Tensile strength anisotropy of Barre Granite

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ABSTRACT: Granitic rocks usually exhibit strongly anisotropy due to pre-existing microcracks induced by geologic loadings. The understanding of the rock anisotropy in mechanical properties such as tensile strength is critical to quarrying and stabilization of underground structures. In this paper, Brazilian tests are conducted in combination with MTS material testing machine and split Hopkinson pressure bar (SHPB) system to measure both static and dynamic tensile strength of anisotropic Barre granite. Samples are cored and labeled using the three principle anisotropic directions of Barre granite. These directions are also chosen as the loading directions for the Brazilian discs. For dynamic tests, pulse shaping technique is used to achieve dynamic equilibrium in the samples during the test. Finite Element Method is implemented to formulate equations that relate the failure load to the material tensile strength employing a orthotropic model for Barre granite. For samples in the same orientation group, the tensile strength shows clear loading rate sensitivity. The tensile strengths exhibit clear anisotropy under static loading; while less anisotropy under dynamic loading. The tensile strength anisotropy of Barre granite is interpreted as interactions of the pre-existing microcracks.

1 INSTRUCTION

Under tectonic loading, rocks may exhibit anisotropy naturally. One cause is the anisotropic elasticity of rock forming minerals and the alignment of the grains in preferred directions, the other cause is the oriented pores and/or microcracks (Phillips & Phillips, 1980). It has been pointed out that the fabric of microcracks in granitic rocks correlates well with the anisotropy of physical properties, such as uniaxial compressive strength (Douglass & Voight, 1969), tensile strength (Peng & Johnson, 1972), and static fracture toughness (Nasseri & Mohanty, 2008). This anisotropy also correlates well with the orientations of splitting planes in granites. Using optical techniques, Schedl et al. (Schedl et al., 1986) concluded that the splitting planes and anisotropy in Barre granite were mainly caused by microcracks. In a related investigation aimed at characterizing the micro-structures and fracture toughness for a selection of granitic rocks, a good correlation among microcrack density, microcrack length and fracture toughness has been demonstrated (Nasseri & Mohanty, 2008; Nasseri et al., 2005).

Rocks are much weaker in tension than in compression. It is thus important to characterize the tensile strength of anisotropic rocks in general and to understand the correlation between strength and the microcrack-induced anisotropy in particular. 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 of rock tensile strength over a wide range of loading rates are thus crucial. Barre granite is chosen for this study because it is one of the most anisotropic rocks and its preferred microcrack orientation has been well characterized (Nasseri & Mohanty, 2008) using a combined ultrasonic and optical methods. In addi-

tion, it was designated as part of a standard rock suite by the U.S. Bureau of Mines (Goldsmith et al., 1976).

Various methods have been proposed for tensile strength measurement of rocks. Given the difficulties associated with experimentation in direct tensile tests, indirect methods serve as convenient alternatives to measure the tensile strength of rocks; some examples are Brazilian disc test (Bieniawski & Hawkes, 1978; Coviello et al., 2005; Hudson et al., 1972; Mellor & Hawkes, 1971), ring test (Coviello et al., 2005; Hudson, 1969; Hudson et al., 1972; Mellor & Hawkes, 1971), and bending test (Coviello et al., 2005). These indirect methods aim at generating tensile stress in the sample by far-field compression, which is much easier and cheaper in instrumentation than direct pull tests. Among those indirect methods, the diametrical compression of thin discs, generally referred to as the Brazilian test. Brazilian test is probably the most popular one due to convenient specimen preparation and experimental implementation. It has been suggested by the International Society for Rock Mechanics (ISRM) as a recommended method for tensile strength measurement of rocks (Bieniawski & Hawkes, 1978) and thus is chosen in this study. Brazilian tests have also been chosen by many researchers to measure the indirect tensile strength of rocks and investigate the effect of anisotropy on the strength respectively, such as Berenbaum and Brodie (Berenbaum & Brodie, 1959) on coal, Evans (Evans, 1961) on coal, Hobbs (Hobbs, 1964) on siltstone, sandstone and mudstone, Mclamore and Gray (Mclamore & Gray, 1967) on shale and Barla (Barla, 1974) on gneiss and schist, Chen et al. (Chen et al., 1998) on four types of sandstone.

