Study and Analysis of Dynamics Brazilian Tensile Strength of Granitic Rocks Using a Numerical Methods

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Abstract: The Brazilian tensile test is an acceptable method for determining the tensile strength of brittle materials such as rock and concrete between low and intermediate strain rate. The dynamic characterization of granite as a brittle material is fundamental to understand the material behavior in the case of heavy earthquakes and dynamic events. The implementation of material constitutive law is of capital importance for the numerical simulation of the dynamic processes as those caused by earthquakes. Dynamic tests are usually conducted using the split Hopkinson bar or Kolsky bar systems, which includes both a split Hopkinson pressure bar (SHPB) and split Hopkinson tension bar (SHTB) systems.In this study, we determined incident strain waveforms which satisfy the stress uniformity within the three kinds of granite samples for dynamic Brazilian test by combining Spilt Hopkinson Pressure bar (SHPB) test by the numerical method using LS-DYNA. The numerical simulation served the stress distribution in the granite specimen under different impact velocities. The pulse shaping technique using a thin copper disk reproduced the determined incident pulses and applied to impact the granite samples. The result shows that the high-frequency vibrations were reduced by increasing the rising time and decay time of applied pressure and stress uniformity around 475μs elapsed time, stress ratio varied around 3 time. Triangular waveform with Applied pressure of 100MPa and rising time is 220μs as showed in figure (Case 2) is acceptable to achieve the stress uniformity of the sample model in a dynamic Brazilian test using SHPB system.

Keywords: Split Hopkinson Pressure Bar, Dynamic Fracture Toughness, Fracture Mechanics

1. Introduction

Dynamic fracture behavior of rock materials is one of the most important concepts in rock engineering applications such as percussive drilling, rock burst, and rock blasts. Studying the dynamic behavior of rocks becomes even more challenging in environments such as deep drilling for geothermal energy, where the confining pressure and temperature change as the depth changes. The tensile strength of rock is much less than its compressive strength, so its breakage in rock engineering is caused by the low tensile strength. Hence, much attention has been paid to methods of determining the tensile strength of the rock. However, the tensile strength is determined (such as the Brazilian test) rather than because of the difficulties of undertaking a direct tension test. Tedesco et al. (1993) showed experimental and numerical dynamic tests of Brazilian disc concrete samples by using Split Hopkinson Pressure Bar (SHPB). They discussed that dynamic stress field in the dynamic investigations is equal to the static one. Cho et al. (2000) carried out dynamic tension-splitting tests of rock disc samples using a developed apparatus, which comprises steel frames and an electric detonator and used high-speed Videography technique to observe the fracture processes of brittle materials. We simulate the dynamic behavior of a rock disc using ANSYS/LS-DYNA. The sample model in the study is the Brazilian cylinder test performed in a split Hopkinson pressure bar. The simulations give accurate incident and transmitted stress waveforms over a wide range of strain rates. To examine the propagation and variation of the stress field in the Dynamic Brazilian test, it carried numerical analyses without fracture process out before considering the influence of the applied pressure–time history which has rectangular and triangular waveforms on the stress uniformity in the disc sample.

2. A Review of Dynamic Brazilian Tests

Split Hopkinson Pressure Bar (SHPB) has been recognized as an efficient experimental technique to get families of stress-strain curves for engineering materials at high strain rates between 102 to 104s-1 (H. Klosky 1949). It bases the SHPBtechnique on two fundamental principles: first, the stress wave in the bars is elastic and one-dimensional; second, the states of stress and strain within the specimen are uniaxial and uniform. There are two relationships between the incident, reflected and transmitted strain pulses related to time, i.e., εI(t), εR(t) and εT(t), and between the incident, reflected and transmitted stress pulses, σI(t), σR(t) and σT(t) in a SHPB system, respectively:

$$\sigma I(t) + \sigma R(t) = \sigma T(t), \varepsilon I(t) + \varepsilon R(t) = \varepsilon T(t) (1)$$

The dynamic Brazilian tests should be carried out in a compressed version of the Hopkinson bar with assumption of stress uniformity in the disc before failure. The tensile strength St can be described as

$$\sigma = \frac{2\sigma_T(t)}{\pi DL} (2)$$

Where D is disk diameter and L is disk thickness. In this study, with an assumption that dynamic stress is uniform through the rock samples before fracturing the sample, it used the equation (1) to estimate the dynamic tensile strength of rocks. To allow the use of the static stress field relation, it to determine the load condition which satisfies stress uniformity in the disc sample need to be determined.

