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Simulation of heterogeneity, creep, damage and lifetime for loaded brittle rocks

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ABSTRACT

A grain-based heterogeneous numerical model originated from the discrete element method is developed and applied for Lac du Bonnet granite. Basing on Voronoi cells, the modelled microstructure considers different mineral components and grain size. The model takes into account elastic grain and elasto-plastic contact deformation, inter- and intra-granular fracturing and lifetime prediction on basis of subcritical crack growth. The procedure is successfully applied to simulate uniaxial compression tests, Brazilian tests and uniaxial creep tests. The damage processes are studied in detail and Mode-I and Mode-II fracture toughness were determined. The proposed modelling allows the simulation of time-dependent behaviour in terms of the damage process during primary, secondary and tertiary creeps until the final failure characterized by macroscopic fracturing (shear band and/or macroscopic tensile fracture). All simulations have shown reasonable agreement with macroscopic results obtained from lab tests on granite, but have in addition delivered deeper insight into the microscopic damage process. The proposed modelling approach is recommended for brittle rocks.

1. Introduction

Geomaterials, and brittle rocks in particular, have a complex mechanical behaviour which is related to its internal microstructure (e.g. Hallbauer et al., 1973). This internal microstructure is governed by different mineral grains and microdefects, which produce heterogeneity (e.g. Lan et al., 2010). In addition, the behaviour of rocks is often characterized by time dependency, nonlinear failure envelopes and a high ratio of uniaxial compression strength to tensile strength (e.g. Hoek, 1983). It has been documented that sophisticated numerical methods can be used to analyse the damage and fracture behaviour of brittle rocks with such characteristics (e.g. Groh et al., 2011; Liu et al., 2004).

In addition to the microdefects the heterogeneity of crystalline rocks at the microscopic scale is primarily governed by the variation in grain size, shape and mineral composition (e.g. Blair and Cook, 1998; Groh et al., 2011; Lan et al., 2010). The Voronoi tessellation technique is suited to build-up grain-based anisotropic models. Models based on Voronoi tessellation could describe not only the micro-mechanical phenomena but also duplicate the macroscopic response (e.g. Espinosa and Zavattieri, 2003; Lan et al., 2010; Li et al., 2006).

Besides the above mentioned aspects, time-dependent strength and deformation (creep) of rocks are important, especially for long-term stability and safety considerations of geotechnical structures such as mines, underground tunnels, nuclear waste repositories or slopes. Also, for time-dependent damage and deformation in tectonics, Griggs (1940) already recommended the application of laboratory experiments to investigate rock fracturing in relation to earthquakes, in particular for the determination of tertiary creep. According to creep theory of aftershocks, Benioff (1951) presented evidence that aftershocks are caused by creep of faults. Main (2000) indicated that time-dependent properties of brittle rock at the micro-scale are very important for understanding the long-term behaviour of rocks in the Earth's upper crust. He assumes that acceleration of deformation and damage during tertiary creep have some similarities with the precursory of seismicity sometimes observed before large earthquakes. Helmstetter et al. (2003) linked the precursory acceleration of seismicity to the progressive damage development. Time dependent deformation of brittle rocks is mainly caused by subcritical crack growth which can be explained by the theory of stress corrosion, considering that strained atomic bonds at crack tips may break by the influence of environmental agents and thermal fluctuations (Potyondy, 2007; Rinne, 2008). Subcritical crack growth takes places at extremely low velocities. Whenever the fracture toughness has been reached — either by reaching a critical crack length or a critical load level — the crack growth velocity suddenly approaches values close to the ultrasonic wave speed, which may cause sudden failure. During this process microcracks will interact and connect to form macroscopic fractures or shear bands as a result of damage accumulation. Therefore, the investigation of subcritical crack growth is the key to evaluate the long-term stability of rocks (Ko and Kemeny, 2013; Konietzky et al., 2009; Li and Konietzky, 2013; Lockner and Madden, 1991).

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So far the different aspects mentioned above were simulated in an isolated manner by different approaches. The approach presented within this paper combines the explicit consideration of heterogeneity, creep, and damage evolution at the grain size level up to final failure including the time-to-failure prediction. The proposed procedure is applied for well investigated Lac du Bonnet (LdB) granite. Lab results obtained from uniaxial compression tests, Brazilian tests and fracture toughness tests are used to calibrate and validate the elasto-plastic model parameters. Creep tests at different load levels are used to determine the parameters for the subcritical crack growth law.

The numerical simulations were performed with the Discrete Element Code (UDEC) by extensive usage of the internal programme language in order to implement the constitutive laws.

2. Time independent rock behaviour

In this section, the effect of heterogeneity of the rock at the grain size level on the process of crack initiation, growth and coalescence is investigated. First, the Voronoi based numerical model set-up is explained, followed by a series of simulations to model different lab test for LdB granite. The constitutive behaviour of the model is governed by two types of constitutive laws: the matrix laws for the grains itself and the contact laws at the grain boundaries, which control the interaction between the grains.

