Determination of Indirect Tensile Strength (ITS) of Rocks

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ABSTRACT

Being brittle materials, rocks exhibit different behaviours under tensile and compressive loading. The tensile strength of rock is orders of magnitude less than its compressive strength. Hence, the determination of the tensile strength of rocks is of crucial important for both civil and rock mechanics applications, such as tunnelling, underground mining, underground repositories, etc. The difficulties associated with performing a direct uniaxial tensile test on a rock specimen have led to a number of indirect methods for assessing the tensile strength. In 1978, the Indirect Brazilian Test (IBT) was officially proposed by the International Society of Rock Mechanics (ISRM) as a method for determining the indirect tensile strength of rocks. However, the Brazilian test has been criticised by many researchers since its introduction. The standard Brazilian indirect tensile test causes catastrophic crushing failure of the disc specimens, rather than the expected tensile splitting failure initiated by a central crack. This finding led to the current investigation of the effect of loading conditions on the failure of Brazilian disc specimens using three steel loading arcs of different angle applied to rock disc specimens. With no international standard for determining the indirect tensile strength of rocks under diametral loading, numerical modelling and analytical calculations were undertaken. Numerical simulations using the RFPA2D software were conducted with a heterogeneous material model. The experimental and numerical results showed that 20° and 30° loading arcs result in diametral splitting fractures starting at the disc centre.

Keywords: diametral loading of rock discs, Indirect Brazilian Test, Indirect Tensile Strength, Rock Fracture Process Analysis

1 INTRODUCTION

The IBT is widely used in engineering practice to indirectly determine the tensile strength of rocks. The difficulties associated with performing a direct uniaxial tensile test on a rock specimen have led to a number of indirect methods for assessing tensile strength. In 1978, the Brazilian test was officially proposed by the International Society for Rock Mechanics (ISRM) as a suggested method for determining the tensile strength of rocks (ISRM 2007). The Brazilian test (splitting tension test) is performed by applying a concentrated compressive load across the diameter of a disc specimen. Fairhurst (1964) first discussed the important issue of the validity of the Brazilian test. He stated that 'failure may occur away from the centre of the test disc for small angles of loading contact area' and indicated that the calculated tensile strength from a Brazilian test is lower than the true value of the tensile strength. Hudson et al. (1972) observed that failure always initiated directly under the loading points if flat steel plates were used to load the specimen, an approach that actually invalidates the test for the determination of tensile strength. However, classical theory assumes that the concentrated load is applied over an infinitesimally small width as a line load. Clearly, this would lead to stresses of very high intensity (ISRM 2007).

The actual loading imposed in the IBT is not concentrated, but is distributed over a finite arc of the disc. The distributed load is more difficult to analyse than a concentrated load. Hondros (1959) analysed the IBT for the case of a thin disc loaded by a uniform pressure applied radially over a short strip of the circumference at each end of the disc. He obtained the full-field stresses in a series solution using the series expansion technique, and applied these solutions to evaluate the Young's Modulus and Poisson's ratio of concrete.

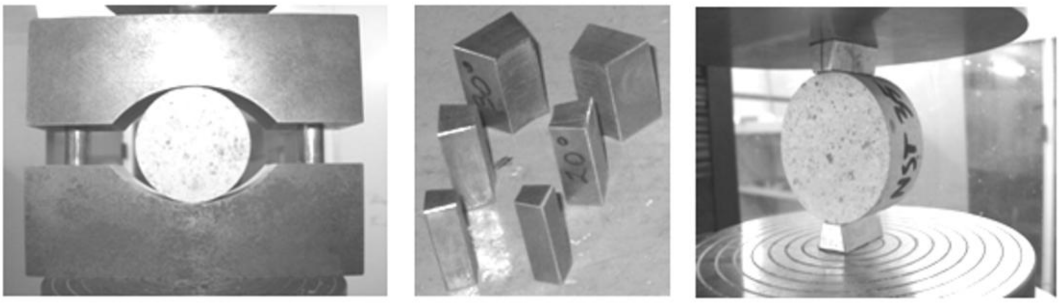
In addition to analytical solutions that assume the rock to be isotropic and homogenous, recently many researchers have included the effect of rock heterogeneity in their experimental and numerical studies (Van de Steen 2001, Van de Steen et al. 2005, Lanaro et al. 2009, and Liu 2004). Van de Steen et al. (2005) experimentally and numerically studied the irregular, granular nature of rock as well as the effect of the presence of defects and weaknesses on the stress distribution in a specimen. A numerical approach called Rock Fracture Process Analysis (RFPA) was used in this study to elucidate the fracturing process in a Brazilian disc under different boundary loading conditions. Liu (2004) listed the main advantages of the RFPA model over other models and gave the description of the RFPA model.

