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Review

Fracture initiation and propagation in intact rock – A review

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ABSTRACT

The initiation and propagation of failure in intact rock are a matter of fundamental importance in rock engineering. At low confining pressures, tensile fracturing initiates in samples at 40%–60% of the uniaxial compressive strength and as loading continues, and these tensile fractures increase in density, ultimately coalescing and leading to strain localization and macro-scale shear failure of the samples. The Griffith theory of brittle failure provides a simplified model and a useful basis for discussion of this process. The Hoek–Brown failure criterion provides an acceptable estimate of the peak strength for shear failure but a cutoff has been added for tensile conditions. However, neither of these criteria adequately explains the progressive coalition of tensile cracks and the final shearing of the specimens at higher confining stresses. Grain-based numerical models, in which the grain size distributions as well as the physical properties of the component grains of the rock are incorporated, have proved to be very useful in studying these more complex fracture processes.

1. Introduction

In order to understand the characteristics of rock and rock masses as engineering materials, it is necessary to start with the behavior of intact rock. From an engineering point of view, this involves studying laboratory-scale samples, such as diamond drill core, with dimensions in the range of 50 mm diameter. For many rock types, the grain size is small enough that samples of this scale can be considered homogeneous and isotropic.

The characteristics that will be discussed in the following text are the strength and deformation characteristics of intact rock. As illustrated in Fig. 1, a number of stress states need to be considered and, as is common in most discussions on this topic, it will be assumed that these stress states can be considered in two dimensions. In other words, it is assumed that the intermediate principal stress σ_2 has a minimal influence on the initiation and propagation of failure in the samples. While some authors consider this to be an over-simplification, a full three-dimensional treatment of the topic would result in complex text which would defeat the purpose of this presentation which is designed to be as clear and understandable as possible.

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2. Theoretical fracture initiation: background

2.1. Griffith tensile theory

Griffith (1921) proposed that tensile failure in brittle materials such as glass initiates at the tips of minute defects which he represented by flat elliptical cracks. His original work dealt with fracture in material subjected to tensile stress but later he extended this concept to include biaxial compression loading (Griffith, 1924). The equation governing tensile failure initiation in a biaxial compressive stress field is

$$\sigma_1 = \frac{-8\sigma_t\left(1+\dfrac{\sigma_3}{\sigma_1}\right)}{(1-\sigma_3/\sigma_1)^2} \tag{1}$$

where σ_t is the uniaxial tensile strength of the material. Note that tensile stresses are negative.

Murrell (1958) proposed the application of Griffith theory to rock. In the 1960s, Griffith's two-dimensional theory was extended to three dimensions by a number of authors including Murrell (1958), Sack and Kouznetsov whose work was summarized in books on brittle failure of rock materials by Andriev (1995) and

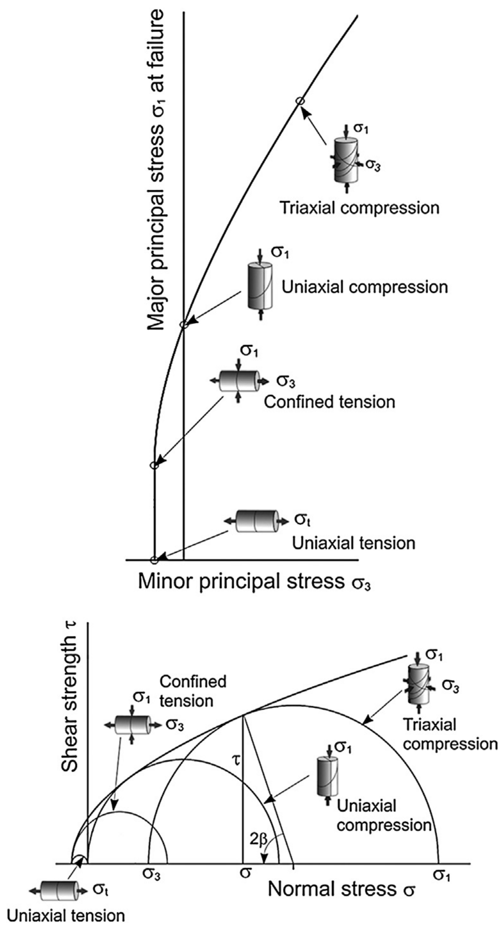

Fig. 1. Typical failure characteristics of intact rock plotted in terms of major and minor principal stresses and Mohr circles and envelope.

