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Static and dynamic tensile failure characteristics of rock based on splitting test of circular ring

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Abstract: Static and dynamic splitting tests were conducted on ring marble specimens with different internal diameters to study the tensile strength and failure modes with the change of the ratio of internal radius to external radius (ρ) under different loading rates. The results show that the dynamic tensile strength of disc rock specimen is approximately five times its static tensile strength. The failure modes of ring specimens are related to the dimension of the internal hole and loading rate. Under static loading tests, when the ratio of internal radius to external radius of the rock ring is small enough (ρ<0.3), specimens mostly split along the diametral loading line. With the increase of the ratio, the secondary cracks are formed in the direction perpendicular to the loading line. Under dynamic loading tests, specimens usually break up into four pieces. When the ratio ρ reaches 0.5, the secondary cracks are formed near the input bar. The tensile strength calculated by Hobbs' formula is greater than the Brazilian splitting strength. The peak load and the radius ratio show a negative exponential relationship under static test. Using ring specimen to determine tensile strength of rock material is more like a test indicator rather than the material properties.

Key words: rock; circular ring; Brazilian splitting test; tensile strength; split Hopkinson pressure bar; failure pattern

1 Introduction

The splitting test, also called the Brazilian test, is a simple and convenient method to obtain the indirect tensile strength of rock and rock-like materials. This method was firstly introduced by CARNEIRO [1] and AKAZAWA [2] in 1943. Over the past several decades, the Brazilian splitting test has received considerable attention. Although the splitting test was officially recommended by the International Society for Rock Mechanics (ISRM) as a method to determine the tensile strength of rock and rock-like materials in 1978 [3], the validity of the test has been always debated even until nowadays [4].

In 1965, the splitting test of a circular ring, disc with a small central hole, for determining the tensile strength of rock was proposed by HOBBS [5]. In his work, the distribution of the stress in a circular ring subjected to a splitting load was studied and a formula was provided to calculate the tensile strength. Since then, the splitting test of a circular ring specimen to determine the indirect tensile strength of brittle material has received considerable attention. The distribution of stress and displacement in a circular ring under diametral compression has already been studied in the range of ρ values (the ratio of ring's radii) [6−8]. CHEN and HSU [9] studied the indirect tensile strength of anisotropic rock by the ring test through numerical methods. The results showed that the tensile strength of anisotropic rocks determined by ring test was not a constant, which depended on various factors. ZHU et al [10] and LIU et al [11] simultaneously considered the influence of ρ value on the tensile strength through numerical methods. The cracking load to determine the indirect tensile strength of rock was proposed [10] and the relation between the indirect tensile strength and the ρ value was obtained [11]. YOU et al [12] experimentally studied the influence of water condition on the tensile strength of rocks. It showed that the water condition could influence the tensile strength when the dimension of the internal hole reached a certain value and an

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exponential equation was proposed to describe the relation between the maximum force and its internal diameter. Moreover, the ring test was proposed as a convenient method to determine the fracture toughness without pre-cracked specimens [13]. ZHANG and LIANG [14] calibrated the maximum dimensionless stress intensity factor for a holed flattened ring specimen.

The dynamic tensile strength of rocks is usually determined by the dynamic splitting test in split Hopkinson pressure bars (SHPB). ZHU et al [15,16] carried out the dynamic splitting test of disc specimen with SHPB driven by pendulum hammer, in order to determine the indirect tensile strength of rock under an intermediate strain rate. The strain rate dependency of tensile strength and the failure pattern of the Brazilian disc specimen under the intermediate strain rate were numerically simulated with RFPA-Dynamic. ZHOU et al [17,18] investigated the stress evolution and failure process of Brazilian disc with SHPB device. It was found that the stress distribution in specimen after equilibrium was similar to its static loading case, and the crack initiated at the disc center and propagated along the loading direction. DAI et al [19] used a SHPB system to quantify the dynamic tensile strength of rocks by the Brazilian disc (BD) specimen. It showed that with proper experimental design, the dynamic tensile strengths of rocks measured by using SHPB were valid and reliable. WANG et al [20,21] measured the dynamic tensile stress of rock by flattened Brazilian disc (FBD) specimens in a pulse shaping SHPB system, and drew a conclusion that the pattern of dynamic stress distribution in the specimen was symmetric and similar to that of the counterpart static loading. However, the dynamic ring test has not been reported in the available literatures.

In this work, the splitting test was used to investigate the static and dynamic properties of ring specimens for marble. The tensile strengths of the circular rock rings under static and dynamic loads were experimentally studied, and the failure patterns of the specimens under different loading rates were discussed.

2 Experimental

2.1 Specimen preparation

The specimens were firstly drilled from a single marble block with good geometrical integrity and petrographic uniformity. The cylindrical specimens were prepared with a diameter (D) of 50 mm and a length/diameter ratio (l/D) of 0.5. Then, most of the discs were taken to prepare circular ring specimens with internal diameters varying from 5 to 25 mm with an interval of 5 mm by water jet cutting technology. It means the ratio of internal radius to external radius of rock ring (ρ) varies from 0.1 to 0.5 with an interval of 0.1.

The specimens were numbered after preparation. The number of the specimen reflected the testing method, the ratio of internal radius to external radius of rock ring and the sequence of preparing. Such as, S0.2-2 indicates that this specimen is the second specimen of the circular ring with an inner diameter of 10 mm and the ratio of 0.2, which is conducted under static compression. While D0-3 indicates that this specimen is the third one of the intact marble disc, which is conducted under dynamic impact test.

2.2 Test apparatus and scheme

The static tests were conducted on an Instron1342 system. Specimens were put directly between the platens. The displacement rate was set at 1.5 mm/min during the splitting test. The dynamic tests were performed on the SHPB system. The cylindrical elastic bars are made of steel with a density of 7.8 g/cm^3, an elastic modulus of 240 GPa and a P-wave velocity of 5400 m/s. Dynamic loads came from the impact of a striker driven by high-pressure gas. Specimens were sandwiched between the incident bar and the transmitted bar during the test. The failure progress of the specimen was monitored by a high-speed camera (FASTCAM SA1.1). The tensile strength of the intact disc specimen was calculated by

$$\sigma_{t,\mathrm{S/D}} = \frac{P}{\pi R t} \tag{1}$$

where $\sigma_{t,\mathrm{S}}$ and $\sigma_{t,\mathrm{D}}$ are tensile strengths under the static and dynamic loads, respectively; P is the maximum force applied on the specimen for the static test or the equivalent maximum force applied on the specimen for the dynamic one; R and t are the radius and the thickness of the specimen, respectively. The equivalent maximum force in the dynamic test can be obtained and calculated by [22]

$$P(t)=EA_\mathrm{e}\varepsilon_\mathrm{T}(t) \tag{2}$$

where E is the elastic modulus of the bar, A_e is the cross-sectional area of the bar, and $\varepsilon_\mathrm{T}(t)$ is the transmitted pulse captured by the strain gauge on the transmitted bar.

According to Hobbs [5] equation, the formula for calculating the tensile strength σ_t^R in a circular ring is

$$\sigma_{t,\mathrm{S/D}}^\mathrm{R} = \frac{P}{\pi R t}\left(6+38\frac{r^2}{R^2}\right) \tag{3}$$

where R and r are the external and internal radii, respectively; $\sigma_{t,\mathrm{S}}^\mathrm{R}$ represents the tensile strength under the static load and $\sigma_{t,\mathrm{D}}^\mathrm{R}$ represents the tensile strength under the dynamic load for rock ring specimens.