Researchers also extended Brazilian tests to the regime of dynamic testing. For example, Zhao and Li (Zhao & Li, 2000) measured the dynamic tensile properties of granite the Brazilian tests; the loading was driven by air and oil. To attain tensile strength of rocks under high loading rates, Brazilian test is accommodated on the standard dynamic testing device, split Hopkinson pressure bar (SHPB). For examples, conventional SHPB tests were conducted on Brazilian disks of marble (Wang et al., 2006) and argillite (Cai et al., 2007) to measure the dynamic tensile strengths. Quasi-static analysis has been used in these works to relate far-field peak load to the tensile strength of the sample without sufficient justification.

Both quasi-static and dynamic tension tests have been conducted on the Barre granite to investigate the loading rate effect and the correlation between the micro-structure induced anisotropy (Goldsmith et al., 1976). However, as pointed out before by Xia et al. (Xia et al., 2008) in the dynamic compression on Barre granite, the effect of micro-structures on the dynamic behaviors of Barre granite was inconclusive due to the lack of control of the loading rate and other deficiencies in the experimental design (Goldsmith et al., 1976). It is thus necessary to revisit the tension tests on Barre granite in a systematic manner, with newly developed techniques on SHPB tests. For instance, the pulse-shaper technique (Frew et al., 2001, 2002) is especially useful to modify the loading pulse and thus facilitate achieving quasi-static equilibrium during the tests. In addition, through a careful design of the pulse-shaper dimension, the resulting loading rates or strain rates can be constant.

This paper continues previous investigation on the effect of microcrack-induced anisotropy on the dynamic compressive response of Barre granite (Xia et al., 2008). Herein, the tensile strength anisotropy and its micro-structural correlation are investigated. Both static and dynamic Brazilian tests are conducted for measuring tensile strength of Barre granite along different splitting planes. Rock blocks are cored and labeled along these orthogonal directions. These directions are also chosen as the loading directions in the Brazilian tests. Static measurement is conducted with a servo-controlled material testing machine and the dynamic experiment is carried out with a 25 mm SHPB system.

2 EXPERIMENTAL SETUP

Static measurement is conducted with an MTS hydraulic servo-control testing system (Fig.1a). TestingSart-II (digital controller) is used to control the testing process and MTS TestingWare-SX software is utilized to set the testing parameters. A constant loading rate of 0.005 mm/s is applied for all the tests. The entire load is measured with a 50 kN load cell. Dynamic test is conducted using a 25 mm SHPB system (Fig. 1b). It is composed of a 200 mm striker bar, a 1500 mm incident bar and a 1200 mm transmitted bar, all made of high strength maraging steel.

The specimen is sandwiched between the incident and transmitted bars. Two strain gauges are mounted at 733 mm and 655 mm away from the bar-sample interfaces on the incident bar and transmission bar, respectively. An eight-channel Sigma digital oscilloscope by Nicolet is used to record and store the strain signals collected from the Wheatstone bridge circuits after amplification.



Fig. 1 (a) MTS hydraulic servo-control testing system; (b) split Hopkinson pressure bar (SHPB) system.

The impact of a 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 (Fig. 2). When the leading edge of the compression wave (incident wave) reaches the bar-specimen interface, it is partly reflected (reflected wave), and the remainder passes through the specimen to the transmitted bar (transmitted wave). These three elastic stress pulses in the incident and transmitted bars are recorded with the strain gauges. Assuming one-dimensional stress wave propagation, the forces on both ends of the sample are:

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

Here P_1 is the force on the incident end of the specimen, and P_2 , the transmitted end. \mathcal{E} denotes strain, and the subscripts i, r and t refer to the incident, reflected and transmitted waves, respectively. A is the cross-sectional area and E denotes the Young's modulus of the bars.



