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Dynamic tensile failure of rocks under static pre-tension

Bangbiao Wu [a,b], Rong Chen [c], Kaiwen Xia [a,b,*]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, School of Civil Engineering, Tianjin University, Tianjin 300072, China
[b] Department of Civil Engineering and Lassonde Institute, University of Toronto, Ontario, Canada M5S 1A4
[c] College of Science, National University of Defense Technology, Changsha, Hunan 410073, China

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ABSTRACT

A modified split Hopkinson pressure bar (SHPB) system is utilized to load Brazilian disc (BD) samples statically, and then exert dynamic load to the sample generated by impact. The pulse shaper technique is used to generate a slowly rising stress wave to facilitate the dynamic force balance in dynamic tests. Five groups of Laurentian granite BD samples (with static tensile strength of 12.8 MPa) under the pre-tension of 0 MPa, 2 MPa, 4 MPa, 8 MPa, and 10 MPa were tested under different loading rates. The results show that the rock dynamic tensile strength decreases with the increase of the pre-tension. It is also observed that under the same pre-tension stress, the dynamic tensile strength increases with the loading rate. However, the total tensile strength of the rock is roughly independent of the pre-tension. The failure patterns of the samples also reveal the rate dependence of the dynamic tensile strength of rocks.

1. Introduction

Tensile failure is a main failure mode of rocks in underground rock engineering projects, in which rocks are subjected to dynamic disturbances while under in situ stresses. As is well known, pores and microcracks are potential sources of failure for rock materials because of stress concentration.[1–4] When disturbed by dynamic loads from blasting, seismicity, or rockbursts, the underground rocks would be vulnerable to tensile failure. For example, tensile failure is an important aspect in hydraulic fracturing. In addition, drilling induced tensile fracture on boreholes is crucial to the determination of crustal stress.

Even though the far-field load is compressive, the local stresses may be tensile as shown in Fig. 1. From a macroscopic point of view, the bending of the roof induces tensile stress at the roof of the opening; from a microscopic view, the discontinuities in the rock result in tensile stress locally. On top of these pre-tension, dynamic disturbance may be tensile in nature and lead to the ultimate failure of the rock material. Therefore, it is necessary to investigate the dynamic tensile failure of rock materials under pre-tension.

Understanding of tensile strength of rocks and other brittle materials bears important engineering and geophysical applications in general. Direct tensile or pull tests[5–9] have been a natural approach to measuring the tensile strength of brittle solids, fracturing of thin walled hollow cylinders has also been proposed for the tensile rupture measurement of glass and granite.[10] However, the stress concentration due to the sample gripping often induces damage near sample ends, causing premature failure of the sample and deviation from the desired uniaxial stress state. Consequently, indirect methods have been developed to determine the tensile strength of rocks; some examples are Brazilian disk test[11,12], ring test[13], and bending test.[11] These methods aim at generating tensile stress in the sample by far-field compression, which is much easier implemented than direct tensile tests.

Over the past few years, significant progress has been made in the characterization of rock failure under high loading rates.[14–16] Testing methods for dynamic compressive strength[15], dynamic tensile strength[17], and dynamic flexural strength[18] have been developed and improved by the authors and other researchers. In these tests, rock samples are stress-free before being subjected to dynamic loading. However in rock engineering practice such as underground rock blasting, rocks are under various tectonic stresses, such as the stress concentration of underground openings. Under the superposed dynamic loads with the static tectonic stress, the rock behaves differently as compared to the material subjected solely to either static stress or impact loading.[19] It is thus desirable to understand the effects of pre-tension on the dynamic properties of rocks. Zhou et al.[20] conducted impact tests on rock materials under static pre-tension. They concluded that the dynamic tensile strength of rock materials decreases with the increase of the static pre-tension. However, a more comprehensive

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[*] Corresponding author at: Department of Civil Engineering and Lassonde Institute, University of Toronto, Ontario, Canada M5S 1A4. Fax: +1 416 978 6813.
E-mail address: kaiwen.xia@utoronto.ca (K. Xia).

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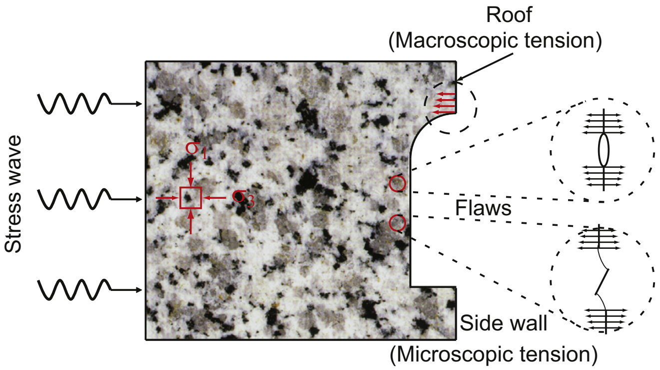

Fig. 1. Potential sources of tensile failure around an underground opening.

set of experiments need to be carried out to examine the influence of both loading rate and pre-tension on the dynamic tensile strength of rock materials.

