Elucidation of microscopic stress state within surface asperities of a rock joint

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ABSTRACT: Field observations suggest that the occurrence of fault-slip related seismicity in deep underground be affected by the non-linear and/or time-dependent behaviour of discontinuity surface asperities. The present study aims at investigating the strain and stress distribution of discontinuity surface asperities on a micro scale by conducting a uniaxial test in a micro-focused X-ray CT, analyzing the CT images with the digital image correlation method, and reproducing the experiment with numerical simulation in the framework of the discrete element method. The experimental result obviously shows strain concentration within asperities on the discontinuity, which is approximately 10 times as large as that in the matrix. Surprisingly, the numerical simulation shows an asperity to matrix strain ratio similar to the experiment, although the absolute value is different. It was then concluded that the difference is attributed to time-dependent and/or brittle failure behaviour of the highly stressed asperity.

Keywords: Discontinuity asperity, DIC, micro-focused X-ray CT, DEM simulation.

INTRODUCTION

The mechanical behaviour of rock joints is of paramount importance in various civil and mining engineering projects, such as underground/open-pit mine development, geothermal energy development, hydraulic power plant construction, and so forth. This is attributed to the fact that the mechanical behaviour of rock mass is significantly affected by that of discontinuities on different scales ranging from millimeter to kilometer and that such discontinuities are inevitably present within rock masses. Hence, a better understanding of the mechanical behaviour of rock discontinuities, e.g., stiffness, strength, post-peak behaviour, and time-dependent behaviour, is indispensable to estimate the deformation of rock mass structures and evaluate their short- and long-term stability.

The advancement of computer technology has made it possible to investigate the mechanical behaviour of rock joints in a more quantitative and comprehensive way with the use of various numerical simulation techniques. Importantly, as a general approach, the numerical analysis result is verified whilst comparing to shear stress-displacement curve, peak shear strength, and/or fracture characteristics within surface asperities (Bahaaddini et al., 2013), among which the first two are considered quantitative verification. It is to be noted that such quantitative comparison is predominantly made from a macroscopic point of view. That is, what is examined is the macroscopic mechanical behaviour, such as peak and residual shear strengths and dilation. In other words, the microscopic deformation and stress state of surface asperities are yet to be sufficiently investigated. It is reasonable to conceive that the complex mechanical behaviour of joint asperities is one of factors that dictate the occurrence of fault-slip events in deep underground.

Considering the research gap, the present study aims to elucidate the microscopic stress state within surface asperities of a rock joint. As a first step to achieve the goal, a rock-like specimen with a throughgoing discontinuity is made of cement to carry out a uniaxial compressive test in the chamber of a micro-focused X-ray CT, followed by image analysis with the Digital Image Correlation technique (DIC) to quantify the microscopic strain distribution on the discontinuity surface. The result is further compared to a numerical simulation result for verification. This study gives an insight into the mechanical state of joint surface asperities subjected to normal stress.

METHODOLOGY

The present study experimentally and numerically investigates the microscopic mechanical behaviour of asperities on a rock joint surface. As for the experiment, a uniaxial compressive test is performed in the chamber of a micro-focused X-ray CT, followed by image analysis based on DIC to quantify the strain distribution inside asperities on a microscale. Numerical simulation is also performed in the framework of DEM for the verification of the experimental result and further quantification of the strain and stress distribution within asperities.

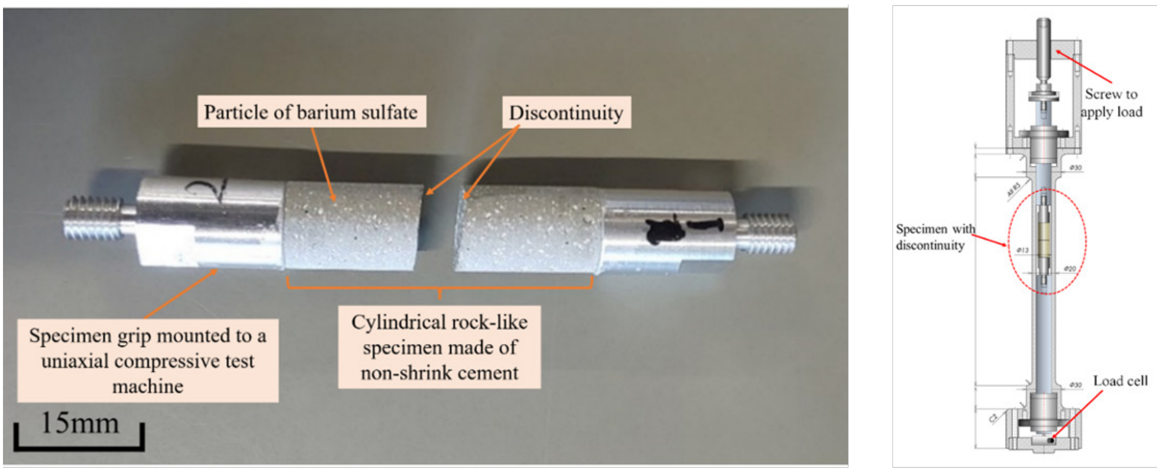
2.1 Uniaxial test in a micro-focused X-ray CT scanner

