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A numerical investigation of brittle rock damage model in deep underground openings

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ABSTRACT

The excavation of underground openings generally causes damage to the rock in the vicinity of the openings. The dominant causes of irreversible rock deformations are damage process and plastic flow. Most of the existing elastic–plastic models employed in the analysis and design of rock structures only consider the plastic flow and ignore the full damage process. The common approach used to model the rock failure, does not model the rock realistically and often the important issues such as stiffness degradation, softening, and significant differences in rock response under tensile and compressive loadings are ignored. Therefore, developments of realistic damage models are essential in the design process of rock structures. In this paper, the basic concepts of continuum damage mechanics are outlined. Then, a more clear and accurate definition of the damage function is established. In the definition of rock damage function, many authors considered only the tensile stress condition. Since quasi brittle materials such as rock degrade under tensile and compressive stress fields, separate tensile and compressive damage functions are introduced. The proposed damage functions are formulated in the framework of a damage model which was coded and implemented into a commercial code. Accordingly, the developed algorithm was applied to the simulation of brittle rocks behavior. Using field measurements from the AECL's (Atomic Energy of Canada Limited) Mine-by Experiment tunnel, the new developed damage model was calibrated and validated for its ability to reproduce the shape and size of excavation damage zone (EDZ) around the Mine-by test tunnel.

1. Introduction

Analysis of stresses and displacements around underground openings is required in a wide variety of civil and geotechnical, petroleum and mining engineering problems such as tunnels, boreholes, shafts, disposal of radioactive waste and mines. In addition, an excavation damaged zone (EDZ) is generally formed around underground openings as a result of high in situ stresses and/or high anisotropic stress ratios even in the absence of blasting effects. The rock mass mechanical and hydraulic properties changed within the EDZ.

The rock materials surrounding the underground excavations typically demonstrate nonlinear mechanical response and irreversible behavior in particular under high in situ stress states. The dominant causes of irreversible deformations are plastic flow and damage process. The plastic flow is controlled by the presence of local shear stresses which cause dislocation to some preferential elements due to existing defects. During this process, the net number of bonds remains practically unchanged. The overall macroscopic consequence of plastic flow is that the elastic properties and, therefore, the stiffness of the material are insensitive to this type of irreversible change [1]. The main cause of irreversible changes in quasi-brittle

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Nomenclature

b	positive constant showing the anisotropy of the damage yield function
D	damage parameter
D_{ij}	second order damage tensor
E_{ijkl}	stiffness tensor
E^0	Young's modulus
F	damage yield function
F^-	compressive damage yield function
F^+	tensile damage yield function
f	loading function
f^+	tensile loading function
f^-	compressive loading function
G_t	tensile fracture energy (dividing the tensile dissipated energy by the specimen cross-section)
G_c	compressive fracture energy
g_{ft}	tensile fracture energy for unit volume
g_{fc}	compressive fracture energy for unit volume
k_c	ratio of elastic energy to total absorbed energy associated with the uniaxial compression test
k_t	ratio of elastic energy to the total absorbed energy in the uniaxial tension test
L	representative of pseudo logarithmic damage tensor
L_{rs}	pseudo logarithmic damage tensor
l^e	element characteristic length
r	resistant function
r_{0c}	elastic energy associated with peak uniaxial compressive strength
r_{0t}	elastic energy associated with peak uniaxial tensile strength
w_c	compressive characteristic length
w_t	tensile characteristic length
w_{ij}	square root of inverse integrity tensor
$\bar{w}_{ij}$	square root of integrity tensor
Y_{ij}	thermodynamic force associated with damage
$-y_{rs}$	thermodynamic force conjugate to pseudo logarithmic damage
$-y^+$	positive thermodynamic force conjugate to pseudo logarithmic damage
$-y^-$	negative thermodynamic force conjugate to pseudo logarithmic damage
δ_{ij}	Delta Kroneker tensor
$\bar{\varepsilon}_{rk}$	effective strain tensor
ν^0	Poisson's ratio
$\bar{\sigma}_{rk}$	effective stress tensor
σ_t	peak uniaxial tensile strength
σ_c	peak uniaxial compressive strength
ψ^e	elastic-damage free energy potential
ϕ_{ij}	inverse of integrity tensor
$\bar{\varphi}_{ij}$	second order symmetric integrity tensor

materials such as rock is the damage process occurring within the material. From a microscopic viewpoint, damage initiates with the nucleation and growth of microcracks. When the microcracks length reaches a critical value, the coalescence of microcracks occurs and localized meso-cracks appear [2].

The macroscopic and phenomenological consequence of damage process is stiffness degradation, dilatation, softening, anisotropy, and significant difference in tensile and compressive response. Various authors have used two different methods for the study of damage process: micromechanical models and damage mechanics. In micromechanical models, the creation, growth, opening, closure, friction, and interaction conditions of microcracks at a microstructure scale are studied by fracture mechanics principles and a damage evolution law is proposed. The macroscopic behavior of material is then obtained through a homogenization procedure. Implementation of micromechanical models for numerical modeling, particularly in 3D and practical conditions, is difficult [3,4]. On the other hand, in the damage mechanics approach the continuum behavior of a solid is studied within the framework of thermodynamic fundamentals, internal state variables, degradation rule and damage function assuming noninteracting microcracks and infinitesimal deformations. The main advantage of continuum damage models is that they provide macroscopic constitutive equations, which can be easily implemented and applied to engineering analyses. The main weakness of these models is that some of the concepts and parameters involved in these