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Review

A review of discrete modeling techniques for fracturing processes in discontinuous rock masses

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ABSTRACT

The goal of this review paper is to provide a summary of selected discrete element and hybrid finite–discrete element modeling techniques that have emerged in the field of rock mechanics as simulation tools for fracturing processes in rocks and rock masses. The fundamental principles of each computer code are illustrated with particular emphasis on the approach specifically adopted to simulate fracture nucleation and propagation and to account for the presence of rock mass discontinuities. This description is accompanied by a brief review of application studies focusing on laboratory-scale models of rock failure processes and on the simulation of damage development around underground excavations.

1. Introduction

A large body of experimental research shows that the failure process in brittle rocks under compression is characterized by complicated micromechanical processes, including the nucleation, growth and coalescence of microcracks, which lead to strain localization in the form of macroscopic fracturing (Lockner et al., 1991; Benson et al., 2008). The evolution of micro-cracking, typically associated with the emission of acoustic energy (AE), results in a distinctive non-linear stress–strain response, with macroscopic strain softening commonly observed under low-confinement conditions (Brace et al., 1966; Bieniawski, 1967; Eberhardt et al., 1997; Martin, 1997). Furthermore, unlike other materials (e.g. metals), rocks exhibit a strongly pressure-dependent mechanical behavior (Jaeger and Cook, 1976). A variation of failure mode, from axial splitting to shear band formation, is indeed often observed for increasing confining pressures (Horii and Nemat-Nasser, 1986). This variation of failure behavior is reflected in a non-linear failure envelope (Kaiser and Kim, 2008) and a transition from brittle to ductile post-peak response (Paterson and Wong, 2004). At rock mass level, the failure process observed during laboratory-scale experiments is further complicated by the presence of discontinuities, such as joints, faults, shear zones, schistosity planes, and bedding planes (Goodman, 1989). Specifically, discontinuities affect the response of the intact rock by reducing its strength and inducing non-linearities and anisotropy in the stress–strain response (Hoek, 1983; Hoek et al., 2002). Furthermore, discontinuities add kinematic constraints on the deformation and failure modes of structures in rocks (Hoek et al., 1995; Hoek, 2006) and cause stress and displacement redistributions to sensibly deviate from linear elastic, homogenous conditions (Hammah et al., 2007).

Aside from the intrinsic uncertainties associated with the determination of reliable *in situ* input parameters, the application of numerical modeling to the analysis of rock engineering problems represents a challenging task owing to the aforementioned features of the rock behavior. In particular, the progressive degradation of material integrity during the deformation process, together with the influence of pre-existing discontinuities on the rock mass response, has represented a major drive for the development of new modeling techniques. In this context, the available numerical approaches are typically classified either as continuum- or discontinuum-based methods (Jing and Hudson, 2002).

The main assumption of continuum-based methods is that the computational domain is treated as a single continuous body. Standard continuum mechanics formulations are based on theories such as plasticity and damage mechanics, which adopt internal variables to capture the influence of history on the evolution of stress and changes at the micro-structural level, respectively (De Borst et al., 2012). Conventionally, the implementation of continuum techniques is based on numerical methods, such as non-linear finite element method (FEM), Lagrangian finite difference method

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(FDM), and boundary element method (BEM), with the incorporation of plasticity-based material models. However, standard strength-based strain-softening constitutive relationships cannot capture localization of failure as the lack of an internal length scale results in the underlying mathematical problem to become ill-posed (De Borst et al., 1993). Among the main consequences of adopting a standard continuum to simulate strain localization is the fact that, by doing so, localization occurs in a region of zero thickness and consequently an unphysical mesh sensitivity arises. To overcome these shortcomings, the description of the continuum must account either for the viscosity of the material, by incorporating a deformation-rate dependency, or for the change in the material micro-structure, by enhancing the mathematical formulation with additional terms (De Borst et al., 1993). The latter technique, known as regularization, includes non-local (e.g. Bažant and Pijaudier-Cabot, 1988), gradient (e.g. Mühlhaus and Aifantis, 1991), and Cosserat micro-polar (e.g. Mühlhaus and Vardoulakis, 1987) models. Alternatively, cohesive-crack models have been proposed under the assumption that damage can be represented by a dominant macro-fracture lumping all non-linearities into a discrete line (e.g. Hillerborg et al., 1976; Bažant and Oh, 1983). That is, a fictitious crack concept is employed to represent the effect of a fracture process zone (FPZ) ahead of the crack tip, whereby phenomena such as small-scale yielding, micro-cracking or void growth and coalescence are assumed to take place. For the case of heterogeneous rocks, strain localization has also been successfully simulated by damage models with statistically distributed defects. A number of variations of this approach have been developed for numerical schemes such as FEM (Tang, 1997), FDM (Fang and Harrison, 2002), smooth-particle hydrodynamics (SPH) (Ma et al., 2011), cellular automaton (Feng et al., 2006), and lattice models (Blair and Cook, 1998).

