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Reference

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ABSTRACT

Failure of brittle rock normally initiates from tensile fracture due to its extraordinary lower resistance to tension rather than to compression. Intensive study on the deformability and accurate acquirement of the mechanical properties of rock under tensile stress is crucial for the stability analysis of rock slope and rock caverns. A new set of centering apparatuses, which consist of the specimen bonding part and the axial pulling part, were developed in this study. The misalignments when bonding the specimen and conducting the uniaxial tensile test can be effectively eliminated. Direct tensile tests were conducted on various brittle rocks cored from several large-scale hydropower station sites in China. The tensile strength, tensile elastic modulus, maximum tensile strain, and complete stress-strain curves were successfully obtained. The direct tensile test results indicated that the fracture surface formed in the central part of the specimen, which was under uniform tensile stress. The fracture surfaces were mostly perpendicular to the specimen axis. Fresh fractures without accumulation of rock fragments can be observed and characterized as tensile brittle failure. The microscopic failure modes of brittle rocks under the direct tensile test were not unique but consisted of the intragranular and intergranular fractures. The direct tensile strength (DTS) was generally lower than the Brazilian tensile strength (BTS) ($DTS/BTS = 0.60-0.71$). The direct tensile test was therefore recommended for the measurement of the tensile mechanical properties in order to ensure the safety of rock engineering.

Keywords

brittle rock, direct tensile test, Brazilian test, tensile failure micro-mechanism, centering apparatus

Introduction

With rapid developments in the field of rock engineering, an increasing number of problems related to the tensile stress-induced deformation, micro-crack initiation, and propagation arise, particularly as engineering projects continue to push the limits of design. One of the most significant features of rock material is that its tensile strength is far lower than the compressive strength. Therefore, failure of hard

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brittle rock usually initiates from areas under tensile stress or tensile-shear stress in the form of tensile failure or tensile-shear fracture (Blümling et al. 2007; Diederichs 2001; Duan and Kwok 2016; Zhang et al. 2017a, 2017b). Accurate acquirement of the mechanical properties of rock under tensile stress is crucial for the design and stability analysis of rock projects.

For a long time, experimental studies on the mechanical properties of rock material have focused on the compressive regime, e.g., the uniaxial, biaxial, and triaxial compression tests (Brace and Bombolakis 1963; Cook 1965; Haimson and Chang 2000; Ma and Haimson 2016; Okubo and Nishimatsu 1985; Wawersik and Fairhurst 1970). Tensile testing was also initiated, and many people use the indirect Brazilian tensile test (Fairhurst 1964). A thorough review on the Brazilian test can be found in Li and Wong (2013). Relatively few direct tensile tests have been reported on rock material due to the many difficulties lying in the specimen preparation, clamping with the test machine, and eccentricity control. In reality, significant differences exist among the mechanical properties of rock under compressive and tensile stress, e.g., the ratio between the uniaxial compressive strength and the Brazilian tensile strength (BTS) is mostly between 2 and 35 (Hoek and Brown 1997; Perras and Diederichs 2014).

In the current rock mechanics test standard and rock engineering practice, the knowledge of the mechanical parameters under direct tensile test is insufficient. So far, indirect methods (e.g., the Brazilian test and bending tests) were mainly adopted to measure the tensile strength of rock (Erarslan, Alehossein, and Williams 2014; Fairhurst 1964; Li and Wong 2013). Although the Brazilian test is a fast and convenient approach, there is a great difference between the strength measured by the Brazilian test and the direct tensile test. In addition, the Brazilian test fails to provide information regarding the deformability of rock under tension (Duan and Kwok 2015; Fahimifar and Malekpour 2012). Analysis of the existing literatures reveals that the BTS is generally higher than the direct tensile strength (DTS). The ratio between DTS and BTS was reported to be 0.9 for metamorphic, 0.8 for igneous, and 0.7 for sedimentary rocks (Perras and Diederichs 2014).

