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Research Paper

Pre-failure damage analysis for brittle rocks under triaxial compression

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ABSTRACT

In this study pre-failure damage characteristics are investigated by conducting a series of conventional triaxial compression tests and corresponding numerical simulations for granite from Kirchberg (Saxony, Germany). First, lab test results are analysed. For evaluation and prediction of damage in the pre-failure range, damage indices are proposed considering increase of dissipation energy density and decrease of secant modulus. It can be concluded that the damage increases slowly before the reversal of volumetric strain and accelerates quickly afterwards. Then, a new failure criterion is deduced based on a correlation of maximum elastic strain energy density with uniaxial compressive strength and confining pressure. Finally, a micro-mechanical grain-based discrete element model using Voronoi blocks to represent minerals is set-up. It considers elastic grains and elasto-plastic contact deformations as well as inter- and intra-granular fracturing. The triaxial compression tests are simulated and the damage process including evolution of damage indices are investigated in detail. The proposed approaches can be used to predict and analyse limit and damage state of brittle rocks.

1. Introduction

The pre-failure damage evolution in rocks can affect the serviceability of rock structures and is of importance for any kind of safety considerations in rock engineering.

Many researchers have tried to analyse the pre-failure damage and the underlying mechanisms by experimental methods. Brace et al. [1] investigated the dilatancy of crystalline rocks in triaxial compression tests and observed that the volume changes are elastic at low stress levels, but become inelastic with dilatancy if stresses become 1/3 to 2/3 of the fracture stress at a given confining pressure. Martin and Chandler [2] conducted a series of lab tests for Lac du Bonnet granite and concluded that both crack initiation and crack damage thresholds exist and appear to be unaffected by the sample size. They discovered that whenever granite is damaged, a portion of its cohesion is lost and friction is mobilized. Eberhardt et al. [3] developed a method of combined use of moving point regression analysis and acoustic emission response to identify crack initiation threshold and also indicated that a significant rate change in strain occurs prior to the crack damage threshold. Eberhardt et al. [4] analysed the progressive pre-peak damage process in pink Lac du Bonnet granite by uniaxial compression tests and showed that the crack initiation and crack damage threshold starts at 39% and 75% of uniaxial compressive strength, respectively. Some researchers have successfully investigated the damage in rocks from the aspect of energy conservation [5,6]. Xie et al. [5] deduced that damage and irreversible deformation within the rocks are produced by dissipated energy. Based on triaxial compression tests on coal, Peng et al. [6] introduced a damage evolution model, which considers stiffness degradation before peak strength to determine the initial damage and the critical damage variables. In the past decades, several failure criterions such as Mohr–Coulomb, Drucker–Prager and Hoek–Brown failure criterion [7–10] are frequently used to analyse failure problems in rocks. Based on a large amount of triaxial test data, Shen et al. [11] proposed a simplified failure criterion for intact rocks on the basis of rock type and uniaxial compressive strength. Peng et al. [12] have derived a negative exponent empirical model to express the parameter m_i for the Hoek–Brown failure criterion as a function of confinement and introduced a new empirical failure criterion for intact rocks. Singh et al. [13] modified the Mohr–Coulomb failure criterion to take into account the non-linearity of failure envelope which is observed during conventional and true triaxial tests for intact rocks. In addition, some statistical constitutive models are frequently used for damage analysis. Wang et al. [14] proposed a damage-softening statistical constitutive model considering rock residual strength to analyse damage and failure mechanism of rocks. Based on maximum entropy distribution, Deng and Gu [15] developed a statistical damage constitutive model for rock.

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Numerical methods, such as discrete element method (DEM) have also been extensively used to analyse the damage and fracture characteristics of rocks. Debecker et al. [16] used UDEC to simulate the fracture pattern of Brazilian tests. Debecker and Vervoort [17] adopted UDEC to study the fracture pattern of layered rock during uniaxial compression tests and discussed the influence of input parameters. Based on a heterogeneous model, Lan et al. [18] investigated the micromechanical behaviour of rocks during compressive tests. Kazerani [19,20] implemented a new constitutive law into UDEC to analyse the influence of micromechanical parameters on the failure process of rocks. Tan et al. [21] used the same code to study the influence of anisotropic strength parameters during Brazilian tests on transversely isotropic rocks. According to simulation results obtained with UDEC, Chen and Konietzky [22] and Chen et al. [23] analysed the damage process for loaded brittle rocks. Potyondy and Cundall [24] simulated elasticity, fracturing and damage accumulation inside a rock based on particle flow code PFC. Based on DEM, Wang and Tonon [25] carried out simulations for triaxial compression tests on granite and concluded that micro level tensile failure occurs first, which is followed by the mobilization of residual friction. Hsieh et al. [26] adopted DEM to research the influence of microscopic properties on macroscopic behaviour of sandstone. Khazaei et al. [27] analysed the damage of intact rocks during uniaxial compression tests using acoustic emission technology and PFC3D. Based on DEM, Yao et al. [28] proposed a modified rigid block spring method to simulate damage and failure in brittle rocks.

