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Validation of a three-dimensional Finite-Discrete Element Method using experimental results of the Split Hopkinson Pressure Bar test

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ABSTRACT

A full-scale 3D analysis of a Split Hopkinson Pressure Bar experiment on granite material using a 3D combined Finite-Discrete Element Method (FDEM) is shown. Previous efforts to simulate Split Hopkinson Pressure Bar experiments using the 2D FDEM had obtained a very good match for the loading portion of the experiment. This work extends those efforts by modeling the entire 3D Split Hopkinson Pressure Bar experimental setup, and reproducing the softening behavior of the sample after breakage. This modeling effort introduces the effect of a compliant interface between the bars and the sample.

1. Introduction

Since its inception, the combined Finite-Discrete Element Method (FDEM) [1,2] has become a widely used tool for addressing problems involving solid fracture and fragmentation. Extensive use and application of the method began after the release of the first publicly accessible research code, Y-Code [2]. Key advantages of the FDEM are the use of finite displacements, finite rotations, and finite strains based on deformability representations combined with a variety of constitutive material laws. These are coupled with discrete crack initiation and crack propagation models to provide complex fracture patterns and eventual fragmentation.

For rock mechanics applications, researchers have employed FDEM to simulate many complex industrial challenges such as block caving, deep mining techniques (tunneling [3], pillar strength [4], etc.), rock blasting [5], seismic waves [6], packing problems, coastal protection [7,8], dam stability [9], rock slope stability [10], masonry wall stability [11], and rock mass strength characterization problems [4,12]. Most of these works were accomplished in a 2D realm.

However, due to recent advances that address FDEM 3D parallel computational techniques [13], researchers can now more appropriately address complex dynamic fracture and fragmentation in 3D (Fig. 1). One interesting type of benchmark problems using 2D FDEM was seen in efforts to model Split Hopkinson Pressure Bar (SHPB) experiments. Simulations using the FDEM method were described in [14,15]. In all of these cases, the numerical results published comprised the evolution of the tensile stress at the center of the sample starting from the beginning of the experiment until the point where the sample failed, i.e. maximum tensile stress. This loading portion is mostly controlled by the finite element formulation in the FDEM method. However, none of these research efforts attempted to address post-failure behavior of the sample.

In this paper, SHPB experiments on weathered granite reported in [16] are simulated using the fully parallel 3D FDEM approach implemented in the MUNROU code. The results show excellent agreement with the SHPB experimental results.

2. SHPB experiment setup

In the SHPB experiment, a prepared test sample was placed between two bars, as shown in Fig. 2a. The bar on the left is called the incident bar, while the bar on the right is called the transmission bar. The pressure pulse is generated on the left hand side of the incident bar by the action of a striker bar. In order to obtain a desired pressure pulse shape a small piece of metal is placed on the left free end of the incident bar. The striker travels at a certain velocity and hits the felt metal, which deforms and transmits the modified pressure wave to the incident bar [17]. The length and the amplitude of the resulting pressure pulse are governed by the

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length and the speed of the striker respectively ([18,19]). Two strain gauges are placed along the length of the incident and transmission bar. The strain gauge on the incident bar measures the strain wave traveling from left to right (Fig. 2a) that is a result of the impact (incident wave) and the strain wave traveling from right to left that is a result of the incident wave reflection from the bar-sample interface (reflected wave). The strain gauge on the transmission bar measures the transmitted strain wave traveling from left to right (transmitted wave). Strain pulses taken from the experiment on the weathered granite sample under investigation are shown in Fig. 2b.

The incident and the transmission bars are supported to avoid any lateral movement and to allow only longitudinal movement. Because of this, the stress state in the bars can be described by the one-dimensional wave equation [19]. The displacement as a function of time for a given point along the bars is given by

$$u(t) = c_0 \int_0^t \varepsilon(t)dt \tag{1}$$

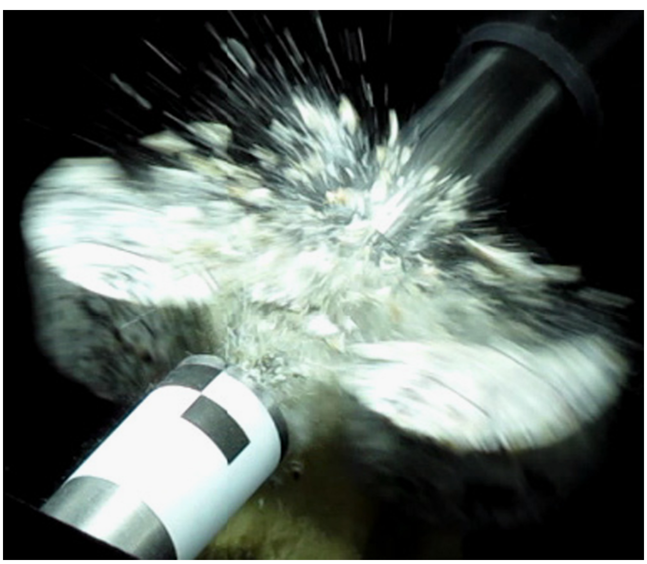

Fig. 1. Dynamic failure of a sample in SHPB experiment.