Paterson and Wong (2005). These extensions involve examining the stresses induced around open penny-shaped cracks in a semi-infinite body subjected to triaxial compressive stresses σ_1, σ_2 and σ_3. It was shown that the intermediate principal stress σ_2 has no significant influence on the crack tip stresses inducing tensile failure initiation. Hence, this criterion is essentially equivalent to loading a penny-shaped crack in a biaxial stress field, as shown in Fig. 2.

The equation governing tensile failure initiation is

$$\sigma_1 = \frac{-12\sigma_t\left(1+2\dfrac{\sigma_3}{\sigma_1}\right)}{(1-\sigma_3/\sigma_1)^2} \tag{2}$$

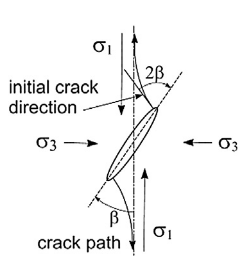

Fig. 2. Tensile crack propagation from an inclined elliptical Griffith crack in a biaxial compressive stress field.

Note that, whereas the original Griffith theory predicts a ratio of compressive to tensile strength $\sigma_c/|\sigma_t| = 8$, the penny-shaped crack version predicts $\sigma_c/|\sigma_t| = 12$. The corresponding Mohr envelope for the penny-shaped crack version is

$$\tau^2 = |\sigma_t|(|\sigma_t|+\sigma)\left(\sqrt{\frac{\sigma_c}{|\sigma_t|}+1}-1\right)^2 \tag{3}$$

where σ_c is the uniaxial compressive strength of the material.

The Griffith theory deals only with the initiation of tensile failure. It cannot be extended to deal with failure propagation and eventual shear failure in compression. However, under certain conditions when tensile stresses exceed the tensile strength, tensile failure initiation can lead to crack propagation. In these cases the tensile cracks propagate along the major principal stress (σ_1) trajectory as shown in Fig. 2.

2.2. Modifications to Griffith theory for closed cracks

The original Griffith theory was derived from analyses of crack initiation at or near the tips of open elliptical cracks. In the case of rocks, most of the defects from which tensile cracks originate are grain boundaries which are usually cemented and have to be considered as closed cracks. McClintock and Walsh (1962) proposed that tensile fracture from closed Griffith cracks can be predicted on the basis of the conventional Mohr–Coulomb equation: where ϕ is the angle of friction and τ_0 is the shear strength at zero normal stress.

$$\tau = \tau_0 + \sigma\tan\phi \tag{4}$$

Hoek (1965) discussed the transition from the Griffith theory for open cracks, which applies for confining stresses $\sigma_3 < 0$, and the modified theory for closed cracks which applies for compressive confining stresses. For the principal stress plot, this transition occurs at $\sigma_3 = 0$, while for the Mohr envelope, the transition occurs at the tangent points on the Mohr circle representing the uniaxial compressive strength σ_c of the intact rock. The transition is illustrated in Fig. 3 in which the principal stress plots are shown for friction angles of 35°, 45° and 55°.

A much more comprehensive discussion on this topic is given in Paterson and Wong (2005) but the plotted results are essentially the same as those shown in Fig. 3. Hence, for the purpose of this discussion, Eq. (4) above is adequate.

Zuo et al. (2008) examined the growth of microcracks in rock-like materials on the basis of fracture mechanics considerations. They assumed a sliding-crack model which generates wing cracks, similar to those shown in Fig. 2, from close to the crack tips when the frictional strength of the sliding surfaces is overcome. They found that the failure initiation criterion can be expressed by the following equation:

$$\sigma_1 = \sigma_3 + \sqrt{\frac{\mu}{\kappa}\frac{\sigma_c}{|\sigma_t|}\sigma_c\sigma_3 + \sigma_c^2} \tag{5}$$

where μ is the coefficient of friction which is equal to the tangent of the friction angle, i.e. $\mu = \tan\phi$.

The coefficient κ is used for mixed mode fracture and it can be derived from various approximations based on a maximum stress criterion or a maximum energy release criterion (Zuo et al., 2008). Plots for Eq. (5), when μ = 0.7, 1 and 1.43 (ϕ = 35°, 45° and 55°), κ = 1 and $\sigma_c/|\sigma_t| = 12$, are included in Fig. 3. Note that the same transition from open to closed crack behavior has been assumed as for the Mohr–Coulomb criterion (Eq. (4)) discussed above.