Full-field strain evolution in Brazilian Disc tests using Digital Image Correlation and Adelaide University Indirect Tensile strength test (AUSBIT)

Rupesh K. Verma
Aurelia Metals, New South Wales, Australia
(formerly, The University of Adelaide, Adelaide, Australia)

Giang D. Nguyen
The University of Adelaide, Adelaide, Australia

Murat Karakus
The University of Adelaide, Adelaide, Australia

Abbas Taheri
Queen's University Kingston, Ontario, Canada
(formerly, The University of Adelaide, Adelaide, Australia)

ABSTRACT: Strain energy storing and dissipation characteristics of rock govern the dynamics associated with its failure mode. Such failure, especially in indirect tensile strength tests occurs in a split second, which practically disables the efficient application of image-based instrumentations to obtain the full-field strain evolution during the fracturing process. This paper presents the application of our recently developed innovative experimental methodology, named Adelaide University Snapback Indirect Tensile Strength test (AUSBIT), to indirect tensile testing of strong and brittle rocks. AUSBIT enables control of the disc specimen's cracking process in indirect tensile strength tests and captures the complete class II (snapback) post-peak load-displacement response. These experiments, in conjunction with advanced instrumentations based on Digital Image Correlation (DIC), provide us with full-field strain distributions over the surface of disc specimen. The results obtained are promising, showing both snapback post-peak responses and the evolution of full-field strain distributions.

Keywords: Brazilian disc, Digital Image Correlation, strain burst, strain energy storing, dissipation, tensile strength.

1 INTRODUCTION

The tensile strength material parameter is essential to evaluate the mechanical response of any geomaterials, including rocks (Perras & Diederichs, 2014; Verma et al., 2022, 2018; Verma & Chandra, 2020; Yu et al., 2009). Its accurate estimation is essential, and requires direct tensile strength testing, which is often inconvenient, especially in brittle materials like rocks. Consequently, the indirect tensile strength test was developed, named the Brazilian Disc test (ISRM, 1978). It is a simple experiment requiring the diametrical cracking of disc specimens under the influence of vertical loading. The peak load is linked with the tensile strength estimation, which often may not be very accurate (Fairhurst, 1964; Hudson, 1969; Li & Wong, 2013; Perras & Diederichs, 2014; Verma et al., 2018). Researchers suggested numerous modifications in this testing setup, which often requires geometric alteration of the simplistic disc specimen or empirical modifications in its theoretical formulation (Hudson et al., 1972; Li & Wong, 2013; Perras & Diederichs, 2014; Verma et al., 2021a). In addition, in such experiments, the disc specimen cracks immediately after the peak load in an uncontrolled manner, which makes it impractical to capture the correct post-peak behavior, thus the strain energy storing/releasing feature of the rock specimen. Due to abrupt cracking, it also disables the efficient application of advanced instrumentation, including Digital Image Correlation (DIC), limiting its applications to adding visual effects without any quantitative insight into the local scale material response (Mazel et al., 2016; Shara et al., 2018; Sharafisafa et al., 2020; Stirling et al., 2013)

In this view, our recently developed Adelaide University Snapback Indirect Tensile (AUSBIT) test could play a crucial role. The AUSBIT enables the disc to crack gradually over a prolonged duration, and captures the much needed post-peak snap-back feature (Verma, 2020; Verma et al., 2019, 2021; Verma et al., 2021a, 2021b). This paper combines AUSBIT experimentation with advanced instrumentations, including DIC, and assesses its mechanism to control the specimen cracking using local-scale experimental data. A brief outline of the experimental setup is presented in the subsequent section. The results on the sample scale load-displacement response are assessed with the DIC based full-field strain evolution. It provides a good insight into the strain energy evolution across the controlled disc cracking, which in principle, controls the dynamics associated with the specimen cracking.

