Determining True Tensile Strength from Brazilian Tensile Strength Laboratory Testing

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ABSTRACT
The tensile strength of rock and rock-like materials is a critical material property in rock engineering design and the prediction of rockmass behaviour to mitigate any potential failure that may affect personnel safety or damage property. This study presents new instrumentation guidelines for the Brazilian Tensile Strength (splitting disc tensile strength) test to enhance data analysis techniques to determine true tensile strength. For this study, a total of 74 specimens of various lithologies and rock types were instrumented, tested, and reviewed to determine their true tensile strengths based on the First Crack Theory.

RÉSUMÉ
La résistance à la traction des roches et des matériaux similaires est une propriété matérielle essentielle pour le design en génie géomécanique et la prédiction du comportement d'une masse rocheuse afin d'éviter toute défaillance potentielle qui pourrait affecter la sécurité du personnel ou endommager l'infrastructure. Cette étude présente de nouvelles directives d'instrumentation pour l'essai de résistance à la traction brésilien (résistance à la traction du disque par fendage) afin d'améliorer les techniques de traitement de données pour déterminer la véritable résistance à la traction. Pour cette étude, un total de 74 spécimens de diverses lithologies et types de roches ont été instrumentés, testés et examinés afin de déterminer leur véritable résistance à la traction basé sur la "Théorie de la première fissure".

1. INTRODUCTION

In the analysis of rock and rockmass behaviour, the tensile strength of the material is an important and fundamental property. As the demand for underground space increases, constructed excavations are becoming larger, built at deeper horizons, and in increasingly complex rockmasses. Continued improvement of testing methods and data processing guidelines to meet these advances in engineering design is a critical research area.

The importance of tensile strength as a fundamental geomechanical property is well-reflected in industry, as multiple entities associated with the standardization of laboratory testing have published governing documents for determining tensile strength, including the American Society for Testing and Materials (ASTM) (ASTM 2016; 2020) and the International Society of Rock Mechanics (ISRM) (ISRM, 1978).

In the determination of tensile strength, direct tensile testing is considered the most valid method for measuring true tensile strength as there are minimal outside influences when the test is completed properly (Hoek, 1964). However, due to relatively complex sample preparation and the limited availability of laboratories with tensile loading frames, conducting direct tensile strength tests is difficult.

The most popular method for determining the tensile strength of rock and rock-like materials is the indirect Brazilian Tensile Strength (BTS) test (also known as the splitting tensile strength test). The BTS laboratory test was originally developed by Carneiro (1943) and Akazawa (1943). Both studies on the new method to measure the tensile strength of concrete were developed independently and published within months of one another. The first application of the BTS test on rock was completed by Berrenbaum and Brodie (1959), and from this point forward the continued development and study of the BTS test is extensively documented by Li and Wong (2012).

The continued study and improvement of laboratory testing procedures and data processing methods is critical for the engineering design processes, as these derived parameters are used as inputs for advanced numerical modelling software that helps inform decision-making. This paper presents an instrumentation recommendation for the BTS test in the form of adding lateral strain gauges and data processing techniques to determine tensile crack initiation and the true strength of the specimen as based on the first crack theory (Diederichs, 1999; Perras and Diederichs, 2014).

2. DETERMINATION OF TENSILE STRENGTH

The measurement of tensile strength is prescribed by two commonly used method documents that are recognized in industry. The ISRM Suggested Method (ISRM, 1978) has guidelines for both direct and indirect tensile strength measurements, and the ASTM has published a standard for both direct (DTS) D2936-20 (ASTM, 2020) and indirect D3967-16 (ASTM, 2016) tensile strength measurements.

The BTS testing method is an indirect testing method as shown in Figure 1.

