Damage and Fracture Strength Behavior of Jointed Rockmass

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Abstract: The strength of rockmass from two aspects is analyzed. Firstly, the strength of the rockmass is mainly controlled by the critical stress value of rock, and the contribution of joints is to increase the effective stresses of rock and to decrease the damage strength of rockmass according to the macro-damage mechanics of rockmass. Secondly, the strength of rockmass is mainly controlled by the fracture strength of joints. Based on the comprehensive analysis and comparison for the damage strength of rockmass and the fracture strength of joints, a composite damage theory of rockmass may be established.

Key words: damage strength; rockmass; fracture strength; composite damage and fracture strength

1 Introduction

For microscopic or macroscopic voids in rockmass, fracture mechanics is frequently used to explain some relevant experimental or geological phenomena. The assumption of the well-known Griffith theory is that the strength of brittle materials is governed by crack-like flaws and is applied and developed in the strength theory of rock mass. Dey & Wang¹ posed a model of inhomogeneous stress fields and interaction that has been suggested as mechanisms for accompanying rock failure, i.e., splitting under uniaxial load conditions and the suppression of splitting by the application of a few tens to a hundred bars of confining pressure. These mechanisms also indicate how a shear fault may be extended under triaxial conditions by the extension and coalescence of micro-cracks in front of it. Segall² discussed a number of features of the formation and growth of extensional fracture sets. His analysis is consistent with the field observation of crack and the absence of crack branching. Model tests and theoretical studies suggest the growth path of oriented and closed joints and determine the critical strength value in terms of equilibrium conditions on the shear failure surface³⁵⁶. Above mentioned studies account for tensile cracks paralleling to the maximum compression originated under compressive and shear loads and their effects on stable growth of joints. These may explain experimental phenomena and field geology observations to some extent. The principal objective of this paper is to discuss the effects of joints on rockmass strength from two aspects. The first is to consider the influence of joints upon effective stresses of rock, and furthermore to analyze the damage strength of rockmass. The second is to discuss the growth modes of joints under several loading conditions and to analyze the stable and unstable growth processes of joints in order to set up the fracture strength of the joints. Comprehensive analysis and comparison from two aspects would propose a composite damage and fracture strength theory of rockmass.

2 Damage Strength of Rockmass

By trial-to-error method, Hoek and Brown⁵ have derived the relation between principal stresses of rock failure according to their theoretical work and practical experience as follows:

\[
\sigma_1 = \sigma_3 + \left( m \sigma_3 + s \sigma_3^2 \right)^{1/2}
\]

where \(\sigma_1\) and \(\sigma_3\) are major and minor principal stresses respectively at rock failure, \(\sigma_0\) is the uniaxial compressive strength of intrinsic rock, and \(m\) and \(s\) are constants depending on rock properties and the degree of rock failure before stresses reach the values of \(\sigma_1\) and \(\sigma_3\), \(s = 1\) for intrinsic rock and \(s < 1\) for damage rock.

Due to the geometric distributions of joints in rock mass, great changes of rock stresses in rockmass take place. Determining effective stresses of rock, together with equation (1), may give the rock strength in rockmass. By means of macro-damage mechanics of rockmass⁶, the relation between the average volumetric stress \(\bar{\sigma}\) of rockmass and effective stress \(\sigma\) of rock is given as

\[
\bar{\sigma} = \sigma \cdot (I - \Omega)
\]

where \(I\) is unit tensor and \(\Omega\) is damage tensor of rockmass

If there is a set of two-dimensional parallel joints in rockmass, the damage tensor of rock mass is:

\[
\Omega = 2f\sin\theta\cos\theta N/V_i
\]

where \(f\), \(a\), \(l\), \(N\) and \(n\) are, respectively, factors due to...
to the inhomogeneous damage distribution of rock mass, mean half length, mean line space, number and unit normal vector of joints, \( t \) is the thickness of joints in z direction and \( V_L \) is the volume of volumetric element of rock mass.

\[
\Omega = \sum_{i=1}^{s} \Omega_i
\]

where \( \Omega_i \) is the damage tensor of rock mass according to the \( i \)-th of parallel joints obtained by equation (3).

