Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 116–124

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Dynamic rock tensile strengths of Laurentian granite: Experimental observation and micromechanical model

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ARTICLE INFO

Article history:
Received 24 March 2016
Received in revised form
2 August 2016
Accepted 8 August 2016
Available online 8 December 2016

Keywords:
Dynamic tensile strength
Brazilian disc (BD) test
Semi-circular bending (SCB)
Direct tension
Split Hopkinson bar

ABSTRACT

Tensile strength is an important material property for rocks. In applications where rocks are subjected to dynamic loads, the dynamic tensile strength is the controlling parameter. Similar to the study of static tensile strength, there are various methods proposed to measure the dynamic tensile strength of rocks. Here we examine dynamic tensile strength values of Laurentian granite (LG) measured from three methods: dynamic direct tension, dynamic Brazilian disc (BD) test, and dynamic semi-circular bending (SCB). We found that the dynamic tensile strength from direct tension has the lowest value, and the dynamic SCB gives the highest strength at a given loading rate. Because the dynamic direct tension measures the intrinsic rock tensile strength, it is thus necessary to reconcile the differences in strength values between the direct tension and the other two methods. We attribute the difference between the dynamic BD results and the direct tension results to the overload and internal friction in BD tests. The difference between the dynamic SCB results and the direct tension results can be understood by invoking the non-local failure theory. It is shown that, after appropriate corrections, the dynamic tensile strengths from the two other tests can be reduced to those from direct tension.

1. Introduction

Rocks are considerably weaker in tension than in compression, and thus characterizing tensile parameters of rocks is of great importance in many engineering and geophysical applications. For instance, tensile failure is believed to be the main failure mode in underground rock excavations. Tensile strength, which is defined as the failure stress of a rock element under pure uniaxial tensile loading, is thus an important material parameter of rocks.

Following the fundamental definition of tensile strength, direct pull test appears to be best suited for tensile strength measurement. The International Society for Rock Mechanics (ISRM) has suggested a direct tension method to measure the static rock tensile strength (Bieniawski and Hawkes, 1978). However, in practice, the ideal uniform stress state in the specimen is very hard to be achieved. Premature failure due to stress concentration around grips and bending effects due to instrumental misalignments can introduce significant errors to the measurement results.

Because of the difficulties associated with experimentation in direct tensile tests, a variety of indirect methods have been proposed as convenient alternatives to measure the tensile strength of rocks, for example, Brazilian disc (BD) test (Mellor and Hawkes, 1971; Hudson et al., 1972; Bieniawski and Hawkes, 1978; Coviello et al., 2005), ring test (Hudson, 1969; Hudson et al., 1972; Coviello et al., 2005), and bending test (Hudson, 1969). The various indirect tension testing methods aim at generating tensile stress in the specimen by far-field compression, which is much easier and cheaper in instrumentation than direct pull tests. In addition, these methods usually can give repeatable results. However, the interpretation of these indirect tension results tends to rest on the generally dubious assumption of the stress distribution prior to fracture. Direct tension is thus still needed to verify the accuracy and robustness of the indirect tests (Mellor and Hawkes, 1971).

Existing attempts to measure rock tensile strength are mostly limited to quasi-static loading, primarily due to the difficulties in the dynamic experimentation and subsequent data interpretation. However, in many mining and civil engineering applications, such as quarrying, rock cutting, drilling, tunneling, rock blasts, and rock bursts, rocks are stressed dynamically. Accurate characterizations

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2016.08.007

of rock tensile strength over a wide range of loading rates are thus crucial.

Due to the same reasons discussed above for static tension tests, few dynamic direct tensile tests have been attempted (Goldsmith et al., 1976), and research efforts have concentrated on extending the indirect methods from quasi-static to dynamic loading. Zhao and Li (2000) measured the dynamic tensile properties of granite with the BD and three-point bend (TPB) techniques; the loading was driven by air and oil and thus had a limited loading rate range. To attain the tensile strength of rocks under high loading rates, most researchers used the standard dynamic testing facility, split Hopkinson pressure bar (SHPB), to apply the dynamic load (Xia and Yao, 2015). For example, conventional SHPB tests were conducted on BD and flattened BD specimens of marble (Wang et al., 2006) and on BD specimens of argillite (Cai et al., 2007). These attempts followed the pioneer work on dynamic BD tests of concretes using the SHPB (Ross et al., 1989, 1995).

The dynamic BD test using the SHPB was recently used to study the loading rate dependence of rock tensile strength (Dai et al., 2010a) and rock tensile strength anisotropy (Dai and Xia, 2010). Furthermore, a dynamic semi-circular bending (SCB) method was used in combination with the SHPB to measure the flexural tensile strength of rocks (Dai et al., 2008) and the anisotropy of the flexural tensile strength of rocks (Dai et al., 2013). Unlike earlier attempts on dynamic indirect tests where quasi-static data regression was used without sufficient validation, the conditions under which the quasi-static stress analysis is valid were carefully addressed in these recent studies. This concept was further adopted in the first batch of ISRM suggested methods for measuring dynamic properties of rocks (Zhou et al., 2012). However, there is still a need to validate the dynamic BD tests using the direct tension tests, due to the same reason as in the static case (Mellor and Hawkes, 1971). Partially motivated by the foregoing issues, we developed a split Hopkinson tension bar (SHTB) system to measure the dynamic direct tensile strength of Laurentian granite (LG) (Huang et al., 2010).

