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Research Paper

Physical and numerical evaluation of rock strength in Split Hopkinson Pressure Bar testing

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ABSTRACT

Split Hopkinson Pressure Bar (SHPB) testing was used to evaluate the strength characteristics of sandstone under uniaxial compressive loading. The physical results suggest that rock strength increases under dynamic loading. A hybrid bonded particle-finite element model was used for numerical simulation of SHPB tests. A parameter called rock strength enhancement coefficient was introduced which is multiplied by the relative velocity of particles at the contact points to increase the bond strength between the particles. It is shown that a much better match between the physical and numerical results is realized if this enhancement coefficient is applied in the numerical simulation.

1. Introduction

Some of the operations on rock materials from mining and road structures to dam foundations include dynamic application of load to the rock. Examples include blasting, quarrying, rock burst, rock drilling, and so forth. Rocks are pressure sensitive and rate dependent materials and show a drastically different behavior under dynamic loading, the studying of which has turned to be the point of interest lately. Since the loading of the rocks under dynamic loading is applied at variety of loading rates, it is essential to study of the dynamic strength parameters of the rocks and fracture properties over a wide range of loading rates.

There are three main methods for testing rock materials under dynamic loading condition which have been suggested by the International Society for Rock Mechanics or ISRM [1]. These methods include dynamic compression test, dynamic Brazilian test, and dynamic notched semi-circular bend (NSCB) test. All these tests are performed using the split Hopkinson pressure bar (Kolsky bar) to apply and measure the dynamic loading. The strain rate for the static loading is usually less than 10^{-1} s^{-1} while the split Hopkinson Pressure bar (SHPB) creates strain rates in the specimen with the range between 10^2 and 10^4 s^{-1} [2].

A comprehensive review of the SHPB testing of rock has been reported by Xia and Yao [3] which covers the compressive and tensile testing of rock. In the study of dynamic strength of some carbonate rocks, Demirdag et al. [4] performed some SHPB physical tests. They concluded that the dynamic compressive strength of the rock is greater than its static value and that the dynamic strength is affected by rock density and porosity. Dai et al. [5] used the SHPB apparatus to study both the compressive and tensile strength of rock. For the measurement of the tensile strength, Brazilian tests were conducted. They showed that both the compressive and tensile strengths of rock are increased as the applied stress rate increases. Using the flexural tensile testing of rock, Dai et al. [6] showed that the tensile strength of the Laurentian granite increases with an increase in the loading rate. A nonlocal numerical approach was utilized in their work in an attempt to reproduce the physical tests results.

The SHPB testing has been simulated numerically by some researchers. Both the finite element and discrete element techniques have been employed for this purpose. Li and Meng [7] used a plasticity model in the ABAQUS computer program to study the mechanical behavior of concrete in the numerical SHPB compression tests. Lu et al. [8] applied the Drucker-Prager constitutive model in ABAQUS to investigate the dynamic strength enhancement. Zhong et al. [9] developed a nonlinear finite element model to simulate the effect of friction in the interfaces of the specimen and the incident and transmission bars. They suggested that the presence of friction at the specimen ends can cause lateral confinement of the specimen. As a consequence of this lateral confinement, the measured dynamic strength is overestimated. Park et al. [10] used the finite element method and investigated the effect of the aggregate volume on the strength enhancement.

Discrete element and bonded particle methods have been successfully used in the static and dynamic simulation of rock. Cundall [11]

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developed the discrete element method to simulate the interaction of blocks in a rock mass. The technique is very powerful and has been utilized in the simulation of many geotechnical problems including hydraulic fracturing [12], direct shear testing [13], rock blasting [14], and rock fracturing ([15,16]). Li et al. [17] used the particle flow code [18] to simulate the SHPB test. In order to increase the rise time in the incident stress pulse, a cone shape striker bar was used in their study. Mahabadi et al. [19] employed a finite element-discrete element code to study the dynamic tensile strength of rock. In their work, the Coulomb model combined with the maximum tensile stress cut-off was employed.

In this work, some physical SHPB tests were conducted to study the behavior of the Pennsylvania Blue sandstone under dynamic loading. Different pulse shapers were utilized to control the pulse shape and the loading rate. The numerical simulation was performed using a hybrid discrete-finite element system. The numerical and physical tests results are compared and discussed.

2. Theoretical study

The main assumption in performing the SHPB test is that the waves which propagate along the bars are elastic and one dimensional. Thus, the basic wave propagation theory is appropriate to calculate the response of the sample from the measured strains from stain gauges mounted on the bars. The incident (ε_i) and reflected (ε_r) strain pulses are measured by the strain gauges mounted on the incident bar while the transmitted pulse (ε_t) is measured by the strain gauges installed on the transmission bar.