2 EXPERIMENTAL SETUP

AUSBIT experiments were performed on Hawkesbury sandstone. The disc specimens of 42 mm diameter were diametrically compressed via an MTS loading frame (i.e., Model – LPS305) with flat loading platens. Four air-dried specimens, conforming to the ISRM standards, were tested at room temperature (ISRM, 1978). The loading frame has a capacity of 300 kN with in-built digitized servo control. In AUSBIT experimentation, the vertical displacement rate of the disc specimen was continuously adjusted to maintain a pre-defined lateral strain rate of 1.6×10^{-7} per second, equivalent to 0.6μm/min. Lateral displacement is used as feedback to the servo-controlled loading machine to adjust the vertical displacement (Verma et al, 2019). The vertical deformation of disc specimen was measured by two Linear Variable Differential Transformers (LVDT). An overview of the experimental setup is shown in Figure 1.

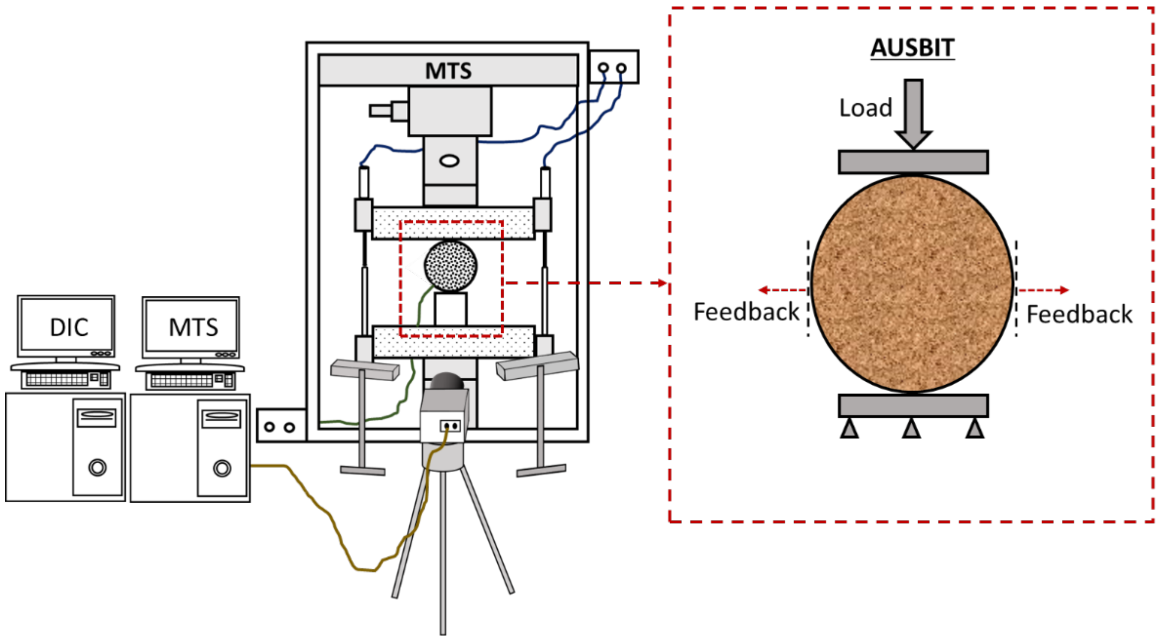

Figure 1. AUSBIT experimental setup (Verma, 2020; Verma et al., 2019; Verma et al., 2021a).

The above experimentations were complimented with advanced instrumentation, including Digital Image Correlation (DIC) and Acoustic Emission. For DIC application, the front surface of specimen was exposed to black dots with white background forming a randomly distributed speckle pattern. Specimen images were captured continuously throughout the experiment with a rate of 2 frames per second (fps). For post-processing of the captured images, the commercial image processing software package, i.e., Correlation Solution (VIC-snap 2D) was used (Correlation Solutions, 2009). The further details of these advanced instrumentation setups are presented in (Verma et al., 2021a; Verma et al., 2023). Further details of AUSBIT experimentation are presented (Verma, 2020; Verma et al., 2019, 2021; Verma et al., 2021a, 2021b).

