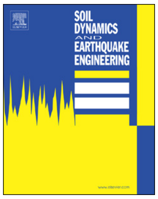
Soil Dynamics and Earthquake Engineering 110 (2018) 195–211

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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



Effects of strain rate on the mechanical and fracturing behaviors of rock-like specimens containing two unparallel fissures under uniaxial compression

Peng Feng, Feng Dai*, Yi Liu, Nuwen Xu, Tao Zhao

State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource and Hydropower, Sichuan University, Chengdu, Sichuan 610065, China

ARTICLE INFO

Keywords:
Strain rate dependence
Unparallel fissures
Mechanical behaviors
Crack coalescence
Discrete element method

ABSTRACT

Rocks containing unparallel fissures are likely to be subjected to dynamic loading resulting from earthquakes in various civil engineering structures. Since dynamic loading rate significantly affects the mechanical behaviors of fissured rocks, understanding the mechanical properties and fracture mechanism of fissured rocks under different loading rates is thus crucial in rock engineering applications. This study investigates the effects of strain rate on the mechanical and fracturing behaviors of rock-like specimens containing two unparallel fissures with varying inclination angles (α_2). Our experimental results demonstrate that α_2 and strain rate significantly affect the strength and deformation characteristics and the failure modes of fissured specimens. Both the strength and elastic modulus of the rock-like specimens highly depend on the strain rates, and the strain rate dependence is more sensitive for fissured specimen than that for the intact specimen. Under the same strain rate, the strength of fissured specimens decreases as α_2 increases up to 60°, and then increases. The fissured specimens with greater α_2 are characterized by higher elastic modulus. Furthermore, the fracture mechanism of the fissured specimen is numerically revealed, and the energy characteristics of fissured models are also analyzed on a micro-level.

1. Introduction

In geotechnical earthquake engineering, dynamic loadings are likely to be encountered in various rock structures [1,2]. Dynamic loads significantly affect the rock strength and deformation characteristics [3,4]. In practice, engineering rock masses generally contains numerous unparallel fissures with different orientations [5]. When subjected to the external loads, the initiation and propagation of stress-induced cracks from unparallel fissures are necessary precursor to the failure of engineering rocks, eventually leading to the notch formation, borehole breakout and abrupt failure [6]. Therefore, investigating the mechanical and fracturing behaviors of rocks containing unparallel fissures under dynamic loading is highly relevant to disaster prevention in rock engineering.

In the existing literatures, the studies on the mechanical behaviors of fissured specimens were mainly focused on the static loading [7–9]. Utilizing scanning electron microscope [10], computerized tomography (CT) scanning [11,12], digital image correlation [13], acoustic emission (AE) technology [14], the mechanical properties and fracturing characteristics of fissured specimens with varying fissure geometrical configurations were systematically studied. The preexisting fissures leads to the degradation of the mechanical parameters (e.g., strength and elastic modulus) of the rock or rock-like materials; and the degradation of mechanical parameters are significantly affected by geometrical parameters of fissures, such as fissure inclination angle, fissure length, spacing and density [15,16]. However, existing literatures on the dynamic mechanical properties of fissured specimens are limited. So far, some scholars investigated the effects of loading rate on the crack initiation and propagation of prismatic specimens containing a single fissure with different orientations [17,18]. They reported that the cracks generally initiate from the tip or periphery of preexisting fissure, forming an "X" shape on the surface of prismatic specimens at the end of loading regardless of the fissure inclination angle; the strength and the elastic modulus of specimens increase remarkably with increasing loading rate. Zou et al. [19] analyzed the strain rate effects on the mechanical behaviors of specimens containing two fissures. They reported that the initiation of first cracks in the fissured specimens subjected to dynamic loading is similar to those under static loading condition, whereas the secondary crack patterns quite differ from those under static loading.