Fig. 2 Schematics of a split-Hopkinson pressure bar (SHPB) and the X-t diagram of stress waves propagation

A newly developed pulse shaping technique of SHPB method is utilized for all dynamic tests. The pulse shaping technique in SHPB is especially useful for investigating dynamic response of brittle materials such as rocks (Frew et al., 2001, 2002). Without proper pulse shaping, it is difficult to achieve dynamic stress equilibrium in such materials because the sample may fail immediately from its end when it is impacted by the incident bar. In the modified SHPB test, we use the C11000 copper as the main shaper to transform the incident wave from a rectangular shape to a ramped shape. In addition, a small rubber disc is placed in front of the copper shaper to further reduce the slope of the pulse to a desired value. During tests, the striker impacts the pulse shapers before the incident bar, thus generating a non-dispersive ramp pulse propagating into the incident bar and thus facilitating the dynamic force balance for the specimen (Frew et al., 2001, 2002).

3 MICROCRACK ORIENTATION AND SAMPLE PREPARATION

Barre granite is obtained from the southwest region of Burlington in Vermont, USA. This granite is an intrusive deposit of Devonian age, concordant on a regional scale but discordant at local contacts. It is a fine to medium grained rock with mineral grain sizes ranging from 0.25 to 3 mm. Quartz makes up 25% (by volume) of this rock and has an average grain size of 0.9 mm. Feldspar is the dominant mineral (65%) and has an average grain size of 0.83 mm. The average grain size for biotite (6%) is 0.43 mm. The microcracks are of either the intragranular or intergranular type and are found in quartz and feldspar grains, and along cleavage planes of biotite grains (Xia et al., 2008).



Fig. 3 3D block diagram showing longitudinal wave velocities and the sampling location of Brazilian discs prepared along each plane with respect to exaggerated microcrack orientations in Barre granite; the first index for sample numbering represents the direction normal to the splitting plane, and the second index indicates the propagation direction of the crack.

Micro-cracks orientation in Barre granite has been investigated and it has been reported that there is a strong concentration of micro-cracks within the rift plane (plane of easiest splitting) and the hard way (plane of hardest splitting) (Nasseri & Mohanty, 2008; Nasseri et al., 2005). Our Barre granite block is directly taken from quarried stones with clear identification of three splitting planes. P-wave velocities are measured along three orthogonal axis of the block, which is then labeled as X, Y and Z axes with respect to slow (3.57 km/s), intermediate (4.00 km/s)and high P-wave velocity (4.75km/s) respectively (Fig. 3). Sano et al. determined the prin-

cipal axes of Barre granite by measuring the P-wave and S-wave velocities in various directions of propagation and polarization. In their paper, the p-wave velocities along three principal axes are 3.540 km/s, 3.985 km/s and 4.655 km/s respectively (Sano et al., 1992), very similar to our results. Micro-structural examination of thin sections (Nasseri et al., 2005) are then conducted to further confirm the three orthogonal principal directions of the chosen block. Fig. 3 illustrates the 3D relationships between the three sets of microcracks inferred form the petrographical studies along the three orthogonal axes marked with P-wave velocities. The dominant microcrack first set (rift plane) runs parallel with the YZ plane. The sub-dominant microcrack second set (grain plane) was found to be parallel with the XZ plane and the least dominant third set (hard way or most resistive plane) runs parallel with the XY plane in Barre granite (Nasseri & Mohanty, 2008).

The disc samples of Barre granite are then cored and labeled using the three principle anisotropic directions shown in Fig. 3. Rock cores with a nominal diameter of 40 mm are first drilled along X- Y- and Z- directions from the same rock block. For each core, the other two principle directions are also marked. We then slice the rock cores to obtain disk samples with an average thickness of 16 mm according to the two principal directions. All the disc samples are polished afterwards resulting in surface roughness of less than 0.5% of the sample thickness. The diametric loadings are chosen along a pair of orthogonal principal axes (in-plane of the Brazilian disc surface) respectively. Therefore for disc samples in this research, six groups (configurations), namely XY, XZ, YX, YZ, ZX, and ZY are prepared. The rule of nomenclature for the Brazilian disc groups is also shown schematically in Fig. 3, with the first index represents the direction normal to the fracture plane and the second index indicates the propagation direction of the crack.

