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Investigating the effects of micro-defects on the dynamic properties of rock using Numerical Manifold method

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HIGHLIGHTS

- Decomposing displacement technique is used to calculate the stress intensity factors.
- A dynamic crack growth criterion is adopted in the Numerical Manifold method.
- Effects of micro-crack properties on rock dynamic mechanical properties are studied.
- Effect of confining stress on the granite dynamic behavior is investigated.

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ABSTRACT

In this study, the Numerical Manifold method (NMM) is extended to investigate the effects of micro-defects on the dynamic mechanical properties of rock under different strain rates. The displacement decomposition technique is incorporated in the NMM to estimate the mixed mode stress intensity factors at the crack tip. A dynamic crack growth criterion is also incorporated in the NMM for crack growth analysis. The developed NMM is first validated by a simple sliding crack model. The developed model is then applied to investigate the effects of the micro-cracking properties such as initial micro-crack length, initial micro-crack inclination angle and initial micro-crack separation distance on the dynamic mechanical properties of a granite under different strain rates ranging from 10^{-4}/s to 10^{0}/s. The effect of confining stress on the granite dynamic strength is also investigated. Simulation results illustrated that the initial micro-crack length and the confining stress have a significant effect on the dynamic strength. The effect of micro-crack separation distance, on the other hand, is heavily dependent on the ratio of separation distance to the initial micro-crack length.

1. Introduction

In blasting, earthquake, landslide and rock bursts, rocks are subjected to various loads at different strain rates. Therefore, the dynamic behavior of rock materials under different strain rates is of great concern. Since rock material is typically inhomogeneous, containing initial micro-defects, such as micro-cracks, cleavages and grain boundaries. As defined by Simmons and Richter [1], a micro-crack is: "an opening that occurs in rocks and has one or two dimensions smaller than the third. For flat microcracks, one dimension is much less than the other two and the width to length ratio, termed crack aspect ratio, must be less than 10^{-2} and is typically 10^{-3}–10^{-5}. The length typically is of the order of 100 μm or less." Micro-cracks not only significantly influence wave propagation through rock, but also significantly affect the dynamic mechanical properties and failure process of the rock [2–5]. Therefore, it is important to quantitatively understand the effects of these micro-defects on the mechanical properties and failure process in rocks under different strain rates.

Extensive studies have been conducted to investigate the influences of the micro-defects on the mechanical properties and failure processes of rock, which are based on either experimental studies or theoretical studies. Using the scanning electron microscope (SEM) and acoustic emission (AE) examinations, it is revealed that the failure process and macroscopic mechanical properties of rock material are dominated by the growth and nucleation of these micro-cracks [6–11]. Based on these observations, various micromechanics-based crack models [10–12] have been proposed and successfully adopted to study the mechanical properties of rock materials under various loading conditions theoretically [12–22].

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Compared with theoretical and experimental studies, numerical modeling provides a convenient and economical way to study the effects of micro-cracks on the dynamic behavior of rock materials, especially for complicated cases where theoretical solutions are impossible to obtain and experiments are difficult to conduct.

Nowadays, different numerical tools are available for modeling continuous-discontinuous rock masses. The most popular ones are the finite element method (FEM), boundary element method (BEM), finite difference method (FDM), and discrete element method (DEM), etc. For example, joints or faults are modeled as a kind of special "joint elements" in FEM [23], whereas in FDM joints or faults can be simulated using slide-lines [24]. However, these treatments are inefficient when numerous discontinuities exist. Another big issue for continuum-based methods is its incapability of handling the response of a fractured rock mass under dynamic loading [25]. By treating rock material as an assemblage of independent grains, the discontinuities along the grain boundaries can be easily captured by DEM. By simply de-bonding the elements, the nucleation of cracks is simulated. Due to its capability in dealing with discontinuities, DEM has also become popular for studying the cracking behavior in rock [26–33]. However, the crack trajectories predicted by DEM are not arbitrary, but dependent on the prior block discretization configuration.

Modeling cracking problems demands high performance numerical methods and computer codes, especially for handling the fracturing and dynamic behavior. It is often unnecessary restrictive to using only one method to provide adequate representations for the most significant features and processes [34]. The situation becomes even worse for rock since countless micro-cracks are generally distributed over the bulk of rock material and propagate under dynamic loading. Due to the geometric features of micro-cracks in rock, their effects on the macroscopic mechanical properties of rock material is usually modeled either by using micro-crack based continuous damage models [35–39] or direct simplification of the micro-cracks [40,41] method.

As a hybrid method, the Numerical Manifold method (NMM) [42,43], which has been successfully extended to simulate 2D cracking processes [44–53], 2D cracking involved failure processes [54–56] and 3D rock failure processes [57,58], can easily deal with problems with thousands of micro-cracks. Therefore, not only the growth and nucleation of these micro-cracks can be captured, but also the interaction between these micro-cracks can be considered directly.

