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The application of Digital Image Correlation to Brazilian testing of sandstone

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1. Introduction

The conventional Brazilian test indirectly establishes the tensile strength of brittle materials assuming biaxial linear elasticity in two-dimensions. Theoretically, the sample is considered to fail within the central portion of the disc, where the tangential stress ($\sigma_{\theta y}$) will overcome the uniaxial tensile strength under the application of a radially compressive stress (σ_{ry}) (Figure 1), [1].

Figure 1: Stress distribution along line YY' in the Brazilian test where, r =radial distance, R =disc radius and P =applied load (after Fairhurst, [2]).

Fairhurst [2] proposed that the tensile strength calculated from Brazilian test results is highly dependent upon the loading method used. The ASTM adopts the use of flat platens, where loading is applied to the disc at diametrically opposing points (Figure 2a), with recommended thickness (t) /diameter (D) ratios ranging between 0.2 – 0.75 [3]. The ASTM method has been criticised as sample crushing resulting from stress concentration has been found to initiate failure at the loading points rather than at the centre of the disc, which is critical in ensuring the validity of the test [4] and [5]. Several authors, including Andreev [6] and Yu, et al. [1] have attempted to mitigate the crushing behaviour through the positioning of ‘cushions’ and spacers of materials of various stiffness relative to the sample under investigation to decrease the localised stress. This has been shown to reduce the crushing effect of point loading, however adds a layer of complexity. In contrast, the ISRM recommends the application of load through a curved platen of radius 1.5 times that of the sample whose t/D ratio should be 0.5 (Figure 2b) [7]. This method requires the manufacture of loading platens of differing curvature depending upon the diameter of the sample disc being tested in order to retain a consistent loaded section of the circumference.

In order to address these issues, Wang & Xing [8] proposed a modified flattened Brazilian disc that allows a good contact between the sample and flat loading platens (Figure 2c) while minimising the crushing associated with point loading. Wang & Xing [8] found that, providing these flattened, parallel surfaces form an angle of $2\alpha \geq 20^\circ$, fracturing will develop from the centre of the disc during testing, thus ensuring the reliability of results [5] and [1].

These three loading methods are presented in Figure 2. The area of the disc over which the load (P) is applied is indicated. Figure 2b and c share a common angle, 2α , which defines the boundaries of the loaded area, though the area loaded in Figure 2b is greater (as it is applied through the use of curved platens) than that of the flattened disc geometry of Figure 2c [2].

Figure 2: Loading methods a) Flat-point [3], b) Arch-arch [7] and c) Flat-flat [8].

Attempts to observe the development of local compressive and extensional strains during Brazilian tests have been carried out using strain gauges adhered to the surface of specimens in both the horizontal and vertical orientation by [9], [10] and later by [11] and [12]. Whilst this method can provide accurate results, they are time consuming and cumbersome to prepare and may not be suitable for weak, friable lithologies. Strain measurements are also highly localised and can be affected by the stiffness of the gauge and adhesive.

The 3D Digital Image Correlation (DIC) system is a method for identifying the distribution and development of strains without the need for direct sample contact. The theoretical basis of the DIC technique was first proposed by Chu, et al [13] and has since been used in many fields of material testing, although its application in geo-mechanics is not well publicised [14]. Using high-resolution image capture, the displacement of an applied speckle pattern coated on the surface of a sample is tracked on the basis of pixel distortion before being converted into a measure of strain.

In using two calibrated parallax cameras, this apparatus can measure the development of strains in the vertical and horizontal axes to a high degree of accuracy whilst

also enabling measurement of out-of-plane displacements. Its advantages also include its ease of use following setup, measurement of the full strain field and compatibility with soft or friable specimen surfaces to which more traditional means of local strain measurements would not adhere.

The work herein aims to demonstrate the application of DIC as a substitute to more traditional strain gauges in Brazilian testing. This study initially applies the DIC technique to qualitatively and quantitatively assess the influence of loading geometry on strain localisation across the sample face. A comparative study is presented whereby the effect of ASTM, ISRM and flattened disk loading styles (presented by Wang & Xing, [8]) is examined with respect to localised straining behaviour at the top and bottom of the disk and location of fracture initiation. A second study considers varying disc t/D ratio in order to assess out-of-plane displacement.