In this work, the Brazilian disc (BD) sample is adopted for the measurement of dynamic tensile strength of rock materials under pre-tension.[21] The Brazilian disc specimen is loaded by a modified split Hopkinson pressure bar (SHPB) system, using which static tensile load is applied to the rock sample and maintained before applying the dynamic load. The pre-tension is applied along the bar axis direction through a hydraulic press, and the dynamic loading is exerted using a low speed gas gun, as in a conventional SHPB system.

2. Sample preparation and testing methodology

2.1. Specimen preparation

The rock samples are Laurentian granite (LG) taken from the Laurentian region of Grenville province of the Precambrian Canadian Shield, north of St. Lawrence and northwest of Quebec City, Canada. Rock cores with a nominal diameter of 40 mm are drilled from the same block. Special care was taken to prepare the Brazilian disc specimens with a diameter of 40 mm and thickness of 16 mm. All specimens are polished to have a surface roughness of less than 0.5% of the sample thickness.[21] The mineral grain size of LG varies from 0.2 to 2 mm with the average quartz grain size of 0.5 mm, and the average feldspar grain size of 0.4 mm, with feldspar being the dominant mineral followed by quartz and biotite. The physical and mechanical properties of LG are summarized in Table 1.[22]

2.2. Experimental apparatus and data analysis

The tests were conducted on the modified Split Hopkinson pressure bar (SHPB) system, which includes three bars (a striker bar, an incident bar, and a transmitted bar)[21] and the pre-tension system (Fig. 2). The elastic bars are made of high strength maraging steel with density of 8100 kg/m^3 and Young's modulus of 200 GPa. The pre-tension system is mainly composed of a pressure chamber that provides axial preload to the bars and sample, and a rigid mass at the incident bar end that is connected to the chamber by tie-rods. The pre-tension system is similar to that innovated by Frew et al.[23], who developed a modified SHPB system for dynamic tests under hydrostatic confinement. However, there is a main difference between the current design and those of Few et al.[23] and Zhou et al.[20] In their designs, the bars are connected by the tie-rods from the impact end of the incident bar to the free end of the transmitted bar, while in the current design, the bars are connected near the other end of the incident bar through a flange (Fig. 2). The total length of the compressed bars in the current design is much shorter and thus is less prone to buckling.

Table 1
Summary of physical and mechanical properties of Laurentian Granite.

Density	Porosity	Young's modulus	Poisson's ratio	Brazilian tensile strength	UCS
2.63 g/cm^3	0.64%	92 GPa	0.21	12.8 MPa	259 MPa

The recording system consists of the foil strain gauges, a signal conditioner, and an oscilloscope. There are two strains gauges with resistance of 1000 Ω on each bar attached at the symmetrical position, and they are connected to a signal conditioner through a Wheatstone bridge. The oscilloscope is connected to the signal conditioner using two channels, one for the signal on the incident bar and the other for the signal on the transmitted bar. After the check of the resistance of the strain gauges and the balance of the Wheatstone bridge, the readout voltage level of the incident wave channel is set as 200 mv and the transmitted wave channel 50 mv. The trigger voltage lever is set as – 19.6 mv and the sampling rate 10 MHz.

During the tests, the static pre-tension is applied to the sample by the pressure loading unit attached to the end of the transmitted bar through the elastic bars and flange supported by a rigid mass. When the desired pre-tension is achieved, dynamic loading is applied from the impact of the striker bar on the free end of the incident bar. The incident pulse propagates along the incident bar before it hits the sample, leading to a reflected stress wave and a transmitted stress wave that are recorded by the strain gauges attached on the incident and transmitted bar surfaces. Fig. 3 shows the time series of signals captured by the strain gauges on the bars, the dash line represents the signal of the incident wave and reflected wave, while the solid line delineates the signal of the transmitted wave. The motion induced by the incident wave is to the right and thus the flange has no effect on the wave propagation. The strains of incident wave, reflected wave and transmitted wave are denoted by $\varepsilon_{\rm i}$, $\varepsilon_{\rm r}$ and ε_t, respectively.

Based on the one dimensional stress wave theory, and assuming stress equilibrium during loading[21] (i.e.,$\varepsilon_i + \varepsilon_r = \varepsilon_t$), the history of the force on the sample is:

$$P(t) = P_0 + P_d(t) \tag{1}$$

where P_0 is the static preload on the bars, $P_d(t)$ is the dynamic force history on the bars after the impact. The tensile stress history at the center of the disc sample can be determined as:

$$\sigma(t) = \sigma_0 + \sigma_d(t) = \frac{A_0 E_0 \varepsilon_t(t)}{\pi RB} \tag{2}$$

where σ_0 is the pre-tension at the center of the disc, and

$$\sigma_0 = \frac{P_0}{\pi RB} \tag{3}$$

$\sigma_d(t)$ is the dynamic tensile stress, E_0 is the Young's Modulus of the bars, A_0 is the cross-sectional area of the bars; R is the radius of the sample and B is the thickness of the sample. The tensile strength is the maximum value of the tensile stress when the rock sample is damaged. There is an approximately linear region in $\sigma_d(t)$ (Fig. 4), and its slope is taken as the loading rate.

3. Testing results

3.1. Dynamic force balance

The pulse shaper technique is applied to achieve the force balance in the specimen during the experiments. This technique