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Application of the distinct element method and the extended finite element method in modelling cracks and coalescence in brittle materials

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ABSTRACT

In this paper we study the performance of the discrete element method (DEM) and the extended finite element method (XFEM) modelling the crack initiation, propagation and coalescence in fractured rock masses. Firstly, the crack propagation in a rock sample with single closed and open flaws and subjected to an uniaxial compression is simulated by the DEM and XFEM. The results obtained by the two methods are then compared with the experimental results reported by Park and Bobet (2009). Under an uniaxial compression load, two types of cracks are observed including the tensile or wing cracks, and the shear or secondary cracks. The results obtained by the DEM are in good agreement with the experimental results, viz., both wing and shear cracks are accurately modelled. The XFEM, on the other hand, can predict the tensile (wing) cracks, but fails to model the shear cracks. In second part of this study we consider the analysis of fracture propagation and coalescence in rock masses containing two open or closed flaws. The results predicted by the DEM and XFEM are then compared with experimental test results. Coalescence is produced by the linkage of two flaws and a combination of wing and secondary cracks. In the crack propagation and coalescence problem, the DEM is able to predict all cracks involved in rock fracturing, such as the wing and secondary cracks, as well as the crack linkage between two adjacent flaws and their subsequent coalescence. However, the XFEM results only represent the wing cracks, and the method fails to predict the shear cracks. Finally, the effect of filling materials in open flaws on the crack propagation is investigated. The results indicate that the initiation and propagation of cracks and their coalescence in a material containing open flaws significantly change when the flaws are filled with a weak material.

1. Introduction

It is well known that brittle materials, such as rocks and concrete, contain pre-existing micro-cracks, which significantly affect their behaviour. Rock masses are generally discontinuous in nature, and contain fractures (joints) with corresponding spacing and rock bridges, which play an important role in the strength of a rock formation. The propagation and coalescence of cracks initiating from such pre-existing defects, on a variety of scales, are the dominant failure mechanisms controlling the strength and integrity of brittle materials. A rock mass is not necessarily a continuous medium, nor a totally discrete medium but a kind of defect material which contains cracks, joints and faults. The nonlinear deformation behaviour of a rock mass is induced by the propagation and coalescence of cracks and joints under the external loads. Therefore, in rock engineering problems it is important to analyse the propagation and coalescence process of cracks existing in a rock mass subjected to loads. The study of crack initiation and propagation is also important for better understanding of rock mass behaviour which, in turn, plays an important role in rock engineering applications, such as tunnels, foundations and slopes, as well as hydrocarbon and geothermal energy extraction. Cracking mechanisms have been studied experimentally in the laboratory, or in the field, and numerically on computers. A brief history of experimental and numerical investigations in crack propagation and coalescence in rock masses is presented in the following.

One of the first experimental studies on the cracking mechanism in rocks was conducted by Brace and Bombolakis [1]. Studies specifically addressing coalescence include those conducted by Shen et al. [2], Bobet and Einstein [3], Wong and Chau [4], Wong et al. [5], and Li et al. [6]. Recently, coalescence experiments have been conducted using high speed cameras to determine the initiation, propagation direction, and mode of cracking associated with flaw pairs [6–8]. In terms of numerical modelling, researchers have

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attempted to simulate crack initiation, propagation and coalescence in the rock type materials. From early twentieth century, many researchers developed a few criteria to describe the initiation, propagation and coalescence of cracks in brittle materials. Specifically, several crack initiation and propagation criteria based on the stresses, strains, and energy fields around a flaw tip have been developed and implemented in the Boundary Element (BE) and the Finite Element (FE) codes [9–19]. In recent years, models such as the hybrid experimental–numerical methods [20–22], the extended finite element models (XFEM) with cohesive zone [23–26], and with p-order spectral elements [27], and peridynamics [28,29] have been used to simulate quasistatic and dynamic crack propagation problems. Also, the Distinct Element method (DEM) was employed to simulate crack initiation and propagation in a rock slope subjected to dynamic loading [30].

The finite element method (FEM) has been used to investigate crack growth and coalescence. In the finite element-based methods, singular crack-tip elements are frequently adopted [31]. This implementation requires the finite element mesh to coincide with cracks. When growth of cracks and the update of their shape are taken into account, remeshing cannot be avoided [31,45]. In addition, state variables such as displacements, stresses and strains need to be remapped to a new mesh. Furthermore, in large deformation problems, mesh distortion may cause a significant loss of accuracy in the finite element interpolation. In order to overcome the mesh distortion a remeshing technique, in which radial concentric meshes have been introduced at each crack tip, was presented for crack growth. The remeshing technique is based on a precise control of several boundaries within a single mesh and enables the analyst to consider several cracks [31]. Another remeshing technique, in which the high quality two-dimensional meshes are generated by defining the outer boundary geometric domains using Planar Straight Line Graphs, was proposed in [45].