Based on the one-dimensional (1D) stress wave theory, the dynamic forces (see Fig. 1) on the incident end (P_1) and the transmitting end (P_2) of the specimen are (Kolsky, 1949, 1953):

$$P_1 = AE(\varepsilon_i + \varepsilon_r),\ P_2 = AE\varepsilon_t (3)$$

where E is the Young's modulus; A is the cross-sectional area; ε_i and ε_r are the incident strain signal and reflected strain signal, respectively.

The velocities at the incident bar end (V_1) and the transmitted bar end (V_2) are:

$$V_1 = C(\varepsilon_i - \varepsilon_r)\ , V_2 = C\varepsilon_t (4)$$

where c is the 1D longitudinal stress wave velocity of the bar. The displacement of the incident bar end (U_1) and the transmitted bar end (U_2) are thus:

$$U_1 = C\int_0^t (\varepsilon_i - \varepsilon_r)dt\ , U_2 = C\int_0^t \varepsilon_t\ dt (5)$$

where t is the time.

One aim of an SHPB test is to determine the material dynamic stress-strain curve, from which it can derive the mechanical properties, e.g. dynamic failure strength, dynamic failure strain, and dynamic Young's modulus.

3. Numerical Analyses of Dynamic Brazilian Tests Using SHPB System

It has also adopted in SHPB to conduct indirect tension tests for determining the tensile strength of brittle solids like rocks. It bases the Brazilian Disk method Brazilian Disk method is because the rock is much weaker in tension than in compression and thus the loaded rock disc specimen fails due to the tension along the loading diameter near the center. It shows schematically the Brazilian Disk specimen in the SHPB system in Figure 1 where the sample disc is sandwiched between the incident bar and the transmitted bar. Provided it has achieved a quasi-static state in the sample during the test, the dynamic tensile strength is determined by the equation (1). In this study, the SHPB system comprises an incident bar and a transmitter bar, with a small specimen placed between them. In addition, a striker bar launched by a gas gun impacts the incident bar and produces a longitudinal compressive pulse which propagates toward the specimen. The amplitude and shape of the pulse depend on the material properties, impact velocity and the length of the striker. The diameter of the bar used in this study is 37 mm and the length of the incident bar and transmitted bar is 3600mm and 1600mm. The diameter and thickness of the rock sample model are 54 mm and 27mm. Considering hard rock, it set the elastic wave velocity of the rock sample model up as 5000m/s. Figure 1 shows the finite element layout for dynamic Brazilian test using SHPB system. The A, B, C of the model shows the monitoring points for observing the stress variation. Table 1 summary of the input parameter for dynamic elastic analyses. Figures 2. (a, b, c) shows the pressure waveforms which apply on the end side of the incident bar as load condition. The rectangular incident waveform as shown in Figure 1 (a) is a typical incident waveform which occurs in the traditional SHPB test. The rising time keeps time and decaying time of Figure 1. (a) was set at 10, 100, 10μs referring from the experimental data. The triangular incident waveforms showed in Figure 2. (b) and Figure 3. (c) is controlled incident waveform which occurs in the SHPB system adopting a pulse shaping technique. The rising time keeps time and decaying time of Figure 2. (Case 2) and it set Figure 2. (Case 3) as 100, 10, 100μs and 150, 10, 150μs.The material propertyvalues for E, ν, ρ and model parameters used in the simulations here are given in Table 1. for granite rock in general.

Table 1. Input parameter of bar and rock sample for elastic analysis.