As the first step to investigate the microscopic mechanical state within joint surface asperities, it is ideal to use as a homogeneous material as possible, because heterogeneous materials, such as concrete and sandstone, contain grains and/or aggregates with different stiffnesses, hence causing unexpected stress concentration on a microscale. For this reason, non-shrink cement is employed to create rock-like specimens without the addition of any fine and coarse aggregates, such as sand and gravel, except barium sulfate, which is intended to facilitate DIC analysis as tracer. To enhance the accuracy of DIC analysis as much as possible, barium sulfate was brayed in a mortar, resulting in an average particle size of 2.28 μm with a standard deviation of 1.03 μm.

The cylindrical specimen is broken into two pieces in the manner of three-point bending test to produce a throughgoing discontinuity at the centre. Thereafter, end faces of the two pieces are cut with a cutting machine (Buehler IsoMet LS) whilst paying the most attention so that the end faces are parallel with each other. Figure 1(a) shows the cylindrical specimen (two pieces) glued on specimen grips with epoxy resin for a small-scale uniaxial compressive test device. As can be seen in the figure, the throughgoing discontinuity is located at the centre, whilst the end faces are smooth and attached to the grips.

The specimen grips to which the rock-like specimens are glued are then installed to the small-scall uniaxial compressive test machine as depicted in Figure 1(b). In the device, uniaxial load applied by tightening the screw in the upper part is transferred to the specimen through the bar. A load cell (CLS-2KNB produced by Tokyo Measuring Instruments Lab.) is installed at the bottom of the device so that the load can be precisely controlled and monitored with a data logger.

A TOSHIBA micro-focused X-ray CT scanner (TOSCANNER 32300) owned by X-Earth Center at Kumamoto University is used for this study. The technical settings of CT scanning are as follows. The scan geometry is cone beam, and tube current and voltage are set at 250 μA and 120 kV, respectively. The number of views is 2213, and exposure time is 249 ms. The CT image has pixel resolution of 1024 × 1024, and the pixel size is 10 μm. During the uniaxial compressive test, the load is increased in a stepwise manner staring at 0 N and ending at 2000 N with an interval of 250 N. At each stage, CT scanning is performed, which takes approximately 20 to 30 minutes. After completing the uniaxial compressive test, three-dimensional image reconstruction is performed for each loading stage.



(a) (b)

Figure 1. (a) Rock-like specimen with a throughgoing discontinuity at the centre, (b) self-developed uniaxial test machine installed in the chamber of a micro-focused X-ray CT.

2.2 *DIC analysis*

After the CT image reconstruction, the deformation of the specimen during the loading test is evaluated with the DIC method. DIC is a method that tracks a patten with a high correlation in a series of images, whereby the deformation of an object can be quantified. As a value of grayscale level is assigned to CT images depending on the density of grains existing in the rock-like specimen, non-uniform random patterns appear in the CT images, particularly owing to the specific gravity of barium sulfate added to the cement when preparing the rock-like specimen.