3 RESULT ASSESSMENT

The AUSBIT enables controlling the disc specimen's vertical cracking under diametrical compression, which in conventional scenario, occurs in a split-second timeframe, as shown in Figure 2(a). This is challenging for advanced image-based instrumentation, given it is impossible to capture the failure process within such a short timeframe. The detailed discussion on result interpretation, significance, comparison with conventional approach and applications of advanced instrumentation is presented in (Verma, 2020; Verma et al., 2019, 2021; Verma et al., 2021a, 2021b; Verma et al., 2023). This paper focuses on the AUSBIT's physical mechanism for specimen post-peak controlled cracking.

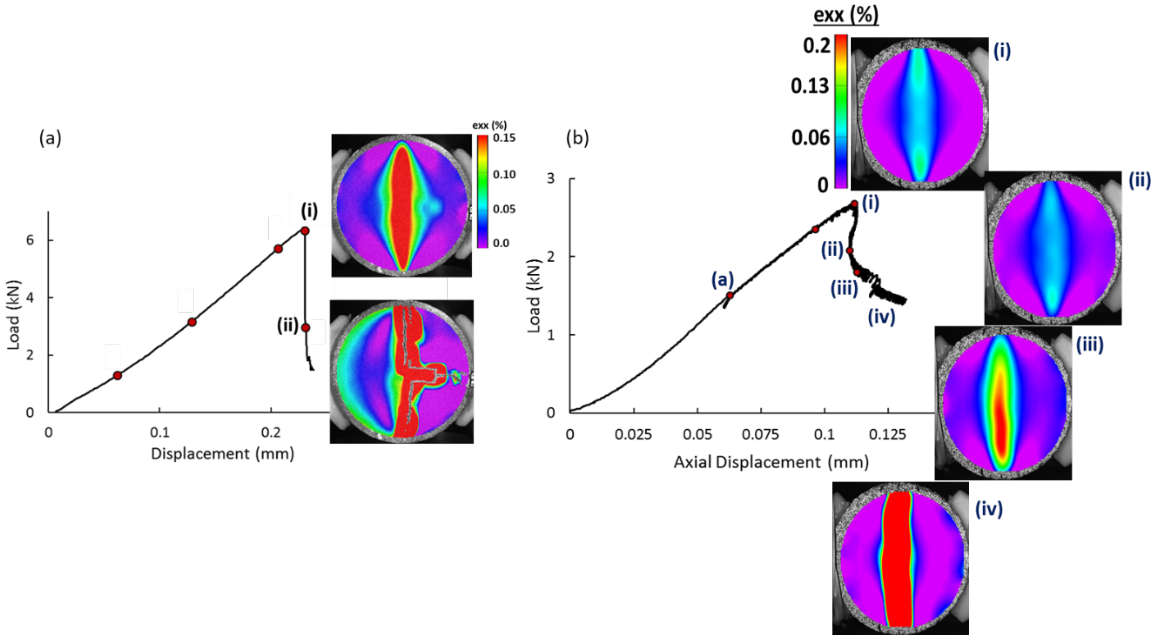

Figure 2. Load versus displacement response with DIC full-field strain evolution, (a) Conventional Brazilian Disc Test, (b) AUSBIT.

In this view, Figure 2(b) presents the load versus displacement result with four instances of post-peak response, indicating different stages of controlled cracking. The horizontal strain component (ε_{xx}) from DIC full field strain field is considered in these stages. The macro scale response demonstrates a consistent increase in load with displacement until the peak loading stage (i), indicating the pre-peak elastic response. The change over at point (a) suggests the switch of control, from conventional axial/vertical (with 0.2 mm/sec displacement rate) to AUSBIT's lateral strain-lateral (i.e., 0.2 um/min lateral displacement rate) controlled loading approach (Verma et al., 2021a). The peak loading stage (i) is characterized by intensified stress across the vertical diametrical axis. This stress intensification is relatively higher on the loading ends. The potential reasoning behind such observations in disc splitting tests is also discussed in (Verma et al., 2018). From this peak stage onwards, if the specimen is continuously compressed, it will undergo uncontrolled post-peak splitting failure, which is common in the conventional approach. The prime reason for this is the excess elastic strain energy accumulated in specimen at peak loading stage, which can also be indicated in the AUSBIT enabled post-peak snap-back response. In order to control the cracking process, it is inevitable to remove this excess stored elastic strain energy gradually.

