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Full-field measurements of strain localisation in sandstone by neutron tomography and 3D-volumetric digital image correlation

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Abstract

Recent studies have demonstrated that the combination of x-ray tomography during triaxial tests ("in-situ" tests) and 3D-volumetric Digital Image Correlation (3D-DIC) can provide important insight into the mechanical behaviour and deformation processes of granular materials such as sand. The application of these tools to investigate the mechanisms of failure in rocks is also of obvious interest. However, the relevant applied confining pressures for triaxial testing on rocks are higher than those on sands and therefore stronger pressure containment vessels, *i.e.*, made of thick metal walls, are required. This makes *in-situ* x-ray imaging of rock deformation during triaxial tests a challenge. One possible solution to overcome this problem is to use neutrons, which should better penetrate the metal-walls of the pressure vessels. In this perspective, this work assesses the capability of neutron tomography with 3D-DIC to measure deformation fields in rock samples. Results from pre- and post-deformation neutron tomography of a Bentheim sandstone sample deformed *ex-situ* at 40 MPa show that clear images of the internal structure can be achieved and utilised for 3D-DIC analysis to reveal the details of the 3D strain field. From these results the character of the localised deformation in the study sample can thus be described. Furthermore, comparison with analyses based on equivalent x-ray tomography imaging of the same sample confirms the effectiveness of the method in relation to the more established x-ray based approach.

Keywords: Rocks; Tomography; Digital Image Correlation; Neutrons; X-rays

1. Introduction

In recent years considerable advances have been made in full-field measurements of deformation during triaxial tests on geomaterials, including sand and clay rocks, using *in-situ* testing in x-ray tomography facilities (*e.g.*, Viggiani et al., 2004; Lenoir et al., 2007). In these studies, digital image processing has allowed the heterogeneous evolution of strain and porosity, including localisation, to be quantified, *e.g.*, using Digital Image Correlation (DIC) as in Hall et al.

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(2010). The study the mechanical behaviour of rocks, which are the materials of interest in the present work, at the laboratory scale generally requires higher confining pressure than the ones used for soils. Despite some studies having involved testing at higher pressure than those normally used for sand (*e.g., Andò et al., 2013*), only a few publications have really considered triaxial testing for rocks in the pertinent pressure ranges (tens of MPa) (*e.g., Bauer et al., 2006*). The key limiting factor for the higher pressure triaxial testing with 3D imaging by xray tomography has been the poor penetration of x-rays through triaxial pressure cells capable of sustaining the elevated fluid pressures. Such a restriction is reduced if neutron imaging is used in place of x-ray imaging, as neutrons are more able to penetrate the thick metal walls of the confining vessels. There have been no publications, to the authors knowledge, of *in-situ* triaxial testing with neutron imaging, but some studies have been published involving neutron diffraction (*e.g. Covey-Crump et al., 2006*).

In-situ neutron imaging for mechanics (*e.g.*, rock, soil, or solid mechanics) has largely lagged behind its x-ray counterpart. This stems in part from the greater ease of access to x-ray sources both at synchrotrons and also in lab tomograph facilities. The other main contributing factor has been the long acquisition times of neutron imaging compared to synchrotron x-ray imaging. Spatial resolution has also often been a contributory factor in the slow take up of neutron imaging, but this has been largely overcome in recent years with significant advances now providing resolutions down to about 13 microns.

The aim of this work is to assess the possibility to use neutron tomography of rock samples for full-field strain mapping based on 3D-volumetric digital image correlation (3D-DIC). The effectiveness of the method is validated by comparison with 3D-DIC analysis carried out on x-ray tomographies. A Bentheim sandstone sample was scanned before and after triaxial compression test (*i.e., ex-situ*) using both neutrons and x-rays. This procedure has been successfully employed for a similar material using x-rays (*e.g.*, Charalampidou et al., 2011). The challenges in utilising neutron tomography are to assess if the image contrast in such material is sufficient to permits 3D-DIC analysis and if the image resolution is high enough to resolve the localisation of the deformation.

2. Experimental setup

To obtain the strain field within the tested sample, 3D-volumetric Digital Image Correlation (3D-DIC), presented in the following section, is performed on 3D images from x-ray and neutron tomography acquired before and after deformation experiments on the test specimen. Both measurements were carried out at the Helmholtz-Zentrum Berlin (HZB). Neutron images were acquired at the beam line CONRAD (Hilger et al., 2006) with a L/D of 500, a voxel size of about 30 μm and an acquisition time for each radiography of 30 seconds, which gives a total time of about 6 hours for a complete scan of 600 images. A picture of the acquisition system is shown in Figure 1(a). A scintillator transform the neutron beam, traversing the sample, in visible light that is then reflected and captured by a CCD camera. X-ray tomographies were acquired through a lab source with a voltage of 120 kV, a current of 83 μA and an acquisition time for each radiography of 1.3 s, which give a total time of about 2.5 hours for a complete scan of 1300 projections (each projection resulted from the mean of 5 repeated images). To compare the results of the 3D-DIC on the two kind of images, the voxel size of the x-ray tomography was chosen to be the same as for the neutron tomography.