The numerical manifold method (NMM) [33] can also be applied to the crack propagation analysis. The numerical manifold method (NMM) [33] is a combination of the FEM and the discontinuous deformation analysis (DDA) [34]. It provides a unified framework for both continuous and discontinuous problems using mathematical covers that are independent of the physical domain of the problem. The NMM has been used for solving discontinuous problems involving stationary crack and crack propagation. However, the crack tips are constrained to stop at the edges of the element, which will reduce the accuracy if a crack tip happens to stop inside the element. In order to improve the accuracy, the singular physical covers containing the crack tips are enriched with the asymptotic crack-tip functions. Then the stress intensity factors (SIFs) can be accurately evaluated by using a regular and relatively coarse mathematical cover system [35].

It is possible to apply a meshless approach to model the growth of cracks. The meshless methods require only a description of geometrical boundary and a set of nodes, but do not need any mesh. A number of meshless methods have been proposed, such as the Meshless Local Petrov–Galerkin method (MLPG) [36] and the Element Free Galerkin (EFG) method [35]. The EFG can provide highly accurate solutions for crack propagation problems using the moving least-squares interpolation. However, more nodes must be added along the crack path when crack growth is modelled [36].

The boundary element method (BEM) is another numerical method that is widely applied to model crack propagation. The BEM has been recognised as an accurate and efficient numerical technique for solving crack growth problems. In fracture mechanics analyses, the BEM requires only boundary and the crack surface discretisation. Therefore, the BEM requires less computational effort to generate new elements to model crack growth. The BEM is also particularly efficient in mixed-mode crack propagation problems because remeshing can be avoided [38]. However, the BEM cannot easily model the coalescence and localisation phenomena.

In order to overcome the difficulties with remeshing of the FEM in modelling propagation of cracks, some modifications to the FEM have been developed within the framework of the partition of unity method (PUM) [37], such as the extended finite element method (XFEM). This method, which can be used to solve discontinuous mechanical problems, was proposed in 1999 [40]. It was shown that the XFEM is effective in modelling discontinuities in problems such as interface growth, crack propagation, and complex fluid material [40]. There are three main advantages for the extended finite element method [38]. First, the details of substructure are neglected, and the mesh is generated according to the geometry of model. Second, in order to track the growth of cracks other methods, such as the level set method, are adopted. Then, the location of cracks is accurately determined. Finally, in order to model the propagation of cracks, only the shape function of the element containing the crack is modified. Therefore, the properties of stiffness matrix remain the same as its properties in the standard finite element method. The concept of XFEM was introduced as a technique to model crack growth without remeshing [38–40]. The XFEM is based on the partition of unity property. Local enrichment functions, with additional degrees of freedom, are included in the standard finite element approximation. However, the XFEM requires some external criteria in order to predict crack growth. Moes et al. [45] incorporated discontinuous displacement enrichment using Heaviside functions to capture the displacement discontinuity near a crack tip. The concept of a stress intensity factor was employed to determine when the crack growth occurred, and the maximum circumferential stress criterion was applied to determine the direction of crack growth. Later, a cohesive law was used to model crack growth in the XFEM. Tractions on the crack surface were governed by the traction-separation law [41].

The discrete (or distinct) element method (DEM) is a discontinuous analysis method proposed by Cundall et al. [47] for studying two-dimensional slope stability problems in jointed rock masses. In DEM the objects are modelled as systems of discontinuous bodies interacting with each other. Based on the Newton's second law, the equations of motion are integrated using an explicit time-marching scheme. The discrete element method can take into account many kinds of discontinuities and material failure characterised with multiple fractures, making it a suitable tool to study rock fracturing.

In many mechanisms of geotechnical failure, the overall rupture surface is formed by the union of several pre-existing discontinuities that propagate by coalescence process. It is notable that crack propagation under compressive conditions is caused by tensile stresses that act near the tips of pre-existing cracks [42]. Under these conditions, propagation is initiated, forming primary tensile cracks that propagate in the direction of the applied load (wing cracks) [43–45]. In studies performed by Park and Bobet [10] on gypsum specimens subjected to uniaxial compression, up to three types of fractures propagated as a result of the applied load; primary cracks generated by tension (Mode I), which initiated at the edges of the crack and contained no pulverized material, and two types of secondary cracks (coplanar and oblique), which were generated by shear (Mode II) and feature pulverized material on the failure surface. These cracks are depicted in Fig. 1.

Coalescence is defined as the connection of pre-existing cracks and discontinuities in a rock material via propagation. The connection type depends on the position of the cracks and the type of propagation involved. Several authors have studied this mechanism. For example, Ghazvinian et al. [48–52] analysed the influence of the distance between two co-planar cracks in the coalescence between them using the shear test results and numerical