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Determination of spalling strength of rock by incident waveform

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Abstract. An experimental technique for determining the spalling strength of rock-like materials under a high strain rate is developed. It is observed that the spalling strength of a specimen can be determined by only knowing the wavelength, loading peak value and length of the first spallation of an incident wave under a specific loading waveform. Using this method in combination with a split-Hopkinson pressure bar (SHPB) and other experimental devices, the spalling strength of granite specimens under a high strain rate is tested. Comparisons with other experimental results show that the new measuring method can accurately calculate the dynamic tensile strength of rock materials under a high strain rate.

Keywords: Hopkinson bar; spalling; incident waveform; dynamic tensile strength

1. Introduction

A compressive stress wave propagating from a medium of high wave impedance to a medium of lower wave impedance is reflected by a tensile stress wave through the contact surface. Moreover, when the tensile strength under superposition of both the reflected wave and the incident wave is higher than the dynamic tensile strength of a material, dynamic tensile fracture is induced. If the stress wave is slowly rising, subsequent failure can possibly occur after the first one, and spalling occurs. The spalling phenomenon was first observed by Hopkinson in 1914, it is also called Hopkinson spallation. Rock and rock-like materials are likely to undergo spalling failure under an impact load (Cho *et al*. 2003).

The occurrence of spalling failure is determined by the dynamic tensile strength of materials. Thus the dynamic tensile strength of brittle materials, such as rocks and concrete, is often determined by spalling tests in a laboratory by using a split-Hopkinson pressure bar (SHPB). Li *et al*. (Li *et al*. 2009, Li and Meng 2003, Lu and Li 2011) analysed strain-rate effect on the tensile strength of various concrete-like materials. Erzar and Forquin (2010) measured the dynamic tensile strength of brittle materials under high strain rates. Kubota *et al*. (2008) determined the dynamic tensile strength of sandstones by spalling experiments. Cho *et al*. (2003) investigated the relationship between rock tensile strength and its applied strain rate. Lu and Li (2011) determined the dynamic tensile strength of concrete (Lu and Li 2011, Zhou *et al*. 2016). Zhang, Schuler and

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many other scholars (Fan *et al*. 2012, Schuler *et al*. 2006, Shen and Karakus 2014, 2015, Wu *et al*. 2005, Zhang *et al*. 2009) investigated the correlation between dynamic tensile strength and strain rate of concrete and other brittle materials.

Based on the Hopkinson bar device, the present paper developed a technique of measuring spalling strength. The technique proposes that using spalling experiments under a specific waveform, the dynamic tensile strength can be calculated only by knowing incident wave peak, incident wave length and the length of first-layer spalling. In addition, the spalling experiment process of granite under high strain rate is conducted by taking use of Hopkinson devices. The technique is verified by comparing with other experimental results, which indicate the new measuring method can accurately calculate the dynamic tensile strength of rock materials under a high strain rate.

2. Conservational technique and computing methods of spalling strength

Spalling problems constitute an important area of research in impact engineering and underground engineering that involves a dynamic constitutive model and the fracture features of materials. Within in this context, the spalling strength represents the dynamic tensile strength. Thus, the experimental determination of spalling strength of materials is one of the most important subjects of spalling research. Currently, there are two main methods for determining materials' spalling strength by using Hopkinson devices: the pull-back velocity method and the spalling block velocity method.

The pull-back velocity method was first proposed by Novikov (Novikov and Chernov 1982) and then developed by Gathers (1990), and it has been applied by Schuler *et al*. in testing rock-like materials (Schuler *et al*. 2006, Zhang *et al*. 2009, Li *et al*. 2017). The experiment involves the stress wave propagating in three media: Hopkinson input bar, specimens and air. When the input bar is stroked by the striker, the incident wave is generated and it propagates along the input bar, and when it reaches the interface of the input bar and specimen, waves are reflected and transmitted, and the transmitted waves continue to propagate until it reaches the free surface of the specimen, and reflected as tensile wave. In this process, it will cause vibration, and particle velocity in the free surface of the specimen. Based on the propagation process of wave, the spalling strength of specimens can be approximately calculated by the particle velocities of its free surface, as follows

$$\sigma_t = \frac{1}{2}\rho C\left(v_1 - v_2\right) \tag{1}$$

where σ_t is the spalling strength, ρ and C represent the density and stress wave velocity of the specimen, and v_1, v_2 represent the particle velocity of free surface of the specimen. $v_1 - v_2$ is so-called the pull-back velocity.

In addition, damage evolves during the spalling process and the measured pull-back information corroborates the results obtained for the evolution of damage, and thus, it is inevitable that error arises in the final results.