In this paper, pre-failure damage evolution of Kirchberg-II granite from (Saxony, Germany) during conventional triaxial compression tests are first analysed based on the energy conservation theory. Two quantitative damage indices defined by dissipation energy density and the secant modulus respectively are introduced to evaluate the evolution of damage in the pre-failure range. Subsequent to this, a new failure criterion is proposed on the basis of maximum strain energy density equation and lab testing results. Finally, a grain-based discrete element model is developed to simulate the damage evolution of the granite during triaxial tests and to determine the damage index.

2. Triaxial compressive tests of Kirchberg-II granite

Conventional triaxial compressive tests were carried out using MTS 815 rock testing system (Fig. 1). The servo-controlled system consists of a pump unit (No. 1 in Fig. 1a) with nominal confining pressure up to 40 MPa, a loading frame (No. 2 in Fig. 1a) with nominal axial load of 3600 kN (error < 0.05%; sensitivity = ±0.5 kN) and a data acquisition unit (No. 3 in Fig. 1a). The circumferential and axial deformation is measured by a Linear Variable Differential Transducer (LVDT) attached to a chain wrapped tightly around the sample (No. 4 in Fig. 1b) and an axial LVDT (No. 5 in Fig. 1b), respectively. Cylindrical sample of Kirchberg-II granite (50 mm diameter and 100 mm height), as shown in Fig. 2, were tested applying compressive stress σ_1 and constant confining pressures $\sigma_2 = \sigma_3 = 10, 20, 30$ MPa, respectively. The samples were hydrostatically compressed until the level of desired circumferential pressure was reached. Then, the sample was vertically further compressed with a rate of 2 MPa/min until failure. Basic mechanical parameters of the granite are listed in Table 1.

Failed samples with typical fracture pattern are shown in Fig. 2 and corresponding test recordings are shown in Fig. 3. The points b_1, b_2 and b_3 in Fig. 3 indicate the peak loads (σ_1) at confining pressures of 10, 20 and 30 MPa, respectively. The points c_1, c_2 and c_3 mark the reversal points in respect to volumetric strain at confining pressures of 10, 20 and 30 MPa, respectively.

3. Damage analysis based on energy consideration and secant modulus degradation

3.1. Energy analysis

Based on the law of energy conservation, the work W_F done by outer forces is transferred into elastic strain energy W_E and dissipation energy W_D as shown in Eq. (1). The dissipation energy W_D is assumed to include released energy due to crack development and irreversible plastic deformation according to [5].

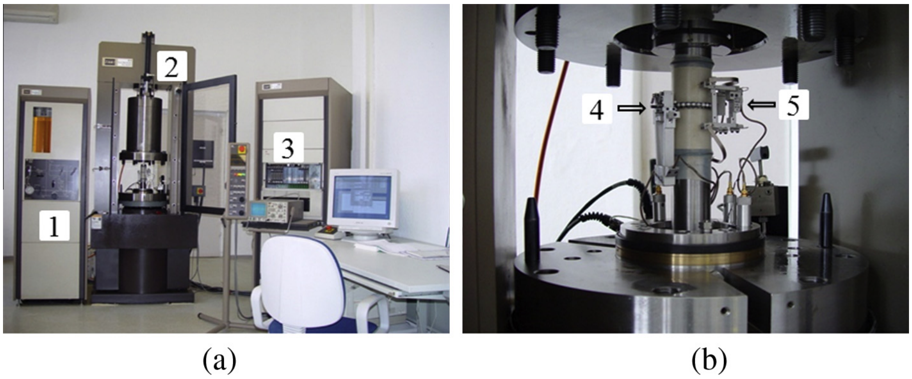
$$W_F = W_E + W_D \tag{1}$$

The work done by outer forces can be calculated as follows:

$$\begin{aligned} W_F &= \int_0^{l_1} F_1\,dl_1 + \int_0^{l_3} F_3\,dl_3 \\ &= \int_0^{\varepsilon_1} \sigma_1 \frac{\pi}{4} D^2 H\,d\varepsilon_1 + \int_0^{\varepsilon_3} \sigma_3 \pi D H \frac{D}{2}\,d\varepsilon_3 \\ &= \frac{\pi}{4} D^2 H \left(\int_0^{\varepsilon_1} \sigma_1\,d\varepsilon_1 + 2\int_0^{\varepsilon_3} \sigma_3\,d\varepsilon_3 \right) \\ &= \frac{\pi}{4} D^2 H U_F \end{aligned} \tag{2}$$

where D and H are diameter and height of the sample, F_1 and F_3 are the outer forces in axial and lateral direction, l_1 and l_3 are displacements in axial and lateral direction, ε_1 and ε_3 are axial and lateral strains, and U_F is the kinetic energy density done by the outer forces. Therefore, elastic and dissipative energies can be written as follows:

$$W_E = \frac{\pi}{4} D^2 H U_E \tag{3}$$



(a) (b)

Fig. 1. Conventional triaxial compressive test: (a) MTS 815 rock testing system and (b) triaxial cell.