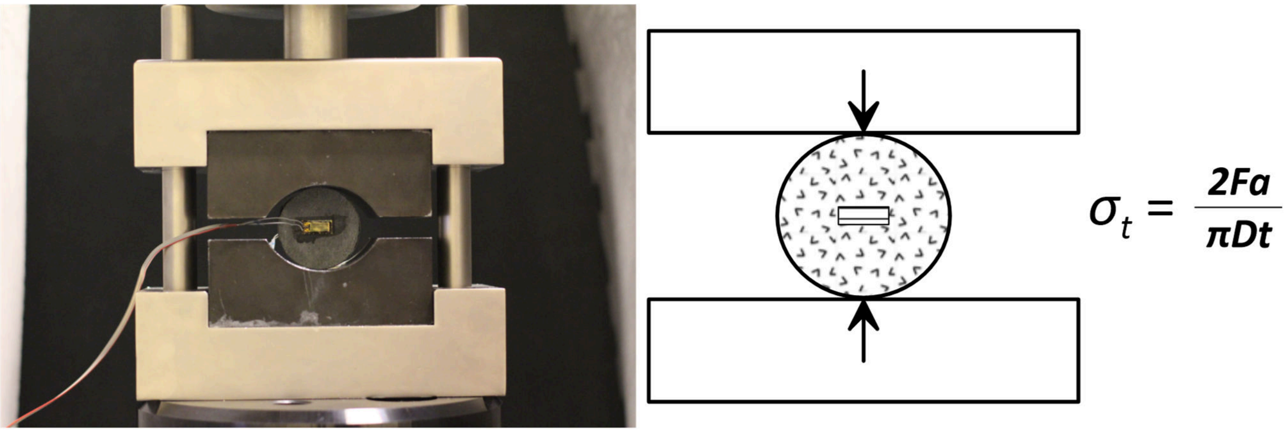

Figure 1: (left) Photograph of a BTS test setup with a recommended horizontal strain gauge and (right) a simplified representation of the BTS test where σ_t is the tensile strength (MPa), F_a is the maximum applied force (N), D is the diameter of the specimen (mm), and t is the thickness of the specimen (mm).

For the BTS test, the stress at failure (σ_t) is a function of the applied load (F_a), the diameter (D), and the thickness (t) at the centre of the specimen (Equation 1).

$$\sigma_t = \frac{2F_a}{\pi Dt} = 0.636\frac{F_a}{Dt} \qquad [1]$$

3. LABORATORY TESTING PROGRAM

BTS specimens used in this study were selected out of a combination of drill core and specimens cored from quarried rock blocks. In total, seventy-four (74) test specimens from seven (7) lithologies tested within the Queen's University Advanced Geomechanics Testing Laboratory between 2017 and 2019 are included in this study. The individual number of specimens per lithology is shown in Table 1.

Table 1: Summary of BTS tests analyzed in this study.

Lithology	Number of Tests
Cobourg Fm. Limestone	15
Sudbury Meta-Volcanics	12
Westerly Granite	1
Pointe Du Bois Tonalite	25
Pointe Du Bois Amphibolite	3
Lac Du Bonnet Granite	20

All Sudbury Meta-Volcanics (LeRiche, 2017), Cobourg Limestone, Pointe Du Bois Tonalite, and Amphibolite specimens were selected from NQ3 (45 mm diameter) and NQ (47.6 mm) diameter drill core. Westerly Granite and Lac Du Bonnet Granite (Ahmed Labeid, 2019) are typically 50 mm in diameter, and were cored out of rock blocks. Rock blocks were drilled with a Kitchen-Walker radial drill using diamond core bits. Examples of the specimens are shown in Figure 2.

All lithologies tested in this study are considered isotropic and homogenous; therefore, the orientation of the specimen in the loading frame did not have to be considered. The lithologies tested also span a wide range of mineral crystal sizes from very fine (Cobourg Limestone) to very coarse (Lac Du Bonnet Granite and Pointe Du Bois Tonalite): the Lac Du Bonnet Granite has a crystal size approximately five times (5x) larger then the Westerly Granite. Both the Westerly Granite (Quinn, 1963) and the Lac Du Bonnet granite (Davidson et al., 1982) are considered "standard rock materials" due to the extensive research undertaken on both lithologies for the last 50 years.

