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Damage and fracture evolution of hydraulic fracturing in compression-shear rock cracks

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ABSTRACT

Compression-shear fractured rock under high pore fluid pressure was studied to determine an appropriate model for describing the Initial Cracking Law and the Evolution Law of the stress intensity factor at the tip of a wing crack. Considering the interaction of wing cracks and the additional stress caused by rock bridge damage, this paper proposes an intensity factor Evolution Equation of multiple rock cracks which combines the action of compression-shear stress and pore fluid pressure. The interaction of multiple wing cracks resulting in rock bridge damage makes the stress intensity factor at the crack tip larger than that of a single wing crack, and wing crack propagation under high pore fluid pressure takes a turn from stable expansion to unstable expansion. Based on the rock fracture mechanics criterion, the damage fracture mechanical models of a compression-shear rock mass are established when the rock bridge happens axial transfixion failure, tension-shear combined failure, or wing crack shear connection failure under the combined action of compression-shear stress and high pore fluid pressure. This theory provides the basis for the quantitative investigation of the hydraulic fracturing process.

1. Introduction

A micro-fracture and its nucleation, expansion, and interaction have a significant effect on the mechanical properties of rock mass; that is, as frictional force is overcome by shear stress induced by far-field stresses on the crack surface, the crack surface would slide over each other, causing stress concentration on the tip of the crack and finally leading to the initiation and splitting propagation of wing crack [1–3]. In addition, these defects existing in rock not only change the mechanical properties of rock masses, but also trigger a serious effect on their permeability. Seepage field and stress field interaction is an important characteristic of rock which cannot be ignored. Pore fluid pressure aggravates the trend of the micro-fracture and the faulty degradation of the fractured rock mass. With the development of rock mechanics engineering, a growing number of cases are being related to pore fluid pressure. Accounting for the seepage field and stress field coupling problem is a crucial step in preventing major project accidents in hydraulic mining and rock engineering. In fact, many engineering crash cases worldwide are considered to be the result of hydraulic pressure [4,5]. Two examples include France Malpasset arch dam had an accident in 1959, and the left bank of Italy Vajiont arch dam occurred large landslide in 1963. Research studies on the action of rock mechanics under pore fluid pressure are gradually becoming problem of interest in the field of geotechnical engineering. Generally, the instability in rock engineering is due to the aggravated geological environment or stress redistribution, which may result in constant creep, propagation and coalescence of cracks in rock masses. When the interpenetrated cracks are formed in rock masses, they may turn into the main channel of groundwater seepage, and the scale, space distribution features and physical mechanical properties play a critical role in the groundwater seepage. In order to conduct further research on rock stress-seepage coupling mechanism, the water–rock coupling effect of the fractured rock masses must be taken into account. Such research will include investigating including the rock mechanical properties, the law and mechanism of seepage evolution during the course of micro-cracks seeding, propagation and coalescence. Moreover, a series of coupling issues related to micro-crack initiation and evolution must also be considered. Some efforts were conducted by scholars to study the hydraulic pressure effect on fracture mechanical properties of rock masses, extensive experiments

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[6,7], theoretical research [8,9] and numerical simulation [10,11] on these subjects were carried out. Up to the present, scholars have setup hundreds of constitutive models that are influenced by the pore fluid and stress field coupling effect of fractured rock under permeable conditions. However, a reasonable model for the evolution law of stress intensity factor at the wing crack tip subjected to hydraulic pressure and far field stresses is still lacking. Moreover, only a few studies explore the damage and fracture evolution mechanism of fractured rock masses under high pore fluid pressure. Adopting the concept of damage to study and analyze the hydraulic properties of fractured rock mass and thereby establishing stress-seepage coupling constitutive relationship of multi-cracks rock masses is rare to be seen.

Fractured rock mass is a complex medium, which frequently encountered in hydraulic and mining and others rock engineering. Hydraulic fracturing has become prominent issue in rock mechanics and a scientific problem in practical engineering that needs to solved. A solution involves the coupling of three processes: (i) the mechanical deformation induced by the fluid pressure on the crack surfaces; (ii) the flow of fluid within the crack; and (iii) the crack propagation. The mechanical state on the crack surface of a fractured rock mass will be changed under high pore fluid pressure. With no pore fluid pressure or low pore fluid pressure, the effective stress at the crack tip is located in a compressive state. Under high pore fluid pressure, the effective stress at the crack tip is in a tensile state, which in turn will cause tension-shear crack to occur on the fractured rock mass [12]. Referring to previous studies and utilizing the rock fracture and damage mechanics criterion, this paper studies the features of gradual fracture and the damage evolution of compression-shear rock cracks under high pore fluid pressure. This investigation is based on the compression-shear crack initiation, wing crack growth, and the wing rock bridge connection law of the fractured rock mass under high pore fluid pressure.

