Numerical simulations visually reproduce the process of crack initiation, propagation and coalescence in rock, which are well tallied with experiments in laboratory.

Introduction

Failure of rock with pre-existing flaws, such as cracks, pores and other defects is a very important topic in rock mechanics research. A number of studies have been done on crack initiation, propagation and coalescence in solids in the past decades. For example, the works of Ingraffea and Heuze on the limestone [1], Hoek and Bieniawski on glass [2], Petit and Barquins on sandstone [3], etc, are all on pre-existing flaws. More recently, Shen et al. [4], Bobet and Einstein [5, 6], Wong and Chau [7] and Vassarhelyi and Bobet [8] have investigated crack propagation and coalescence in rocklike materials containing two inclined flaws. It is recognized that under the compressive loading, both tensile and shear stress concentrations can develop at pre-existing cracks in rock.

Great process has been achieved on crack initiation, propagation and coalescence in rock; however, the mechanism of mixed crack propagation and coalescence has been a puzzle. To better understand the failure mechanism of rock with pre-existing cracks, a series of numerical analyses and corresponding similar materials simulations were carried out to investigate the behavior of crack propagation and coalescence in rock samples. Our investigation should provide the fundamental understanding of crack propagation, interaction and coalescence in rock with pre-existing cracks under uniaxial compression.

Short Brief Outline of RFPA^{2D}

Numerical simulation is currently a popular and effective method used for modeling deformation behavior of heterogeneous materials before failure, so does it for rock. Even though the process has been made in numerical simulation of failure occurring in rocks [9], there is a lack of satisfactory models, which can simulate the progressive failure in a more visual way, including simulation of the failure process, failure induced seismic events and failure induced stress redistribution.

In the past, most material characterizations had been based on the approximation of representing the rock by one of the classical mathematical models such as elasticity, plasticity and viscoelasticity. This kind of approximation can't capture the complete fracture process of rock as characterized by initiation, propagation and coalescence of micro cracks. The macroscopic features can be explained in terms of the material structures at a low level, i.e. mesoscopic level, at which the heterogeneous material properties should be incorporated in the numerical model. The demand for new tools, which

may contribute to a better understanding of the failure mechanisms of brittle rocks, initiated the development of RFPA^{2D} (Rock Failure Process Analysis code). Details of the RFPA2D code has been described in published literatures [10-11] and so only a brief outline will be given here.

RFPA^{2D} (Rock Failure Process Analysis) is a progressive elastic damage model. There are two features distinguishing RFPA^{2D} from other numerical methods: 1) By introducing heterogeneity of rock properties into the model, the RFPA^{2D} code can simulate nonlinear deformation of a quasi-brittle behavior with an ideal brittle constitutive law for the local material; 2) By introducing a reduction of material parameters after element failure, the RFPA code can simulate strain-softening and discontinuum mechanics problems in a continuum mechanics mode. In RFPA, the heterogeneity of material properties is introduced into the model by assigning the element strengths and elastic modulus as statistically distributed values within the model mesh using a Weibull distribution as defined in Eq. (1).

$$f(\sigma_c) = \frac{m}{\sigma_0}\left(\frac{\sigma_c}{\sigma_0}\right)^{m-1} \exp\left(-\frac{\sigma_c}{\sigma_0}\right)^m \tag{1}$$

where σ_c is the parameter of element (such as strength or elastic modulus), the scale parameter σ_0 is related to the average of element parameter and the parameter m defines the shape of the distribution function. The parameter *m* defines the degree of material homogeneity, is called homogeneity index. According to the definition of Weibull distribution, the value of parameter m must be larger than 1.0. In the past years, the RFPA^{2D} had been successfully used to the numerical simulation of the rock failure and induced seimicity and crack propagation in rock, and the numerical results were well agree with the experimental results.

Numerical Simulation and Experimental Results

Numerical Model and Simulated Results. Many researches have shown that new cracks initiating from pre-existing ones can be classified as wing crack induced by tensile stress and secondary crack induced by shear stress on mechanism. Because resisting tension strength is smaller than resisting compression strength, wing cracks, which are extensive and propagate in the bigger angle direction from pre-existing fracture, always grow from the tip of pre-existing fracture where stress concentrates at first. The outer wing cracks propagate rapidly in general. With the new crack occurring and propagating continuously, stress field modifies by itself, and tensile stress concentration at the tip of the cracks is becoming weak. When the tensile stress is perpendicular to main stress, compressive stress concentration occurs at the tip and cracks will not grow any more along the direction of main compressive stress. But secondary cracks are generally found only when crack approaches to coalescence, and initiate from the tip of crack and propagate stably along pre-existed surface, which is the main cause of coalescence.

