Engineering Geology 197 (2015) 198–210

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Numerical investigation of rock heterogeneity effect on rock dynamic strength and failure process using cohesive fracture model

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ARTICLE INFO

Article history:
Received 3 January 2015
Received in revised form 23 August 2015
Accepted 31 August 2015
Available online 4 September 2015

Keywords:
Cohesive fracture model
Rock dynamic failure
Rock dynamic strength
Rock heterogeneity

ABSTRACT

In this study, a cohesive fracture model (CFM), which assumes rock material as assemblage of deformable grains joining together at their cohesive boundaries, is developed to simulate rock fracture and failure behavior in terms of mineral and cement properties. To better represent the structural bonds between the particles and the heterogeneity of rock material, a user-defined material model (UMAT) for the cohesive element with stochastic strengths is incorporated into the developed CFM. The capability of the developed model for rock fracture problems under both static and dynamic loads is first explored. Based on the developed model, the heterogeneity effect of rock on its dynamic failure process and dynamic strength is then studied. The results demonstrate that the developed CFM can be used to investigate the rock fracture problems under both static and dynamic loads. The heterogeneity of rock material not only affects the rock dynamic failure process but also leads to an increase of rock dynamic strength.

Symbols

$\mathbf{T}_C$	Cohesive traction vector	$\mathbf{T}_e$	Traction vector on the external surface
$\mathbf{u}$, $\ddot{\mathbf{u}}$	Displacement and acceleration vectors	R^{ext}, R^{int}	External and internal forces
$\boldsymbol{\sigma}$, $\boldsymbol{\varepsilon}$	Stress and strain vectors	$\mathbf{M}$	Mass matrix
$\bar{\mathbf{t}}$	Applied force array	t	Time
β, γ	Newmark's parameters	h_e	Element mesh size
λ, μ	Lame coefficients	ρ	Material density
δ_{eff}	Effective relative displacement	k_t, k_s	Initial contact stiffness in tension and shear
t_c	Contact tensile strength	c_c, ϕ_c	Cohesion and friction angle of contact
D	Contact damage	δ_1, δ_2, δ_3	Tangential and normal relative displacements
δ_{ct}	Critical tensile displacement of contact	δ_{ut}	Ultimate tensile displacement of contact
δ_c	Critical shear displacement	$k_{penalty}$	Penalty stiffness
η	Micro-mechanical strength of cohesive element	η_0	Average micro-mechanical strength of cohesive element
λ	Homogeneity index	E, ν	Young's modulus and Poisson's ratio
r	Distance away from the crack tip	C_g	Model geometry parameter
F_P	Force F_P acting on a plane segment	P_{max}	Amplitude of the incident compressive stress
S_w	Wave propagation velocity	f_{td}	Dynamic tensile strength

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http://dx.doi.org/10.1016/j.enggeo.2015.08.028
0013-7952/

1. Introduction

The dynamic failure of rock is a highly significant and timely problem in solving engineering problems involving dynamic loading conditions such as blasting, earthquake, landslides, rock bursts and defense engineering involving nuclear blasting. It is therefore essential to understand the fracture initiation and propagation under different loading rate to provide better understanding of rock failure process and dynamic strength in the engineering fields.

Since the early studies of Rinehart (1965), the loading rate-dependent dynamic strength, has been widely studied in the following decades. Dynamic laboratory measurements using compressive (Blanton, 1981; Brace and Jones, 1971; Frew et al., 2001; Green and Perkins, 1968; Kumar, 1968; Li et al., 2004; Lindholm et al., 1974; Olsson, 1991; Xia et al., 2008), torsion (Lipkin and Grady, 1977) and tension (Cho et al., 2003; Goldsmith et al., 1976; Khan and Irani, 1982; Kubota et al., 2008; Wang et al., 2006, 2009) Hopkinson bar techniques have identified that rock material strengths generally increase with increasing loading rate, especially when the strain rate exceeds 1.0 s^{-1}. Experiments on specimen containing pre-existing flaws have revealed that the dynamic fracture toughness, which describes the ability of a material containing a crack to resist fracture from propagation, is also dependent on the strain rate (Dai et al., 2011; Hodulak et al., 1980; Kalthoff and Burgel, 2004; Zhang and Zhao, 2013, 2014; Fan et al., 2012, 2013b). Though these studies provided phenomenological descriptions of dynamic effects in rock behavior, their attempts on rock fracture and failure are limited to macroscopic measurements. The micromechanics behind the observed rate dependent quality such as the initiation, propagation and coalescence of the crack under dynamic loading conditions have not been fully explored.