4 TENSILE STRENGTH DETERMINATION

4.1 Stress distribution

For the static test, the disc samples are compressed diametrically with loading platens in the MTS hydraulic servo-control testing system (see Fig. 1a). Fig. 4a schematically shows the loading scheme of a Brazilian disc, where *D* and B are the diameter and the thickness of the disk, respectively. P is the diametrical loading. For the dynamic test, the disc specimen in the SHPB system is shown schematically in Fig.4 b, where the sample disc is sandwiched between the incident bar and the transmitted bar.



Fig. 4 Schematics of the Brazilian test (a) in a MTS machine (b) in a SHPB system.

Let x, y, z be a global Cartesian coordinate system shown in Fig. 4 with the y-axis defining the loading direction and the z-axis denoting the axial direction of the disc. Assuming a quasi-static

elastic equilibrium in the disc, for any point (x, y) within the disc, the components of the stress field can be expressed as follows:

$$\sigma_x = \frac{2P}{\pi DB} \cdot f_{xx}, \ \sigma_y = \frac{2P}{\pi DB} \cdot f_{yy}, \ \tau_{xy} = \frac{2P}{\pi DB} \cdot f_{xy}$$
(2)

where, σ_x , σ_y and τ_{xy} are three components of the stress tensor depending on the coordinates (x, y) of a point of interest, the loading direction as well as the compliance constants of the elastic model. f_{xx} , f_{yy} and f_{xy} are the corresponding dimensionless components of the stress tensor. The sign convention here is: positive for compression and negative for tension.

To measure the indirect tensile strength of anisotropic rocks by Brazilian test, a thorough analysis of the stress state in the anisotropic disc is required. In this work, finite element analysis with a commercial software ANSYS is conducted to analyze the stress state in the anisotropic rock disc for all our eight sample configurations. Quadrilateral eight-node element PLANE82 is used in the analysis, and the finite element model consists of 4,800 elements and 14,561 nodes in total (Fig. 5). Barre granite is considered orthotropic and the material constants has also been documented (Sano et al., 1992). The nine elastic constants C_{ijkl} used in the finite element analysis are: C_{1111} = 32.70 GPa, C_{2222} = 41.69 GPa, C_{3333} = 56.17 GPa, C_{2323} = 20.59 GPa, C_{3131} = 17.67 GPa, C_{1212} = 15.78 GPa, C_{2233} = 6.43 GPa, C_{3311} = 3.93 GPa, C_{1122} = 3.45 GPa. For comparing purpose, the stress state in an isotropic rock disc is also analyzed.



Fig. 5. Meshing scheme of the Brazilian disc for the finite element analysis.

For the isotropic case, Fig.6a, b and c show the distribution of the dimensionless stress components $f_{xx} (= \sigma_x / \frac{2P}{\pi DB})$, $f_{yy} (= \sigma_y / \frac{2P}{\pi DB})$ and $f_{xy} (= \tau_{xy} / \frac{2P}{\pi DB})$ respectively.

The calculated values of f_{xx} , f_{yy} and f_{xy} at the centre of the disc (potential failure spot) are $f_{xx} \sim$ -1, $f_{yy} \sim 3$ and f_{xy} =0, respectively. For anisotropic case, eight sample configurations XY, XZ, YX, YZ, ZX, and ZY are analyzed; and the similar symmetrical stress contours as the isotropic case are observed. As a demonstration, the stress trajectories of the f_{xx} , f_{yy} and f_{xy} for sample YX are illustrated in the Fig. 6d to f, respectively. The stress distribution near the centre of the disc is quite uniform for the anisotropic YX sample (Fig. 6d), very similar to the isotropic case (Fig. 6a). The shear stress components (Fig. 6f) along the loading diameter and the horizontal diameter are zero due to the intentional coring and loading along three predetermined material symmetrical plane X, Y and Z. Therefore, the f_{xx} and f_{yy} along the loading direction in the Fig. 6d and Fig. 6e actually represent the dimensionless in-plane principal stress σ_1 and σ_3 .



Fig. 6. Stress trajectories of a Brazilian disk- quasi-static deformation; (a) f_{xx} , (b) f_{yy} and (c) f_{xy} , for isotropic case; (d) f_{xx} , (e) f_{yy} and (f) f_{xy} , for sample YX; (positive for compression, neg. for tension).

