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Dynamic response and failure mechanism of Brazilian disk specimens at high strain rate

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ABSTRACT

The effect of strain rate on the failure mechanism of rocks is one of the most important aspects in the field of rock dynamics and has been considered in many research works due to its extensive application. This study focuses on dynamic features and failure mechanism of Brazilian disk specimens under high-rate loading. For this purpose, particle flow code 2-dimensional (PFC2D) was used for simulation of Brazilian disk samples. The numerical models were validated by comparing with results of uniaxial compression, Brazilian and Split-Hopkinson Pressure Bar (SHPB) laboratory tests and it is demonstrated that the result of numerical modeling has a good agreement with those of the experimental measurements. The validated numerical model was used for further study of the mechanical behavior of rock specimen at high strain rate. The results of numerical models revealed that there are three different of failure modes for Brazilian disk specimens at different strain rate: (1) tensile splitting failure mode for specimen at strain rate smaller than 150 (1/s), (2) branching failure mode when strain rate varies in range of 150–600 (1/s) and (3) crushing failure mode when the strain rate increases to more than 600 (1/s).

1. Introduction

Study of dynamic response of rocks exposed to high-rate loading has been paid more attention in recent years due to its extensive applications for design of rock structures. On the other hand, mechanical characteristics of rocks under dynamic loading are strongly different from those loaded in static mode [1]. Dynamic response and failure mechanism of rock specimens have been considered in many rock engineering research works due to its extensive application [2–4]. It is revealed that the loading rate has a significant influence on mechanical properties of rocks. Rock peak strength, strain, and elastic modulus rise with the increase of loading rate. Crack branching or bifurcation is a common phenomenon in dynamic fracture which is observed in brittle and ductile materials [5]. With emphasis on the difference between static and dynamic failure, Zhu and Tang showed that more cracks are developed in rocks under dynamic loading compared to the static loading condition [6]. Under a high state of stress, the propagating crack can split into two or more branches and it can divide into a river delta crack pattern or micro-bifurcation [7].

Split Hopkinson Pressure Bar (SHPB) testing system is most commonly used to obtain the dynamic response of rock materials under high strain rate. Shan et al. [8] used SHPB apparatus to obtain complete dynamic stress-strain curve. They presented some typical complete dynamic curves for marble and granite and discussed the shapes of the curves in detail.

Li et al. [9] investigated the dynamic characteristics of granite under intermediate loading rate. They found that energy absorption of fractured samples increases linearly with strain rate. Also they claimed that energy absorption of the samples is consumed by forming new fracture surfaces of the fragments and the size distribution of the fragments is related to energy absorption.

Dai et al. [10] examined some fundamental issues associated with SHPB and showed that with proper experimental designs that address these issues, the dynamic compressive strength and dynamic tensile strength of rocks measured using SHPB are valid and reliable.

Xu et al. [11] numerically simulated dynamic fracturing of the notched semi-circular bend rock specimen in SHPB testing using discrete element method and evaluated in both micro level and energy points of view. They confirmed the validity of this model to reproduce the dynamic fracturing and the feasibility to simultaneously measure key dynamic rock fracture parameters, including initiation fracture toughness, fracture energy, and propagation fracture toughness.

Although, extensive research works have been done to evaluate failure of rock specimen under impact loading, there still remain many illusions on the failure process and failure mechanism of brittle rocks under dynamic loading especially at high strain rate. For example, the

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failure pattern of specimens subjected to impact loading has not been precisely explained. Most of the previous studies only emphasized that rock specimen under impact loading fragments to small pieces, and failure evolution process of specimens have not been discussed in detail.

On the other hand, a large number of rock engineering projects such as drilling, blasting and excavation are likely to subject to high-rate loadings [12–14]. Therefore, it is necessary to investigate the failure mechanism and dynamic response of rocks under high strain rate and it would be applicable for reliable simulation and safe design of rock structures [12]. The present study attempts to help in understanding failure mechanism of Brazilian disk specimen under diametrical compression at different strain rate more in depth.

Particle flow code 2-dimensional (PFC2D) was used to investigate the strain rate effect on failure evolution process of rock specimens. Firstly, some Laboratory tests were performed to calibrate the micromechanical properties of intact rock. Then, by use of an inverse-modeling approach, the rock micromechanical properties to be used in the PFC were calibrated to match the uniaxial compression, Brazilian and SHPB laboratory test results obtained for intact rock. In other words, the simulation was verified by comparing with experimental results. Finally, the validated numerical model was used for further study of the mechanical behavior of rock specimen at high strain rate.

2. Experimental tests

Experimental tests were performed on a homogeneous type of Sandstone. The main purpose for planning of the experimental tests is calibration of numerical model for obtaining a valid simulation. Uniaxial compression and Brazilian tests were performed under quasi-static rate and dynamic SHPB test was conducted at high strain rate.