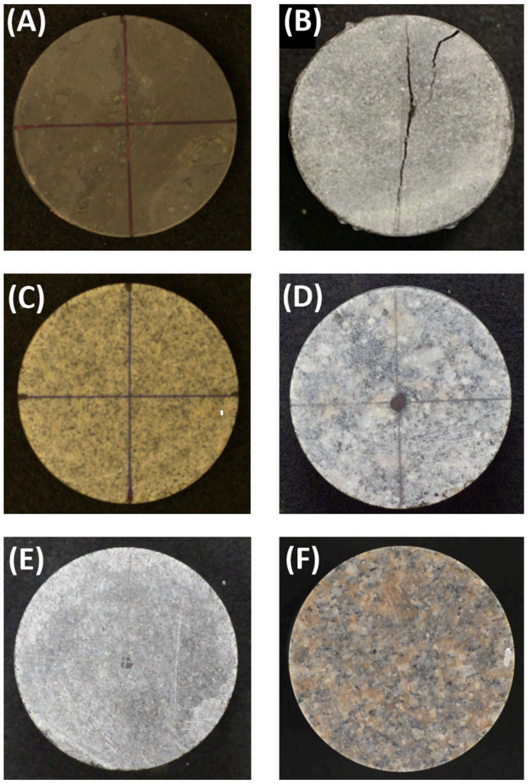

Figure 2: Various lithologies tested in this study (A) Cobourg Fm. Limestone, (B) Sudbury Meta-Volcanics, (C) Westerly Granite, (D) Pointe Du Bois Tonalite, (E) Pointe Du Bois Amphibolite, (F) Lac Du Bonnet Granite

All specimens tested in this study are free of veins, strong foliations, and healed fractures. Specimens were cut to final thickenss using a diamond saw, where a final thickness to diameter ratio of 0.5 was desired in order to meet the requirements of the ASTM D3967 standard. Prior to testing, specimens were outfitted with two (2) strain gauges with a foil length of ten millimeters (10 mm) positioned at the center of the specimen's face, aligned perpendicular to the loading direction to record the lateral deformation.

All BTS tests were completed with an MTS 815 Rock Mechanics Testing System which has a closed-loop, computer-controlled, servo-controlled compression machine. The system consists of:

- MTS 315.02 load frame with 2700 kN compression rating, including a differential pressure (ΔP) transducer (which monitors the difference in pressure on each side of the actuator piston and is calibrated to represent the force output of the actuator)
- MTS Model 505.07 Silent Flo Hydraulic Power Supply
- MTS FlexTest 60 controller
- Computer with the MTS controlling software

4. DATA PROCESSING PROCEDURES

The determination of "true" tensile strength is done through the analysis of the lateral strain gauges on the test specimen. Figure 3 shows a schematic of data processing steps required to calculate the true tensile strength. The measured mid-sample strain response is plotted in tensile stress (σ_t) versus mid-sample horizontal strain ($\varepsilon_{lateral}$) space for both instruments on the specimen (Figure 3A). For both instruments, a line is fit to each stress – strain plot (Figure 3B) and the first significant non-linearity point (after seating) of the calculated tensile strength versus horizontal strain response is measured as the "true" tensile strength (Figure 3C). In the case of the instruments measuring different "first crack" points, the two values are averaged to come up with the "true" tensile strength of the specimen (Figure 3D).