When the closure effect of joints is considered under a compressive stress state, the effective stress tensor of rock is modified as

\[
\sigma = \sigma \cdot (I - \Omega)^{-1} - \sum [c_n \sigma n + c_r r] \cdot (I - \Omega)^{-1}
\]

where \( c_n \) and \( c_r \) are the transmitting rates of normal stress \( \sigma \) and shear stress vector \( r \) on the joints surface respectively.

If average principal volumetric stresses \( \sigma_1 \) and \( \sigma_3 \) are applied in rock mass, the effective stress tensor \( \sigma \) applied in rock may be obtained by equation (2) or (5), then its principal stresses \( \sigma_1 \) and \( \sigma_3 \) are represented by

\[
\sigma_{1,3} = \frac{1}{2} (\sigma_{11} + \sigma_{33}) \pm \left[ \frac{1}{2} (\sigma_{11} - \sigma_{33})^2 + \sigma_{13}^2 \right]^{1/2}
\]

If \( \sigma_3 \) maintains constant or let \( \sigma_3 = \sigma_0 \), combining with equations (1), (2), (5) and (6) will obtain the damage strength of rock mass:

\[
\sigma = F(\sigma_1, m, \Omega, k)
\]

where \( F \) is a very complex function which is solved by numerical computation, and \( m \) is selected according to results by Hoek and Brown [4] and \( s = 1 \).

3 Fracture Strength of Joint in Rockmass

Under uniaxial or biaxial compressive loading, although tensile cracks parallel to the maximum compression occur in front of joints, the final failure direction is along the joint plane, i.e. the mutual linking up between parallel joints. This failure mechanism is illustrated as Fig. 1. Tensile cracks originate at the tips of joints (Fig. 1b); with the increase of shear stress, tensile cracks propagate stably along the rock bridges between joints (Fig. 1c); the further increase of shear stress makes many tensile cracks coalesce and form a new growth surface in the rock bridges, and the further growth may lead to unstable failure and linking up of joints. Although tensile loading experiments are rarely carried out by present equipment, normal tensile stress would make joint growth along its plane through theoretical analysis, thus the above mentioned growth mechanism of joints is applicable for \( \sigma > 0 \).

Therefore, the fracturing growth of joints in rock mass may be summarized as follows:

(a) The rock bridges between joints are the weak link, thus the joint fracture will grow along the direction of rock bridges, namely the direction of the joints plane;
(b) the joints fracturing growth is divided into two stages, i.e. the stable and unstable fracturing growth processes;
(c) in the stable growth of joints, their growth resistance increases with the growth of joints, and this increasing relation can be assumed as

\[
R' - (a'(a')^n R
\]

where \( n \) is the increasing index of joint growth resistance, \( R \) is the critical growth resistance of joints, \( a' \) is the characteristic half length of joints after stable growth and \( R' \) is the growth resistance corresponding to \( a' \).

Atkinson and Rawlings [2] implied through tests that under the condition of containing water, \( R'/R \) is greater than 3 at least (\( R^* \) is the unstable growth resistance of joints).

In the plane strain case, the growth force \( G \) of joints related with stress intensity factors \( K_I \) and \( K_{II} \) is:

\[
G = 1 - v^2 (K_I^2 + K_{II}^2)
\]

or is further expressed as

\[
G = \frac{(1-v^2)\pi a}{E} \left( k_I p^2 H < \sigma > + k_{II} (1-c_{II} H < \sigma >)^2 \right)
\]

where \( k_I \) and \( k_{II} \) are coefficients affected by the joint interaction respectively, \( E \) and \( v \) are elastic constants of rock.

If a joint plane orients itself at angle \( \beta \) with the principal stress \( \sigma_1 \), its normal stress \( \sigma \) and shear stress \( r \) applied are respectively:

\[
\sigma = \frac{1}{2} (\sigma_1 + \sigma_3) - \frac{1}{2} (\sigma_1 - \sigma_3) \cos 2\beta \quad (11a)
\]

\[
\sigma = \frac{1}{2} (\sigma_1 - \sigma_3) \sin 2\beta \quad (11b)
\]

Using the unstable growth condition of joints, the fracture strength criterion of joints is expressed as

\[
k_I p^2 H < \sigma > + k_{II} (1-c_{II} H < \sigma >)^2 \tau = Y \quad (12)
\]