The spalling block velocity was mainly introduced by Klepaczko (Klepaczko and Brara 2001). When a stress wave propagates from a portion of the incident bar to a specimen, there are continuity conditions that govern the power and velocity at the interface and momentum conservation conditions, the tensile strength of the specimen is

$$\sigma_t = \rho_b C_b V_{Tb} \tag{2}$$

σ_t is the spalling strength of the specimen, V_{Tb} is the particle velocity of the spalling falling area, and V_{Tb} approximately equals the falling velocity of the spalling block. Therefore, the approximate spalling strength σ_t of the sample can be obtained by using velocity measurement devices once the physical properties density ρ_b and wave velocity C_b of the specimen are known. However, it is clear that the weakness of the method is that the falling velocity of the spalling blocks is not precisely equal to the particle velocity of the falling area, and errors may arise.

3. A new spalling strength testing technique based on Hopkinson devices

The foregoing analysis indicates that there are some limitations to the two common methods of testing spalling strength. To simplify the test steps and reduce cost, a new spalling strength testing method for rock materials is suggested. Based on the theory of wave propagation, when a stress wave is reflected through a free surface, the waveform does not change. Therefore, the spalling strength can be determined by analyzing the superposition of the stress waves after the incident wave reflects through the free surface by analyzing the spalling position. For example, when the incident compressive wave is a slowly rising wave, after free surface reflection, the wave may be composed of only a reflecting tension wave; under this condition, spalling fracture is a net dynamic tensile process. Currently, along with the use of an SHPB device, several methods can be used to shape the incident wave and to produce a slowly rising stress wave, such as modifying the shape of the striker bar (Cloete *et al*. 2009, Li *et al*. 2005) or using a pulse shaper (Frew *et al*. 2002, Naghdabadi *et al*. 2012, Song and Chen 2004). Fig. 1 shows a sketch diagram of the Hopkinson bar spalling process under a half-sine stress wave.

Considering a slowly rising half-sine wave generated by modifying the shape of the striker bar, we assume the period is τ, and the peak stress is σ_m, the stress-time curvilinear function $\sigma(t)$ of the half-sine stress wave can be expressed as follows

$$\sigma(t) = \sigma_m \sin\left(\frac{\pi}{\tau}t\right), \ 0 \le t \le \tau \tag{3}$$

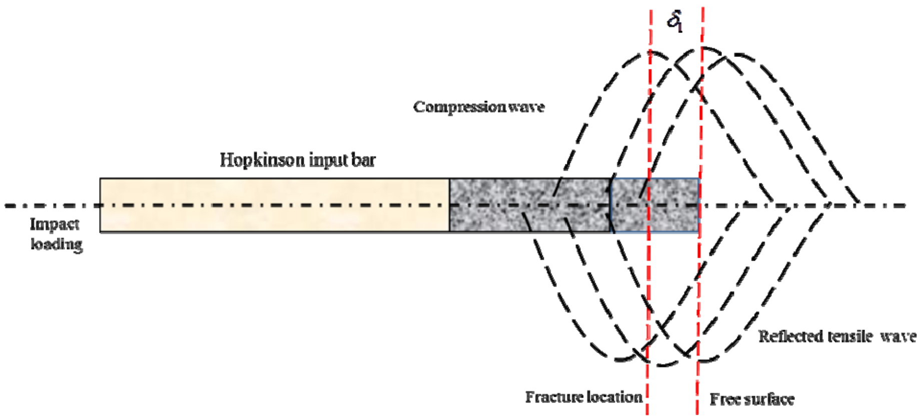


Fig. 1 Incident and reflected half-sine stress wave in the specimen

Fig. 1 illustrates the reflection process of wave on the free surface, the strength of the incident compressive stress wave is always greater than that of the reflected tensile wave from the moment when the compressive stress wave reaches the specimen's free surface (assuming t = 0 at this moment) to time $t = \tau / 2$. In this case, there is no net tensile stressed zone and no spalling. However, after time $t = \tau / 2$, i.e., after one half-period, the strength of the reflected tensile stress wave is gradually higher than that of the incident compressive wave, and a net tensile stressed zone appears, when the net tensile strength is higher than the spalling strength, spalling occurs. As shown in Fig. 1, if spalling occurs at a position δ_1 away from the free surface, where it reaches the largest tensile stress for the first time, i.e., the tensile strength of the reflected wave minus the strength of the incident wave equals the specimen's spalling strength, spalling occurs, in this location, the value of the incident compression strength is

$$\sigma_m \sin\left[\frac{\pi}{\tau}\left(\frac{\tau}{2}+\frac{2\delta_1}{C}\right)\right] \tag{4}$$

And the value of the reflected tensile strength is

$$-\sigma_m \sin\left[\frac{\pi}{\tau}\left(\frac{\tau}{2}+\frac{\delta_1}{2C}\right)\right] \tag{5}$$

Thus, the value of the superposition strength is

$$\sigma_t = \sigma_m \sin\left[\frac{\pi}{\tau}\left(\frac{\tau}{2}+\frac{\delta_1}{2C}\right)\right] - \sigma_m \sin\left[\frac{\pi}{\tau}\left(\frac{\tau}{2}+\frac{2\delta_1}{C}\right)\right] = \sigma_m\left(\cos\frac{\pi\delta_1}{2\tau C} - \cos\frac{2\pi\delta_1}{\tau C}\right) \tag{6}$$

σ_t is the spalling strength, thus, the spalling strength can be calculated by measuring the length of the first spalling block once the incident loading waveform function and the stress wave velocity spread among specimens are known.