2. Material Description

The material tested in this work was Springwell sandstone, originally sourced from the Springwell Quarry in Gateshead, Tyne and Wear, UK. The brown-yellow fine grained sandstone consists of sub-rounded to sub-angular, well sorted grains and forms part of the middle Pennine coal measures deposited in the Upper Carboniferous period.

The rock comprises predominantly quartz (85%), clay mineral (8%), alkali feldspar (5%) and mica (2%) [15]. The rock is ideal for these tests as it has been found to show no preferred orientation and has been described as “medium strong, linear elastic, homogeneous and isotropic in terms of both its strength and elastic properties” [16]. A summary of physical and mechanical properties is provided in Table 1.

Table 1: Physical and mechanical properties of the Springwell sandstone, (after [16]).

Property Measured	Symbol	Value	Unit
Porosity	n	10.74	%
Dry density	γ_d	2226	Kg/m ³
Uniaxial compressive strength	σ_u	44.113	MPa
Young's modulus	E	7.527	GPa
Poisson's ratio	ν	0.261	-
Indirect tensile strength	σ_t	3.725	MPa

3. Experimental Procedure

Samples were cored from the parent block with an 81.5mm external diameter diamond core barrel. This resulted in a consistent sample set known to have originated from the same vertical sequence and within a 1m³ volume. Disturbance during transportation was minimised as sample preparation and testing were carried out in-house. The discs were finished on a surface grinder to ensure their faces were flat to the required degree of parallelism and that the t/D ratio was accurate to within 0.01. Both the ASTM and ISRM methods require the use of circular discs as shown in Figure 3a. Samples that required the flattened disc geometry for comparison between loading methods were cut to the specification of Wang & Xing [8] as shown in Figure 3b. The rock disks were oven dried for a period of 48 hours.

Figure 3: Rock disc geometries; a) ISRM and ASTM and b) Flattened (after [8]).

The testing schedule consisted of two stages, the first being a comparative study of the loading methods stated in the ISRM and ASTM standards and that proposed by Wang & Xing, [8], using the DIC technique to observe the development of strain with the aim of identifying the location of crack initiation and loading induced out-of-plane deformation. A t/D ratio of 0.5 was maintained for the purpose of comparison between tests. The second stage was aimed at investigating the effect of varying thickness with reference to the ASTM recommended t/D ratio range and the ability of DIC to observe out-of-plane deformation. The test ratios and adopted nomenclature are provided in Table 2.

Table 2: Sample geometries and loading methods.

Test ID	t/D Ratio	Testing Method	# Samples Tested	Loading Rates (kN/min)
I0.5_	0.5	ISRM [7]	3	3.225
A0.5_		ASTM [3]	3	
W0.5_		Wang & Xing [8]	4	
A0.1_	0.1	ASTM [3]	3	0.645
A0.2_	0.2		3	1.290
A0.75_	0.75		3	4.839

All testing was conducted using an Instron 5585H universal testing machine. This device is able to apply either a constant loading rate or rate of displacement. Both the ISRM and ASTM standards recommend stress controlled testing, applying a constant rate of load such that samples will fail within a reasonable timeframe. In order to achieve failure in accordance with the standards, a loading rate of 3.225kN/min was back-calculated from the average tensile failure strength of Springwell sandstone (3.73 MPa) as observed by Alsayed [16] for a desired time to failure of approximately 5 minutes. This rate was used during all stage 1 tests. Rates used during stage 2 tests are shown in Table 2 and are derived from the thickness of the samples tested.

Work conducted by Andreev [6] has highlighted the inaccuracy in the application of different materials in cushioning the transfer of load to the disc. In addition to this, the suggested use of cardboard and plywood in the ASTM standard is arbitrarily defined and in the interest of consistency between methods, no cushioning was used in this work. Furthermore this work adopts the following sign convention: positive strain = compression; negative strain = extension.

4. Digital Image Capture and Processing

The Vic-Snap photogrammetry system was employed to monitor the samples in a contactless manner [17]. Two cameras were mounted on a tripod and profile bar then centred symmetrically about the sample position. The cameras were fitted with telephoto lenses of 28mm focal length and a 2mm relative aperture. In order to provide the desired degree of out-of-plane resolution for a sample at around 500mm distance from the cameras, an approximately 30° angle of incidence was chosen, as suggested in the user guide [17]. The DIC setup is shown in Figure 4.