Material	Density (Kg/m^3)	Elastic Modulus (GPA)	Poisson's ratio
Rock	2640	17	0.264
Steel bar	7806	195	0.25

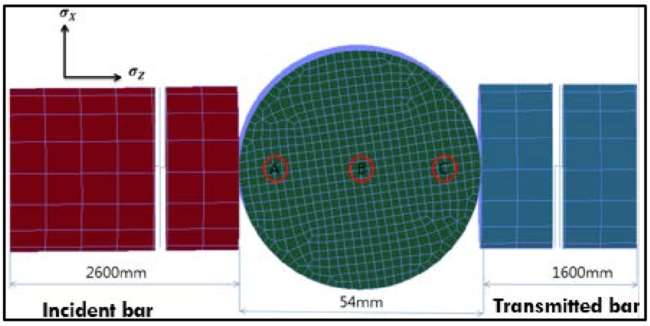

Figure 1.A part of finite element layout for dynamic Brazilian test (Points A, B, C: measuring points).

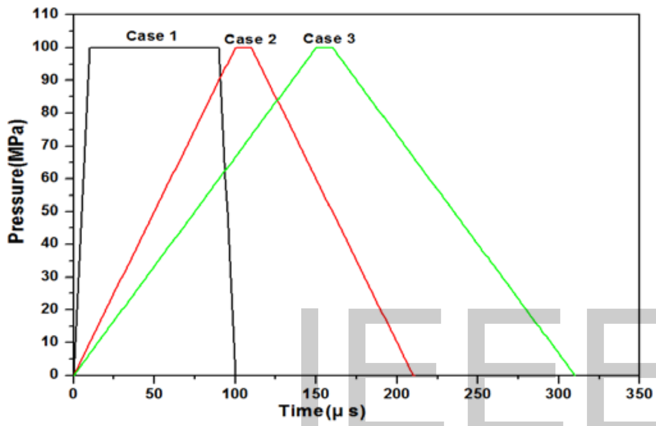

Figure 2. Applied pressure waveforms on the incident bar.

4. Numerical Simulation Results

Incident and transmitted stress waves monitored at the center of the bars for three case load conditions as showed Figure 2. are displayed in Figures 3 and 4. Figure 3 showed a typical incident stress wave and transmitted waves which were monitored at the center of the incident bar and transmitted bar respectively. Note that a negative value shows compression. The compressive waves arrive at the center of the incident bar after 330μs elapsed time and come back as tensile waves after 220μs. The reflect waves vary with the differences between impedances of sample and bar and sample geometry. The stress waves are reflected in the incident bar and transmitted through the sample model. The transmitted waves arrive at the center of the transmitting bar after 560μs elapsed time as compressive stress. Figure 4 Showed incidents and transmitted stress waves monitored on the bars. The triangular shape of compressive waves arrives at the center of the incident bar and come back as a tensile wave.At point**B**, the crack propagates with high speed, this observation indicates that the fracture initiates inside the samples and then propagates to the surface only after the sample has already reached its maximum stress.

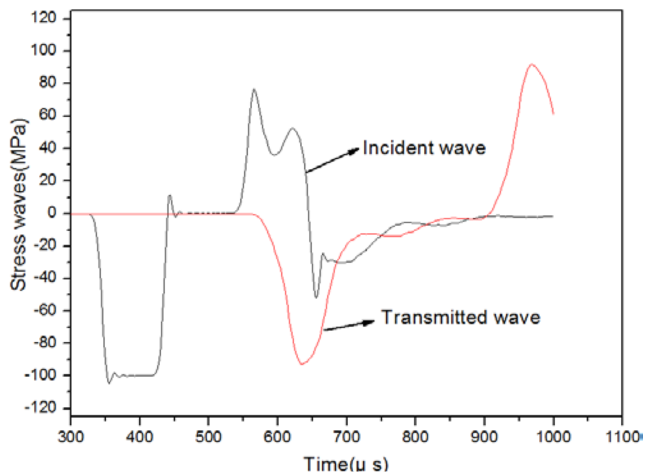

Figure 3. incident stress wave and transmitted waves which were monitored at the center of the incident and transmitted bars.

