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Modeling of anisotropic damage and creep deformation in brittle rocks

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Abstract

A new constitutive model is proposed for the description of induced anisotropic damage in brittle rocks. The formulation of the model is based on relevant results from micromechanics consideration. The distribution of microcracks is approximated by a second-order damage tensor. The effective elastic properties of damaged material are derived from the free enthalpy function. The evolution of damage is directly related to the growth of microcracks in different space orientations. The volumetric dilatancy due to sliding crack opening is taken into account. The model is extended to the description of creep deformation in brittle rocks. The time dependent deformation is seen as a consequence of the sub-critical propagation of microcracks due to stress corrosion process. The proposed model is applied to a typical brittle rock, the Lac du Bonnet granite. A general good agreement is obtained between numerical simulations and experimental data.

Keywords: Anisotropic damage; Creep deformation; Microcracks; Granite; Brittle materials

1. Introduction

In many rock engineering applications (civil engineering, oil industry, mining engineering and geological storage of nuclear waste), the stability and safety analysis of underground cavities requires experimental investigation and numerical modeling of rock behavior in complex loading condition. In brittle rocks like granite, it is now recognized that rock failure is mainly caused by propagation and coalescence of microcracks. The growth of microcracks may affect not only mechanical strength of rock but also hydraulic properties like permeability [1]. Further, depending on environmental conditions like humidity and temperature, sub-critical propagation of crack may appear leading to time dependent creep deformation and failure [2–4]. Therefore, it is essential to formulate advanced constitutive models for the description of hydromechanical behavior of rock in complex loading conditions. The aim of this paper is to propose a unified continuum damage model for the description of induced anisotropic damage and creep deformation in brittle rocks. Such a model will take into account main features observed in experimental investigations. The proposed model can be easily implemented in computer code to provide an efficient tool for numerical analysis of rock engineering problems. As the damage evolution will be related to crack growth rate, the proposed model can be extended to include damage effect on hydraulic diffusion properties, which are essential data for some specific applications like geological storage of nuclear waste storage.

Many experimental tests have confirmed various mechanisms of nucleation and growth of microcracks in brittle rocks. Under compressive stresses, sliding wing cracks seem to be the principal propagation mode of microcracks [5–10]. Due to roughness of crack surfaces in geomaterials, crack sliding may induce an associated aperture which is the origin of volumetric dilatancy in these materials [8,11]. When the crack length reaches some critical values, the coalescence of microcracks occurs and localized macro-cracks appear leading to the failure of material. The kinetics of failure is controlled by confining

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Nomenclature

$\boldsymbol{\varepsilon}$	total strain tensor
$\boldsymbol{\sigma}$	Cauchy stress tensor
$\boldsymbol{\sigma}^{d}$	deviatoric stress tensor
$\mathbf{S}^{0}$	fourth-order elastic compliance tensor of undamaged material
r_0	average radius of initial cracks
r_f	critical value of crack radius at failure state
$\vec{n}$	unit normal vector of crack
$r(\vec{n})$	crack radius in the orientation $\vec{n}$
ξ	normal displacement jump through crack
γ	shear displacement jump through crack
h	crack compliance of cracked solid
$\omega(\vec{n})$	crack density function
N	crack number in the unit volume
W_c	elastic enthalpy of cracked material
$\boldsymbol{D}$	second-order damage tensor
$\boldsymbol{\varepsilon}^{r}$	damage related irreversible strain tensor
$\mathbf{S}(\boldsymbol{D})$	fourth-order elastic compliance tensor of damaged material
σ_n	normal stress applied to crack
$\tilde{q}(\vec{n})$	normal projection of deviatoric stress tensor to crack
σ_t	equivalent tensile force applied to fictitious crack
f_c	uniaxial compression strength of rock
f_t	uniaxial tensile force of rock
N_g	number of integration points in space orientation
λ_k	weight coefficient for numerical integration scheme

pressure and there is a transition from brittle failure to ductile failure when the confining pressure increases [12–14]. The main consequences of induced microcracks are: non-linear stress–strain relations, deterioration of elastic properties, induced anisotropy, volumetric dilatancy, irreversible strains due to residual crack opening, unilateral response due to crack closure, and hysteresis associated with frictional mechanism. These features have to be considered in the constitutive modeling. Two families of damage models have been developed for the description of induced damage: micromechanical approaches and phenomenological models (we do not give here an exhaustive list of many models reported in the literature). The main advantage of micromechanical approaches is the ability to account for physical mechanisms involved in the nucleation and growth of microcracks. For the construction of a micromechanical model, two steps are generally performed. The first step consists in the evaluation of the effective elastic properties of material weakened by microcracks. The second step is to propose a suitable damage evolution law for microcrack growth. The main features related to microcrack growth, opening and closure, friction, interaction between cracks, could be taken into account in such micromechanical models. The macroscopic behavior of material is then obtained through a homogenization procedure. This renders these models difficult to be applied to practical applications. Phenomenological models use internal variables to represent the density and orientation of microcracks, for instance, scalar variable for isotropic damage, second and fourth rank tensor to describe anisotropic damage. The constitutive equations are generally formulated using the concept of effective stresses based on the principle of strain and energy equivalence [15] and from the standard derivation of a thermodynamic potential [16,17]. The damage evolution law is determined according to the principles of the irreversible thermodynamics. The main advantage of such models is that they provide macroscopic constitutive equations, which can be easily implemented and applied to engineering analyses. The main weakness is that some of the concepts and parameters involved in these models are not clearly related to physical mechanisms. A number of phenomenological and micromechanical models have been successfully used in the analysis of structures with metals, composites and concrete. However, most models have focused on the description of damage induced by tension-dominated stresses. Specific features of damage in brittle rocks induced by compressive stresses have not been properly taken into account. For example, many models use a tensile strain-based damage criterion. Laboratory results on brittle rocks show that such a criterion could not correctly describe the high-pressure sensitivity of such materials. Therefore, the validity of these models in the compression regime is not clearly proved. This paper presents a new phenomenological model with the emphasis on the description of anisotropic damage in brittle rocks subjected to compression-dominated stresses. The basic idea is to include relevant micromechanics features in the phenomenological formalism. Further, it is assumed that in brittle rocks, the induced damage is the essential energy dissipation mechanism. Plastic deformation due to dislocation can be neglected. Macroscopic irreversible strains are related to residual opening and mismatching of the crack faces of microcracks during loading–unloading process.

Another important feature in brittle rocks is time dependent deformation [4,18–20]. The development of this creep deformation is an essential factor for long term safety in many structures in civil engineering and oil engineering, for instance, facilities for the storage of nuclear wastes. In the classic approaches, the creep deformation is generally described by the viscoplastic theory [21]. The viscoplastic models indeed provide a simple mathematical framework for the modeling of creep deformations, but they do not take into account physical mechanisms related to these deformations. In the case of brittle rocks, experimental data have shown that the creep deformation is essentially