It is noted that the fissures in the aforementioned studies are parallelly oriented. The mechanical properties and cracking mechanism of specimens containing unparallel fissures are rarely investigated. Some scholars investigated the effects of geometrical parameters of unparallel fissures on the mechanical behaviors of brittle materials, including fissure inclination angles [14,20] and crack openings [21]. Zhang et al.

---

* Corresponding author.
E-mail address: fengdai@scu.edu.cn (F. Dai).

https://doi.org/10.1016/j.soildyn.2018.03.026
Received 22 December 2017; Received in revised form 27 February 2018; Accepted 20 March 2018

[5] numerically analyzed the stress and crack coalescence of specimens with two unparallel fissures which are completely overlapped, partially overlapped and not overlapped. They found that the mechanical behaviors of specimens with unparallel fissures quite differ from that of specimens with parallel fissures. Compared with specimens with parallel fissures, the stress distribution in the bridging region of unparallel fissures is more complicated, which significantly affects the crack initiation and coalescence modes between preexisting fissures.

Apart from laboratory experiments, myriads of numerical methods have also been employed to investigate the mechanical behaviors of fissured specimens subjected to different loading conditions, including finite element method (FEM) [22], discrete element method (DEM) [23,24], peridynamic method (PD) [25,26], extended finite element method (XFEM) [27–29], general particle dynamics (GPD) [30,31]. Among these methods, DEM has been widely employed to investigate the crack propagation and the failure patterns of rock materials under static loads [32–34], the generated acoustic emissions during rock fracture [35–37], and brittle fracture under dynamic loading [38–40]. Although in DEM, fracture is closely related to the size of elements, and cross effect exists due to the difference between the size and shape of elements with real grains [41], the DEM method can directly and conveniently simulate the micro-cracks initiation and macro-fractures formation by bond breakage between particles, instead of using fracture mechanics theories where complex mathematical equations relevant to the stress intensity factor at the crack tip should be implemented [23].

According to the available literatures, effects of strain rate on the mechanical behaviors of specimens containing unparallel fissures have never been systemically studied. In this study, we conducted a series of uniaxial compression tests on fissured specimens with different inclination angles under the strain rates varying from $10^{-4}\ s^{-1}$ to $10^{-2}\ s^{-1}$. This range of strain rates (i.e., $10^{-4}\ s^{-1}$ to $10^{-2}\ s^{-1}$) covers the main strain rates of rock-like materials experienced by earthquake loading [42,43]. Since directly observing the fracture process of fissured specimens in laboratory tests still remains a challenge due to the limitations of experimental techniques, discrete element method (DEM) is employed to reveal the progressive fracture mechanism of fissured specimens. The remainder of this text is organized as follows. Section 2 briefly introduces the experimental and numerical approaches, including the specimen preparation, the testing procedure and the energy calculation. The experimental and numerical results are presented and discussed in Sections 3 and 4, respectively. Section 5 summarizes the whole study.

2. Specimen preparation and testing

2.1. Specimen preparation

Since directly fabricating fissures in natural rocks is difficult without inadvertently damaging the experimental specimen [44], artificially rock-like materials are usually utilized to simulate fissured rock specimens in laboratory experiments. In this study, rock-like materials are composed of Portland cement, standard sand, silicon powder, water and water reducing agent, and the mass proportion of $M_{\text{Portland cement}}$: $M_{\text{standard sand}}$: $M_{\text{silicon powder}}$: M_{water}: $M_{\text{water reducing agent}}$ is 1: 1.2: 0.15: 0.35: 0.015. The standard sand plays a role as grains in the specimen influencing the frictional behavior of synthetic material, and Portland cement acts as the adhesive material between the grains [45,46]. The dimensions of prismatic specimens containing two unparallel fissures are selected as 100 mm × 100 mm × 200 mm (height × breadth × thickness). The uniaxial compression strength, tensile strength and the elastic modulus of this rock-like material are 64.8 MPa, 6.1 MPa and 10.34 GPa, respectively. As shown in Fig. 1, the fissure geometry is defined by five geometrical parameters: fissure length (b), fissure inclination angle I (α_1), fissure inclination angle II (α_2), bridging angle (β) and rock bridge length (d). To comprehensively investigate the effect of fissure inclination angle II on the mechanical behaviors of fissured specimen, the fissure inclination angle II (α_2) are designed as 30°, 45°, 60° and 75°. Whereas, the other fissure parameters, i.e., the fissure inclination angle I, fissure length, bridging angle and rock bridge length are fixed to 45°, 15 mm, 30° and 20 mm, respectively. Moreover, a series of intact rock-like specimens are prepared and tested to provide the referenced mechanical parameters for fissured specimens.