Rock mechanics tests in the laboratory can be performed within a wide strain rate range. The loading rates of quasi-static tests are in the range of 10^{-7}–10^{-4} 1/s, whereas the strain rate obtainable in SHPB test is on the order of 10–10^4 1/s [15]. Static and dynamic loading tests have been conducted using different experimental apparatus on cylindrical rock specimens.

2.1. Quasi-static test

Uniaxial compression test for determination of elastic modulus and uniaxial compressive strength were performed based on ISRM suggested methods [16] on a cylindrical specimen with 124 mm and 54 mm in length and diameter, respectively. Also a cylindrical specimen of sandstone with 54 mm in diameter and 42 mm in thickness was applied for Brazilian tests. The loading rate was kept at 0.5 MPa/s during uniaxial compression test and a loading rate of 200 N/s applied for Brazilian test.

2.2. SHPB test

SHPB is an apparatus for testing the dynamic stress-strain response of materials and consists of a striker bar, an incident bar and a transmission bar, with a specimen sandwiched between the incident and transmission bars, as shown in Fig. 1. When the striker bar impacts the incident bar, a compressive pulse is generated and propagates towards the specimen. Upon reaching the interface between the incident bar and the specimen, a portion of the stress pulse travels through the specimen and then transmits into the transmission bar as a compression pulse, while the remaining portion is reflected back into the incident bar as a tension pulse. Strain gauges are usually mounted at midpoints along the length of the incident and transmission bars to record the stress pulses [17].

All the bars that used in SHPB are AISI 4340 alloy steel with 19.7 mm in diameters. Length of the striker bar, incident bar and the transmission bar are 20 cm, 153 cm and 120 cm, respectively. The specimen used for SHPB test is 40 mm in length and 20 mm in diameter. The SHPB tests were performed at 360 1/s strain rate. The results of performed quasi-static and SHPB tests are presented in Table 1.

3. Numerical modeling

The PFC2D computer program was used to simulate the dynamic response of rocks at high strain rate. In the discrete system of PFC2D, it is assumed that some rigid circular particles bonded together which simulate the interaction behavior between grains of rock. Simplifying the particle shapes to circles and the assumption of rigidity of the particles reduce the computational time of the simulation. Therefore, structures containing relatively large numbers of particles, with the use of Newton's second law, can be analyzed while the main behavior of the geomaterial can be captured [18]. The grains interact through normal and shear springs and the particles can translate, rotate and change their positions according to forces and moments acting on their centers. Generally, the interaction behaviors of particles can be simulated using three models including (1) contact-stiffness model, (2) slip model, and (3) bond model [19]. The stiffness model describes the elastic behavior that relates the contact force and relative displacements in the normal and shear directions. The slip model provides a friction coefficient, or residual friction angle, between particles, controlling the frictional strength of the particles. The bond model allows the particles to be cemented together and then it is suitable for simulation of intact rocks [20].

3.1. Bonding model in PFC

The Particles, in PFC, are not bonded by default, but they are allowed to be bonded together at contact with different bonding models. The two early bonding models supported in PFC are contact-bond model (CBM) and parallel-bond model (PBM).

Although the behavior of PBM for simulation of rocks is more reasonable than CBM and it has been applied to a wide range of problems related to rock, some basic limitation are associated with using PBM [20]. For example, one of the fundamental limitations of conventional bonding models (CBM and PBM) is an unrealistically low unconfined compressive strength to tensile strength (q_u/σ_t) ratio in the range of 3–7. This means that the conventional bonding models are suitable only for modeling of low brittle rocks [21], while a wide range of rocks contain a high degree of brittleness and the ratio of q_u/σ_t can be raised to 25. Many research works have been done to overcome this limitation and finally Potyondy [22] proposed a flat joint bonding model which can successfully simulate a brittle rock with the ratio of $q_u/\sigma_t = 24$. In flat joint bonding model each disk-disk contact simulates the behavior of a finite-length interface between two disks likes the parallel-bonded model. The main advantage of the flat joint model compared to the parallel-bond model is the partial interface damage and continued moment-resisting ability. In the flat-joint model, the interface is segmented and all the segments are bonded by default. When the bonded segments break, the interface behavior changes from a fully bonded state to a frictional state and then a fully broken interface can resist relative rotation while with breaking of the parallel bond model, interface behavior decays to a zero-length interface [22]. In the present study, flat joint model was used as a bonding model for simulation of the sandstone with the ratio of $q_u/\sigma_t = 13.74$.

3.2. Preparation and calibration of the numerical model

Generally, model generation in PFC2D involves four steps: (1) Particle generation (2) applying a low isotropic stress (3) elimination of floating particle, and (4) installation of bonding model.

A rectangular vessel consisting of planar frictionless walls with the same dimensions of laboratory test specimens is created, and an assembly of particles is generated to fill the vessel. The particles in the model were generated randomly with a normal particle-size