Based on experimental studies, several micromechanical fracture models have been developed to describe these rate dependent fracturing and failure mechanisms. Al-Hassani et al. (1997) proposed a simple theoretical model to characterize the average continuum behavior of the dynamic spalling process. Many damage models have been developed to study the dynamic damage evolution of rock with micro-cracks (Chong et al. 1980; Grady and Kipp, 1979; Huang et al., 2002; Li et al., 2001, 2009; Taylor et al., 1986). However, these models still cannot explicitly describe the dynamic initiation, growth and connection of micro-cracks at the grain level.

Subsequent to rapid advancements in computer technology, a number of numerical techniques have been developed to realistically model the cracking and failure processes of rock like material under dynamic loading. According to their inherently assumption differences, these methods can be categorized into continuum-based method, e.g. Finite Element Method (FEM) (Camacho and Ortiz, 1996; Dai, 2011; Liang et al., 2004; Liu et al., 2004; Zhu and Tang, 2006), Finite Difference Method (FDM) (Chen et al., 2004, 2007; Granet et al., 2001), Boundary Element Method (BEM) (Pan et al., 1997; Saez and Dominguez, 2001), discontinuum-based method, e.g. Discrete Element Method (DEM) (Cho et al., 2007; Hentz et al., 2004; Kazerani et al., 2010b; Zeghal and Lowery, 2002; Zhang and Wong, 2013), Discontinuous Deformation analysis (DDA) (Hatzor et al., 2004; Ning et al., 2011b; Zhang and Lu, 1998; Z. Zhao et al., 2011), Distinct Lattice Spring Model (DLSM) (Kazerani et al., 2010a; G.-F. Zhao et al., 2011; Zhao et al., 2014), coupled methods, e.g. coupled FEM/DEM (Al-Shayea et al., 2000; Karami and Stead, 2008; Morris et al., 2006), BEM/DEM (Lorig et al., 1986; Wei and Hudson, 1998), FEM/DDA(Chiou et al., 2002; Fan et al., 2013a; Ning et al., 2011a; Wu et al., 2013; Zhang et al., 2010; Zheng and Xu, 2014; Zheng et al., 2015) and Mesh-Free Methods, e.g. Smoothed Particle Hydrodynamics (SPH) (Pramanik and Deb, 2015), Cracking Particle Method (Rabczuk et al., 2009), General Particle Dynamics (GPD) (Zhou et al., 2015a, b).

Mechanical behavior of rock, as a heterogeneous and grained composite material, is deeply affected by its microstructure, which is constituted by minerals (grains) and mineral cement. As experimentally observed by Whittles et al. (2006), rock fractures through the weakest mineral, grains interface, or mineral cement. To more realistically reflect the rock micro-mechanical effect on the rock failure process, a cohesive fracture model (CFM), which assumes rock material as assemblage of deformable grains joining together at their cohesive boundaries, was first proposed by Dugdale (1960). Due to its ease of implementation and the clear physical picture, the CFM has gained popularity over the years and has also been successfully used for modeling fracture related problems in geomaterials (Amarasiri and Kodikara, 2011; Hillerborg et al., 1976; Kazerani et al., 2012; Yao, 2012). However, few studies have examined mixed-mode fracture and most studies are still focused on mode-I case in geomaterials, especially under three-dimension (3D) condition.

In this study, a 3D based CFM, which takes both tensile and compressive-shear behavior into consideration is developed to simulate the rock fracture and failure behavior in terms of mineral and cement properties. To implement the CFM, the explicit dynamic FEM code LS-DYNA (Corporation, 2012) is selected due to its powerful capabilities in modeling dynamic problems and relative ease of development. A pre–processor program is developed to discrete the LS-DYNA generated deformable arbitrarily sized hexahedral particles (solid elements) and insert no thickness cohesive elements at particle boundaries in between. To better represent the structural bonds between the particles and the heterogeneity of rock material, a user-defined material model (UMAT) which differentiates the tensile contact behavior from compressive-shear behavior for the cohesive element with stochastic strengths is developed and incorporated into the LS-DYNA Solver by creating Dynamic Link Libraries (DLL) in FORTRAN environment. The developed CFM is then validated by three rock fracture problems under either static or dynamic load. Based on the developed model, the effect of micro-defects induced heterogeneity on rock failure process and strength under dynamic load is then studied.

