Application of Digital Image Correlation for Analysis of Anisotropic Materials Under Tension

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ABSTRACT: Tensile strength of rock and similar materials is a critical material property in rock engineering design. Anisotropic materials do not necessarily follow the behaviour as originally assumed when the Brazilian Tensile Strength test was created; therefore, additional care is required when analyzing tensile strength measurements of these materials. This study presents guidelines and recommendations for the analysis of strain accumulation in disc specimens with anisotropic geological fabrics using 2-dimensional digital image correlation. In addition, strain maps of specimen faces generated with digital image correlation are used to corroborate the mechanistic behaviour of a proposed three part anisotropic tensile strength criterion.

Keywords: Brazilian Tensile Strength, Laboratory Testing Procedures, Anisotropic Geological Fabric, Foliation, Digital Image Correlation, True Tensile Strength.

1 INTRODUCTION

The importance of tensile strength as a critical geomechanical property is well reflected as multiple agencies including the International Society of Rock Mechanics (ISRM) and the American Society for Testing and Materials (ASTM) have published a suggested method (ISRM, 1978) and a testing standard (ASTM, 2016). The most popular method to determine tensile strength of rock is the splitting tensile test (also known as the Brazilian Indirect Tensile Strength (BTS) test), which is a well-known and well-studied laboratory test that is relatively fast and easy to perform when compared to direct tension methods. However, very few guidelines have been created to aid in the processing and understanding of BTS test results for anisotropic materials.

For homogenous, isotropic rock and similar materials, the stress distribution internal to the BTS disc specimen should develop according to the theory as originally developed by Hertz (1883) and further described by Hondros (1959). Their description of a tensile fracture that propagates from the center outward to the rock-platen contact may not always hold true for anisotropic materials. Tensile strength testing on anisotropic materials has shown the anisotropy does have an effect on the measured tensile strength (e.g. Barla and Innaurato 1972; Chen et al. 1998). Foliation or other geological fabrics in rock are known to act as planes of weakness during compressive loading;

however, as tensile testing can be complicated, the development of anisotropic tensile strength is not as well understood. Recent studies have shown that fractures may develop either in tension or a combination of tension and shear which may be guided by the foliation (Dan and Konietzky 2014; Packulak et al. 2023a).

Measurement of the strain response of a BTS disc specimen during loading is typically straightforward as foil strain gauges can be installed on the disc face(s). While foil strain gauges are cheap, reliable, and considered industry standard measurement tools, they lack the ability to provide a strain direction or fracture mode. In cases where multiple strain gauges are installed in different orientations on the face of a disc, the strain gauges would have to be small enough to measure the same region of interest and would provide only one measurement point. To overcome these limitations and measure the strain response throughout the face of the disc specimen, a full field strain measurement technique such as digital image correlation (DIC) should be employed.

DIC is a non-contact, full field, photography-based strain measurement technology that uses computer vision software to track unique points on a surface undergoing deformation. The use of DIC has increased in popularity in rock mechanics as equipment and software becomes more accessible (e.g. Nath and Mokhtari, 2018). This paper presents a new procedure to determine the fracture development mode and strain response of anisotropic specimens during BTS tests from DIC. In addition, the insights from DIC measurements presented in this paper also provide mechanistic evidence for the three-part anisotropic tensile strength criterion proposed by Packulak et al. (2023).

2 SPECIMEN DESCRIPTION

All specimens in this study were selected from NQ size (47.6 mm diameter) diamond drill core. The drill core was procured from the Government of New Brunswick Madran core storage facility from two distinct boreholes, AB-14-02 and HL10-04. Borehole AB-14-02 is from the Armstrong East Property (Wolfden Resources Corp. 2016) and HL10-04 is located on the Fly Tent Brook Property (Votorantim Metals Canada Inc. 2010), which are both located in the Bathurst Mining Camp.