To remain the mechanical properties of rock-like specimens as consistent as possible, the manufacturing procedures are strictly controlled: (I) fully mixing all solid ingredients and adding the appropriate water, and then sufficiently stirring; (II) daubing the release agent inside the fabricated mold to ensure the specimen not sticking to the mold (Fig. 2a); (III) inserting steel sheets (length × thickness = 15 mm × 0.4 mm) into the corresponding slots in the fabricated mold; (IV) pouring the synthetic materials into the fabricated mold, and then vibrating the mold on a shaking table to minimize the air bubbles in the rock-like materials; (V) removing the metal sheets from the mold after 10 h and disassembling the mold after 24 h; (VI) placing rock-like specimens into a special curing room for 28 days. The prepared fissured rock-like specimens with designed geometrical configuration are shown in Fig. 2b.

2.2. Test schemes and procedure

Uniaxial compression tests of rock-like specimens are conducted utilizing the MTS-793 rock testing system (Fig. 3). This testing system provides closed-loop control on the servo-hydraulic equipment, including software applications and hardware components; it has a 2750 kN and a 2500 kN load capacity for static and dynamic loading, respectively. Specimens are sandwiched between two loading platforms. To minimize the end effect, two Teflon films coated with petrolatum are glued on the two loading ends of specimens. The axial load and displacement of specimens can be simultaneously recorded during the entire testing process. Different strain rates are performed by varying the loading velocity of platform. The static load is applied in a displacement-controlled condition with a loading velocity of 0.005 mm/s, corresponding to a strain rate of $2.5 \times 10^{-5}\ s^{-1}$. The Dynamic loads are applied by varying the loading velocity from 0.02 to 2 mm/s, corresponding to strain rates from $10^{-4}\ s^{-1}$ to $10^{-2}\ s^{-1}$. The detailed testing scheme of fissured specimens with different loading conditions is tabulated in Table 1. Furthermore, an industrial camera (JAI SP5000M-USB) is employed to monitor and characterize the fracturing behavior of specimens during the entire testing process. The resolution of image obtained by this camera is 800 × 1400 pixels.

2.3. DEM and energy definition

The open-source DEM code ESyS-Particle [47] is employed to numerically evaluate the fracture mechanism of fissured specimens by analyzing the spatial development of cracks and stress distribution in the numerical model. The fissured specimen is modeled by an assembly of rigid particles bonded together at their contact points. Once the maximum tensile /shear stress surpass the tensile /shear strength of bond, the bond breaks and forms a micro-crack between two adjacent particles. Meanwhile, bond breakages induce the immediate decrease in macro stiffness of the fissured model. During the numerical simulation, the discrete particles in the numerical model have finite displacements and rotations. The Newton's second law is utilized to describe the individual motion of each particle, and the interaction between particles is defined by a force-displacement law applied to each contact [48]. Furthermore, this numerical system can provide a more straightforward access to tracing all kinds of energies in the fissured model. The total input energy (E), strain energy (E_s), friction energy (E_f), and kinetic energy (E_k) in the numerical system can be recorded via Eqs. (1)–(4) [32,39]:

$$E = \sum_{N_i} (F_i \cdot ds + M_i \omega_i) \tag{1}$$