4. Validation of the new technique by conducting a spalling test

Using a conventional SHPB device, in the previous studies, our group generated a slowly rising half-sine wave by modifying the striker (Li *et al*. 2011). Thus, to validate the new spalling testing method, a granite specimen spalling test was conducted using the modified Hopkinson bar devices at Central South University. The geometric parameters of the spindle striker and input bar were described in our previous work (Li *et al*. 2007, 2008, Li and Tao 2015, Tao *et al*. 2012, 2016). The striker and input bar was made of 40 Cr alloy steel with a density of 7,810 kg/m^3 and exhibited an elastic longitudinal wave velocity of 5,410 m/s. The incident bar measured 50 mm in diameter and 2 m in length and was made of the same material as the striker. A long cylinder granite specimen with cross-sectional dimensions of Φ 50 mm was used as the test specimen. The surfaces are carefully polished. The surface perpendicularity and roughness of the specimens are less than 0.01 mm and 0.02 mm, respectively. The experimental device is shown in Fig. 2.

To meet the conditions required for spalling to occur, the incident peak stress should be lower than the specimen's uniaxial compressive strength but higher than its dynamic tensile strength. Moreover, the specimen's tips were polished completely to guarantee good contact between the

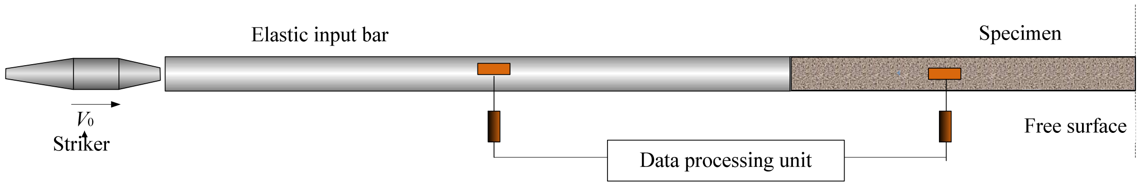
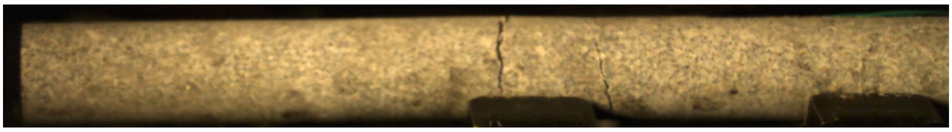


Fig. 2 Hopkinson experimental device

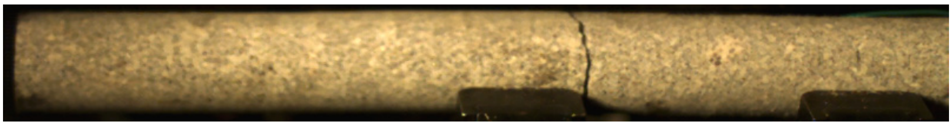
Table 1 Material properties of rock

No.	Length /m	Density /(kg·m^{-3})	Velocity /(m·s^{-1})
Granite-1	1.17	2675	4831.02
Granite-2	1.17	2597	4759.13
Granite-3	1.17	2656	4687.06
Granite-4	1.17	2686	4744.14

