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Dynamic response of a rock fracture filled with viscoelastic materials

W. Wu [a,*], J.B. Zhu [b], J. Zhao [a]

[a] Ecole Polytechnique Fédérale de Lausanne (EPFL), School of Architecture, Civil and Environmental Engineering, Laboratory of Rock Mechanics (LMR), CH-1015 Lausanne, Switzerland
[b] Graduate Aeronautical Laboratories and Department of Mechanical and Civil Engineering, California Institute of Technology, Pasadena, CA 91125, USA

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ABSTRACT

Rock fractures filled with viscoelastic materials, such as sand, usually contribute to rock mass instability under the influence of seismic waves and dynamic loads. The purpose of this study is to verify that the specific fracture stiffness and the specific initial mass of the filling sand are two key fracture parameters in interrelating the physical, mechanical and seismic properties of a rock fracture filled with dry sand. A series of dynamic tests using a split Hopkinson rock bar was conducted on a simulated sand-filled fracture. The experimental results show that stress wave attenuation across the filled fracture is strongly affected by wave reflection and transmission at the fracture interfaces and the dynamic compaction of the filling sand. With the comparison between the analytical predictions by the displacement discontinuity model and the displacement and stress discontinuity model and the experimental results from the laboratory tests, it is found that both models can predict a filled fracture with a smaller thickness (i.e., less than 10 mm). The displacement and stress discontinuity model may be used to predict a fracture with a larger thickness by considering the specific initial mass of filling materials. The wave transmission coefficient for a filled fracture generally increases with increasing specific fracture stiffness.

1. Introduction

Rock fractures, including the non-welded contact and filled fractures, universally exist in rock masses. Fracture displacement (e.g. opening, closure, and slip) has long been recognized as resulting in rock mass instability (Zhao, 1997; Indraratna et al., 2010). When stress waves propagate across fractured rock masses, fractures are commonly considered as displacement discontinuity boundaries (Schoenberg, 1980; Cai and Zhao, 2000). Each fracture is treated as a non-welded contact with negligible thickness compared with the incident wavelength. The specific fracture stiffness is the link parameter between continuous stresses and discontinuous displacements.

Although the displacement discontinuity model (DDM) has been widely adopted to investigate the dynamic response of a rock fracture, it may be imprecise to study a fracture filled with viscoelastic materials, such as weathered rock, sand and clay. Rokhlin and Wang (1991) used a mass per unit area of filling materials in the boundary conditions of two solid semi-spaces separated by a viscoelastic layer. The stress across the filling layer thus becomes discontinuous, due to the viscoelasticity that expressed by an imaginary part in the elastic constants. Meanwhile, the thickness of filling materials may not be overlooked compared with the wavelength. A newer and more precise model to describe the boundary conditions of a filled fracture, the displacement and stress discontinuity model (DSDM), has been developed by Zhu et al. (2011). It proposes that the stress discontinuity across a filled fracture is caused by the specific initial mass of filling materials and the displacement discontinuity is determined by the transmitted stress and the specific fracture stiffness.

There are many experimental methods to investigate stress wave generation and propagation across artificial rock fractures, such as an ultrasonic wave (Zhao et al., 2006a; Li and Zhu, 2012) and a pendulum hammer (Leucci and Giorgi, 2006; Li and Ma, 2009). In this study, a split Hopkinson rock bar (SHRB) apparatus (Wu et al., 2012, 2013) was used to study the effects of fracture properties and loading conditions on the dynamic response of a rock fracture filled with dry sand. The advantages of this technique include the following: (1) characterization of the interaction between a stress wave and rock fractures; (2) observation of a low-frequency wave generation and propagation in a rock medium; (3) measurement of the stress–time responses of fracture interfaces independently, considering dynamic stress non-equilibrium across a filled fracture. Furthermore, the low tensile strength of rock materials can withstand a low loading rate impact, which is suitable for the study of stress wave propagation across rock fractures. A high loading rate impact is usually provided by a conventional split Hopkinson pressure bar (SHPB) (Wu et al., 2010; Chen and Song, 2011), which may induce fracturing and fragmentation of rock materials. It is thus unnecessary to consider the fracture response and should focus on the material behavior.