4.2 Tensile strength

With Eq. (2), the stress state at any point within the disk can be fully determined by the three dimensionless stress components f_{xx} , f_{yy} and f_{xy} . Fig. 6 illustrates that for points along the loading diameter of the anisotropic Brazilian disc, the shear stress is zero, the tensile stress is almost constant near the center of the disc and the corresponding compressive stress is very similar to the isotropic case with around three times of the tensile stress. The vanishing fashion of

the shear stress components along the loading diameter implies the coincidence of the in-plane principal stress σ_1 and σ_2 with σ_x and σ_y . For the tensile strength determination for anisotropic Barre granite in this study, since rocks are much weaker in tension than compression, we made the same assumption as Chen et al. (Chen et al., 1998) that the indirect tensile strength is given by the maximum absolute value of the tensile stress σ_x perpendicular to the loading diameter at the disc center.

$$\sigma_t = \frac{2P_f}{\pi DB} \cdot F \tag{3}$$

where P_f is the load when the failure occurs. σ_t is the tensile strength. F equals to minus f_{xx} at the center of the disc with coordinates (0, 0). F is a dimensionless stress, which depends on the orthotropic elastic constants for each sample group and can be calibrated using finite element analysis as discussed before. The calculated dimensionless stresses F for each sample configuration are given as: $F_{XY} = 0.9215$, $F_{XZ} = 0.8334$, $F_{YX} = 1.0452$, $F_{YZ} = 0.9112$, $F_{ZX} = 1.1058$, $F_{ZY} = 1.0769$.

For Brazilian tests conducted in the MTS system, the quasi-static equation Eq. (3) is reasonable to be used. For dynamic Brazilian tests in the SHPB system, a quasi-static stress state in the sample disc during the test has to be checked before Eq. (2) can be used to determine dynamic tensile strength. This is because that in the dynamic tests conducted on SHPB apparatus featuring high loading rates, there is a load inertial effect as shown by Böhme and Kalthoff (Bohme & Kalthoff, 1982). This inertial effect will lead to error in data reduction in general, if we used quasi-static analysis. The newly developed pulse shaper technique in SHPB tests has been widely used to achieve dynamic force equilibrium in the specimen during the experiment. This technique was discussed in detail by Frew et al. for SHPB tests of brittle materials (Frew et al., 2002) and was recently used by the authors in dynamic compressive testing (Xia et al., 2008) and tensile testing (Dai et al., 2008) of rocks using SHPB. We demonstrated that in the conventional SHPB tests, the dynamic forces on both ends of the specimen are very different. The resulting inertial effect dominates in the test and thus invalidates the quasi-static data reduction. On the other hand, in a modified SHPB test with proper pulse shaping, the dynamic force balance can be achieved for the entire loading period and the tensile stress state at the failure spot in the sample can be calculated with quasi-static analysis using the far-field measurements as inputs (Dai et al., 2008). Thus, given dynamic force balance achieved with pulse shaping, a simple quasi-static data reduction is valid to determine the dynamic tensile strength. The dynamic tensile strength σ_{i} is generally believed to be loading rate dependent and the corresponding loading rate is measured from the slope of the pre-peak linear portion of the tensile stress σ_{xx} history till failure.

5 EXPERIMENTAL RESULTS

5.1 Failure sequence of the dynamic Brazilian test

A Photron Fastcam SA1 high speed camera is utilized to monitor the fracture processes of the dynamic Brazilian test. The high speed camera is placed perpendicular to the sample surface with images taken at an inter frame interval of 8 μ s. Frames with representative features are illustrated in Fig. 7, in which the time zero corresponds to the moment when the incident pulse arrives at incident bar-sample interface. The first two frames exhibit the disc sample before fracture initiates. At around 80 μ s, the sample disc cracks near the center and a primary crack occurs, propagating bilaterally to the loading ends afterwards. The last three frames illustrate the fracture trajectory of the sample; and the disc specimen is split completely into two identical fragments (Fig. 7). It is noted that several secondary cracks are visible near the loading ends in the last frame at time instant 200 μ s. Since those secondary cracks emerge after the initiation and complete propagation of the primary crack, they have no influence on the tensile strength determination with Eq. (3)