In the current study, we first overview the three dynamic tensile strength measurement methods: dynamic BD, dynamic SCB and dynamic direct tension. The values of dynamic tensile strength for the same rock (LG) obtained from these three methods are then compiled and compared. It is found that the dynamic direct tensile strength is consistently lower than the dynamic BD tensile strength (Dai et al., 2010a), and the dynamic BD tensile strength is consistently lower than the dynamic flexural tensile strength obtained using the dynamic SCB test (Dai et al., 2010b). It is thus the primary objective of this work to rationale of these differences.

To understand the difference between the dynamic direct tensile strength and the dynamic BD tensile strength, we propose two mechanisms for the strength over-estimation in the dynamic BD method: the overload effect and the internal friction effect. We conduct dynamic BD tests using SHPB to illustrate the overload effect, and the frictional effect is qualitatively derived based on the micromechanical failure mechanism of rocks. After corrections based on these mechanisms, the dynamic BD tensile strength can be reduced to the dynamic direct tensile strength. The difference between the dynamic flexural tensile strength and the dynamic direct tensile strength can be explained by invoking a non-local failure theory as we used earlier (Dai et al., 2010b).

2. Overview of three dynamic tensile strength measurement methods

2.1. Split Hopkinson pressure bar

The SHPB system is composed of three bars: a striker bar, an incident bar, and a transmitted bar (Grag and Blumenthal, 2000). A specimen is sandwiched between the incident bar and the transmitted bar. The impact of the striker bar on the free end of the incident bar induces a longitudinal compressive wave propagating in both directions. The left-propagating wave is fully released at the free end of the striker bar and forms the trailing end of the incident compressive pulse ε_i (Fig. 1). Upon reaching the bar–specimen interface, part of the incident wave is reflected as the reflected wave ε_r and the remainder passes through the specimen to the transmitted bar as the transmitted wave ε_t.

Based on the one-dimensional stress wave theory, the dynamic forces on the incident end (P_1) and the transmitted end (P_2) of the specimen are (Kolsky, 1949, 1953):

$$P_1 = AE(\varepsilon_i + \varepsilon_r), \ \ P_2 = AE\varepsilon_t \tag{1}$$

where E is the Young's modulus, and A is the cross-sectional area of the bars.

2.2. Dynamic Brazilian disc method

A 25 mm diameter SHPB system is used in the study. A close-view of the dynamic BD test in the SHPB system is schematically shown in Fig. 2, where the disc specimen is sandwiched between the incident bar and the transmitted bar. The principle of the BD test comes from the fact that rocks are much weaker in tension than in compression, and thus the diametrically loaded rock disc specimen fails due to the tension along the loading diameter near the center. The tensile stress at the central disc along the loading direction is

$$\sigma(t) = \frac{2P(t)}{\pi DB} \tag{2}$$

where $P(t)$ is the load; D and B are the diameter and the thickness of the disc, respectively. It is usually believed that at the maximum load, the corresponding tensile stress is the material tensile strength σ_t. In the dynamic case, the load is P_1 ($=P_2$) obtained using Eq. (1). The loading rate is the slope of the pre-peak linear portion of the tensile stress curve (Zhou et al., 2012).

It is noteworthy that the prerequisite for using Eq. (2) for dynamic BD tests is the dynamic stress equilibrium in the BD specimen (Dai et al., 2010a). With the pulse shaping technique (Zhou et al., 2012; Xia and Yao, 2015), the dynamic force balance for a typical BD test is achieved and shown in Fig. 3. The dynamic forces P_1 and P_2 are calculated using Eq. (1). As shown in Fig. 3a, the dynamic forces on both ends of the BD specimen are almost identical during the dynamic loading. In rock specimen, the force equilibrium state can be achieved when the stress wave propagates in the rock specimen for about 3–4 times of the round-trip (Zhou et al., 2012). Thus, the initial time for dynamic stress equilibrium in the BD specimen can be estimated by the propagation distance and the P-wave velocity of the rock specimen. Since the P-wave velocity of LG is 5000 m/s (Yin et al., 2012), the stress equilibrium time for a 40 mm diameter BD specimen is theoretically about 48–64 μs. In the typical BD test, the ratio of P_1 to P_2 is calculated (Fig. 3b) during the dynamic loading period. It illustrates that the absolute value of ratio of the forces on both ends of the BD specimen $|P_1/P_2|$ has drastic fluctuations at the beginning, and then equals 1 at about 51 μs, after which the force balance is reached. The starting time (t_0) for the force balance in the typical BD test is in the range of the theoretical force balance starting time. It is also noted that at the peak load, the ratio is almost 1. Thus, the pulse shaping technique is an efficient method to achieve the force balance in the rock BD specimen and the dynamic force equilibrium is reached for all dynamic BD tests. In addition, in our earlier work (Dai et al., 2010a),