2 METHODOLOGY

The aim of the testing was to determine the most reliable means of estimating the tensile strength of Brisbane tuff by indirect testing. Numerical analyses and analytical calculations are used to investigate this further.

2.1 Sample preparation and test methodology

The tests reported herein were carried out on Brisbane tuff, since it is a host rock of Brisbane's (Queensland, Australia) first motorway tunnel project, the CLEM7, from which rock core samples were obtained. The test specimens prepared were standard Brazilian discs with a diameter of 52 mm and thickness of 26 mm (a diameter:thickness ratio of 0.5). The load was applied by a stiff hydraulic Instron loading frame, with a loading rate as suggested by ISRM of 200 N/s (ISRM 2007). Four series of indirect tension tests were conducted, with: (1) standard Brazilian jaws, (2) 15° steel loading arcs, (3) 20° steel loading arcs, and (4) 30° steel loading arcs (Figure 1). The steel loading arcs were machined from standard mild steel, as recommended by ISRM (2007). Up to four repetitions were carried out.



(a) (b) (c)

Figure 1. (a) disc between standard Brazilian jaws, (b) steel loading arcs, and (c) disc between loading arcs

2.2 Numerical estimation of Brazilian tensile strengths

The RFPA code was used to simulate the behaviour of Brazilian discs under various diametral loading conditions (Erarslan et al. 2011). In order to model the typical brittle failure of Brisbane tuff, the following characteristic parameters are used in the numerical simulations. Based on experiments and a series of numerical tests, the heterogeneity index for the simulated rock is 4.0. The mean value of the uniaxial compressive strength and elastic modulus for the rock are 202.5 MPa and 26 GPa, respectively, and the Poisson's ratio and friction angle are 0.25 and 35°, respectively. With regard to the loading steel arcs, the heterogeneity index is a sufficiently high value for the rock to be considered almost homogenous. The mean strength and elastic modulus are 1,500 MPa and 100 GPa, respectively. The stress is applied by a constant displacement of 0.0025 mm per step on the top of the steel arc, while the bottom arc is fixed in the vertical direction. The numerical model represents a plain stress problem.

3 RESULTS

3.1 Experimental results

The tensile strength of the rock specimens tested using the standard Brazilian jaws was calculated using the formula given by ISRM (2007). Since the loading boundaries of the steel loading arcs are different from that of the standard Brazilian jaws, the formula given by ISRM (2007) cannot be used to calculate the ITS of the specimens tested under the loading arcs. The tensile strength of the specimens tested under the loading arcs was calculated from the maximum tensile stress calculated at the centre of the disc, using the analytical solutions given in Erarslan and Williams (2011).

The detailed test results are given in Table 1. The maximum recorded failure load was obtained using 30° loading arcs. The second highest failure load was obtained with the standard Brazilian jaws, which also produced the highest standard deviation among the ultimate loads.

Table 1. Detailed test results

Description	Recorded Maximum Load (kN)			
	Standard Brazilian jaws	15° loading arcs	20° loading arcs	30° loading arcs
Replicate 1	25.00	12.50	17.06	21.10
Replicate 2	16.77	16.39	19.82	24.60
Replicate 3	15.43	15.65	20.23	21.13
Replicate 4	21.00	14.70	19.41	22.17
Average	19.60	14.81	19.20	22.30
Standard deviation	4.34	1.69	1.64	1.64

Loading with Brazilian jaws caused catastrophic crushing failure of the disc specimens of Brisbane tuff (Figure 2a). However, a single failure plane emanated from the loading axis, with secondary cracks, under the 15° loading arcs (Figure 2b). In contrast to the results under the 15° loading arcs, a single axial splitting failure plane through the diametral loading axis was obtained using the 20° loading arcs (Figure 2c). Unlike the results obtained under the Brazilian jaws and the 15° and 20° loading arcs, arrested and vertically-aligned central cracks were obtained using the 30° loading arcs (Figure 2d).