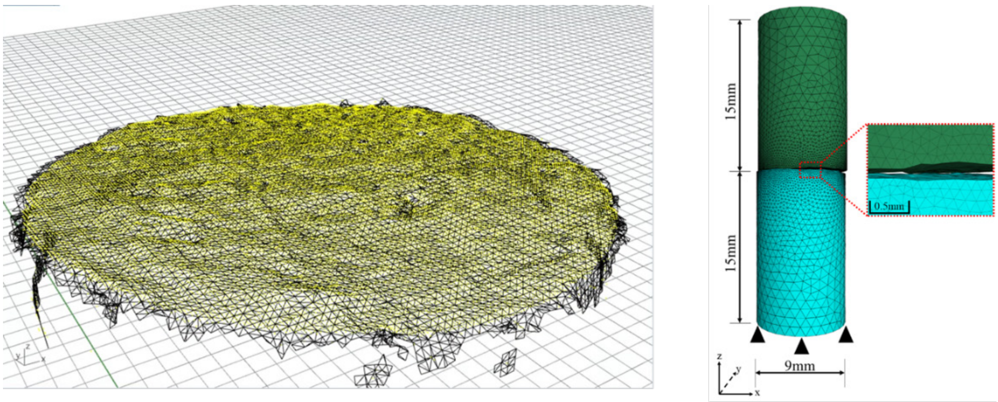
The DIC program used in this study is tomowarp developed by Hall et al. (2009), which employs a cross-correlation criterion based on three-dimensional subsets in the CT image reconstructed. Importantly, the success of DIC is highly susceptible to the distance between subsets (DIC step) and the size of subset. The parameters need to be carefully optimized to ensure the accuracy of the DIC analysis. In this study, the optimization was performed by conducting DIC analysis based on a uniaxial compressive test in the chamber of the micro-focused X-ray CT using a rock-like specimen without the throughgoing discontinuity. The DIC analysis provides us with a stress-strain curve during the uniaxial compressive test, based on which the Young's modulus of the rock-like specimen was evaluated. Then, the Young's modulus derived from the DIC analysis was compared to that estimated from a uniaxial compressive test performed with a universal testing machine using a large-scale rock-like specimen with a diameter and length of 50 mm and 100 mm, respectively. Eventually, the subset size and DIC step were set at 15 and 10, respectively, which resulted in Young's modulus of 13.6 GPa comparable to that of the large specimen.

2.3 *Numerical simulation*

2.3.1 *Numerical model construction*

The present study employs 3DEC Ver. 7.0 (Itasca 2020) code in the framework of the distinct element method. To construct a numerical model, the discontinuity surface of the rock-like specimen was precisely scanned with a laser displacement sensor (Keyence CL-3000) having a sensing accuracy of 0.015 μm and a spot diameter of 38 μm. The scanning is performed for the entire surface with a measurement grid of 10 mm × 10 mm at an interval of 50 μm, i.e., the surface geometry is measured at 40,000 points. The 3D topography of the surface is shown in Figure 2(a).

The coordinates measured are then input to Rhinceros 3D (McNeel et al., 2010), which is a commercial three-dimensional graphics software. As the number of grid points on the surface was found to be too large to construct a three-dimensional numerical model with an ordinal PC with RAM of 64 GB, the resolution was reduced to 100 × 100 when generating surface meshes on Rhinoceros 3D. Then, based on the surface geometry, rigid blocks for 3DEC are generated with Griddle 2.0 (Itasca, 2021). Thereafter, the rigid blocks are further discretized with zones on 3DEC to make it deformable. The numerical model constructed is shown in Figure 2(b). As can be seen, the near-discontinuity region is densely discretized with zones with an edge length of as small as 0.1 mm, whilst the zone size is gradually increased towards the edges of the upper and lower specimens.



(a) (b)

Figure 2. Numerical model construction: (a) discontinuity surface measured by a laser displacement sensor, (b) numerical model constructed with a discontinuity at the centre of the model.

2.3.2 Boundary conditions and model input parameters

The bottom boundary of the model is fixed in the direction perpendicular to the boundary, whilst a compressive stress is applied to the top boundary. These boundary conditions correspond to those of the uniaxial loading test in the X-ray CT scanner.

Regarding the mechanical parameter of the asperity contact, a further preliminary analysis was performed using a rock-like specimen with a smooth discontinuity. In the experiment, the rock-like specimen with a smooth discontinuity was uniaxially compressed with the test device in the X-ray CT scanner. From the experiment, the normal stiffness of the discontinuity was estimated, and it ranges from approximately 150 GPa/m to 750 GPa/m with the increase in the normal stress. According to the study (Bandis and Barton, 1983), the normal stiffness calculated based on the DIC analysis falls within a reasonable range. It should be noted that the contact area of the asperity on the discontinuity surface is on the order of μm, which is significantly smaller than that of the smooth joint surface. Considering the scale effect, the stiffness of asperity contact is finally set at 2,000 GPa/m. Preliminary analysis indicated that the shear stiffness has no influence on the mechanical state within the asperity. The other parameters were determined based on experiments and general characteristics of cement: E = 14 GPa, Poisson's ratio = 0.3, friction angle = 45º, cohesive strength = 19.1 MPa, and tensile strength = 9.2 MPa whilst employing a perfect elasto-plastic model.