The purpose of this study is to verify that the specific fracture stiffness and the specific initial mass of filling materials interrelate the physical, mechanical and seismic properties of a fracture filled with viscoelastic materials. The fracture thickness is a fracture physical property, the

* Corresponding author. Tel.: +41 216933962; fax: +41 216934153.
E-mail address: wei.wu@epfl.ch (W. Wu).

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filling material type determines the specific fracture stiffness, which reflects a fracture mechanical property, and the wave transmission coefficient represents a fracture seismic property. Dry quartz sand was used to represent viscoelastic materials. The experimental investigation on the filled fracture was performed with various fracture properties and under different loading conditions, including fracture thickness, particle size of the filling sand, and loading rate of an incident wave. The experimental results are then compared with the analytical predictions by the DDM and the DSDM. This study lastly discusses the key fracture parameters in interrelating the physical, mechanical and seismic properties of a filled fracture.

2. Analytical models

In the DDM (Cai and Zhao, 2000), a rock fracture is considered as an interface between two elastic half-spaces with the same seismic impedance. When a normally incident P-wave propagates across a single rock fracture, the stresses across the fracture are continuous, whereas the displacements are discontinuous and equal to the stress divided by a constant normal specific stiffness

$$\begin{aligned} &\sigma^{-}(t)=\sigma^{+}(t)=\sigma(t) \\ &u^{-}(t)-u^{+}(t)=\frac{\sigma(t)}{k_{\mathrm{n}}} \end{aligned} \tag{1}$$

where σ is the normal stress, u is the displacement along the normal direction, k_{n} denotes the specific fracture stiffness, which is the stress change per unit fracture closure, and the superscripts "−" and "+" denote the front and rear fracture interfaces, respectively.

The wave transmission coefficient for one-dimensional P-wave propagation across the fracture with linear deformation is described as

$$T_{\mathrm{d}}=\frac{2\left(k_{\mathrm{n}}/Z_{\mathrm{p}}\omega\right)}{-i+2\left(k_{\mathrm{n}}/Z_{\mathrm{p}}\omega\right)} \tag{2}$$

where i is the imaginary unit, Z_{p} is the seismic impedance of the rock material for the P-wave, which is the product of the rock density, ρ, and the longitudinal wave velocity, c, and ω is the wave angular frequency.

In the DSDM (Zhu et al., 2011), for a rock fracture filled with dry sand, the Kelvin model, consisting of one spring and one dashpot in parallel, can be adopted to describe the dynamic response of the filled fracture. The specific viscosity is set to zero for a fracture filled with dry sand. Thus the stress and displacement boundary conditions become

$$\begin{aligned} &\sigma^{-}(t)-\sigma^{+}(t)=-\omega^{2}m_{\mathrm{n}}u^{+}(t) \\ &u^{-}(t)-u^{+}(t)=\frac{\sigma^{+}(t)}{k_{\mathrm{n}}} \end{aligned} \tag{3}$$

where the specific initial mass of the filling sand along the normal direction, m_{n}, is equal to the product of the sand density, ρ_{s}, and the initial thickness of the fracture, h. The specific initial mass is defined as the initial mass per unit area (i.e., the cross-section of the bars).

The wave transmission coefficient for the filled fracture can be written as

$$T_{\mathrm{s}}=\frac{2}{2-id_{\mathrm{n}}-i/\left(k_{\mathrm{n}}/Z_{\mathrm{p}}\omega\right)} \tag{4}$$

where d_{n} is the impedance ratio between the filling sand and the rock material and expressed as

$$d_{\mathrm{n}}=\frac{Z_{\mathrm{e}}}{Z_{\mathrm{p}}}=\frac{\omega m_{\mathrm{n}}}{Z_{\mathrm{p}}}=\frac{\omega\rho_{\mathrm{s}}h}{Z_{\mathrm{p}}} \tag{5}$$

where Z_{e} is the effective seismic impedance of the filling sand.