Within continuum models, two approaches are commonly employed to account for the presence of rock mass discontinuities. If the number of discontinuities is relatively large, homogenization techniques are typically adopted. The most widely used homogenization approach consists of reducing, within a conventional elasto-plastic model, the rock mass deformation modulus and strength parameters to account for the degrading effect induced by the local geological conditions (Hoek et al., 2002; Hoek and Diederichs, 2006). More advanced models can also include transversely isotropic elastic response induced by preferably oriented joints (Amadei, 1996) or failure-induced plastic anisotropic behavior (e.g. Mühlhaus, 1993; Dyszlewicz, 2004). However, the classic homogenization approach is typically limited by the fact that slip, rotations and separation as well as size effects induced by discontinuities cannot be explicitly captured (Hammah et al., 2008). Alternatively, if the problem is controlled by a relatively low number of discrete features, special interface (or joint) elements can be incorporated into the continuum formulation (e.g. Goodman et al., 1968; Ghaboussi et al., 1973; Wilson, 1977; Pande and Sharma, 1979; Bfer, 1985). This technique, also known as the combined continuum-interface method (Riahi et al., 2010), can accommodate large displacements, strains and rotations of discrete bodies. However, it is accurate as long as changes in edge-to-edge contacts along the interface elements are negligible throughout the solution (Hammah et al., 2007). That is, owing to the fixed interconnectivity between solid and joints and the lack of an automatic scheme to recognize new contacts, only small displacement/rotations along joints can be correctly captured (Cundall and Hart, 1992).

Discrete (or discontinuous) modeling techniques, commonly referred to as the discrete element method (DEM), treat the material directly as an assembly of separate blocks or particles. According to the original definition proposed by Cundall and Hart (1992), a DEM is any modeling technique that (i) allows finite displacements and rotations of discrete bodies, including complete detachment; and (ii) recognizes new contacts automatically as the simulation progresses. DEMs were originally developed to efficiently treat solids characterized by pre-existing discontinuities having spacing comparable to the scale of interest of the problem under analysis and for which the continuum approach described above may not provide the most appropriate computational framework. These problems include: blocky rock masses, ice plates, masonry structures, and flow of granular materials. DEMs can be further classified according to several criteria regarding, for instance, the type of contact between bodies, the representation of deformability of solid bodies, the methodology for detection and revision of contacts, and the solution procedure for the equations of motion (Jing and Stephansson, 2007). Based on the adopted solution algorithm, DEM implementations are broadly divided into explicit and implicit methods. The term *distinct element method* refers to a particular class of DEMs that use an explicit time-domain integration scheme to solve the equations of motion for rigid or deformable discrete bodies with deformable contacts (Cundall and Strack, 1979a). The most notable implementations of this group are arguably represented by the universal distinct element code (UDEC) (Itasca Consulting Group Inc., 2013) and the particle flow code (PFC) (Itasca Consulting Group Inc., 2012b). On the other hand, the best known implicit DEM is the discontinuous deformation analysis (DDA) method (Shi and Goodman, 1988). Despite the fact that DEMs were originally developed to model jointed structures and granular materials, their application was subsequently extended to the case of systems where the mechanical behavior is controlled by discontinuities that emerge as natural outcome of the deformation process, such as fracturing of brittle materials. Specifically, the introduction of bonding between discrete elements allowed capturing the formation of new fractures and, thus, extended the application of DEMs to simulate also the transition from continuum to discontinuum.

As observed by Bićanić (2003), the original boundary between continuum and discontinuum techniques has become less clear as several continuum techniques are capable of dealing with emergent discontinuities associated with the brittle fracture process. In particular, the hybrid approach known as the combined finite–discrete element method (FDEM) (Munjiza et al., 1995; Munjiza, 2004) effectively starts from a continuum representation of the domain by finite elements and allows a progressive transition from a continuum to a discontinuum with insertion of new discontinuities.

The goal of this review paper is to provide a summary of selected discrete element and hybrid finite–discrete element modeling techniques that have recently emerged in the field of rock mechanics as simulation tools for fracturing processes in rocks and rock masses. Specifically, the commercially available codes PFC (Itasca Consulting Group Inc., 2012b), UDEC (Itasca Consulting Group Inc., 2013) and ELFEN (Rockfield Software Ltd., 2004) as well as the open-source software Yade (Kozicki and Donzé, 2008) and Y-Geo (Mahabadi et al., 2012a) are considered. Also, extensions of the DDA method to simulate fracturing processes are described. For each code, the fundamental implementation principles are illustrated with particular emphasis on the approach specifically adopted to simulate fracture nucleation and propagation and to account for the presence of rock mass discontinuities. The description of the governing principles is accompanied by a brief review of application studies focusing on laboratory-scale models of rock failure processes and on the simulation of damage development around underground excavations. For more extensive reviews of numerical methods in rock mechanics, the reader can refer to the work of Jing and Hudson (2002) and Jing (2003), with a detailed illustration of fundamentals and applications of DEMs