Figure 4: DIC and testing rig setup.

In preparing the samples for DIC, a black-on-white speckle pattern was applied to the prepared face using fine aerosol paint to achieve a 50:50 coating that was both non-repetitive and isotropic [17]. Upon DIC system setup, this pattern was confirmed to meet the 2-30 pixel per speckle requirement and additional LED (cold source) lighting was used in order to maintain sufficient contrast of the pattern. Minor flaws in the contoured output may result from the accumulation of paint, highlighting the importance of an even speckle pattern. Image capture was conducted at intervals of 50ms (20fps). This was deemed sufficient to record sample deformation. A reference image was captured prior to application of load in order that subsequent relative sample deformation could be computed.

Following compilation of test images, an area-of-interest (AOI) was marked on the reference image consisting of the speckled face of the sample (Figure 5). An analysis grid large enough to ensure a sufficiently distinctive pattern was included within the AOI to allow for correlation. A single level of grid discretisation was used for all analyses as this relates to the use of a consistent speckle pattern. In addition to this, two analysis seed points, from which analysis begins, were placed within the AOI where least deformation was expected i.e. away from loading contacts and the disc centre. Two seed points were used to ensure the continuation of analysis either sides of the potential fracture. It must be noted that due to the prescription of this grid and only complete squares being analysed, a varying area around the circumference of the AOI is lost despite a fine grid spacing being set (Figure 5). This resulted in the flattened geometry of W0.5_ samples not being apparent in the post-processed output. Once the analysis specification was made using the reference image, all subsequent deformation of the speckle pattern in the test images was then tracked using the system software, Vic-3D [17]. The DIC data is converted to a triangular mesh defined on the

tangential plane of the sample surface and strains are computed in much the same way as conventional Finite Element analyses.

Figure 5: Reference image and analysis area selection.

5. Loading method comparison

All samples were loaded until the resulting fracture was seen to propagate through the whole specimen diameter. Following ASTM and ISRM guidance, tensile strengths (σ_t) of samples were calculated using Equation 1. This expression assumes the material to display linear elasticity until failure and that maximum tensile stresses are therefore induced normal to the loaded diameter such that failure is initiated at the centre of the disc. The scenario is essentially treated as a two-dimensional problem. The validity of the two-dimensional solution traditionally used in calculating the tensile strength has also been investigated by Wijk, [18]. Three-dimensional corrections to the traditional solution have been proposed, although the complexity of the process and assumptions made make this approach prohibitive for the majority of routine tensile testing and thus they are not considered here.

$$\sigma_t = \frac{2P}{\pi Dt} \quad 1$$

$$\sigma_t = k \frac{2P}{\pi Dt} \quad 2$$

The tensile strength of samples cut with the flat loading geometry was calculated using the adapted Equation 2 with the introduction of coefficient, k , which is related to the angle, α (Figure 3b). When $2\alpha=20^\circ$, $k=0.9644$ [5]. Secant elastic moduli, E_{sec} , were calculated from local horizontal strain data measured using the DIC. Table 3 shows the calculated tensile strength and DIC measured stiffness of all samples tested during stage 1 of this study.

Table 3: Tensile strength of Springwell sandstone with different loading methods.

Test	Testing Method	Failure Load, P (kN)	Tensile Strength, σ_t (MPa)	DIC Modulus, E_{sec} (GPa)
A0.5_A	ASTM [3]	14.30	3.32	8.83
A0.5_B		14.99	3.49	10.51
A0.5_C		13.77	3.20	9.44
I0.5_A	ISRM [7]	14.71	3.42	10.59
I0.5_B		13.93	3.24	10.73
I0.5_C		10.10	2.35	8.22
W0.5_A	Wang & Xing [8]	17.92	4.02	9.35
W0.5_B		18.49	4.15	7.27
W0.5_C		15.16	3.40	10.21
W0.5_D		18.54	4.16	9.29

Tensile strengths were derived from the load (P) corresponding to failure as observed from the externally measured load-strain relationship (Figure 6). Failure is defined by an abrupt loss of stiffness often accompanied by a fracture (although not necessarily visually apparent) and where a constant loading rate may no longer be maintained. Prior to the failure load, no fractures have developed and samples are assumed to behave in a linear elastic manner. This is supported by the load-strain relationships in Figure 6.