Specimens for this study are from the Nepisiguit Falls Formation (Fm) (Tetagouche Group), which is composed of coarse grained, crystal-rich tuffs and tuffites, and fine grained tuffaceous sedimentary rocks (Lentz 1999). The specimens are light greenish-grey and have a very fine grained groundmass. Crystals range in size from <0.5 to 4 mm and consist of quartz, plagioclase feldspar, muscovite, epidote, and chlorite (Figure 1). The weak to moderate foliation is defined by the alignment of micaceous minerals. In this paper the lithology is referred to as meta-sediment.

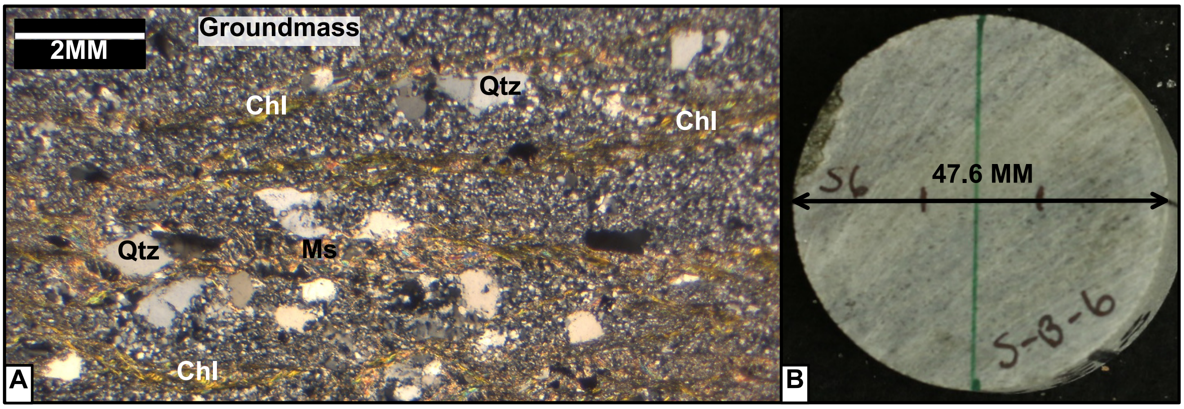


Figure 1. (A) Nepisiguit Falls Fm as seen in thin section under cross polarized light showing the very fine-grained ground mass, larger angular quartz (Qtz) grains, and foliation as defined by chlorite (Chl) and muscovite (Ms); (B) example BTS test specimen from this unit (47.6 mm diameter drill core).

3 LABORATORY TESTING PROGRAM AND DATA INTERPRETATION PROCEDURES

All BTS tests in this study were completed with an MTS 815 Rock Mechanics Testing System which is a closed-loop, computer-controlled, servo-controlled compression machine. The system consists of the following components:

1. An 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),
2. An MTS Model 505.07 Silent Flo Hydraulic Power Supply,
3. An MTS FlexTest 60 controller, and
4. A computer with the MTS controlling software.

DIC was completed using a 5 megapixel (MP) (2448 x 2048 pixels) Triton Camera from Lucid Vision Labs. The camera was equipped with a 25 mm lens from Edmund Optics and programmed to capture images of the specimen at 1 hertz (Hz) during the test. The camera was located approximately 30 cm from the specimen, resulting in a resolution of 0.05 ± 0.01 mm/pixel allowing for a theoretical tracking displacement resolution of 0.005 mm, which is equivalent to $1x10^{-4}$ mm/mm strain resolution. A 5500 K diffused light source was placed directly behind the camera to illuminate the surface of the BTS specimen. It should be noted that the equipment and setup of the DIC system has a significant effect on the captured strain results; readers are directed to Gagnon et al. (2023) for more details.

The specimens chosen for testing were free of heterogeneity flaws (e.g. veins), and anisotropic features were considered to be planar. Specimens were cut to final length using a diamond circular saw with attention given to the quality of the cuts, so they remained parallel in order to meet the ASTM D3967 (2016) standard.

