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Numerical simulation of Brazilian disk rock failure under static and dynamic loading

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Abstract

A numerical simulator based on RFPA (Rock Failure Process Analysis) is used to study the deformation and failure process of a Brazilian disk of heterogeneous rock when subjected to static and dynamic loading conditions. In this simulator, the heterogeneity of rock is considered by assuming that the material properties of elements conform to a Weibull distribution; an elastic damage-based law that considers the strain-rate dependency is used to describe the constitutive law at mesoscopic scale; and a finite element program is employed as a basic stress analysis tool. The simulator is firstly validated by simulating the dynamic spalling of a homogeneous rock bar and by comparing with the theoretical and experimental results. Then, the failure process of a Brazilian disk of rock subjected to static and dynamic loading is numerically simulated, and the numerical results are compared with the available experimental results. Particular attention is given to the typical failure patterns of the rock disk when the incident compressive stress waves with different amplitudes are applied. The numerical simulation also identifies the failure mechanisms of rock during dynamic failure processes that are closely related to the propagation of the stress wave.

Keywords: Rock failure; Brazilian disk; Dynamic loading; Numerical simulation

1. Introduction

Better understanding of the dynamic fracture processes of rocks promises benefit in many areas from rock mechanics to mining engineering and earthquake prediction. It is essential to understand how fractures initiate and propagate under different loading conditions in order to provide understanding of rock fracture process that occur in the engineering fields. During the past several decades, researchers have carried out many dynamic tests of rock using the apparatus such as the Split Hopkinson pressure bar (SHPB). From these experimental investigations, it has been understood that the mechanical properties (or responses) and failure characteristics of rock are sensitive to the strain rate. It is also a well-established fact that rocks exhibit increases in strength as the loading rate or strain rate increases [1–11]. Based on these experimental results, failure criteria considering the strain rate effect of rocks are proposed [12,13]. However, not so well understood is the dynamic failure process and failure mechanism, which are closely related to the microstructural behavior in terms of activation, growth, and coalescence of cracks when the rock is subjected to different loading conditions.

With regard to the SHPB experiments, they are widely used to determine strain-rate dependency of the dynamic strength of rock, but not to study the failure process and failure mechanisms that are closely related to the stress wave propagation in heterogeneous rock.

Continuum damage mechanics is considered to be appropriate to describe the failure process resulting from dynamic loading. Based on this approach, many theoretical models were developed to study the dynamic damage evolution of brittle materials such as rock and

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Nomenclature

A	parameter to reflect the stress rate effect on strength
b	width of load-bearing strip
$\mathbf{C}$	damping matrix
D	diameter of rock disk
E, E_0	damaged and undamaged (initial) elastic modulus of element
f_{c0}, f_{t0}	dynamic compressive and tensile strengths, respectively, of element
f_{cr} , f_{tr}	residual dynamic compressive and tensile strengths, respectively, of element
f_{cs0}	static uniaxial compressive strength
k	ratio of tensile and compressive strength
$\mathbf{K}$	stiffness matrix
m	homogeneity index, shape parameter of Weibull distribution
$\mathbf{M}$	mass matrix
p	applied incident stress
p_{max}	amplitude of stress wave
$\mathbf{R}$	vector of externally applied loads
u	parameter of elements that conforms to Weibull distribution, such as elastic modulus and strength
$\mathbf{U}$, $\dot{\mathbf{U}}$, $\ddot{\mathbf{U}}$	displacement, velocity, and acceleration vectors of elements
u_0	scale parameter of Weibull distribution
ε	strain
ε_0	strain at peak stress
ε_1, ε_2, ε_3	principal strain
ε_{c0}	strain at the peak compressive stress
ε_{t0}	strain at the peak tensile stress
ε_{tu}	ultimate tensile strain
$\bar{\varepsilon}$	equivalent strain
ϕ	internal friction angle
η	ultimate tensile strain coefficient ($\eta = \varepsilon_{tu}/\varepsilon_{t0}$),
λ	residual strength coefficient ($\lambda = f_{tr}/f_{t0}$)
μ	Poisson's ratio
σ	stress
σ_1, σ_2, σ_3	principal stress
ω	damage variable

concrete with microstructures [12,14–20]. Most of these models are developed based on combining the theory of damage mechanics or fracture mechanics with some statistic treatment to account for the random distribution of microcracks. Because many micromechanical parameters such as crack density must be used to describe the crack distribution in these damage models, it is often difficult to implement such models in a numerical code [21]. Therefore, there is a real need for further developments in the material modeling of rock to reflect more closely the physical mechanisms responsible for failure.

In the numerical simulation with the discrete element method, the basic fracture patterns of rock and concrete subject to dynamic tension are captured [22]. But in the discrete element model, there is no accepted general method of averaging the contact displacement between particles in order to obtain the value of resulting macroscopic strain or stress [22]. The explicit non-linear finite element code DYNA 2D/3D is used to analyze a variety of dynamic problems, which is generally concentrated on collision analysis, such as an elastic sphere on an elastic–plastic metal material and sheet metal forming. Although DYNA 2D had been also used to calculate the response of jointed rock subjected to blasting [14,23], it was not focused on capturing the dynamic failure mechanism of rock.

In fact, the stress distribution and damage initiation in the rock is closely related to stress wave propagation; moreover, the local damage in rock can in turn affect the propagation of the stress wave. Numerical simulation of rock subjected to dynamic loading conditions requires the implementation of a constitutive relation capable of capturing the major features of the failure process during the propagation of stress waves. The Rock Failure Process Analysis (RFPA) Code, which had been developed and introduced by Tang [24,25] in many documents, has been successfully used to simulate the fracture process and failure mechanism of rock under static loading. In RFPA, in order to numerically denote the heterogeneity of rock, the rock sample is discretized into many mesoscopic elements and their material properties are conformed to the Weibull distribution [26,27]. The constitutive law of these mesoscopic elements is formed based on elastic damage mechanics. In cooperation with Professor Chau [28] at the Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, the author proposed a stress-rate dependent constitutive law and implemented it into the original RFPA code [24,25], and therefore the RFPA is extended for analyzing the failure process of rock under dynamic loading [28,29]. From January 2003 on, based on that, Zhu et al. [29] have made many further improvements in utilizing the faster finite element solver and introducing more boundary conditions, and all these have been also implemented into the original RFPA code [24,25]. Therefore, this upgraded simulator used in this study is also called RFPA.

The contribution of this work is to validate the simulator by reproducing the dynamic spalling of