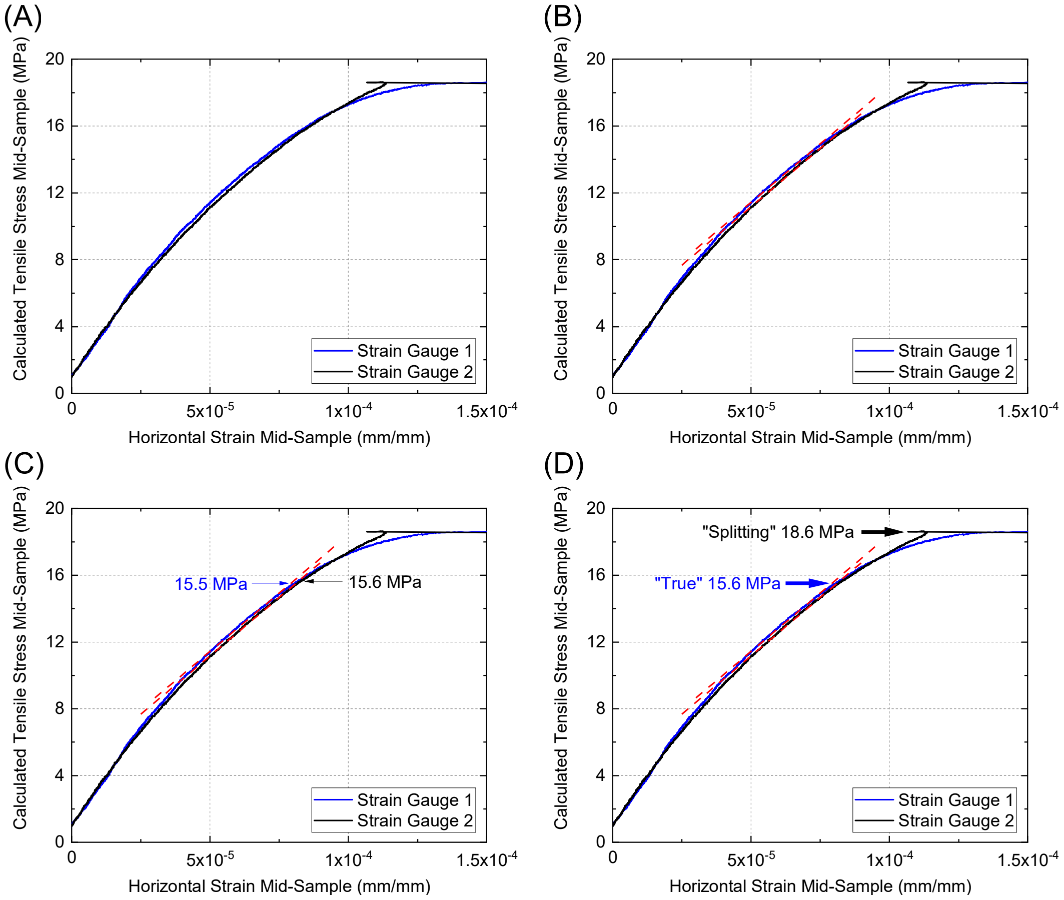

Figure 3: Procedure for measuring "true" tensile strength from an indirect BTS specimen. (A) Plot measured mid-sample horizontal strain vs calculated tensile stress (mid-sample), (B) Determine linear portion of the stress – strain curve after seating has occurred. (C) Determine the point of most significant non-linearity on the curve ("first crack") for both instruments. (D) If the two instruments have different measurement points for "true" tensile strength, average the measurements.

5. RESULTS

The objective of this analysis is to evaluate the first crack theory proposed by Diederichs (1999) and Perras and Diederichs (2014).

In total, seventy-four (74) indirect BTS tests are incorporated into this study. Two compilations of true tensile strength measurements (TTS) and BTS measurements are graphically shown based on lithology (Figure 4) and by overall rock type (Figure 5) where the average ratio of TTS to BTS is 0.86 for carbonates, 0.82 for igneous rocks and 0.78 for metamorphic rocks. Reference lines 0.93:1, 0.86:1, and 0.68:1 are best fit ratios for metamorphic, igneous, and sedimentary rocks respectively, as suggested by Perras and Diederichs (2014).