Figure 6: Representative load-strain results.

The failure load marked the end of tests carried out in accordance with ASTM standards, as the samples fell apart and could carry no more load. The load-strain behaviour of samples tested following ISRM guidance and Wang & Xing, [8] flattened geometry typically showed a temporary plateau following failure where load remained approximately constant and rapid vertical compressive straining was observed as the Instron attempted to

maintain a constant loading rate. In these cases, the load imposed upon the sample continued to rise following this plateau until testing was stopped manually. This is thought to be an effect of the sample being constrained by the testing platens and beginning to shear.

Omitting post-failure behaviour, caused by sample constraint, the externally measured load-strain relationship of the Springwell sandstone is presented for each test in Figure 7. These results show a relatively high level of consistency in apparent stiffness and load at failure within each testing method, with the exception of test I0.5_C which was likely caused by an unseen flaw within that sample. Samples tested using the flattened disc specification provided by Wang & Xing [8], indicate a stiffer response to load, with samples failing at marginally higher loads and undergoing less strain than those following the ASTM and ISRM standards. Failure loads, and therefore tensile strengths, of the ASTM and ISRM tests were similar, as too was the apparent stiffness prior to failure. However, the externally measured strain behaviour of the samples upon initial loading differed greatly, with significantly higher vertical strain being observed in ISRM testing. This may be partially due to total displacements incorporating additional compliance in the case of the ISRM curved platens. However the effect of bedding-in is seen in the externally measured strains of all three testing methods where initially softer responses are seen at the onset of loading.

For the purposes of comparison, representative tests of each loading method have been selected for analysis. Vertical strain between the top and bottom of the disk were measured locally using DIC and are presented alongside externally measured load-strain data in Figure 8. The DIC method is recognised to have excluded the area immediately around the circumference of the disk due to the prescription of an analysis grid subset. Therefore, as is the case with all local strain measuring tools, total vertical strains calculated using this software do not include those associated with bedding-in, localised crushing at the loaded surfaces or apparatus compliance. This has resulted in more competent load-strain behaviour being captured than is seen using only external measurements. By using the DIC to measure horizontal extensional strains, comparable tensile stiffness of between 7.3 and 10.7GPa can be calculated for all tests regardless of loading method. Values presented in Table 3 are found to be of a comparable magnitude to that established under compressive testing shown in Table 1.

Figure 7: Load-corrected displacements recorded externally for all tests.

Figure 8: Load-corrected displacements recorded internally (DIC) and externally for representative samples.

Post-fracture behaviour has been captured photographically via the DIC system and is shown in Figure 9. The fracture geometry of a representative ASTM sample after reassembly is shown in Figure 9a. Owing to the high fracture velocity, propagation could not be captured using DIC. Asymmetrical notches can clearly be seen at the sample top and bottom as a result of circumferential crushing brought about by point loading. The curved platen loading geometry of the ISRM specification holds the sample in place post-failure, allowing image capture of the fracture as shown in Figure 9b. The dominant fracture is typically accompanied by secondary fractures that open from the circumference at the outer points of contact with the curved platens.

The growth of fracture in tests using the flattened disc geometry of Wang & Xing [8] was easily captured due to the relatively slow stepwise propagation. Figure 9c shows a representative flattened disc immediately prior to failure with no fracture visible. Subsequent images, at the times shown, depict the propagation of the highlighted fracture, which originates across the centre of the disc in Figure 9d and opens diametrically. The final fractured state is presented in Figure 9f and shows the stepped geometry that incorporates the central fracture. Failure load (P) was taken at the instant the initial central fracture opened according to the load-displacement data. However it should be noted that the load continued to increase as the fracture propagated steadily through the sample until the fracture spanned the whole sample diameter.

Figure 9: Disc samples during and post-failure a) Sample A0.5_A post failure, b) 10.5_B at onset of fracture and c-f) W0.5_A fracture growth post-failure.