Strains are related to particle velocities as follows [20]:

$$\varepsilon_i = \frac{-1}{c}\dot{u}_i \tag{1}$$

$$\varepsilon_r = \frac{1}{c}\dot{u}_r \tag{2}$$

$$\varepsilon_t = \frac{-1}{c}\dot{u}_t \tag{3}$$

In which $\dot{u}_i$, $\dot{u}_r$, and $\dot{u}_t$ are the particle velocities due to the incident, reflected, and transmitted waves, respectively. In the above equations, c represents the wave velocity in the bars. Considering the left and right interfaces between the bars and the specimen (points a and b in Fig. 1), the displacements in the incident bar (u_a) and the transmission bar (u_b) at points a and b can be obtained from Eqs. (4) and (5), respectively:

$$u_a = \int_0^t (\dot{u}_i + \dot{u}_r)dt = c\int_0^t (-\varepsilon_i + \varepsilon_r)dt \tag{4}$$

$$u_b = \int_0^t (\dot{u}_t)dt = -c\int_0^t \varepsilon_t dt \tag{5}$$

Therefore, the average strain in the specimen is:

$$\varepsilon_s(t) = \frac{u_b - u_a}{L} = \frac{c}{L}\int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t)dt \tag{6}$$

where L is the length of the specimen. Furthermore, the forces at

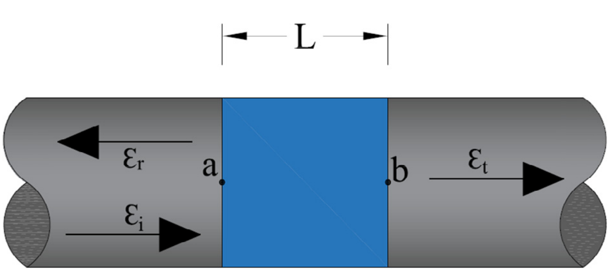

Fig. 1. Strains of the bars in the longitudinal motion. The rock specimen is shown in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

points a and b can be calculated from Eqs. (7) and (8), and hence the average force can be obtained (Eq. (9)):

$$F_a = EA(\varepsilon_i + \varepsilon_r) \tag{7}$$

$$F_b = EA\varepsilon_t \tag{8}$$

$$F_{average} = \frac{F_a + F_b}{2} = \frac{EA}{2}(\varepsilon_i + \varepsilon_r + \varepsilon_t) \tag{9}$$

In which A is the cross sectional area of the bars. Therefore, the strain rate and the average stress in the specimen can be calculated as follows:

$$\dot{\varepsilon}_s(t) = \frac{\dot{u}_b - \dot{u}_a}{L} = \frac{c}{L}\int_0^t (\dot{\varepsilon}_i - \dot{\varepsilon}_r - \dot{\varepsilon}_t)dt = \frac{c}{L}(\varepsilon_i - \varepsilon_r - \varepsilon_t) \tag{10}$$

$$\sigma_s = \frac{F_a + F_b}{2A_s} = \frac{EA}{2A_s}(\varepsilon_i + \varepsilon_r + \varepsilon_t) \tag{11}$$

In the case of the state of stress equilibrium (dynamic equilibrium), we have:

$$F_a = F_b \rightarrow \varepsilon_i + \varepsilon_r = \varepsilon_t \tag{12}$$

From Eqs. (12), (6), (10), and (11), for the situation of dynamic equilibrium, it is easy to show that:

$$\varepsilon_s(t) = -\frac{2c}{L}\int_0^t \varepsilon_r dt \tag{13}$$

$$\dot{\varepsilon}_s(t) = \frac{\dot{u}_b - \dot{u}_a}{L} = \frac{c}{L}\int_0^t (\dot{\varepsilon}_i - \dot{\varepsilon}_r - \dot{\varepsilon}_t)dt = -\frac{2c}{L}\varepsilon_r \tag{14}$$

$$\sigma_s = \frac{F_a + F_b}{2A_s} = \frac{EA}{2A_s}(\varepsilon_i + \varepsilon_r + \varepsilon_t) = \frac{EA}{A_s}\varepsilon_t \tag{15}$$

where A_s is the cross-sectional area of the specimen in Eqs. (11) and (15). In this study the cross-sectional areas of the bars and the specimens are the same.

3. Physical tests

The SHPB apparatus in our study which is composed of three bars, striker, incident, and transmission bars is illustrated in Fig. 2. The bars are made of maraging steel with the modulus of elasticity of 200 GPa, Poisson's ratio of 0.3, density of 8100 kg/m^3 and longitudinal wave velocity of 4970 m/s. The lengths of incident and transmission bars are 1830 mm and 1218 mm, respectively. The diameter of the bars is 12.7 mm. Strain gages mounted on the incident and transmission bars are used to measure the stress waves during the test.

3.1. Rock specimen and static tests

Cylindrical specimens of the Pennsylvania Blue sandstone were prepared for both the dynamic and static testing. Static tests were performed to measure the elastic properties of rock and its uniaxial compressive strength. The length of the specimen is larger than its diameter to follow the ISRM recommendation of having a specimen length greater than 2 times its diameter [21]. For the dynamic tests, the specimen diameter is 12.7 mm as for the static tests but the specimen length is shorter; a length to dimeter ratio of 1 is used for the dynamic tests. Shorter specimens in dynamic tests helps to more easily achieve the dynamic equilibrium of the specimen. Further, with smaller size specimens, the effect of the inertia on the test results can be minimized. Based on lessons learned from some physical tests, Dai et al. [5,6] suggested an aspect ratio of one for SHPB specimens. The cores and specimens with flat and smooth surfaces ready to be tested are shown in Fig. 3a.

The results of two static uniaxial compressive tests are shown in Fig. 3b from which an average elastic modulus of 24 GPa and an average uniaxial compressive strength of 122 MPa were obtained, which are consistent with those reported in the literature [22].