Fig.7 High-speed video images of a dynamic Brazilian test

5.2 Dynamic equilibrium

In order to guarantee a quasi-static state in the dynamic Brazilian test, a pulse shaping technique is employed for all our dynamic tests. The dynamic force balance on the two loading ends of the sample is critically assessed. To compare the force histories of these two, the time zeros of the incident and reflection stress waves are shifted to the sample-incident bar interface and the time zero of the transmitted stress wave is shifted to the sample-transmitted bar interface invoking 1D stress wave theory. Fig. 8 compares the time-varying forces on both ends of the sample in a typical test. The dynamic forces on both sides of the samples are almost identical before the critical failure point is reached during the dynamic loading.



Fig.8 Dynamic force balance check for a typical dynamic Brazilian test with pulse shaping



Fig.9. (a) Tensile stress σ_x (b) Compressive stress σ_y histories at the specimen center (potential failure spot) from the dynamic finite element and quasi-static analyses in a dynamic Brazilian test with pulse shaping.

For a conventional dynamic compressive or direct tension testing in SHPB, the samples are cylindrical and thus the force balance on the ends ensures the stress equilibrium throughout the sample. However, the samples used for dynamic indirect tensile testing are two dimensional (2D); force balance on the boundaries does not necessarily ensure stress equilibrium within the entire sample. One needs to compare the stress history at a chosen point obtained from full dynamic analysis with that from quasi-static analysis to validate this assumption. Herein, in order to validate the quasi-static data reduction, we conduct a transient dynamic analysis on disc sample to determine the tensile stress at the potentially failure spot and then compare that with a quasi-static data reduction. The dynamic finite element analysis supposedly represents the real stress history. Assuming linear elasticity, this analysis solves the following equation of motion with the Newmark time integration technique:

$$\nabla \cdot \sigma = \rho \ddot{u} \,, \tag{4}$$

where σ is the stress tensor, ρ denotes density, and \ddot{u} is the second time derivative of the displacement vector u. The input loads P_1 and P_2 in the finite element model (Fig. 5) are taken as the dynamic loading forces exerted on the incident side and transmitted side of the specimen, respectively. The transient dynamic stress history at the disc center (potential failure spot) is calculated and compared with that from quasi-static analyses where the transmitted force is used as loading input. The histories of the stress components σ_x (in tension) and σ_y (in compression) for dynamic and quasi-static finite element analyses (Fig. 9) are compared in Fig. 9a and b; the shear stress components are zero and not compared here. It is evident that the stress states at the disc center from both data reductions match with each other. Thus, provided force balance achieved on sample ends, the quasi-static analysis with the far-field loading as input can adequately represent the stress history in the sample.

5.3 Static tensile strength anisotropy

The static strength values are taken as the average of three individual tests for each sample group. Fig. 10a depicts the variation of static tensile strength measured along six different directions for Barre granite. The measured static fracture toughness exhibits very strong anisotropy. The average tensile strength for the two sample configuration with the same splitting plane X (i.e. XY, XZ) yields the lowest tensile strength of 9.4 and 8.8 MPa respectively; configurations with the splitting plane Y (i.e. YX, YZ) owns intermediate tensile strength of 13.2 and 11.7 MPa; whereas the configurations with the splitting plane Z (i.e. ZX, ZY) exhibit the highest

strength values of 17.1 and 16.3 MPa, respectively. The highest toughness value (17.1 MPa for sample ZX) is almost twice of the smallest one (8.8 MPa for sample XZ). This ratio is referred as the maximum tensile strength anisotropic ratio in this research. Fig. 10b shows the apparent tensile strength if an isotropic rock is assumed for all the sample groups. The X plane remains the weakest plane to split while Z plane is the toughest. However, the apparent maximum tensile strength anisotropic case and anisotropic case. The discrepancy between those two treatments (isotropic case and anisotropic case) reveals that for tensile strength determination of anisotropic granite with indirect method such as Brazilian test, an accurate analysis of actual stress state at the potential failure spot is of vital importance.