Other approaches that can be used to measure the tensile strength of rock are bending tests (Ju, Liu, and Xie 2003; Unlu and Yilmaz 2014; Zuo, Zhou, and Liu 2010). However, further improvements are still necessary for this method, as on one hand, the preparation of specimens for the bending test is very difficult, and on the other hand, tensile strength measured from the bending test is normally higher than that measured from the Brazilian test and direct tensile test (Huang, Zhu, and Pang 2007; Zhao, Zuo, and Pei 2012).

The direct tensile test is the most efficient way to investigate the tensile deformation and failure characteristics of rock. To date, studies have been conducted on the direct tensile test apparatus (ASTM D2936-08; Fahimifar and Malekpour 2012; Hoek 1964; ISRM 1978; Liao et al. 1997; Unlu and Yilmaz 2014)

and direct tensile test approach (Coviello, Lagioia, and Nova 2005; Erarslan and Williams 2012). Because of the brittle nature of rock material, conducting a direct tensile test with the clamping method can easily lead to the occurrence of tensile fracture around the end due to stress concentration at the gripping point. To eliminate the problem of stress concentrations, a dog-bone-shaped specimen was adopted by some researchers (Fuenkajorn and Klanphumeesri 2011; Hoek 1964; Li et al. 2013; Tolooiyan, Mackay, and Xue 2014). For brittle rock, preparation of the dog-bone-shaped specimen is not only time consuming but also expensive. In addition, some other researchers used steel cables to apply tensile stress on the metal sleeve, which was bonded to the rock specimen (Hawkes, Mellor, and Garipey 1973). No-torsion wire rope was necessary in this test besides the complex structure of the metal sleeve.

Gluing specimen ends to centering metal top and bottom caps became a frequently adopted technique to conduct tensile tests (Coviello, Lagioia, and Nova 2005; Liao et al. 1997; Perras and Diederichs 2014). However, the gluing process was normally conducted manually, which may easily lead to the unevenness of the gluing material and the subsequent occurrence of bending moments during testing. Moreover, the thickness of the gluing layer plays a crucial role on the test, as a sufficient gluing layer is required to ensure the tensile strength, but it may significantly alter the measured tensile strain if the thickness of the gluing layer is too large. In most of the previous studies, the bonding eccentricity between the rock specimen and pulling head is not considered, which may easily lead to the eccentric tension of the rock specimen.

To overcome the limitations of previous direct tensile tests, centering apparatuses for the direct tensile test were designed in this study, which consisted of the centering apparatus for bonding the specimen and the centering apparatus for conducting the pulling test. With the aid of these apparatuses, direct tensile tests were successfully conducted on brittle rocks cored from various large-scale hydropower station sites in China. Tensile mechanical parameters obtained in this study provided important parameters for the design and stability evaluation of these projects.

Development of the Centering Apparatus

THE DESIGN PRINCIPLES

The key to whether direct tensile test can be successfully conducted depends on how to avoid the rock specimen under eccentric tension. There are mainly two reasons that may cause the eccentricity. First, eccentricity may originate from the misalignment between the specimen axis and the axis of pulling heads when bonding them together, as this operation is performed manually and relies heavily on the experience of the operator. Second, eccentricity may arise from the misalignment between the axis of the specimen and the test machine pulling rod when pulling the

specimen. Therefore, to ensure the rock specimen is strictly under uniaxial tensile stress, the following principles should be followed when designing the centering apparatuses:

- (1) The apparatus should be able to avoid the eccentricity when gluing the specimen with the pulling heads.
- (2) The apparatus can eliminate the eccentricity when conducting a pulling test on the specimen.
- (3) The apparatus should be easily connected to the material testing machine.
- (4) The apparatus should be easy to operate and convenient to assemble and disassemble.