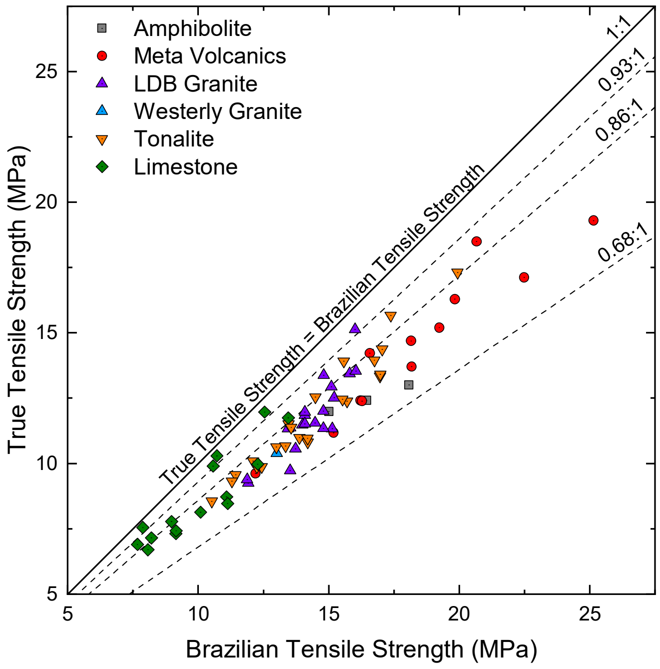

Figure 4: Relationship between measured TTS and BTS for all specimens, separated by lithology.

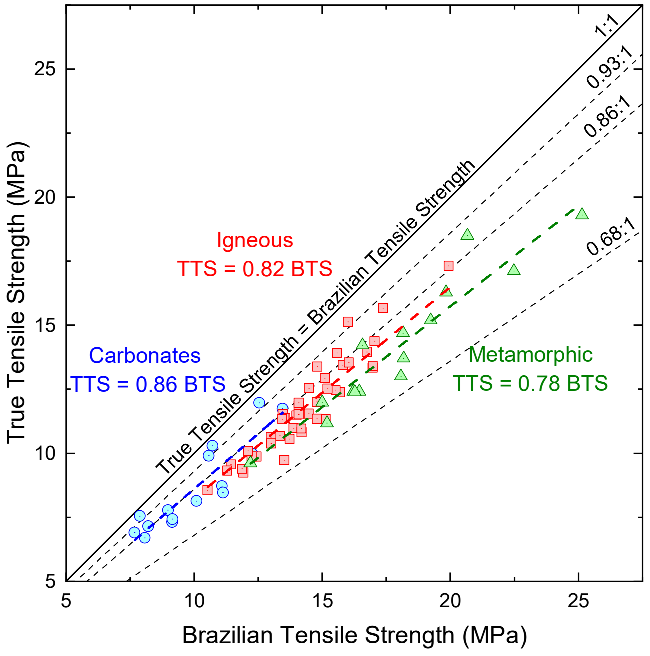

Figure 5: Relationship between measured TTS and BTS for all specimens, separated by rock type.

6. DISCUSSION

The relevance of tensile strength on the behaviour of rock is well known, as it is recognized that the initiation of fractures in brittle materials can be a tensile phenomenon. In some cases, the tensile strength of rock may govern the material's ability to resist fracturing and ultimately failure.

The Brazilian tensile strength test is considered to overestimate the true tensile strength of intact rock and rock-like materials. This overestimation is hypothesized to occur due to the confinement of the specimen based on the test geometry. However, as stated by ISRM (1978), the difference between the load, the primary fracture, and the ultimate load does not suggest that suppressed growth is the primary factor causing the splitting strength of the material to be higher than the direct tensile strength.

Based on previous testing programs, including a study comparing the strain response of the Lac Du Bonnet Granite during direct tension tests and Brazilian tensile strength tests, it was concluded that the rupture point in a direct tension test is associated with crack initiation in the Brazilian Test. Subsequently, the disc specimen in a BTS test undergoes four strain rate changes: crack initiation (First Crack), systematic cracking, critical crack, and rupture (Brazilian Tensile Strength) (Diederichs, 1999).