To achieve this, the AUSBIT adopts a servo-controlled enabled continuous adjustment to the vertical loading rate to maintain a pre-defined rate of specimen's lateral deformation (or lateral strain rate) throughout the post-peak regime. The intent here is not to mechanically unload the specimen but to avoid delivering any energy additional to the fracture requirement or excess strain energy. This excess energy component is responsible for the dynamics associated with the uncontrolled disc splitting. Consequently, the strength of the specimen gradually degrades over prolonged post-peak duration under the influence of already stored elastic strain energy, i.e., the specimen is undergoing damage even without any considerable external work done. At stage (ii) in the post-peak regime, the strain intensification across the vertical diametric axis is diminished as compared to the previous stage. Despite this, the lateral deformation of disc specimen exhibits linear increase with pre-defined rate despite the specimen strength degradation, shown in Figures 2, 3(a), and 3(b). This assures that the specimen is undergoing material damage under the influence of already stored strain energy, not elastic unloading.

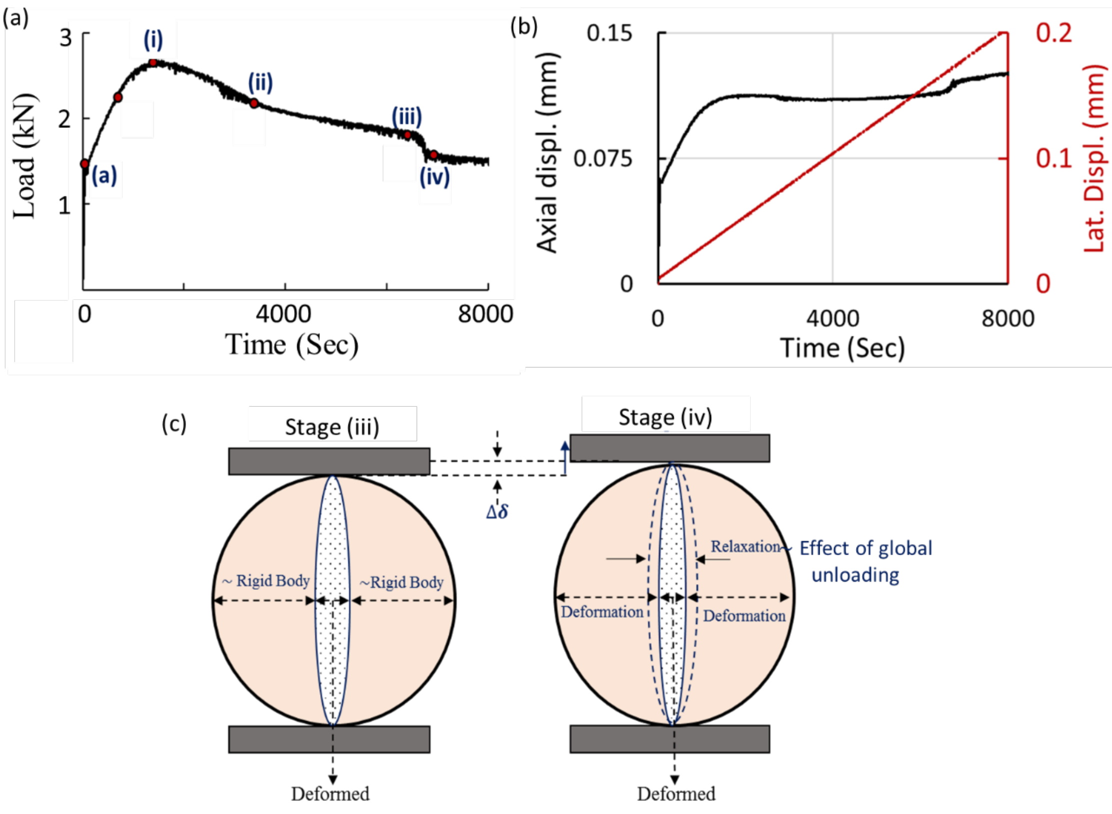

Figure 3. (a) Load versus time, (b) deformation versus time, (c) AUSBIT cracking mechanism.