LAYOUT AND STRUCTURE OF THE APPARATUSES

Centering Apparatus for the Bonding of Specimen

The design sketch and the picture of the centering apparatus for the bonding of the specimen are illustrated in **Fig. 1**. The overall size of this apparatus is 480 by 600 mm (width by height). This centering apparatus is composed of the base plate, the columns, the top plate, the positioning sleeve for the top/bottom pulling head, the clamping sleeve, the clamping ring, the support plate, the top/bottom pulling head, the top/bottom fine adjustment knob, the pneumatic pull rod, the pneumatic pull plate, the pneumatic bar, the air cylinder, the electric motor, the air tube, and the operation platform. The columns, which are fixed to the base plate, are used for the precise positioning of other components. The top plate is connected to the columns and is used to hold the air cylinder in place. The lower positioning sleeve is fixed on the

columns, whereas the upper one can be shifted up and down to adjust the position of the pulling head as well as to ensure that it is coaxial with the specimen. The clamping sleeve can be used to grip the clamp ring and to ensure the axis of the specimen is aligned with the axis of the top and bottom pulling heads. The clamping ring (**Fig. 2a**) consists of four wedge-shaped clamping pieces (**Fig. 2b**). The inner wall of the clamping ring has the same cylinder surface with the rock specimen, whereas the outer wall is machined to be inclined. The clamping ring is placed in the clamping sleeve, which can fall under gravity and then lock the clamp ring, so as to clamp the rock specimen. The fine adjustment knobs can be adopted to control the thickness of adhesive between the ends of the specimen and the pulling heads when bonding the specimen. The specimen can be taken out by raising the clamping sleeve through the pneumatic control system once the bonding procedure is completed (**Fig. 2c**). The support plate is designed to hold the clamping ring when removing the bonded specimen.

The centering apparatus for the bonding of the rock specimen was manufactured using the precision machine tools. The error during the machining and assembling process of each component was within 0.01 mm, which can guarantee the coaxial between the specimen and the pulling heads when bonding them together.

Centering Apparatus for Conducting Tensile Test

Fig. 3 illustrates the design sketch and the photo of the centering apparatus, which can be used to eliminate the eccentricity between the rock specimen and the loading frame when conducting the

FIG. 1 (a) Design scheme and (b) the photograph of the centering apparatus for the bonding of rock specimen with pulling heads. (c) Zoomed-in view of the specimen with top and bottom pulling heads and the fine adjustment knobs (the part in the dashed box). The scale of the rock specimen is 50 by 100 mm (diameter by height). 1. Base plate; 2. Column; 3. Top plate; 4. The upper positioning sleeve for pulling head; 5. The lower positioning sleeve for pulling head; 6. Clamping sleeve; 7. Clamping ring; 8. Support plate; 9. Top pulling head; 10. Bottom pulling head; 11. Top fine adjustment knob; 12. Bottom fine adjustment knob; 13. Pneumatic pull rod; 14. Pneumatic pull plate; 15. Pneumatic bar; 16. Air cylinder; 17. Electric motor; 18. Air tube; 19. Operation platform; 20. Circular grooves used to place the pulling heads.

FIG. 2 Photos of different components for the bonding of rock specimen. The clamping ring (a), which consists of four wedge-shaped clamping pieces (b) used to hold the rock specimen. (c) The rock specimen cemented with the pulling heads at the two ends. (d) Connection between the T-shaped slider and the pulling heads bonded with rock specimen. (e) The T-shaped chute with the ball hinge.

direct tensile test. This apparatus was composed of the universal ball hinge, the T-shaped slider (Fig. 2d), the T-shaped chute with the ball hinge (Fig. 2e), and the pulling heads. The universal ball hinge allows its rod to rotate 360° freely, which may eliminate the

eccentricity during the pulling of the specimen. The T-shaped slider is connected to the pulling head through the threaded screw. An identical radius is designed on the T-shaped chute and the slider. The slider can easily slip into the chute and then be fixed with the stop key. This centering apparatus was also manufactured using precision machine tools with errors no more than 0.01 mm, which can efficiently avoid the specimen eccentricity.

FIG. 3 (a) Design scheme and (b) the photograph of the centering device for conducting the direct tensile test. 1. Rod of the ball hinge; 2. Universal ball hinge; 3. T-shaped chute with ball hinge; 4. T-shaped slider; 5. Pulling head; 6. Resin adhesive; 7. Rock specimen.