Local strain was calculated during post-processing of the DIC images captured during all tests. For the purposes of comparison, representative tests of each loading method have been selected as in Figure 8 and contour plots of percentage horizontal and vertical strains are presented in Figure 10. Plots represent the captured state immediately prior to failure and therefore fractures have not yet developed.

Figure 10: Strain distributions immediately prior to failure a-b) ASTM, c-d) ISRM and e-f) Flattened.

In theory, samples are expected to fail within the central portion of the disc. By examining the development of local strains using DIC, it is possible to compare the locations of strain concentrations between loading methods.

Qualitative assessment of Figure 10a, showing the ASTM loading method, highlights two regions of dominant horizontal extension located to the top and bottom of the disc. These areas are seen to be within a relatively narrow band of extension occurring across the vertical diameter. Compressive strains caused by loading the top and bottom points of the disc can be clearly seen in Figure 10b. Greatest vertical compressive strain occurs exactly at the edges of the disc, whereas horizontal extension is located inward of these areas. The regions of high vertical compression are accompanied by the maximum horizontal

compression located at [A] in Figure 10a. This is thought to be evidence of crushing behaviour as greatest compression is shown here in both orientations and corresponds well with the observed fracture pattern in Figure 9a.

For the ISRM arch-platen loading method, a sub-diametric region of horizontal extension and associated vertical compression in Figure 10c & d is shown respectively. Areas of greatest compression are seen to be located to the top and bottom of the disc, as seen in the ASTM method. However, with the use of curved-platens, these areas are seen not to be perfectly, diametrically opposed where load is transferred to the sample off-centre, as in Figure 10d. This eccentric behaviour has also been observed by several authors and is a function of an imperfect interface between the sample curvature and that of the loading platen [9]; [11]; [8] and [5]. The lateral extent of the sub-vertical strain concentration is shown to be comparable to that of ASTM testing despite a theoretically greater contact area due to the use of curved platens.

For the flattened disc procedure provided by Wang & Xing [8], horizontal compression is seen to be located at the loaded ends of the disc at [B] in Figure 10e, although in this case this is not associated with the extensional maximum. Instead, the dominant region of horizontal extension can be clearly observed to have formed at the centre of the disc, representing the best compliance with suggested theory. In contrast to the standard methods, upon loading at flattened disc ends, a broader distribution of vertical compressive strains is evident with reduced magnitude at the loading positions (Figure 10f). This is due to load being applied over a greater area of the disc circumference to that of the ASTM method, although theoretically the contact area is comparable to the ISRM loading method. In order to quantitatively compare the development of tensile strain and hence, comment upon the likely associated generation of tensile stress, strain profiles have been taken from across the loaded diameter (depicted in Figure 10b, d and f) and are presented in Figure 11.

Figure 11: Strain profiles across loaded diameter immediately prior to failure.

It can be seen in Figure 11a, showing the ASTM loading method, that exclusively compressive vertical strain has developed across the sample with the greatest vertical strain of 0.36% exhibited to have developed at the loading points, as would be expected. Horizontal strain is entirely extensional over the disc diameter across which the sample was loaded.

Along this profile two regions where extensional horizontal strain increases are visible and it can be seen that these correlate with the area of maximum compressive strain. The minimum horizontal strain, -0.11% is found to be located at the centre of the disc. Assuming linear elasticity, two distinct regions of maximum tensile stress are found to be located approximately 5mm inward from each loading point. This would suggest that fracture

of the disc ultimately initiated in one of these regions, which is counter to the observations made by Yanagidani, et al. [10], using more traditional local strain gauges and is counter to the Brazilian test theory.

A similar vertical compressive trend may be seen in Figure 11b) where curved-platens were used. The maximum vertical compressive strain, and therefore it is assumed stress, is found at the loading points, with the greatest strain of 0.44% at the top of the disc. The distribution of horizontal strain is found to be more even across the disc diameter with an average of -0.1%. Greatest horizontal extension is measured in the lower half with a maximum strain of -0.16%. This suggests that for the tests carried out, failure initiated within the sample close to the lower contact.