At stage (iii), the strain across the vertical diametric axis intensifies with unified distribution maintaining a constant predefined lateral strain rate. This is unlike its previous peak loading stage, indicating the effect of stress-redistribution caused by the systematic loading-unloading cycles to remove the excess strain energy. This re-distributed stress and corresponding strain indicate intensified tensile stress across the vertical diametrical axis dominant at the specimen center and the lower region. Physically, during this post-peak failure process, the highly stressed diametrical region controls the disc specimen's lateral deformation. The region surrounding this localized vertical diametrical axis primarily acts as a rigid body, as shown in Figure 3(c). As the servo-controlled based global unloading happens, it induces a localized unloading effect on the highly stressed centralized region. Consequently, this localized region observes strain relaxation causing recovery of the elastic component of localized deformation. This localized unloading caused strain (or deformation) intensification in the surrounding portion. In other words, the release of excess strain energy from this stressed localized portion adds-on to the deformation of the surrounding portion. The specimen strength (or recorded load) reduces despite the systematic axial unloading. Subsequently, a slight increase in vertical compression is observed from stage (iii) to (iv). It shows that the net energy available at stage (ii) was insufficient to maintain a constant lateral strain rate. Consequently, the loading mechanism provides more energy to maintain a constant overall lateral strain rate, eventually resulting in specimen failure at stage (iv).

4 CONCLUSIONS

This paper collaborates the AUSBIT experimentation with advanced instrumentation, including DIC to assess the mechanism of controlled cracking. The load versus displacement response demonstrates the excess strain energy available accumulated over the elastic deformation at the peak loading stage. This excess strain energy controls the dynamics associated with the uncontrolled cracking commonly observed in the conventional Brazilian disc test. The AUSBIT experimentation approach systematically removes this excess strain energy component over the prolonged duration of controlled post-peak disc specimen cracking. Consequently, one can capture the true post-peak behavior with the snap-back feature. The full-field strain evolution indicates that the tensile strain, thus stress concentration across the vertical diametric axis, which controls the overall lateral deformation of the disc specimen. The remaining portion of the specimen mainly undergoes rigid body movement and deforms slightly under stress relaxation enabled by the AUSBUT servo-controlled loading mechanism. The AUSBIT also enables the redistribution of stress across the vertical axis to diminish its concentration at loading ends, commonly observed in the conventional approach. Overall, the results obtained are promising in terms of its potential applications to improve the rock material property estimation and assessment.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Australian Research Council (ARC) and OZ Minerals Ltd for their financial support for this research through the Linkage Projects LP150100539 and LP200100038.

REFERENCES

Correlation Solutions. 2009. *Vic-2D Reference Manual* (pp. 1–59). www.CorrelatedSolutions.com

Fairhurst, C. 1964. On the validity of the "Brazilian" test for brittle materials. *International Journal of Rock Mechanics and Mining Sciences And*, *1*(4), 535–546. https://doi.org/10.1016/0148-9062(64)90060-9

Hudson, J. A. 1969. Tensile strength and the ring test. *International Journal of Rock Mechanics and Mining Sciences*, *6*(1), 91–97. https://doi.org/10.1016/0148-9062(69)90029-1

Hudson, J. A., Brown, E. T., & Rummel, F. 1972. The controlled failure of rock discs and rings loaded in diametral compression. *International Journal of Rock Mechanics and Mining Sciences*, *9*(2), 241–248. https://doi.org/10.1016/0148-9062(72)90025-3

ISRM. 1978. International society for rock mechanics commission on standardization of laboratory and field tests. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *15*, 99–103. https://doi.org/10.1016/0148-9062(78)90003-7

Li, D., & Wong, L. N. Y. 2013. The brazilian disc test for rock mechanics applications: Review and new insights. *Rock Mechanics and Rock Engineering*, *46*(2), 269–287. https://doi.org/10.1007/s00603-012-0257-7

Mazel, V., Guerard, S., Croquelois, B., Kopp, J. B., Girardot, J., Diarra, H., Busignies, V., & Tchoreloff, P. 2016. Reevaluation of the diametral compression test for tablets using the flattened disc geometry. *International Journal of Pharma*, *513*, 669–677.