While the crack initiation thresholds in DTS and BTS tests are the same, the main difference between the two tests is that crack initiation does not immediately lead to unstable rupture. Additional stress is required to overcome toughness hardening and produce crack coalescence and rupture (Diederichs, 1999). Previous studies on the stress threshold sensitivity of brittle materials have shown that crack initiation should be considered a true material property, as it is relatively insensitive to confinement and loading rate when compared to the crack damage threshold (Diederichs et al., 2004; Ghazvinian et al., 2015; Jaczkowski et al., 2017).

It should be noted that this is not the first study to suggest modification and instrumentation of the Brazilian Tensile Strength test with strain gauges or extensometers (Li et al., 2019; Jaczkowski et al., 2017; Patel and Martin, 2018).

Li et al. (2019) proposed an instrumented BTS test to measure two elastic parameters: Young's Modulus € and Poisson's Ratio (*v*). The evaluation of elastic parameters and first crack has also been evaluated by digital image correlation (DIC) (Belrhiti et al., 2017; Naik Parrikar and Mokhtari, 2020). In the study completed by Naik Parrikar and Mokhtari (2020), DIC was used to capture the full field deformation behaviour of rocks during the BTS test and detail the fracture initiation, location, and fracture propagation. Based on testing completed during the DIC study, it was observed that the measured BTS was variable and that the size of the crack of failure was also inconsistent, which may explain the variation. From the two tests reported in detail, the first fracture was initiated at 70% and 74% of peak stress which is around the same value that Perras and Diederichs (2014) suggested (68%) as a correlation between BTS and DTS for sedimentary rocks.

The measured first crack of the BTS tests completed in this study show a discrepancy compared to the relationships recommended by Perras and Diederichs (2014). The data set presented in this study was limited by the available lithologies previously tested in the Queen's University Advanced Geomechanics Testing Laboratory with two distinctions. Firstly, the Perras and Diederichs (2014) data set for sedimentary rocks considered both carbonate and non-carbonate materials. The addition of a sandstone, siltstone, or mudstone testing suite would provide for a more balanced data set that is all encompassing of the varying sedimentary materials available. Secondly, the TTS:BTS ratio for metamorphic materials, with a measured ratio of TTS = 0.78 BTS in this study compared to the suggested ratio of TTS = 0.93 BTS by Perras and Diederichs (2014). The metamorphic materials tested in this study were relatively isotropic and lacking foliations or other planes of weakness. A ratio of TTS = 0.93BTS suggests that tested materials underwent unstable rupture with little additional strain once crack initiation occurred. As many metamorphic materials are foliated, fractures have the opportunity to propagate along foliation planes and planes of weakness. In cases where the foliation plane is at an angle which facilitates foliation-guided fracturing, it may influence the data set toward a ratio closer to 1 as unstable crack growth may be reached at lower relative strains.

Overall, the strain behaviour captured during the BTS tests analyzed in this study exhibit the same behaviour as in previously mentioned studies. For homogenous specimens, the use of strain gauges is preferable to other methods of measuring strain as it is a relatively easy to implement and, from a practical standpoint, will provide the data required to determine true tensile strength. However, for specimens that are transversely isotropic or anisotropic, a non-contact full-field strain measurement system, such as DIC, in addition to strain gauges is recommended to capture any instances of strain accumulation along planes of weakness which may not be captured by one strain gauge.

7. CONCLUSION

In this paper, a modification to the standard Brazilian Tensile Strength Test was used to determine the "True" tensile strength (first fracture) of multiple BTS tests of varying lithologies. For isotropic specimens, we recommend that lateral strain gauges be mounted on the front and back of the specimen, which should measure the same response in the sample, providing redundancy in the case of instrument malfunction. In the case of anisotropic specimens, the same strain response on the front and back of the specimen may not always occur due to phenomena such as foliation-guided fracturing.

The addition of strain gauges to the BTS test is considered to be non-prohibitive to the economics of conducting BTS testing, as the additional time required for sample preparation and data processing is minimal and the required instrumentation, while consumable, is inexpensive when compared to traditional direct tensile strength testing. The modification to the BTS can also be implemented in commercial laboratories with ease.

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