2.1. Grain-based heterogeneous model

The mineral composition of LdB granite is characterized by 7.1% biotite, 51.1% K-feldspar, 31.8% quartz and 10% plagioclase. The smallest grains have a diameter of about 1 mm. They are randomly distributed within a piece of rock. The numerical model was created by Voronoi cells with equivalent diameter of about 1 mm. The percentages of the mineral components were considered and the allocation was performed in a random manner, so that the model matches the grain size distribution in an approximate manner and also bigger grain clumps (mineral clumps) were automatically produced (Fig. 1). The Voronoi cells itself are unbreakable and behave elastically. The parameters for the mineral components and Voronoi cells, respectively, are given in Table 1.

The contact behaviour is elasto-plastic and characterized by a Mohr–Coulomb failure criterion with tension cut-off and softening (Fig. 2). For each mineral component, a corresponding set of contact parameters is specified (Table 2). At the contacts between the grains, the arithmetic average of the parameters is applied. In the normal and shear direction, the stress-displacement relation below the strength limit at the contacts is assumed to be linear and governed by the normal stiffness k_n and the shear stiffness k_s. If the tensile strength is reached, the contact breaks and the tensile strength is set to zero. If the shear strength is reached, sudden softening takes place and cohesion and friction of the contact are set to residual values. Eqs. (1) and (2) describe the contact behaviour:

Table 1
Grain parameters (Bass, 1995; Chen et al., 2004; YU et al., 2012).

Mineral	Elastic modulus (GPa)	Poisson's ratio
Biotite	35	0.25
K-feldspar	62	0.27
Quartz	91	0.20
Plagioclase	69	0.23

$$\begin{cases} \sigma_n = -k_n u_n \\ if \ \ \sigma_n < -J^T, \ \ \sigma_n = J_r^T = 0 \end{cases} \tag{1}$$

$$\begin{cases} \tau_s = k_s u_s \\ \tau_{\max} = J^C + \sigma_n \tan\varphi \\ if \ \ |\tau_s| \geq \tau_{\max}, \ \ \tau_s = sign(\Delta u_s) \cdot \left(J_r^C + \sigma_n \tan\varphi_r\right) \end{cases} \tag{2}$$

where σ_n and τ_s are normal stress and shear stress, respectively, u_n and u_s are normal displacement and shear displacement, respectively, J^T and J_r^T are tensile strength and residual tensile strength, respectively, $\tau_{\max}$ is shear strength, J^C and J_r^T are cohesive strength and residual cohesive strength, respectively, φ and φ_r are friction angle and residual friction angle, respectively, and Δu_s is the incremental contact shear displacement.

Within the model the damage and fracture process associated with plastic deformations is controlled by the breakage of contacts and relative movement along or across them.

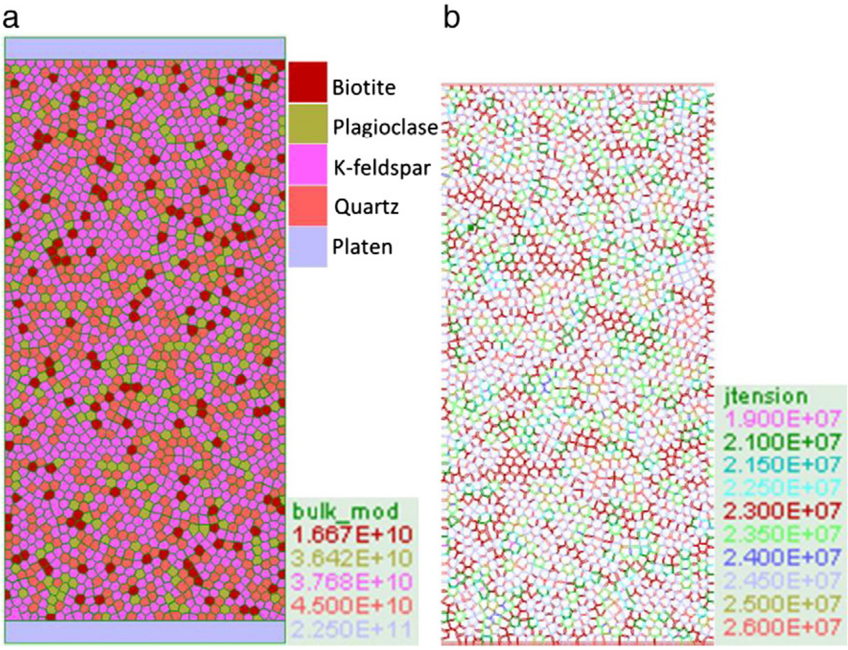

Fig. 1. Model set-up: (a) Voronoi blocks representing different minerals, (b) contacts between minerals.