The maximum horizontal extension found within the flattened disc using Wang and Xing's [8] method is located to the centre (Figure 11c), which is in significant contrast to the results for tests using ASTM and ISRM methods. As with these loading methods, vertical strain is found to be greatest towards the points of loading (0.28%) though is generally more evenly distributed across the sample owing to the larger area over which the load is imposed. However, horizontal strain is seen to be compressive at these points, brought about by the restraint offered by the relatively large contact area. Extensional straining is seen to develop increasingly from the sample ends to a maximum at the approximate centre of the flattened disc. This indicates the greatest tensile stress concentration to be located here and corresponds with the observed initiation of fracturing and to Brazilian test theory.

Although samples tested in accordance with the ISRM and those with flattened geometries share a similar theoretical loading area, as defined by the angle 2α , the two methods produce very different results. Several authors including Wang, et al., [5] and Jianhong, et al., [11] have stated that although the theoretical purpose of the curved loading platens is to distribute load over a known area, in practice confidence in the ability to maintain this area throughout the test is limited. This is borne out by the results of this work (Figure 10c and d). The Wang & Xing [8], method is believed to reduce this uncertainty when used with stiff, well cemented materials, as the sample ends can be cut and ground to be parallel with a high degree of accuracy, all but removing 'bedding-in' errors, as can be seen in Figure 7.

Further to these results, the DIC was able to calculate the development of out-of-plane displacement during each test. Figure 12 displays the final surface profiles taken vertically at the centre of samples immediately prior to failure. It can be seen that tests conducted to ASTM specification consistently exhibit an outward (positive) protruding region towards the top and bottom of the disc, in the area proximal to loading contact. Again, this is likely related to sample crushing. Tests conducted to the ISRM standard exhibit a similar behaviour, though limited to a single end of the disc. It may be noted that ISRM tests are

located higher on the vertical axis as samples were mounted within the additional curved platens relative to the DIC cameras. Surface profiles for tests conducted on flattened discs using Wang & Xing [8] specification show a more level face indicating that less sample crushing was occurring due to the load being applied over flat and parallel surfaces. This increased contact area may also have resulted in greater restraint of the sample leading to a lesser degree of sample movement from the $z=0\text{mm}$ reference position at the start of testing.

Figure 12: Vertical surface profiles of representative samples immediately prior to failure.

6. Effect of Disc Thickness

Brazilian tests were carried out to ASTM standard on sandstone disks of varying thickness-diameter ratios. The ASTM standard suggests a ratio range of 0.2-0.75 and these extremes were tested in addition to the 0.5 ratio used in Section 5. To investigate the ability of the DIC system to measure out-of-plane displacement on the disk face, a ratio of 0.1 was also tested as this was anticipated to exhibit greatest displacement in this orientation. Loading rates were calculated to induce failure at a consistent time based upon the sample thicknesses used, as stated in Table 2. All discs were observed to fail in the conventional manner via vertical fracture at approximately 4 minutes. Tensile strengths were then calculated from the failure loads using Equation 1 and are presented in Table 4. It can be seen that a broadly constant tensile strength is attained though the magnitude of load at failure is proportional to the area upon which the disk was loaded, dependent upon thickness.

Table 4: Tensile strengths of Springwell sandstone tested with different disk thickness.

t/D ratio	Test	Failure Load, P (kN)	Tensile Strength, σ_t (MPa)	DIC Modulus, E_{sec} (GPa)
0.1	A0.1_A	2.71	3.15	5.11
	A0.1_B	2.55	2.97	4.66
	A0.1_C	2.72	3.16	5.54
0.2	A0.2_A	5.76	3.35	5.85
	A0.2_B	5.37	3.12	10.99
	A0.2_C	6.45	3.75	7.44
0.5	A0.5_A	14.30	3.32	8.83
	A0.5_B	14.99	3.49	10.51
	A0.5_C	13.77	3.20	9.44
0.75	A0.75_A	18.02	2.79	11.67
	A0.75_B	19.70	3.05	13.68
	A0.75_C	19.60	3.04	10.67

Representative tests have been selected to demonstrate the effect of thickness/diameter ratio on measured out-of-plane displacements. The DIC can be seen to be capable of resolving z-displacements to an accuracy of within ± 0.001 mm. Surface profiles have been taken vertically across the diameter and are provided in Figure 13.

Figure 13: Vertical surface profiles of representative samples immediately prior to failure.