Perras, M. A., & Diederichs, M. S. 2014. A Review of the Tensile Strength of Rock: Concepts and Testing. *Geotechnical and Geological Engineering*, *32*(2), 525–546. https://doi.org/10.1007/s10706-014-9732-0

Shara, M., Shen, L., & Xu, Q. 2018. Characterisation of mechanical behaviour of 3D printed rock-like material with digital image correlation. *International Journal of Rock Mechanics and Mining Sciences*, *112*(April), 122–138.

Sharafisafa, M., Aliabadian, Z., & Shen, L. 2020. Crack initiation and failure of block-in-matrix rocks under Brazilian test using digital image correlation. *Theoretical and Applied Fracture Mechanics*, *109*(July). https://doi.org/10.1016/j.tafmec.2020.102743

Stirling, R. A., Simpson, D. J., & Davie, C. T. 2013. The application of digital image correlation to Brazilian testing of sandstone. *International Journal of Rock Mechanics and Mining Sciences*, *60*, 1–11. https://doi.org/10.1016/j.ijrmms.2012.12.026

Verma, Rupesh K. 2020. A Combined Theoretical- Experimental-Numerical Approach to Characterization and Modelling of Rock Fracture and Rock Burst (Issue June). The University of Adelaide, Australia.

Verma, Rupesh K., Nguyen, G. D., Karakus, M., Golding, S., & Taheri, A. 2019. *Snap Back Indirect Tensile Test (AUSBIT)* (Patent No. 2019101006). 10/2019

Verma, Rupesh K., Nguyen, G. D., Karakus, M., & Taheri, A. 2021. AUSBIT : A novel approach to capturing snapback in indirect tensile testing. *American Rock Mechanics Association*.

Verma, Rupesh K, & Chandra, S. 2020. Polyaxial strength criterion and closed-form solution for squeezing rock conditions. *Journal of Rock Mechanics and Geotechnical Engineering*, *12*(3), 507–515. https://doi.org/10.1016/j.jrmge.2019.06.011

Verma, Rupesh K, Nguyen, G. D., Karakus, M., & Taheri, A. 2021a. Capturing snapback in indirect tensile testing using AUSBIT - Adelaide University Snap-Back Indirect Tensile test. *International Journal of Rock Mechanics and Mining Sciences*, 1–30.

Verma, Rupesh K, Nguyen, G. D., Karakus, M., & Taheri, A. 2021b. Control Concrete Disc Cracking under Diametric Compression using AUSBIT - Adelaide University Snap- Back Indirect Tensile test. *10th Australasian Congress on Applied Mechanics (ACAM)*, *978*.

Verma, Rupesh K, Nguyen, G. D., Karakus, M., Taheri, A., & Bui, H. H. 2022. A combined numerical-experimental approach to analyzing fracture initiation and development in brittle rocks. *Computers and Geotechnics*, *145*(February), 104663. https://doi.org/10.1016/j.compgeo.2022.104663

Verma, Rupesh K, Nguyen, G. D., Karakus, M., Taheri, A., & Bui, H. H. 2018. Numerical Analysis of Fracture Propagation in Brazilian Disc Test. *Australian Conference on Computational Mechanics*, *3*.

Verma, Rupesh Kumar, Nguyen, G. D., Karakus, M., & Taheri, A. 2023. Circular Disc under Diametrical Compression : Insights from DIC and AE based Analysis. In *Rock Mechanics and Rock Engineering*.

Yu, Y., Zhang, J., & Zhang, J. 2009. A modified Brazilian disk tension test. *International Journal of Rock Mechanics and Mining Sciences*, *46*(2), 421–425. https://doi.org/10.1016/j.ijrmms.2008.04.008