TECHNICAL CHARACTERISTICS OF THE APPARATUSES

The technical characteristics of the centering apparatuses can be summarized as following:

- (1) The centering apparatus for the bonding of specimens can precisely control the thickness of cohesive material and effectively solve the eccentric problem when bonding rock specimens with the pulling heads.
- (2) The centering apparatus for conducting a direct tensile test can eliminate the occurrence of eccentric tension through the adoption of the universal ball hinge.
- (3) The complete set of the apparatus was easy to operate and convenient to assemble and disassemble. It was applicable for conducting direct tensile test on brittle rocks.

Direct Tensile Test on Brittle Rocks

TEST CONDITIONS

With the aid of the centering apparatuses, direct tensile tests were conducted on brittle rocks from various large-scale hydropower

TABLE 1 Overview of the rock specimens used in the direct tensile tests and the mechanical properties measured from direct tensile tests.

Sample	Rock Type	Location	Number of Specimens	Tensile Strength (MPa)	Tensile Elastic Modulus (GPa)	Maximum Tensile Strain ($\mu\epsilon$)
1	Granite	Mengdigou hydropower station on the Yalong River	8	5.68 ± 0.20	67.04 ± 7.52	79 ± 3.55
2	Basalt	Xiluodu hydropower station on the Jinsha River	6	7.34 ± 0.43	69.19 ± 6.19	99 ± 6.89
3	Breccia lava	Xiluodu hydropower station on the Jinsha River	6	5.81 ± 0.29	59.66 ± 6.81	84 ± 3.88
4	Diabase	Dagangshan hydropower station on the Dadu River	5	7.39 ± 0.66	69.26 ± 9.30	91 ± 3.70
5	Granite	Dagangshan hydropower station on the Dadu River	5	5.04 ± 0.43	73.24 ± 10.07	65 ± 3.21
6	Marble	Jingping-I hydropower station on the Yalong River	6	2.77 ± 0.15	19.47 ± 1.94	135 ± 8.53

station sites in China. Overview of the rock specimens tested in this study can be found in **Table 1**. Mechanical parameters, including the tensile strength, the tensile elastic modulus, and the maximum tensile strain, were measured and will be discussed in the “Mechanical Properties of the Brittle Rocks under Direct Tensile Test” section.

DIRECT TENSILE TEST METHOD

The centering apparatus should be used together with the servo-controlled material test machine to conduct the direct tensile test on rocks. The test machine used in this study was the WDW-100E, with the maximum axial loading capacity of 100 KN. Tensile strain during the experiment was monitored by strain gauges pasted on the specimen surface. The pulling heads were bonded with the specimen using high-strength resin adhesive (the Letai E-120HP), which can effectively glue the metal to rock. The tensile strength of the adhesive layer was greater than 20 MPa, which exceeds the tensile strength of most of the rocks and thus meets the requirements for conducting the direct tensile test.

In order to eliminate the effect of internal micro-fracture heterogeneity on the direct tensile test, acoustic wave detection was first conducted on specimens taken from the same site during the preparation stage. Only specimens with the similar wave velocity were adopted in the direct tensile tests.

The selected specimens were first cemented with the pulling heads using the centering apparatus illustrated in **Fig. 1**. The detailed test procedures were described as follows:

- (1) The prepared rock specimen was placed into the clamping ring, which was placed inside the clamping sleeve. The bottom of the clamping ring was held by the supporting plate.
- (2) The clamping sleeve was laid down to grip the specimen.
- (3) The resin was first placed on the pulling heads/rock ends. The whole setup was then compressed to a controlled amount. Parametric study revealed that the optimal thickness of cohesive material should be 1–2 mm (Yuan 2016). The gaps between the specimen ends and the pulling heads can be adjusted through the positioning sleeve

and the fine adjustment knobs. After that, the specimen was finally glued with the two pulling heads.