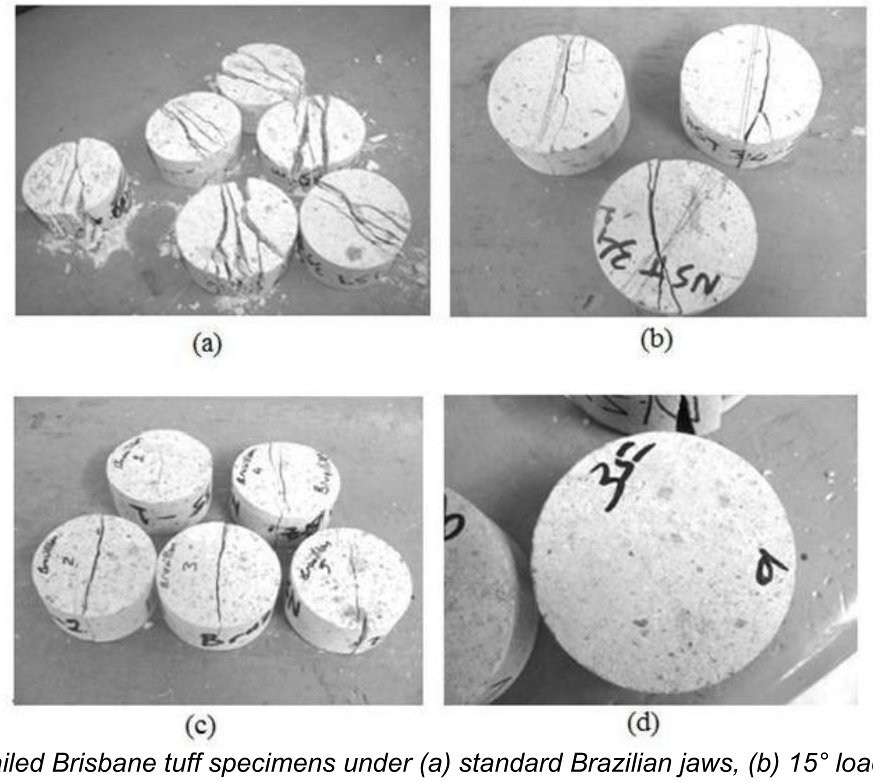


Figure 2. Failed Brisbane tuff specimens under (a) standard Brazilian jaws, (b) 15° loading arcs, (c) 20° loading arcs and (d) 30° loading arcs

Testing Brisbane tuff disc specimens under 30° loading arcs produced central tensile splitting, which is preferred over the crushing produced under standard Brazilian jaws. However, it is not easy to conclude that the failure load obtained under 30° loading arcs best represents the true value of the tensile strength. Hence the need for numerical analyses and analytical calculations presented below.

3.2 Numerical simulation and analytical results

Figure 3 shows the simulated progressive fracture process in heterogeneous Brazilian disc specimens under standard Brazilian jaws and the three different loading arcs. As the loading increases under Brazilian jaws, cracks start at points close to the upper contact along the vertical diameter of the disc (Figure 3a). Subsequently, cracks propagate unstably radially outward in the upper half of the disc, resulting in a diametral fracture plane with small crack coalescence. As the angle of the loading arcs is increased, it was difficult for the fractures to open immediately under the loading point, due to the constraining stress in the horizontal direction under the loading arcs. Hence, no crushed zone immediately beneath the loading arcs, due to the high compressive loading, was observed in the numerical simulations. In all loading arc simulations, the first failure and/or crack initiation occurred at the centre of the disc (Figure 3b, c and d). In contrast, primary crack initiation occurred very close to the loading point in Brazilian jaw simulations. At the end of all fracture process simulations, crack coalescence and failure took place along the vertical diameter of the discs.