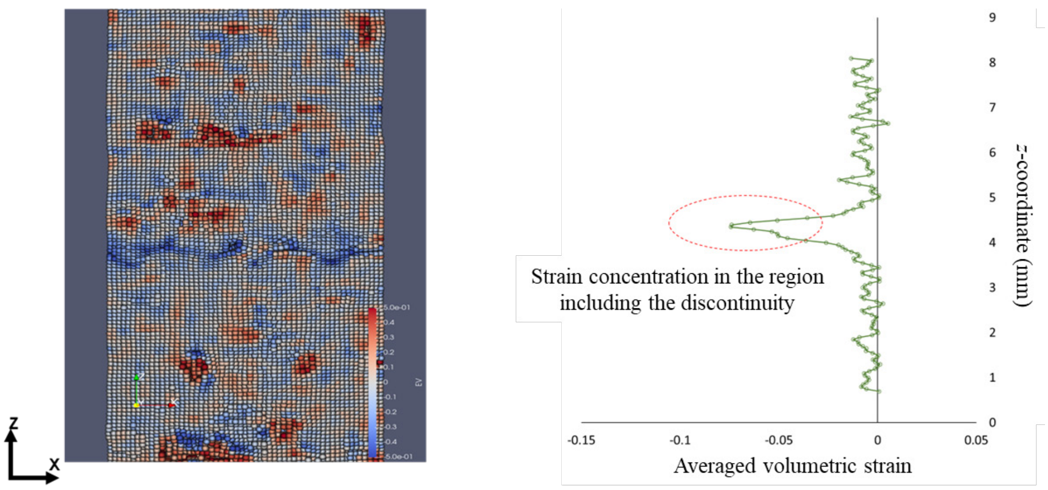
RESULTS AND DISCUSSIONS

Figure 3(a) shows an example of the DIC analysis result illustrating the distribution of volumetric strain at the load of 2000 N on the cross-section through the centre of the specimen in the *x*-*z* plane. In the figure, cool colours correspond to compressive strain, whilst warm colours indicate tension. It is found that compressive volumetric strain is qualitatively taking place at the discontinuity and within the surrounding region. The tensile strain locally taking place away from the discontinuity would be attributed to the deformation of pores in the model as well as DIC-related errors. Hence, in order to reduce the anomalies in local areas, the volumetric strain was averaged and the result is shown in Figure 3(b). As can be seen, the figure clearly shows the volumetric strain concentration occurring at the discontinuity, of which value ranges from 0.05 to 0.08. It is to be noted that the DIC result is the volumetric strain accumulated from 750 N to 2000 N in order to eliminate the rigid movement that could occur at the aperture of discontinuity at earlier stages.

Figure 4 shows the result of the numerical simulation, in terms of strain and stress, on a cross-section including the asperity contact. As shown in Figure 4(a), the maximum compressive volumetric strain occurring in the model is as much as 6.5×10^{-3} around the asperities contacting with each other, whilst the magnitude of volumetric strain in the matrix away from the discontinuity approximately ranges from 2.0×10^{-4} to 8.0×10^{-4}; a larger volumetric strain occurs in the matrix close to the contacting asperities, while the strain is small in the area near the model boundary on the left side away from the asperities. It is found from the strain distribution obtained from the numerical simulation that there is approximately 10 times difference in the volumetric strain between the asperity and the surrounding region in the numerical model.