Prior to testing, all specimens were prepared to be instrumented with one 10-mm foil length strain gauge positioned at the center of a specimen's face and aligned perpendicular to the loading direction to record the lateral deformation. The opposite specimen face was prepared for DIC strain measurement by painting black and white speckle patterns on the face. In order to ensure proper contrast and paint adhesion, the specimen face was first lightly sanded, then cleaned with 99% isopropyl alcohol before applying a layer of black paint via airbrush. Once the black paint was dry, a thin even layer of white paint was applied via airbrush. To create the speckle pattern a commercially available Glowforge computerized numerical control (CNC) laser engraver was used to burn the pattern onto the specimen surface, removing the white paint and exposing the black paint underneath, achieving an average speckle size of 0.2 mm (Figure 2). The quality of the speckle pattern has a large influence on DIC results, as discussed by Woodland et al. (2023).

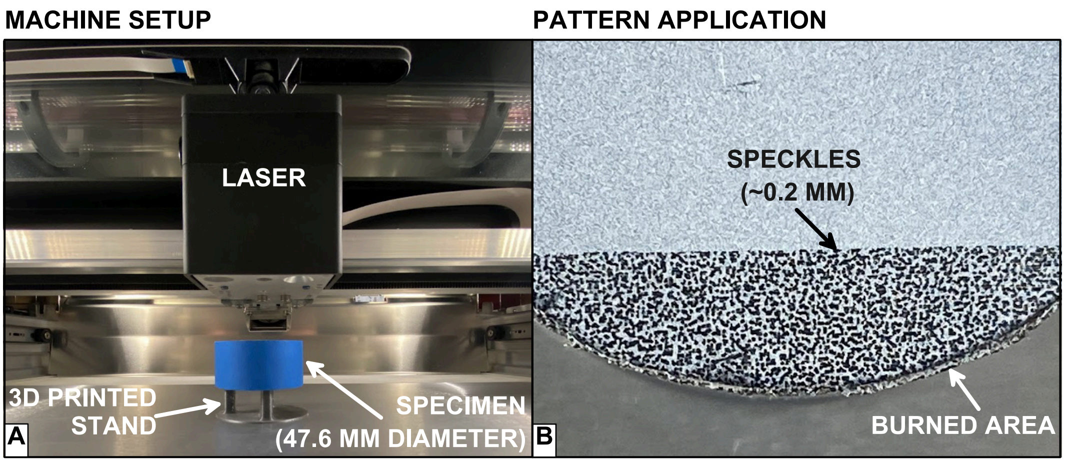
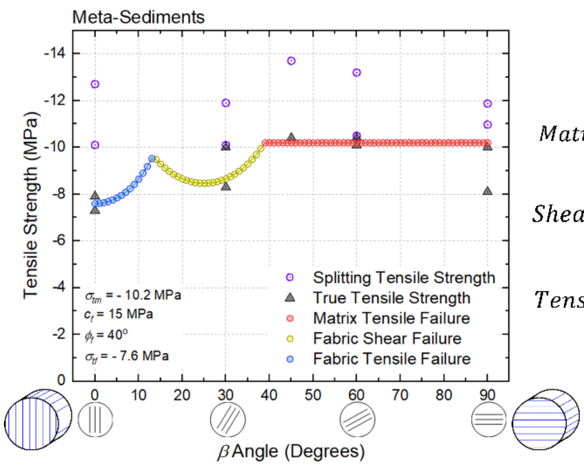


Figure 2. (A) Test specimen in CNC laser; (B) Top – down view of a specimen in the middle of laser engraving, darker region has 0.2 mm diameter speckles burned through the white paint.