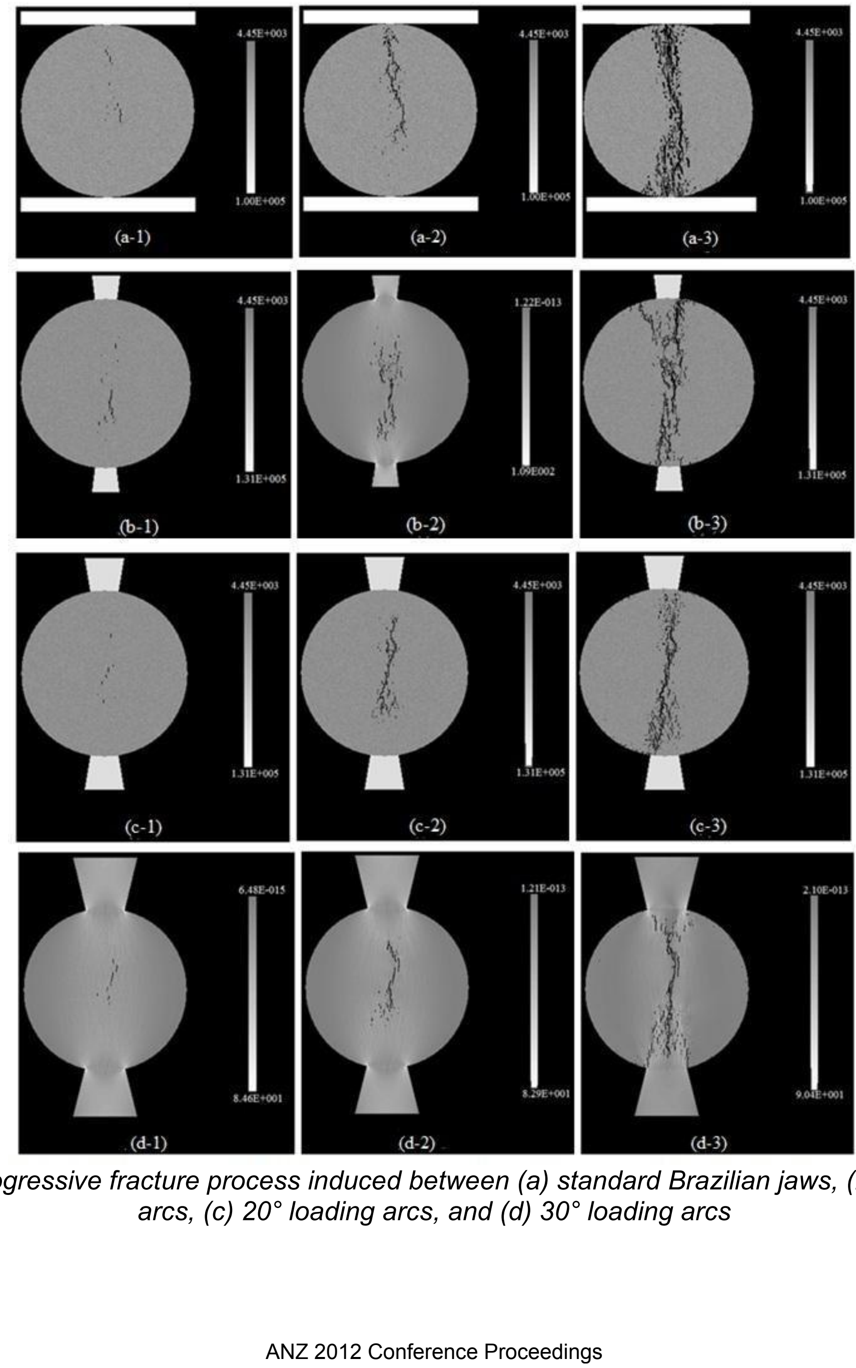


Figure 3. Progressive fracture process induced between (a) standard Brazilian jaws, (b) 15° loading arcs, (c) 20° loading arcs, and (d) 30° loading arcs

A comparison between the analytical solution obtained by Erarslan et al. (2011) for a 20° loading arc and the numerical simulation results of all loading geometries is given in Figure 4. The theoretical horizontal stress distribution is reasonably consistent with the numerical results, although there are clear discrepancies towards the boundaries. The reason for these discrepancies may come from differences in the assumed boundary conditions for the two types of analyses. As shown in Figure 4, tensile stresses reach a maximum at the centre of the disc and persist over more than half of the diameter of the specimen. In general, the analytically-determined tensile stress distribution moves to the centre of the disc at a faster rate than the numerically-calculated distribution. On the other hand, the increment in the tensile stress rate of the Brazilian jaw simulation is the lowest when approaching the centre of the disc in both numerical and analytical simulations. The results indicate that the concentration of the tensile stress under the Brazilian jaws through the centre of the disc is lower than that under a loading arc. As shown in Figure 4, the numerical σ_x stress distribution changes dramatically because of the heterogeneity effect (Liu 2004). For example, at the locations of crack initiation, the tensile stress drops to zero, while at the bridges between the cracks, the tensile stress might rise to values larger than the tensile strength of the rock (Erarslan et al. 2011).