where $\varepsilon(t)$ is the strain in the bar and $c0$ is the elastic wave speed in the bar given by

$$c_0 = \sqrt{\frac{E}{\rho}} \tag{2}$$

where E is the Young's modulus and ρ is the density.

Due to the fact that the incident and reflected waves travel in opposite directions, the displacement in the incident bar as well as at the interface between the incident bar and the sample is obtained as a combination of the effects of these two waves, as follows [19]:

$$\begin{aligned} u_i(t) &= c_0 \int_0^t \varepsilon_i(t)dt - c_0 \int_0^t \varepsilon_r(t)dt \\ &= c_0 \int_0^t \varepsilon_i(t) - \varepsilon_r(t)dt \end{aligned} \tag{3}$$

where $\varepsilon_i(t)$ and $\varepsilon_r(t)$ are the strains due to the incident and reflected waves respectively (Fig. 2a). On the other hand, the displacement in the transmission bar and at the interface between the sample and the transmission bar is solely dictated by the transmitted wave, as follows:

$$u_t(t) = c_0 \int_0^t \varepsilon_t(t)dt \tag{4}$$

where $\varepsilon_t(t)$ is the strain due to the transmitted wave. Following this line of reasoning, the contact surface between the incident bar and the sample moves at velocity $v_i(t)$, which is given by

$$v_i(t) = \frac{\partial u_i(t)}{\partial t} = c_0[\varepsilon_i(t) - \varepsilon_r(t)] \tag{5}$$

while the contact surface between the sample and the transmission bar moves at velocity $v_t(t)$ given by

$$v_t(t) = \frac{\partial u_t(t)}{\partial t} = c_0\varepsilon_t(t) \tag{6}$$

3. Experimental results

For the Brazilian SHPB experiments, researchers established the following test configuration: strain rate ~200 (1/s); sampling rate from strain gages on bars=2.5 MHz, constant 0.2 MPa (30 psi) gas gun pressure, and loading rates averaged 353 GPa/s for pre-damaged or weathered granite.

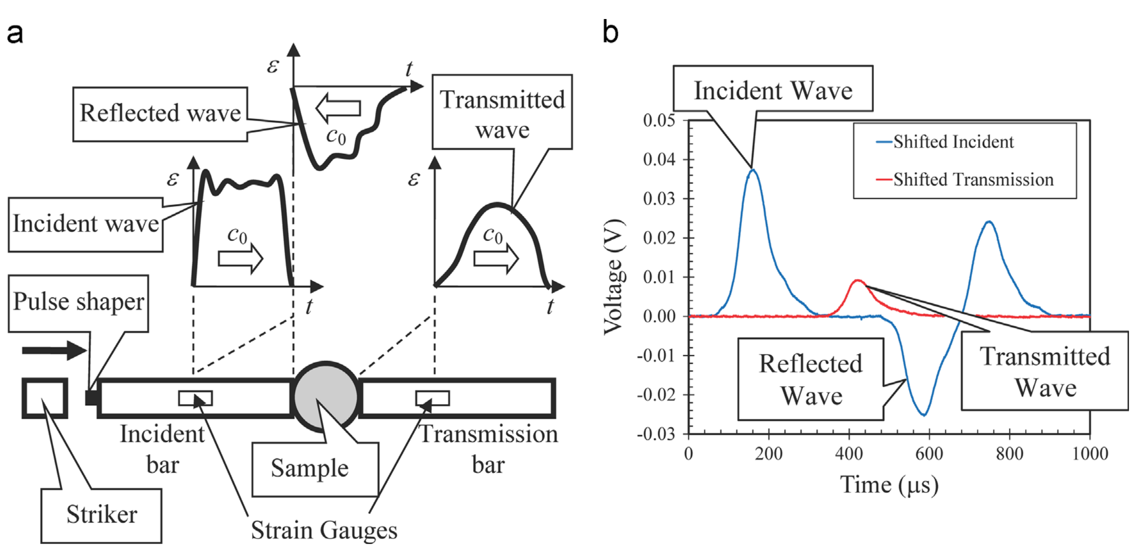

Fig. 2. (a) Setup of the SHPB experiment and (b) incident, reflected and transmitted waves taken from the experiment.