The calculation process of the DDM and DSDM predictions is shown in Fig. 1. The recorded incident wave in the time domain from an SHRB test is first transformed into the frequency domain by the fast Fourier transform (FFT). The derived wave transmission coefficient (i.e., T_{d} or T_{s}) multiplies the incident wave amplitude corresponding to each frequency to obtain the related transmitted wave amplitude. The transmitted wave amplitude is then transformed back to the time domain by the inverse fast Fourier transform (IFFT) to calculate the wave transmission coefficient. The wave transmission coefficient is defined as the ratio of the maximum strain of the transmitted wave to that of the corresponding incident wave in the time domain.

3. Experimental investigation

The experimental study was conducted using an SHRB apparatus (Fig. 2). Similar to a conventional SHPB, the apparatus consists of a pair of square norite bars with the cross-section of 40 mm × 40 mm and 1500 mm in length, a low-rate loading system with a striker bar with the same cross-section and 200 mm in length and a LabVIEW data acquisition unit for signal triggering, recording and storage. The high-quality norite material is an ideal material to study stress wave propagation due to the high density (i.e., 2900 kg/m^3), the high compressive strength (i.e., 284 MPa), a homogenous grain size and few visible cracks. In order to ensure that the bars have few defects that may influence stress wave propagation, the bars are carefully screened under an ultrasonic device. A spring with a stiffness coefficient of 9.52 N/mm is compressed as the energy source to instantaneously launch the striker bar at a low loading rate and to maintain elastic deformation of the bars during the test.

The one-dimensional wave propagation theory is applicable to square bars, if the lateral dimensions of the bars are much smaller than the wavelength (Kolsky, 1953). Two groups of strain gauges are mounted on each long bar, which are connected in the Wheatstone full-bridge to average out the bending strain and to reduce the signal noise. The strain gauge stations are 200 mm and 400 mm away from the fracture interfaces (the rear end of the incident bar and the front end of the transmitted bar). A rubber disc with 10 mm in diameter and 1 mm in thickness is employed as a pulse shaper. It is stuck at the impact end center of the incident bar to generate a non-dispersive low-rate loading pulse and to protect the contacting ends of the striker and incident bars.

As the half-wavelength of a generated sinusoidal pulse is 3000 mm, the short length of the incident and transmitted bars leads to the superposition of the positive and negative waves, which are denoted as waves along and opposite to the loading direction, respectively (Fig. 2). A wave separation method (Zhao and Gary, 1997) is adopted to separate the recorded signal into the positive and negative waves. The strain-time responses at the fracture interfaces can be calculated separately by time shifting the positive and negative waves at the strain gauge stations on each long bar. The stress–time responses at the front and rear interfaces of the filled fracture, $\sigma^{-}(t)$ and $\sigma^{+}(t)$, can then be determined by the Young's modulus of the norite, E, 63.6 GPa, multiplying the strain-time responses at the fracture interfaces on the incident and transmitted bars, $\varepsilon^{-}(t)$ and $\varepsilon^{+}(t)$, respectively

$$\begin{aligned} &\sigma^{-}(t)=E\varepsilon^{-}(t)=E\left(\varepsilon^{p-}(t)+\varepsilon^{n-}(t)\right) \\ &\sigma^{+}(t)=E\varepsilon^{+}(t)=E\left(\varepsilon^{p+}(t)+\varepsilon^{n+}(t)\right) \end{aligned} \tag{6}$$

where $\varepsilon^{p-}(t)$ and $\varepsilon^{p+}(t)$ are the positive waves at the front and rear interfaces, respectively, and $\varepsilon^{n-}(t)$ and $\varepsilon^{n+}(t)$ are the negative waves at the front and rear interfaces, respectively.

The fracture closure-time response, $\Delta u(t)$, can be obtained by the initial thickness of the filled fracture multiplying the strain-time response of the fracture, which is equal to the time integral of the difference of the