- (4) After the cure of the resin, the clamping sleeve was raised through the pneumatic-controlled system, and the rock specimen bonded with pulling heads was then taken out from the centering apparatus (**Fig. 2c**).
- (5) The pulling heads bonded with the specimen were then connected to the T-shaped slider (**Fig. 2d**).
- (6) The T-shaped slider was then slipped into the T-shaped chute, and the rod of the ball hinge on the T-shaped chute was fixed to the clamping apparatus of the test machine. **Fig. 3** shows a sketch of the setup and a picture of specimens installed in the centering apparatus for conducting tensile test.
- (7) The tension centering apparatus with the rock specimen (**Fig. 3b**) was then installed on the test machine. Direct tensile test was conducted through the test machine

FIG. 4 Setup of the direct tensile test system.

(Fig. 4). Pre-tightening load was first applied to ~ 10 N and then gradually pulled the specimen with constant strain rate till the occurrence of failure.

- (8) Mechanical parameters including the tensile strength, the ultimate tensile strain, and the complete tensile stress-strain curve were recorded and calculated after each test, as discussed in the following section.

Mechanical Properties of the Brittle Rocks under Direct Tensile Test

FAILURE PATTERNS

Fig. 5 illustrates the typical failure modes of the brittle rocks. It can be observed that most of the specimens failed on a plane that was approximately perpendicular to the axis. These planes were

positioned at about mid-height of the specimens, where the tensile stress was supposed to be uniformly distributed. The fracture surface tended to be smooth without accumulation of rock residue. The initiation of fractures in these brittle rocks was characterized as typical tensile failure with a crisp sound.

COMPLETE STRESS-STRAIN CURVES

The complete tensile stress versus tensile strain curves obtained from the direct tensile tests are presented in Fig. 6. In general, four typical stages can be identified from these curves.

Microscale Rearrangement Stage (O-A)

At the initial stage, the stress-strain curve appeared to be concave with the slope of the curve gradually increasing. This can be attributed to the complicated microstructure of natural rock that is composed of various minerals as well as preexisting cracks and deficiencies. Therefore, when rock is subjected to tensile stress,

FIG. 5

Failure modes of brittle rock specimens after direct tensile test: (a) Mengdigou Granite; (b) Xiluodu Basalt; (c) Xiluodu Brecciated Lava; (d) Dagangshan Granite; (e) Dagangshan Diabase; and (f) Jinping-I Marble.

FIG. 6 The complete stress-strain curves obtained from direct tensile tests on various rock specimens: (a) Mengdigou Granite; (b) Xiluodu Basalt; (c) Xiluodu Breccia Lava; (d) Dagangshan Diabase; (e) Dagangshan Granite; and (f) Jinping-I Marble.

the unstable mineral bonding surface and the micro-fracture will produce a certain deformation, so that the microstructure of the rock tends to be stable, such that the load application results in a linear stress-strain.

Elastic Deformation Stage (A-B)

The stress-strain curve at this stage basically maintained a straight line and the tensile stress grew linearly with the increase of tensile strain. Micro-cracks inside the specimen evolved in a stable manner.

Nonlinear Deformation Stage (B-C)

In this stage, the tensile stress-strain curve showed the obvious transition from the linear straight line to the nonlinear curve, which indicated that the micro-cracks inside the rock propagated rapidly at this stage, whereas the stress-strain curve exhibited nonlinear properties.

Brittle Fracture Stage (C-D)

The tensile stress instantaneously dropped to zero after the peak value (denoted as point C), and the specimen fractured suddenly,

accompanied by a crisp sound, characterized by a typical brittle tensile rupture phenomenon.