4 RESULTS AND DISCUSSION

The objective of this study is to use DIC as a tool to measure the full field strain of the BTS specimen as well as distinguish the mode of failure of the specimen (matrix tensile failure, shear fabric failure, tensile fabric failure) based on the angle of foliation with regards to the applied load. As the specimens are foliated and can be considered transverse isotropic, both the dip of the foliation with respect to core axis (ψ) and the angle of the foliation structure with respect to the applied load (β) are important to note. Figure 3 shows the Splitting Tensile Strength and the measured True Tensile Strength (TTS) for the meta-sediment specimens tested. The procedure to determine TTS is described by Packulak et al. (2023b). As shown in Figure 3, at a β angle of 40° the mode is interpreted to switch from failing through the matrix in tension to failing in shear along the foliation and at a β angle of 13° the mode is interpreted to switch to a tensile failure along the foliation.



$$Matrix\ Tensile\ Failure = \sigma_{tm}$$

$$Shear\ Fabric\ Failure = \frac{c_f}{-2\sin 2\beta + (1 + 2\cos 2\beta)\tan\phi_f}$$

$$Tensile\ Fabric\ Failure = \frac{\sigma_{tf}}{-1 - 2\cos 2\beta}$$

Figure 3. Measured Splitting Tensile Strength and True Tensile Strength of the meta-sediment specimens (ψ = 90°) and resulting failure envelope.

Measured strain magnitudes from the DIC analysis were compared to the foil strain gauge using a virtual DIC strain gauge which showed good agreement between the two methods. Resulting full field strain maps immediately before failure are shown for β angles of 00°, 30°, and 60° in Figures 4, 5, and 6, respectively. It is expected that the specimen shall fail in tension along the foliation when β is 00°, fail in shear along the foliation when β is 30°, and fail through the matrix of the specimen where β is 60°. As shown in Figure 4, the strain accumulation is along the foliation planes and the resulting fracture is along an undulating surface as indicated in red.

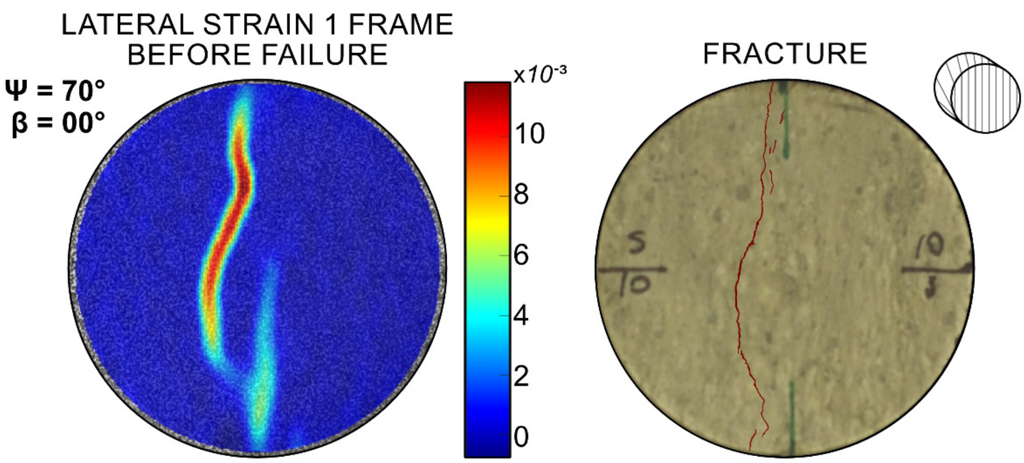


Figure 4. Full field strain map immediately before failure and the resulting fracture (ψ = 70°, β = 00°).