Samples prepared to a ratio of 0.75 exhibit little out-of-plane variation along the diameter except at the bottom of the disk where deflection towards the camera is seen. As the t/D ratio is reduced, the degree of z-plane deformation across the samples diameter

increases, particularly towards the top and bottom of the disks proximal to the points of loading. Samples cut to a ratio of 0.1 display the greatest out-of-plane displacements of all samples, measuring between 0.02mm and 0.06mm.

Furthermore, the locations of the maximum z-displacements of all samples correspond closely with the position of the maximum magnitudes of vertical compressive strains (Figure 14) as a result of Poisson's effect and this localised z-displacement trend may also be evidence of crushing in these regions.

Figure 14: Strain distributions immediately prior to failure for samples of t/D ratios a-b) 0.75, c-d) 0.2 and e-f) 0.1.

Total vertical strains through the central vertical section of the samples measured using DIC increase as the t/D ratio reduces, meaning that thinner samples are undergoing greater vertical strains than thicker ones, despite all samples failing at highly comparable tensile stresses. The greatest horizontal and vertical compression measured for each sample is once again seen to be adjacent to the loading points. It can be seen in Figure 14 that the intensity with which horizontal extensional strain is produced increased with reducing t/D ratio.

When image capture speed has enabled the moment of fracture initiation to be captured, it is possible to compare the location of fracture formation to the development of horizontal extensional strain immediately prior to failure. This is in agreement with work conducted by [19] into the use of DIC for investigating desiccation cracking in clay based materials. A strong correlation between the localisation of inferred tensile stress and the location of cracking is seen, an example of which is presented in Figure 15.

Figure 15: Tensile strain development and fracture correlation in representative sample A0.1_B.

7. Conclusions

The 3D DIC system has been shown to be capable of producing high resolution strain mapping across the surface of rock discs undergoing Brazilian testing. By comparing the effects of loading method and sample geometry upon surface strains and out-of-plane deformations, DIC has allowed the following conclusions to be drawn:

1. The ASTM, ISRM and flattened disk loading methods have shown differing horizontal and vertical strain development throughout the course of the tests.
 - a) The ASTM and ISRM tests have shown greatest tensile strain concentration to have developed toward the points of loading corresponding to

the regions of highest compressive strains in the loaded orientation. This implies that fracture initiation occurs in these regions, though the frame rate employed was insufficient to capture the instance of failure owing to extremely high fracture velocity. Crushing in these areas was further evidenced by out-of-plane movement.

b) The use of flattened disk geometry has shown a consistently central development of extensional horizontal strains in addition to evenly distributed, vertically compressive strain. The use of DIC confirmed the centralised origin of failure.

2. In using a 3D system, it has been possible to observe out-of-plane displacements increasing with decreasing sample thickness. This behaviour has been found to be greatest at the top and bottom of the sample, coincident with the regions of largest vertical compressive strain. Whilst this does not appear to affect the calculated tensile strength, DIC has enabled this behaviour to be observed counter to the solely 2D deformation assumption inherent in Brazilian testing.

In addition to these conclusions, the following general observations on the application of DIC to Brazilian testing have been made:

1. DIC represents a rapid and simple means of measuring strains across the whole analysed surface. Traditional methods of measuring local strains, for example electrical resistance strain gauges and linear variable differential transformers (LVDT's), are limited to a finite number of linear 2D gauge lengths per sample due to space restrictions. By using DIC to measure the development of small-scale displacements, not only are more realistic strain behaviours observed than would be captured externally, this measurement is made throughout the full strain field in 3D rather than between a limited number of discrete points.

2. In post-processing, strain development may be observed throughout the course of the test. The visualisation options include graphical data, still images and video, increasing the accessibility of data for interpretation.

3. In using DIC, assessment of the point of fracture initiation, and therefore test validity, can be deduced via post-processing of strain data and observation of photographs taken automatically by the DIC system.

4. Traditional local strain gauges require sample contact along with knowledge of the relative stiffness of the gauges themselves. The DIC system is contactless and the stiffness of the paint is considered to be negligible.

5. Preparation of multiple samples for application of DIC may be carried out efficiently with reference to time, although the performance of the analysis is

highly dependent upon the user's ability to create a speckle pattern that is both appropriate in size and consistent across samples.

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