It is interesting to note that although the strain magnitude obtained from DIC result is obviously larger than that in the numerical model, the asperity to matrix strain ratio obtained from the DIC result is consistent with that obtained from the numerical simulation. The reason why the numerical simulation shows the result at 1000 N is that the numerical simulation was not converged at 2000 N because of the intense non-linear behaviour observed in the lower substrate of the specimen when the load was increased to 2000 N. Nevertheless, the qualitative similarity between the DIC and numerical simulation results may imply that the numerical simulation can reproduce the microscopic strain distribution of the rock-like material on a micro scale to some extent. Note that the difference in the strain magnitude between the two results would be attributed to not only the load, but also the constitutive model applied to the numerical simulation. As described, the numerical simulation employs the perfect elasto-plastic model to simulate the non-linear behaviour of the asperity. However, in reality, the rock-like material made of non-shrink cement should exhibit failure in a brittle manner, causing larger deformations and strains. In addition to that, it is reasonable to assume that time-dependent behaviour is also taking place within the asperities. This further increases the magnitude of strain in the specimen, especially in the vicinity of the discontinuity asperities.

Figure 4(b) shows the stress distribution on the same cross-section as Figure 4(a). It is found that the stress acting in the asperity is significantly larger than that applied to the model top boundary, implying that the stress would cause non-linear behaviour of the asperities, even when the stress applied to the model boundary is much smaller than the strength of the material. This also corroborates the assumption about the difference in the strain magnitude between the DIC and numerical simulation results. Further study is needed to elucidate and identify the microscopic non-linear behaviour of asperities on the discontinuity surface.



(a) (b)

Figure 3. DIC results (2000 N): (a) Volumetric strain distribution on a cross-section, (b) averaged volumetric strain (compression is negative).

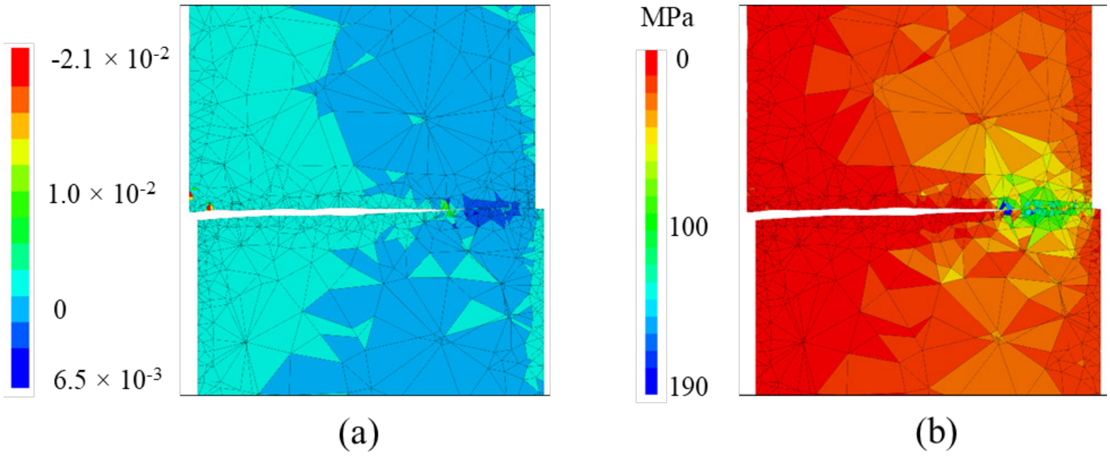


Figure 4. Numerical analysis result (1000 N): (a) volumetric strain distribution, (b) compressive stress distribution. Note that compression has a positive quantity.

CONCLUSIONS

The present study aims at elucidating the microscopic mechanical state of rock joint. To achieve the purpose, a uniaxial compressive test was conducted in the chamber of a micro-focused X-ray CT, using a rock-like specimen, made of non-shrink cement, including a through-going discontinuity. Based on a three-dimensional image derived from CT scanning, three-dimensional DIC analysis was conducted to quantify the displacement inside the specimen and compute volumetric strain increment. To verify the result of the DIC analysis, a numerical model was also constructed, in the framework of the discrete element method. The results indicated that the strain distribution and its magnitude obtained from the numerical simulation are qualitatively comparable to those derived from the DIC analysis in terms of the asperity to matrix strain ratio. However, in terms of the absolute value, the DIC analysis produces the maximum compressive volumetric strain much larger than the numerical simulation. This is deemed quite reasonable since the numerical simulation assumes perfect elasto-plastic behaviour, whilst the DIC analysis provides the result including time-dependent and/or brittle failure that could occur in the specimen during the experiment. A further study is required to characterize the non-linear behaviour of the asperities to gain insight into its effect on the time-dependent behaviour of rock joints.

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