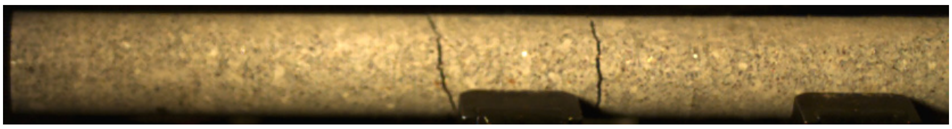


Granite-1

Granite-2



Granite-3

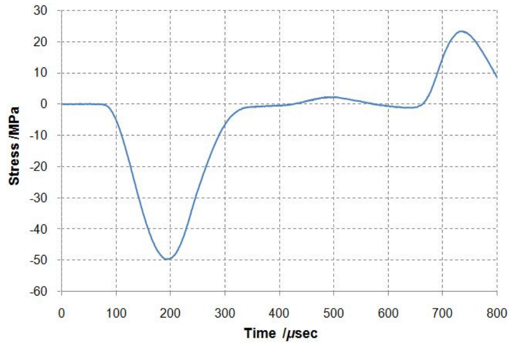


Granite-4

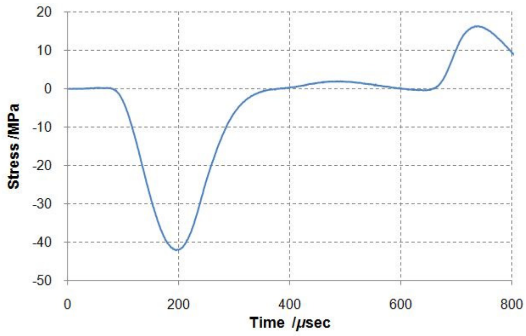
Fig. 3 The first layer spalling (right end is the direction of incident)

specimen and the incident bar. The specimens were obtained from the same location and were processed in the same way. The specific parameters of the specimens are shown in Table 1.

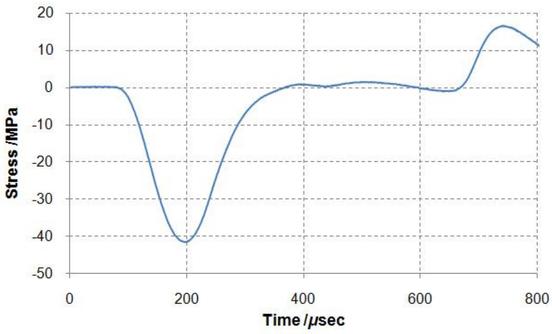
With the rising edge of the half-sine incident wave, after the first spalling, the specimens may have suffered follow-up damage by incident and reflected loading. Therefore, the follow-up spalling may have occurred after first-layer spalling, but first-layer spalling fully captures the results of dynamic tensile failure. Therefore, a high-speed camera was used throughout the entire



Granite-1



Granite-2



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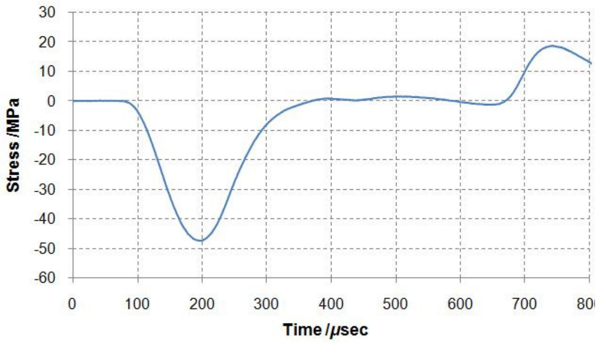

Granite-5

Fig. 4 The incident and reflected stress wave waveform of the specimen

test to record the first spalling, shown in Fig. 3.

Meanwhile, the stress wave waveform shown in Fig. 4 was obtained by a CS-1D super dynamic strain meter and a DL 750 ScopeCorder Digital Oscilloscope. Herein, the stresses are presented with voltage information captured directly by the strain gauges.

The image of the stress waveform shows that the incident stress wave enters the specimen in the form of a half-sine wave. The approximate waveform function is

$$\sigma(t) = \sigma_m \sin\left(\frac{\pi}{2\times10^{-4}} t\right),\ 0 \le t \le 2\times10^{-4} \tag{7}$$

Therefore, this function together with the length of the first spalling, the spalling strength can be calculated by the new method. Moreover, the layer block's fly-out velocity can be approximately calculated using the high-speed camera, thus, the spalling strength also can be calculated by the spalling block velocity method. The spalling strengths calculated by the two different methods are presented in Table 2.

The above-described results demonstrate that the two analysis methods are similar. Moreover, it is observed that the dynamic tensile strength of rocks is much higher than their static tensile strength, and the value calculated by the new and common methods are approximately, which suggests that the dynamic tensile strength of rocks calculated by the new method clearly conforms to the actual value. Thus, the new spalling strength calculation method is reliable.

Table 2 The specimen's spalling strength

No.	τ (μs)	σ_m (MP)	Static tensile strength (MPa)	Block velocity method (MPa)	New method (MPa)	Mean strain rate (s^{-1})
T1	245	42.6	9.04	15.2	16.4	75
T2	245	32.9	9.17	14.5	17.1	69
T3	245	31.5	8.86	15.3	16.5	76
T4	245	29.6	8.72	14.4	15.1	68

5. Conclusions

Based on spalling tests performed using a Hopkinson bar, a new technique for determining the dynamic tensile strength of rock materials was developed. Using the SHPB device, spalling tests on granite specimens were conducted. After analysing the test process and the results obtained, it was demonstrated that the new testing technique is able to measure the dynamic tensile strength of rock materials under a high strain rate.

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