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A discrete approach for modeling damage and failure in anisotropic cohesive brittle materials

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ABSTRACT

This paper presents a numerical study of damage and failure in anisotropic cohesive brittle materials. An extended rigid block spring method (RBSM) is proposed. The representative elementary volume (REV) of brittle materials is characterized by an anisotropic Voronoi assembly of rigid blocks. The macroscopic mechanical behavior is related to the deformation and failure of interfaces between blocks. The mechanical behavior of each interface is described by its elastic stiffness, tensile strength and shear strength. The local elastic stiffness of interface can be related to the macroscopic elastic properties of material. Two failure processes of interface are considered. The tensile failure occurs when the normal stress reaches the tensile strength. The shear failure is described by a nonlinear criterion in terms of the local normal and shear stresses. The proposed method is applied to a typical clayey rock which exhibits a transversely isotropic behavior. Numerical simulations are presented and compared with experimental data.

1. Introduction

The inelastic deformation and failure in cohesive brittle materials such as rocks and concrete are mainly driven by the nucleation, propagation and coalescence of microcracks. The transition from diffused microcracks to localized fractures is the key issue for the description of progressive failure process in such materials. Further, the distribution of induced microcracks is generally anisotropic depending on applied loading paths. During the last decades, a number of phenomenological anisotropic damage models have been developed for cohesive brittle materials in the framework of irreversible thermodynamics (we do not give an exhaustive list of such models here). In these models, the state of microcracks is mathematically represented by tensorial internal variables. However, even with high order tensors, such internal variables are not able to represent complex distributions of real microcracks. Further, some difficulties have been revealed in keeping the continuity of free energy function and state law when the unilateral effects should be considered [1,2]. On the other hand, in order to complete and improve the phenomenological modeling, significant advances have been achieved on the micromechanical modeling of induced anisotropic damage, based on both the linear fracture mechanics theory [3] and linear homogenization schemes [4]. In these models, the anisotropic distribution of induced cracks and unilateral effects can be easily investigated through suitable discrete integration methods. However, nearly all these models deal with the induced anisotropic damage in initially isotropic materials. The interaction between the initial inherent anisotropy and induced anisotropic damage still

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Nomenclature

$\{u\}$, u_x, u_y displacement vector, displacement in x and y direction of any point
$\{u_c\}$, u_{cx}, u_{cy} displacement vector, displacement in x and y direction of the centroid in a block
(x, y) the global coordinates of one point on the block boundary
(x_c, y_c) the global coordinates of the block centroid
$[N]$, $[G]$, $[D]$ matrix used to establish the governing equations
σ_n, σ_s the normal and tangential stress on interfaces
$[K]$, $\{U\}$, $\{Q\}$ the global stiffness matrix, global displacement vector and global force vector
k_n, k_s the normal and tangential stiffness of interfaces
$\{\Delta u\}$, Δu_n, Δu_s the relative displacements respectively in the normal and tangential direction
m, n the components of the unit normal vector of the interface
F_t, F_s functions used to determine tensile failure and shearing failure
A, B, C parameters of the nonlinear shear failure criterion of interfaces
T tensile strength of interface
$l_{\min}$ the minimum distance between inserted points during generation of Voronoi diagram
α the orientation of interface relative to the x axis
φ the orientation of bedding planes relative to the x axis
β the orientation of interface relative to bedding planes
λ, η parameters used to generate an anisotropic mesh
$f(\alpha, \varphi)$ a function used to define the anisotropy of microscopic parameters
a, b, c parameters for the function of $f(\alpha, \varphi)$
k_{n0}, k_{s0} the normal and tangential stiffness coefficients for interfaces with an orientation of φ, the orientation of the bedding planes.
r the ratio between k_s and k_n
E, v predicted elastic modulus and Poisson's ratio
E_1, E_2 predicted elastic modulus for specimens respectively at $\varphi = 90°$ and $\varphi = 0°$
v_1, v_2 predicted Poisson's ratio for specimens respectively at $\varphi = 90°$ and $\varphi = 0°$
h, w height and width of specimen
P average stress calculated over the upper or lower boundary of the specimen
d, d_l, d_r average displacement of the top, left and right boundaries
G_{12} the shear modulus
A_0, B_0, C_0 parameters of the nonlinear shear criterion for interfaces in the direction of φ
T_0 tensile strength of interface in the direction of φ
R_B anisotropy coefficient of the parameter B
E_1^0, E_2^0 experimental elastic modulus for specimens respectively at $\varphi = 90°$ and $\varphi = 0°$
$\underline{v}_1^0$, $\underline{v}_2^0$ Poisson's ratio for specimens respectively at $\varphi = 90°$ and $\varphi = 0°$
$\overline{E}_0$, $\overline{E}$ input elastic modulus to calculate normal stiffness k_n
h_1, h_2 the distances from the centroids of two neighboring blocks to their connecting interface
ε_1, ε_3 average macroscopic axial and lateral strain
k_1, k_2 coefficients of anisotropy degree on strength

remains an open issue and needs further investigations. Indeed, most rock like materials exhibit to certain extent initial inherent anisotropy due to the presence of oriented structural heterogeneities such as bedding planes, cracks, pores and mineral inclusions. The induced damage process in such materials should be more or less affected by the initial inherent anisotropy.

On the other hand, with the coalescence of microcracks, macroscopic fractures are progressively generated, leading the macroscopic failure of materials and structures. The appearance of such fractures is accompanied by the existence of strong displacement discontinuities. The continuum damage models mentioned above generally fail to properly describe such strong discontinuities even with various regularization techniques for post-localization behaviors. Therefore, the description of the transition from diffused damage to localized fracturing remains a serious issue. In the framework of continuum mechanics, various extended finite element methods have been developed to describe the progressive failure process by introducing both global and elementary enrichment methods to capture strong displacement discontinuities [5,6]. These methods provide efficient numerical tools for modeling fracture growth without remeshing. However, in the case of cohesive materials, it is generally not an easy task to define appropriate criteria to determine the onset condition and propagation direction of fractures. Further, it is still an open issue to deal with problems with multiple fractures.

Initially developed for granular materials, various discrete methods have been intensively developed during the last decades. These methods have also been extended to cohesive or bonded materials and provide an interesting alternative way for modeling the crack growth and failure process. Among those methods, the bonded particle model proposed by Potyondy and Cundall [7] is based on the distinct element method and can reproduce a number of features of the mechanical behavior of