2. Analysis of crack initiation and the propagation of the compression-shear rock crack under high pore fluid pressure

2.1. Crack initiation

Several testing results and theoretical calculations show that compression-shear rock cracks are initiated in the direction approximately parallel to the maximum principal stress, with the expansion classified as type I [13]. The initiation and propagation sketch of wing cracks under high pore fluid pressure is shown in Fig. 1.

The fractured rock mass is under far field stress forces σ_1 and σ_3. The angle between the crack and the vertical stress σ_1 is ψ, and pore fluid pressure p is observed in the crack. Assuming that the rock mass is categorized as brittle, the pore fluid pressure is equal in each direction along the crack. Assuming that the rock crack is open and considering the role of pore fluid pressure, normal stress σ_{ne} and shear stress τ_{ne} are:

$$\sigma_{ne} = \sigma_n - p = (\sigma_1 \sin^2\psi + \sigma_3 \cos^2\psi) - p \tag{1}$$

$$\tau_{ne} = \frac{\sigma_1 - \sigma_3}{2} \sin 2\psi \tag{2}$$

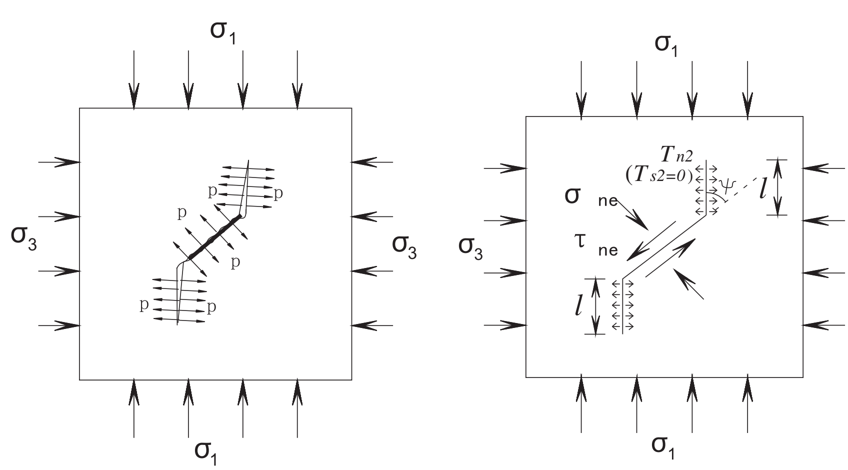
Categorizing crack propagation instability as either a tension-shear combined or a compression-shear combined is determined by the normal stress on the crack surface being either tension or compressive state. As shown in Eq. (1), the shear stress on the crack surface is zero and the crack is in a pure tensile or a pure compressive state when $\psi = 0°$ or $\psi = 90°$. Otherwise, normal stress and shear stress will be produced on the crack surface in other states simultaneously. However, when $\psi = 0°$ or $\psi = 90°$, the crack is either in pure tension or pure compression. It can then be treated as a special state of the tensile-shear damage or a compression-shear damage [14]. Consequently, crack propagation instability is categorized as I–II combined type.

2.2. Analysis of compression-shear crack

When the surrounding rock stress is high and the pore fluid pressure is relatively low, the normal stress on the crack surface is in a compressive state, the crack propagation belongs to the I–II compression-shear type. Then there will generate a friction $\mu\sigma_{ne} + C$ as the shear stress forces the crack to slide, where μ and C are respectively the friction coefficient and cohesion on the crack surface. The shear stress τ_{ne} will also be resistant to this friction. Meanwhile, it may cause part closure of the crack if the crack surface is not smooth. With the introduction of the coefficient β to characterize the connected area against the total area, the pore fluid pressure contribution to the surface becomes βp. Then, the effective shear driving force τ_{eff} and the effective normal stress are given respectively as [15]:

$$\tau_{eff} = (1 - C_v)\frac{\sigma_1 - \sigma_3}{2} \sin 2\psi - \mu\sigma_{ne} - C \tag{3}$$

$$\sigma_{ne} = \sigma_n - \beta p = (1 - C_n)(\sigma_1 \sin^2\psi + \sigma_3 \cos^2\psi) - \beta p \tag{4}$$



(a) The stress state (b) Wing crack propagation

Fig. 1. Sketch of wing cracks seeding and propagation under high pore fluid pressure.