2. Numerical modeling approach

In this section, a brief introduction of the adopted finite element framework is first given. The cohesive contact model and the implementation of the developed CFM in LS-DYNA are then introduced.

2.1. Explicit dynamic FEM

For a dynamic problem with cohesive tractions in body B_0, the weak form of the principle of virtual work can be expressed as (Roe and Siegmund, 2003):

$$\int_V \boldsymbol{\sigma} : \delta\boldsymbol{\varepsilon}\, dV + \int_V \rho\ddot{\mathbf{u}} \cdot \delta\mathbf{u}\, dV = \int_{S_i} \mathbf{T}_C \cdot \delta\mathbf{u}\, dS + \int_{\partial V} \mathbf{T_e} \cdot \delta\mathbf{u}\, dS + \int_V \mathbf{b} \cdot \delta\mathbf{u}\, dV \tag{1}$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor; $\boldsymbol{\varepsilon}$ is the infinitesimal strain tensor; V is the control volume; ρ is the material density; $\mathbf{u}$ is the displacement vector; and $\ddot{\mathbf{u}}$ is the acceleration vector. $\mathbf{T}_C$ is the cohesive traction vector; $\mathbf{T_e}$ is the traction vector on the external surface of the body; S_i is the internal boundary; ∂V is the external boundary of V; $\mathbf{b}$ is the body force vector.

By discretizing the body B_0 with constant stress solid hexahedral elements connected by four points cohesive elements, the discretization form of the principle of virtual work becomes:

$$\mathbf{M}\ddot{\mathbf{d}} + \mathbf{R}^{\mathbf{int}}(\mathbf{d}) = \mathbf{R}^{\mathbf{ext}}(\mathbf{t}) \tag{2}$$

where, $\mathbf{R}^{\mathbf{ext}}$ and $\mathbf{R}^{\mathrm{int}}$ are the external and internal force arrays; $\mathbf{M}$ is the mass matrix, and $\mathbf{d}$ is the nodal displacement array; $\mathbf{t}$ is the applied force array.

Integrate Eq. (2) along the time axis by the second-order accurate explicit scheme, the explicit version of the Newmark scheme is obtained taking the Newmark's parameters to be $\beta = 0.25$ and $\gamma = 0.5$, as

$$\begin{aligned} \mathbf{a_{n+1}} &= \mathbf{M}^{-1}\left(\mathbf{R^{ext}_{n+1}} - \mathbf{R^{int}_{n+1}}\right) \\ \mathbf{d_{n+1}} &= \mathbf{d_n} + \mathbf{v}_n\Delta t + \frac{1}{4}(\boldsymbol{\alpha_v} + \mathbf{a_{n+1}})\Delta t^2 \\ \mathbf{v_{n+1}} &= \mathbf{v_n} + \frac{1}{2}(\mathbf{a_n} + \mathbf{a_{n+1}})\Delta t \end{aligned} \tag{3}$$

where $\mathbf{v}$ and $\mathbf{a}$ are the material velocity and acceleration fields, respectively. In this scheme, the mass matrix $\mathbf{M}$ is lumped and diagonal.

To guarantee the stability of the time integration, the time step Δt must be chosen to be smaller than a critical value, $\Delta t_{\mathrm{stable}}$, which is determined by the dilatational wave speed and the mesh size as:

$$\Delta t = C\Delta t_{\mathrm{stable}} = C \min_{\mathrm{mesh}}\left(\frac{h_e}{\sqrt{(\lambda + 2\mu)/\rho}}\right) \tag{4}$$

where C is time step scale factor which is smaller than 1.0 with an ordinary value equal 0.1; h_e is the element mesh size; λ and μ are the Lame coefficients; ρ is the material density; and $\sqrt{(\lambda + 2\mu)/\rho}$ is the longitudinal wave speed in an unbounded medium.

2.2. Cohesive contact model

In the CFM, the specimen is discretized with ordinary continuum solid elements connected by the cohesive interface elements (Fig. 1a). The bond interfaces between two neighboring elements are treated as possible sites for cracks (Fig. 1b). The intermediate “glue material” of