In this paper, based on rock-like materials, numerical experiments on rock with two inclined pre-existing parallel cracks are conducted to investigate crack propagation and coalescence in uniaxial compression experiment, A. Bobet and H.H. einsein studied the influence of confining pressure on crack propagation and coalescence characteristics systematically, and the results showed that coalescence mechanism is affected by stress state of crack pronouncedly. After loading the specimen with two pre-existing cracks, stress concentration with different characteristics occurs at the tip of crack and the obvious tensile stress concentration near the direction of main compressive stress in general. With cracks propagating, stress field evolutes at the tip of crack and induces new crack occurrence, then interaction of cracks with different characteristics results in different coalescence mechanism. In this paper, the material parameters for model specimens are *E* (2,6000MPa) and σ_c (2,50Mpa), receptively. Fig. 1 is the material modulus picture, it's a two-dimensional rectangle block,

and the two black color lines are the pre-existing cracks. In this model, different gray degrees of color represent different magnitude of modulus or stress of elements. The load type is compressive loading.

It should be mentioned that, although in meso-scale the specimens are more or less heterogeneous, in macro-scale, however, it is statistically homogeneous since the mechanical property parameters are randomly distributed throughout the whole specimen.

Fig. 2 is the numerical simulation results. It shows the simulated stress and cracks evolvement process. It can be observed from Fig. 2 that stress concentration occurs with load increasing. And the cracks grow along the connection line of tip of the two pre-existing fracture where stress concentrates at first (Fig. 2 [a]), with the load increase, It is noticeable from Fig. 2 that stress concentrations between internal cracks tips are extremely sharp prior to the point of coalescence and the cracks coalesce under the interactions of compressive stress and shear stress in the end. Cracks extend until the two pre-existing cracks connect (Fig. 2 [b]). After that, new cracks occur on the outskirt of the two pre-existing cracks (Fig. 2 [c]), i.e. the secondary cracks occur. These results well agree with the experimental results (Fig. 3).

Fig. 1 Configuration results of numerical

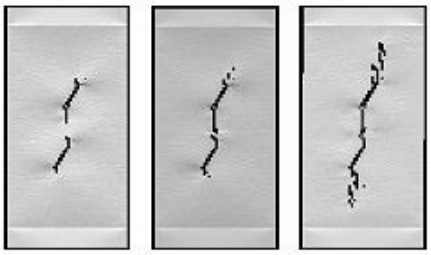

Fig. 2 Numerical simulated results

Experimental Results

Similar materials experiment on rock specimens with pre-existing mixed cracks under compressive loading was carried out in laboratory to investigate the mechanism of crack initiation, propagation coalescence and verify the numerical simulation results. The materials used in the experiment are fine sands, calcium carbonate, gypsum and borax as the numerical simulation model. The materials were mingled at an appropriate mixing ratio to make model specimens with two pre-existing parallel cracks. The similar materials simulated testing results are shown in Fig. 3.

Fig. 3 Experimental results with similar materials

As the same, based on the experimental study, it is also can be seen from the experimental results that two main types of crack were observed: tensile crack and shear crack. In general, it is observed that tensile crack initiates at the inner and outer crack tips, and under this load mode, i.e. uniaxial load, tensile crack always initiates and propagates rapidly in the sharp of a slightly-rough-curve-line and towards the other tip of the pre-existing flaw. It is tally with the numerical simulation.

Although from the experimental results, we can observe the failure pattern, we can't see the failure process, and its stress distribution. Thought numerical simulation using RFPA^{2D} code, we can obtain the failure pattern, failure process, also stress distribution etc.

Discussion and Conclusions

As shown in Fig. 2 and Fig. 3, the mode of crack initiation, propagation and coalescence in numerical simulation is good agreement with that of similar materials simulation in laboratory. The variations of stress field around crack tips and the complete process of crack initiation, propagation and coalescence are both visually duplicated in numerical simulation and similar materials simulation in laboratory. It can be seen from Fig. 2 that stress concentrations occur between cracks tips at the beginning of loading, and with the increase of loading, the stress concentrations at crack tips gradually become sharp enough to lead to the crack propagation and the initiation of branch cracks. The internal cracks between the two preexisting cracks gradually propagate and coalesce in the end under tensile stress. In the meanwhile, the branch cracks also gradually propagate during the coalescence of internal cracks and form serrated cracks. It is noticeable from Fig. 2 that stress concentrations between internal cracks tips are extremely sharp prior to the point of coalescence and the cracks coalesce under the interactions of compressive stress and shear stress in the end. Moreover, the branch cracks initiate from the tips of pre-existing cracks and propagate in a curvilinear path at first and gradually align with the direction of compressive stress, which is known as wing cracks.

In addition, compared with the numerically simulated results, the similar materials simulation shows good agreement with the numerical simulation results stated above, as shown in Fig. 3. As a result, numerical simulation on rock-like materials with pre-existing cracks using RFPA^{2D} is a simple and effective method to investigate the mechanism of rock failure due to the initiation, propagation and coalescence of crack.

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