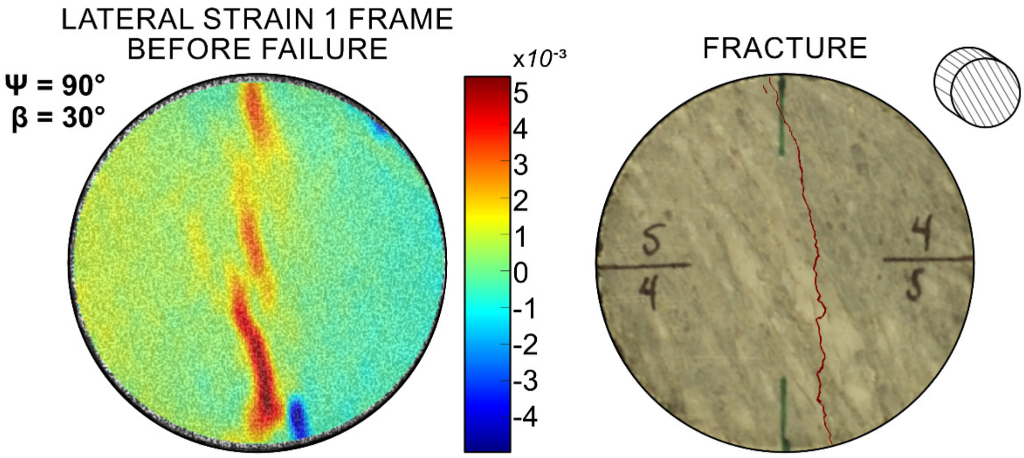


Figure 5. Full field strain map immediately before failure and the resulting fracture (ψ = 90°, β = 30°).

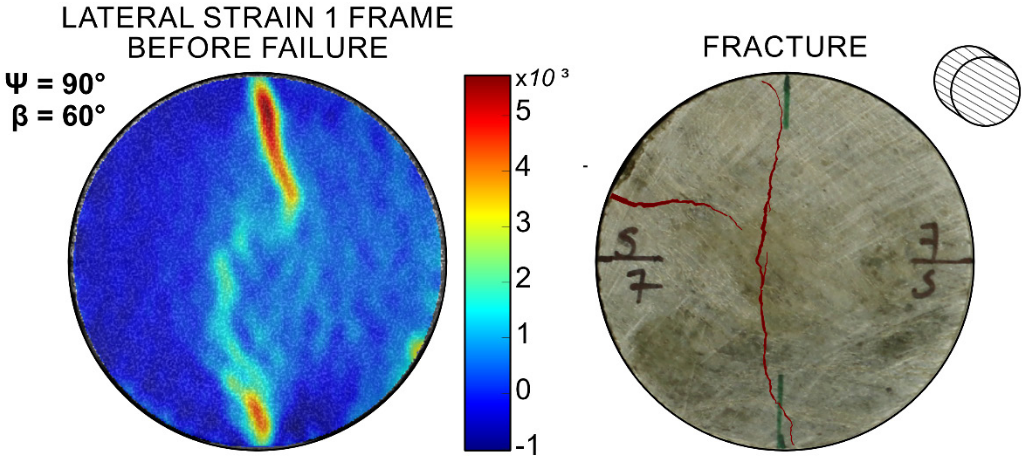


Figure 6. Full field strain map immediately before failure and the resulting fracture (ψ = 90°, β = 60°).

When the angle of the foliation is changed from 00° to 30°, it can be seen in Figure 5 that there is multiple foliation layer strain accumulation and a mixed mode failure where shear predominantly occurs. The increase in β to 60° (Figure 6) also shows foliation layer strain accumulation, however it is not as pronounced and ultimately the specimen fractures across the foliation to fail through the matrix. One thing to note is that all strain maps show strain accumulation that may not match the resulting fracture. This is to be expected as multiple cracks may initiate; however, a localized defect may propagate unstably at a lower strain threshold, thus controlling the resulting fracture. The use of DIC has transformed the way strain can be analyzed in a BTS specimen and has the potential to be a powerful tool as the ability to increase the resolution and photo acquisition rate continue to improve.

5 CONCLUSION

The research in this paper illustrates the development of a failure envelope for anisotropic rocks from BTS testing and how these materials fail when the plane of weakness is at varying 3-dimensional orientations with reference to the applied load. In addition to instrumenting the specimen with foil strain gauges, 2-dimensional DIC is demonstrated to be a tool that provides additional insight into the way strain is accommodated during loading and the way a BTS specimen ultimately fails. The DIC in this study also highlights the different failure modes for the proposed anisotropic tensile failure criterion with explicit evidence showing tensile failure of the fabric, shear failure of the fabric, and tensile failure of the matrix.

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