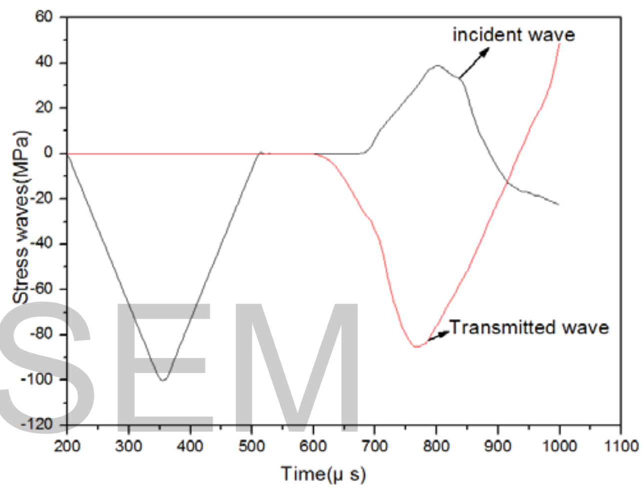

Figure 4. Incident and transmitted stress waves monitored on the bars.

5. Influence of Applied Pressure Waveforms on the Stress Uniformity in Dynamic Brazilain Rock Sample

As is well known, under quasi-static conditions the diametric loading of a disc sample generates tension perpendicular to the loading plane which causes the sample to split. It often takes this quasi-static condition as a basis for interpreting the dynamic Brazilian experiments. It must determine loading condition able to achieve the quasi-static stress condition which satisfies the stress uniformity through the disc specimen for the dynamic Brazilian experiments. Figures 5,6 and 7 showed the Z and X stresses time history along the loading axis and perpendicular to the loading axis, at the measuring points in the sample model. In case of applying the rectangular pressure waveform, flotation is visible on the stress-time history for all points. The compressive stresses around the loading plates (the end sides of the incident and transmitted bar) increased over 200 MPa and the tensile stresses reach to 30MPa.The Z stress at point B increased 100MPa in compression and X stress reach the peak value of 30MPa with some fluctuation. Figure 6 and Figure 7 which apply a triangular pressure waveform showed less vibration on the stress waves. The high-frequency vibrations were reduced by increasing the rising time and decay time of applied pressure. To examine the stress uniformity through the sample model, stress ratios with X stress and Z stress waves at point B were calculated and plotted as showed in Figure 8. All figures showed stress uniformity around 475μs elapsed time, stress ratio of Figure 6 varied around 3 time. Otherwise, Case 1 showed small vibration up to 575μs and then large fluctuations are visible. Figure 6 showed also small vibration up to 750μs and then large fluctuations are visible. It is conceivable that a triangular pressure waveform with 100μs rising time in Figure 2(Case 2) is acceptable to achieve stress uniformity of the simple model in the dynamic Brazilian test using SHPB system.

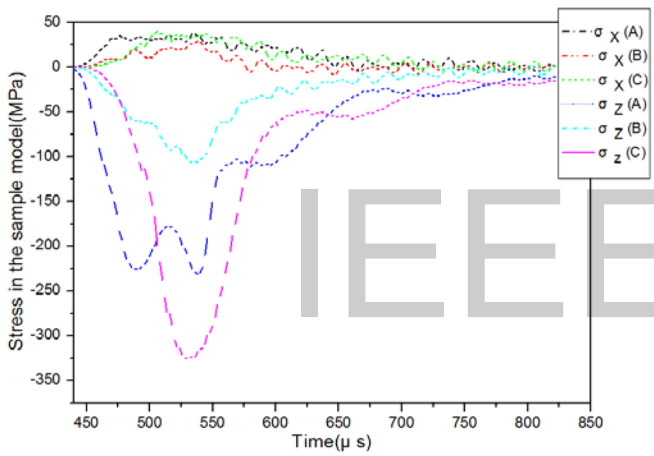

Figure 5. Stress-time histories in the sample models (Applied pressure 100MPa and rising Time 100μs).