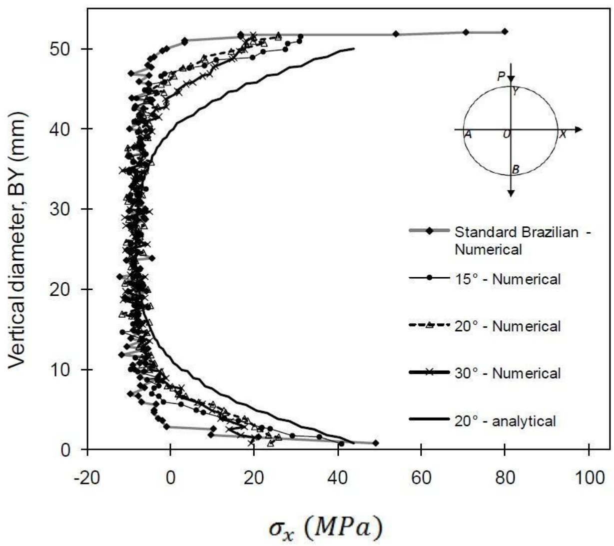


Figure 4. Horizontal stress distribution along vertical diameter (BY) of disc (−σx: tension; +σx: compression)

Fracture toughness values calculated using the relationship given by Wang and Xing (1999) and the numerical simulations under the standard Brazilian jaws, 15° loading arcs, 20° loading arcs and 30° loading arcs, are: 0.85 MPa√m, 0.7 MPa√m, 0.81 MPa√m and 1.24 MPa√m, respectively. In contrast, the mode I fracture toughness of Brisbane tuff was found experimentally to be 1.18 MPa√(m, using the Crack Chevron Notched Brazilian Disc (CCNBD) method suggested by ISRM (1995) (Erarslan 2011). The CCNBD specimens have the same diameter and thickness as standard Brazilian disc specimens; thus, a relationship between fracture toughness and indirect tensile strength of rocks is both helpful and meaningful. The numerical stress intensity value closest to the experimental fracture toughness of 1.18 MPa√m, was obtained with the 30° loading arc simulations (1.24 MPa√m). In order to support this result, a well-known empirical relationship between the mode I fracture toughness (K_{IC}) and the tensile strength of rocks (σ_t) is used (Whittaker et al. 1992). According to this relationship, K_{IC} can be calculated as follows:

$$K_{IC}\ (\mathrm{MPa}\sqrt{m}) = 0.27+0.107\sigma_t\ (\mathrm{MPa}) \quad (1)$$

The ITS value was found to be 8.55 MPa using the experimental mode I fracture toughness value of 1.18 MPa√m. The closest ITS values to this value are obtained from simulations under 20° and 30° loading arcs.

4 CONCLUSIONS

From the results of the experimental studies on Brisbane tuff disc specimens, it is concluded that their ITS value is strongly dependent on the means of application of the load. A general increase in failure load was obtained with an increasing angle of loading arc, for all disc specimens tested. The maximum recorded failure load, corresponding to the finest and most centrally-located crack, was obtained with the 30° loading arcs. The highest failure load standard deviation was obtained with the standard Brazilian jaws, which resulted in catastrophic specimen failure.

The RFPA numerical model successfully simulated rock fracturing in Brazilian disc specimens under line and diametral loading. Experimentally obtained fracture toughness values for Brisbane tuff were compared with the fracture toughness values obtained from the numerical simulations. It was concluded that the loading geometries that best estimate the ITS value are the 20° and 30° loading arcs. This conclusion was supported by applying a well-known empirical relationship between the fracture toughness and tensile strength of rocks.

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