Fig. 10 The variation of static tensile strength (a) anisotropic case (b) isotropic case

5.4 Dynamic tensile strength anisotropy

All the tensile strength values with corresponding loading rates are tabulated in Table 1. Fig. 11 illustrates the variation of strength values with loading rates. Within the range of available loading rates, the tensile strength increases with the increase of the loading rate for each of the six sample group. For example, the dynamic tensile strength is 44.9 MPa for sample ZX under the loading rate of 1700 GPa/s, 2.6 times than the static tensile strength of 17.1 MPa. We also observed from Fig. 11 that the splitting plane of the disc (the first index in the sample terminology) has obvious influence over the tensile strength, while the fracture propagation direction (the second index in the sample terminology) only has slight influence over the strength. Thus, we divided all the results into three groups according to the different splitting plane normal to X axis (XY, XZ), Y axis (YX, YZ) and Z axis (ZX, ZY). The strength values for each splitting plane are shown in Fig. 12a to c, respectively, an almost linear increase with the loading rates Linear fitting yields Eq. (5), (6) and (7) for Fig. 12a, b and c respectively. The tensile strength of samples with Z splitting plane owns the highest values and the X plane yields the lowest values.

$$\sigma_t^X = 0.0142\dot{\sigma} + 16.136 \tag{5}$$

$$\sigma_t^Y = 0.0121\dot{\sigma} + 21.327 \tag{6}$$

$$\sigma_t^2 = 0.0115\dot{\sigma} + 26.60\tag{7}$$

The variation of the maximum tensile strength anisotropic ratio within chosen loading rates is shown in Fig.11d. Compared to the static one, the dynamic anisotropic ratio is much lower. The

maximum anisotropic ratio exhibits sharp decrease with the increase of the loading rates. For example, under the loading rate around 200 GPa/s, sample splitting in Z plane owes the highest tensile strength of 28.9 MPa while X plane shows the lowest value of 18.9 MPa, and the maximum anisotropic ratio is 1.52. When the loading rate is up to 1800 GPa /s, the maximum anisotropic ratio is 1.13. The maximum tensile strength still occurs in sample with Z splitting plane with a value of 47.3 MPa while the lowest one is fixed in sample split in X plane as 41.7 MPa. Thus, Barre granite obviously exhibit stronger anisotropy under static loading, while relatively lower anisotropy during dynamic loading. In addition, the curve in Fig. 12d drops quickly approaching the isotropic value of 1. This implies that under very high loading rates, the tensile strength exhibit negligible anisotropy, more like isotropic. The anisotropic properties of Barre granite might be interpreted as the preferred distribution and orientation of pre-existing microcracks in the rock.

XY			XZ		
No.	$\dot{\sigma}$ (MPa/s)	σ_t (MPa)	No.	$\dot{\sigma}$ (MPa/s)	σ_t (MPa)
1-3	7.2E-08	9.4	1-3	6.9E-08	8.8
4	239.6	19.2	4	175.0	15.1
5	458.5	24.9	5	355.4	21.3
6	745.5	29.2	6	746.7	25.0
7	876.6	32.3	7	845.0	28.6
8	1261.8	34.0	8	1197.4	31.3
9	1480.1	37.7	9	1339.8	34.7
10	1550.0	38.2	10	1558.9	36.6
YX			YZ		
No.	$\dot{\sigma}$ (MPa/s)	σ_t (MPa)	No.	$\dot{\sigma}$ (MPa/s)	σ_t (MPa)
1-3	9.8E-08	13.2	1-3	9.2E-08	11.7
4	303.1	24.4	4	200.4	19.3
5	371.2	27.3	5	433.7	26.2
6	591.0	31.2	6	735.3	30.5
7	867.5	33.3	7	896.0	34.6
8	1226.4	37.6	8	1222.1	33.8
9	1400.2	38.9	9	1498.0	38.7
10	1617.6	40.9	10	1801.1	41.7
ZX			ZY		
No.	$\dot{\sigma}$ (MPa/s)	σ_t (MPa)	No.	$\dot{\sigma}$ (MPa/s)	σ_t (MPa)
1-3	1.10E-07	17.1	1-3	9.69E-08	16.3
4	243.3	28.4	4	236.9	24.9
5	332.1	32.1	5	540.2	33.1
6	656.4	35.6	6	630.8	34.8
7	988.6	38.0	7	892.8	36.4
8	1698.5	44.9	8	1171.5	41.8
9	1281.1	45.1	9	1816.2	44.4