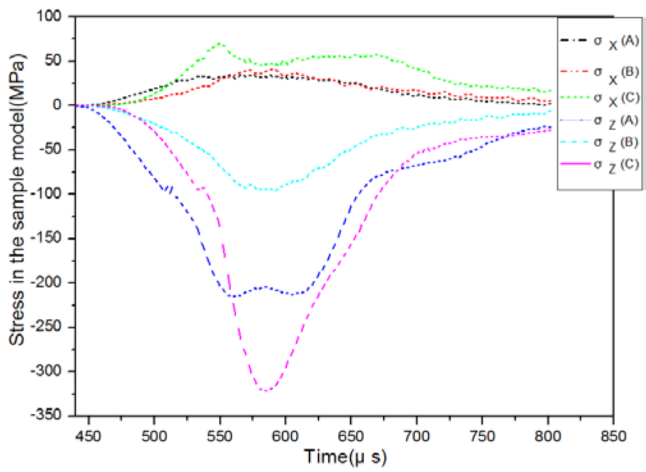

Figure 6. Stress-time histories in the sample models (Applied pressure 100MPa and rising Time 220μs).

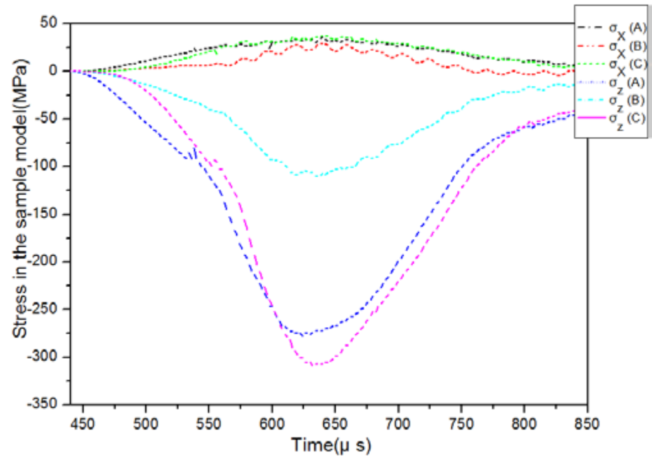

Figure 7. Stress-time histories in the sample models (Applied pressure 100MPa and rising Time 330μs).

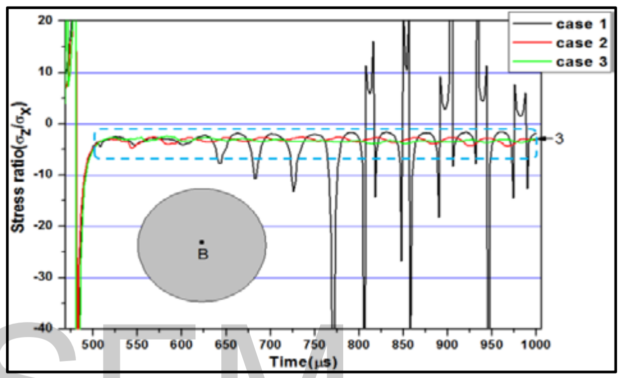

Figure 8. Stress ratio variation with time at point B.

6. Conclusions

Dynamic stress analyses of rock disc with the adapting SHPB system were carried out using ANSYS/LS-DYNA. It investigated applied pressure waveforms which can achieve the quasi-static stress condition which satisfies the stress uniformity through the disc specimen. In case of applying the rectangular pressure waveform, it generates flotation through on the stress-time history of all points. Figure 2. (Case 2 and 3) which used the triangular applied pressure waveforms showed less vibration on the stress waves. The high-frequency vibrations were reduced by increasing the rising time and decay time of applied pressure. All figures showed stress uniformity around 475μs elapsed time, the stress ratio of Figure 6. varied around 3 with time. Otherwise, Figure 5 showed small vibration up to 575μs and then large fluctuations are visible. Figure 7 showed also small vibration up to 750μs and then large fluctuations are visible. Triangular pressure waveform with 100μs rising time in Figure 6 is acceptable to achieve the stress uniformity of the sample model in a dynamic Brazilian test using SHPB system.In the numerical simulation of the Dynamics Brazilian Tensile Strength of Granitic Rocks, this decrease in tensile strength was reproduced by modeling the granite rock induced damage using the embedded discontinuity finite element method.

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