MECHANICAL PARAMETERS FROM TENSION TEST

The tensile stress at which level the specimen fractured was regarded as the ultimate tensile strength, whereas the axial strain at this stage was considered to be the maximum tensile strain. The tensile elastic modulus can be calculated from the stress level equal to 50 % of the ultimate tensile strength. The average value and standard deviation of the mechanical parameters obtained from these tests are listed in **Table 1**. Generally, the mechanical parameters (i.e., the tensile strength, tensile elastic modulus, and the maximum tensile strain) were characterized by a very low deviation (within 10 % of the mean value for most of the cases). The DTS varied from 2.77 MPa to 7.39 MPa, with the maximum value obtained from the Dagangshan Diabase and the minimum value measured from the Jinping-I Marble. The maximum tensile elastic modulus can be as high as 73.24 GPa (Dagangshan Granite), whereas the minimum value was 19.47 GPa, also measured from the Jinping-I Marble. The Jinping-I Marble had the maximum ultimate tensile strain (135 $\mu\epsilon$), which was about twice the minimum value measured from the Dagangshan Granite (65 $\mu\epsilon$).

Micro-Mechanisms of the Tensile Failure of Rock

In order to explore the micro-mechanisms of the tensile fracture, microstructure of the Mengdigou Granite was detected using the scanning electron microscope (SEM). The tests were conducted on the field-emission scanning electron microscopy. **Fig. 7a** shows the micrograph of Mengdigou Granite before the test. It can be observed that the microstructure was compact, with only few pores developed. The macroscopic performances can be characterized as high strength and good stability of mechanical properties.

The element analysis results indicated that the Mengdigou Granite was mainly composed of oxygen and silicon, as well as a small amount of magnesium, potassium, and aluminum. The primary mineral component of the rock was quartz as well as a small amount of the feldspar and biotite. Different minerals were characterized by various crystallization behaviors, e.g., the quartz crystal had larger columnar or bulk particles, whereas the feldspar and biotite were flaky crystal.

The SEM micrographs showing the fracture surface of Mengdigou Granite were given in **Fig. 7b** and **7c**. Two microscopic fracture patterns can be identified, namely, the intragranular fracture (**Fig. 7b**) and the intergranular fracture (**Fig. 7c**). For the former case, obvious fracture traces of the flaky crystal can be noted. The fracture surface was not smooth but with distinct angularity. This failure mode mostly occurred when the crystallization

FIG. 7 The SEM micrograph shows the microstructure of the Mengdigou Granite before the test (a). The SEM micrographs show the microscopic fracture modes at the fracture surface of Mengdigou Granite: (b) intragranular fracture and (c) intergranular fracture.

orientation of the columnar/flaky crystal was parallel with the tensile stress direction. On the other hand, the fracture surface of the intergranular fracture (**Fig. 7c**) was smooth, and a decorative pattern on the crystal surface can be observed. This pattern

FIG. 8 Failure pattern of the brittle rock disk after the Brazilian test. The diameter of the specimen equals to 50 mm, which is equivalent with its thickness.

mostly occurred when the crystal surface was perpendicular to the loading direction. Thus, the microscopic failure modes of the granite under direct tensile test were not unique but consisted of the intragranular and intergranular fractures. The fracture surfaces obtained from the tensile tests were fresh and without accumulation of rock fragments.

Comparison with the Brazilian Test

Brazilian tests (**Fig. 8**) were conducted in this section with the aim of comparing the DTS with the BTS. Moreover, the difference regarding the microscopic failure mechanisms was examined using the SEM.

The comparison between the DTS and BTS can be found in **Table 2** and **Fig. 9**. For the BTS, nine Mengdigou Granite specimens were tested, and six disks were tested for each of the other rock types. The averaged BTS was reported in **Table 2**. The ratio between DTS and BTS lies in the range of 0.60–0.71. The maximum DTS/BTS ratio is obtained from granite, whereas the deviation between DTS and BTS turns out to be most significant

TABLE 2 Comparison between the direct tensile strength (DTS) and the Brazilian tensile strength (BTS).