In this study, the NMM is employed to investigate the dynamic mechanical properties of rocks under different strain rates. The displacement decomposition technique is incorporated in the NMM to estimate the mixed mode stress intensity factors at the crack tip. A dynamic crack growth criterion is also incorporated in the NMM for crack growth analysis under high loading rate. The developed NMM is first validated by a simple sliding crack model. It is then applied to investigate the effects of the micro-crack properties such as initial micro-crack length, initial micro-crack inclination angle and initial micro-crack separation distance on the dynamic mechanical properties of a granite under different strain rates ranging from 10^{-4}/s to 10^{0}/s. The effect of confining stress on the granite dynamic behavior is also investigated.

2. Brief introduction of the NMM

Compared with other partition of unity (PU) methods [59], the most distinguishing feature of the NMM is the adoption of a two cover (mesh) system, on which the nodes and elements are generated. Details of the finite cover systems and cracking evolution techniques can be found in previous Refs. [48,52,60–62]. In the following part, a brief introduction of extending the NMM for linear elastodynamics analysis and calculation of the stress intensity factor is presented.

2.1. Finite cover systems [61, 62]

The finite cover systems [42] in the NMM include both the mathematical cover (MC) and physical cover (PC). The MC, which is used to build PCs, can be of an arbitrary geometry. However, the whole mathematical mesh should be large enough to cover the whole physical domain. The physical mesh includes all the physical boundaries of a problem, such as the joints, cracks, grains, blocks and interfaces of material zones. It is a unique portrait of the physical domain and defines the integration fields of a problem. The intersection of the MC and the physical mesh, or the common area of the two systems, defines the region of the PCs. A common area of these overlapped PCs or an independent PC corresponds to an element in the NMM.

The basic constructing procedures of the finite covering system employed in the NMM are illustrated in Fig. 1. As illustrated in the figure, firstly, the mathematical mesh is formed from the two MCs (rectangular MC M_1 and triangular MC M_2). By intersecting the formed mathematical mesh with the physical boundaries, the PCs are then constructed. For example, intersecting the MC M_1 with the domain boundary Γ_u and the fracture boundary Γ_F leads to the formation of the PCs P_1^1, P_1^2 and P_1^3. Similarly, intersecting MC M_2 with the domain boundary Γ_u and fracture boundary Γ_F leads to the formation of PCs P_2^1 and P_2^2. Since the manifold elements are the common part of these overlapped PCs or an independent area of a PC, the NMM elements are constructed by overlapping these PCs. For example, elements E_3 and E_4 are formed from the overlapping area of P_1^2 and P_2^2, P_1^3 and P_2^2, respectively. Elements E_1, E_2 and E_5 are formed from the independent area of P_1^2, P_1^3 and P_2^2, respectively.

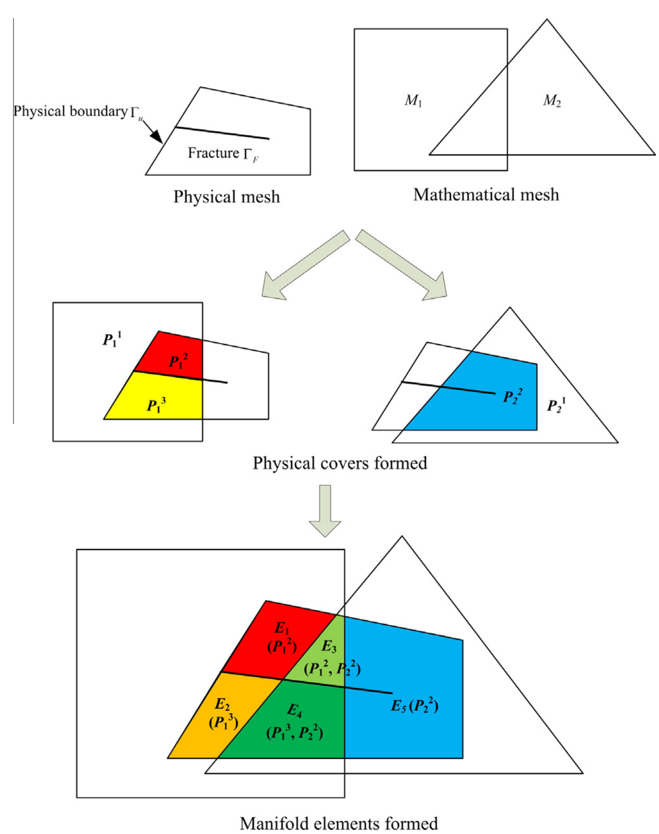

Fig. 1. Illustration of the finite cover system in NMM (modified from [62]).