Table 1 Tensile strengths of Barre granite from both static and dynamic Brazilian test



Fig.11. The variation of tensile strength with loading rates



Fig. 12 The tensile strength with loading rates for samples splitting in the plane normal to (a) X axis (b) Y axis (c) Z axis; and (d) the maximum tensile strength anisotropic ratio of Barre granite with loading rates

6 DISCUSSION

The main purpose of this study is to characterize the micro-crack induced tensile strength anisotropy of Barre granite under both static and dynamic loading conditions. As shown in Fig. 10, Barre granite exhibits strong anisotropy under static loading. This tensile strength anisotropy is mainly attributed to the distribution and orientation of micro-crack sets. Douglass and Voight (Douglass & Voight, 1969) studied the microcrack orientation in Barre granite and demonstrated that a strong concentration of microcracks lies within the rift plane and the secondary concentration was found within the grain plane. In this study, with reference to the dominant three sets of micro-cracks in Fig. 3, YZ plane is considered to be parallel to the rift plane with the dominant microcrack first, and XZ is considered to be the secondary concentration of microcracks for Barre granite. And, the YZ plane, XZ plane and XY plane corresponds to the quarryman's description of "rift plane", "grain plane" and "hard-way plane" respectively. This explains that in our static tensile strength measurements, the minimum tensile strength is obtained from sample XY and XZ, both split in the rift plane YZ (normal to X axis); while the maximum are obtained from sample ZX and ZY with a hard-way splitting plane XY (normal to Z axis). The relationship of the micro-cracks induced tensile strength anisotropy with the principle directions is also consistent with those reported by Goldsmith et al. (Goldsmith et al., 1976), who used orientation 2 (maximum static Young's modulus), orientation 3 (minimum static Young's modulus) and orientation 1(intermediate static Young's modulus) to denote the three orthogonal planes in Barre granite. In our notation, direction 1 is Y, direction 2 is Z, and direction 3 is X.

Under dynamic loading, the anisotropy of tensile strength is much lower than that in the static loading. The maximum anisotropic ratio of tensile strength drops drastically from the static value of 1.72 to the dynamic value of 1.13 with a loading rate of 1800 GPa/s. This is because in the static test, the loading speed is slow enough to allow all microcracks to interact. Thus, the critical crack as well as multiple microcracks will contribute to the catastrophic failure of the sample. In contrast, the loading in dynamic case is transferred in the sample with the elastic wave speed. It takes time for the unloading information to propagate from the critical crack to its neighboring microcracks. As a result, only part of the microcracks will contribute in the response. Seldom are there interactions between microcracks during the deformation. Thus, the anisotropic property of Barre granite due to the presence of microcracks has little influence on the cracking of the primary crack or critical crack dynamically. The effects of anisotropy on the tensile strength of Barre granite are overshadowed by the loading rate effects of tensile strength.

7 CONCLUSION

In this paper, we systematically measured the tensile strength of the anisotropic Barre granite with Brazilian tests statically using a MTS hydraulic servo-control testing and dynamically using a split Hopkinson pressure bar system. The disc samples are cored and loaded along three predetermined material symmetrical planes, resulting in six sample groups. In the dynamic test, with proper pulse shaping, dynamic far-field force balance is achieved and quasi-static analysis is thus valid for deducing the tensile strength from the SHPB measurements. Rate dependence of the tensile strength of Barre granite is observed. The Barre granite exhibits strong tensile strength anisotropy under static MTS loading, while relative lower anisotropy during dynamic loading. Under very high loading rates such as shock wave loading, it is anticipated that the tensile strength anisotropy can be ignored. The reason for the tensile strength anisotropy is interpreted with the dominant micro-cracks orientation in the Barre granite.

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