Rock Type	Average Tensile Strength (MPa)		DTS/BTS
	Direct Tensile Strength (DTS)	Brazilian Tensile Strength (BTS)	
Mengdigou Granite	5.68	8.01	0.71
Xiluodu Basalt	7.34	11.16	0.66
Xiluodu Breccia lava	5.81	9.62	0.60
Dagangshan Granite	5.04	7.64	0.66
Dagangshan Diabase	7.39	11.58	0.64
Jingping-I Marble	2.77	4.15	0.67

FIG. 9 Variation of the direct tensile strength (DTS) and the Brazilian tensile strength (BTS) as well as the ratio between them (DTS/BTS) with various rock types.

for the Xiluodu Breccia Lava. The DTS/BTS ratio obtained in our study was slightly lower than the ranges suggested by Perras and Diederichs (2014) (0.9 for metamorphic, 0.8 for igneous, and 0.7 for sedimentary rocks). The reasons for this deviation are still not clear, and future studies are necessary to be conducted to examine the influence of various factors, e.g., the microstructure and the specimen sizes.

The micrograph of the Brazilian test fracture surface from Mengdigou Granite is shown in **Fig. 10**. Although distinct tensile fracture of flaky crystal can be identified, the fracture surface is crushed on the whole, and the angularities are worn away. Considerable amounts of fragments can be noticed filling in the hollow sites. This phenomenon can be characterized as apparent shear fracture. The fact that the BTS is generally higher than the DTS can be attributed to the following reasons:

FIG. 10 The SEM micrograph shows the microscopic failure patterns of the Mengdigou granite after the Brazilian test.

- (1) The theoretical model of the Brazilian test is inconsistent with the physical reality. The stress state of the rock disk under the Brazilian test turns out to be a complex three-dimensional problem. But the theoretical analysis on the Brazilian test simplifies the nonlinear three-dimensional model to a plane elastic model that deviates from the real stress state and ultimately leads to the inaccurate tensile strength.
- (2) The fracture surface of a rock specimen under direct tensile stress normally appears at the weakest plane in the section under relatively uniform tensile stress state, whereas the assumed fracture surface of the Brazilian test is not necessarily the weakest plane of the specimen.
- (3) The SEM micrograph indicates that the fracture surface of the specimen under direct tensile test was characterized as brittle tensile rupture. The fracture surface was fresh, and there was no accumulation of rock slag and traces of shear or friction. But the fracture surface of the specimen under the Brazilian test was more crushed with the emergence of plenty of rock fragments, which was the evidence for the emergence of shear trace. Therefore, the stress state in the Brazilian test was more complex as opposed to the pure tensile stress state.

The tensile strength measured from the Brazilian test turns out to be 30 %~40 % higher than that obtained from the direct tensile test. Therefore, the adoption of Brazilian test results may cause inaccurate estimation in the stability analysis of engineering project, which is worthy of more attention in the engineering practice. The direct tensile test is recommended for the measurement of rock tensile strength to ensure the safety of the projects.

The limitations of these apparatuses lie in the following aspects: on the one hand, too many procedures were included for the bonding of specimens and conducting of tests; on the other hand, a very long time was needed for the resin to form full strength (~14 days). Therefore, further efforts are necessary to simplify the test procedures and to shorten the specimen preparation period.

Conclusions

1. A centering apparatus was designed in this study to eliminate the eccentricity problems that might be encountered in the direct tensile test on rock. The apparatus consists of the part for bonding specimens with pulling heads and the part for conducting the direct tensile test. The advantages of this apparatus lie in its ease of operation, convenient assembly and disassembly, and high accuracy.
2. Direct tensile tests were conducted on the brittle rocks from various large-scale hydropower station sites in China, including the granite, basalt, breccia lave, diabase, and marble. Mechanical parameters, including the tensile strength, the tensile elastic modulus, the maximum tensile

strain, and the complete tensile stress-strain curves, were successfully obtained.

3. Two major tensile failure mechanisms were identified at the microscale, i.e., the intergranular fracture and the intragranular fracture. Fractured specimens under direct tensile tests were characterized as apparent brittle rupture, whereas the specimens under Brazilian test were under complex stress state, which deviated from the pure tensile fracture.
4. The tensile strength measured from the direct tensile test was normally lower than that measured from the Brazilian test. The DTS/BTS ratio varied from 0.60 to 0.71. Direct tensile test is thus recommended for the measurement of rock tensile strength in order to ensure the accurate estimation of rock engineering stability.

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