A sample of Bentheim sandstone, with diameter of 50 mm and height of 100 mm (see Figure 1(b)), was used to assess the applicability of the method. The rock has an average porosity of about 23%, a mean diameter of the grains of 300 μm and a composition of 95% quartz, 3% kaolinite and 2% orthoclase (see Klein et al., 2001). Since the available field of view at CONRAD, for the desired resolution, is smaller than the height of the samples a notch was machined at the centre of the imaged region to encourage the onset of localised deformation to occur in that area, highlighted in Figure 1(b). The notch was also used, with the help of a laser, to place the sample at the same position when it was scanned after loading. An accurate set-up of the sample is very important when the two scans have to be used for the 3D-DIC. The sample was imaged, by both x-ray and neutron tomographies, before and after being subjected to triaxial deformation under a confining pressure of 40 MPa (a triaxial test in rock mechanics involves the application of a fluid pressure to the surface of a cylindrical sample and the consequent axial compression is applied; such tests are generally performed at a range of different pressures to simulate different sub-surface conditions). After unloading the sample, which was still in one piece, exhibited localised deformation that appears to have developed from the notch to the bottom (see Figure 1(b)); where the localised zone comes to the surface of the sample it can be seen as a fracture.
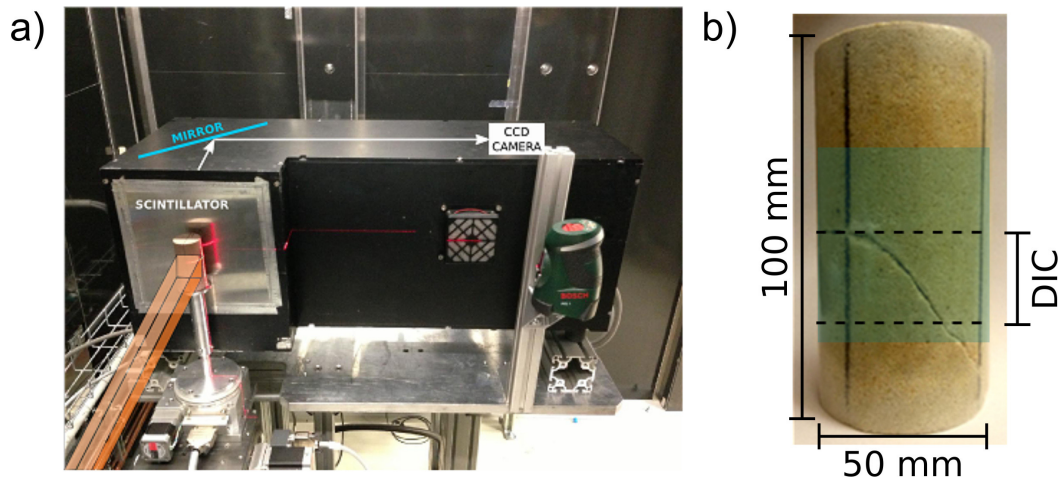
Fig. 1. Experimental setup at the beamline CONRAD at the Helmholtz-Zentrum Berlin (a) and picture of the tested sample (b)

3. 3D-volumetric DIC

In experimental mechanics strains are traditionally calculated from measurements of displacement made at the boundaries of a tested sample, which implies that a homogeneous behaviour of the material has to be assumed. DIC has proven to be a powerful tool that can provide full-field measurement of kinematics and strains at the surface of, or within, objects during their deformation. This is essential in experimental geomechanics since geomaterials are heterogeneous by nature. This method has been used increasingly over the last 20-30 years in a range of experimental mechanics applications (see for example, Sutton et al. (2009); Withers (2008)).

The principle of DIC is to assess the displacements fields, and thus strains fields (if required) by comparison of two images acquired at different stages of deformation. The first image is generally referred to as the reference image and the second, acquired after an increment of deformation, as the deformed image. These two images can be acquired by any kind techniques and can be 2D or 3D. Depending on the available data different types of DIC can be performed:

- 2D-DIC: generally applied to two photos of the surface of the sample; provides a field of two components of displacement vector; applicable to planar objects with in-plane deformation (i.e., plane-strain biaxial tests).
- 3D-surface DIC (stero-vision plus stereo-correlation): requires the acquisition of two photos for each stage and a special calibration of the two cameras; provides a field of three components of displacement vector on the surface; applicable to the evaluation of non-planar objects and out-of-plane deformations, but still restricted to surface analysis.
- 3D-volumetric DIC (also known as Digital Volume Correlation - DVC): requires two 3D images; provides a 3D field of three components of displacement vector; applicable to analysis of 3D deformation including internal deformation.

In general, the first step of the DIC method consists in defining a grid of analysis points over the reference image; then, a group of pixels surrounding each node of this grid, commonly called a subset, is determined. For each node, the most similar subset in the deformed image is identified based on some statistical measure of correlation (*e.g.,* the normalised correlation coefficient) and some mapping function between the subsets. This operation, which is generally performed only within a reduced area of the deformed image (the search window), provides the discrete displacement (integer number of pixels). A more realistic displacement can then be found by performing a sub-pixel refinement that can be achieved using a number of different procedures. In this work an in-house software "TomoWarp2"was used for the 3D-DIC. This python-based code, developed in cooperation between the University of Lund and the Laboratoire 3SR in Grenoble, is based on the earlier TomoWarp code (*e.g., Hall et al., 2009)* and uses

an interpolation of the correlation coefficient for the sub-voxel refinement of the displacement vectors. This method involves the interpolation of a set of correlation coefficients corresponding to integer displacements by a mathematical function. The maximum of this function gives the sub-pixel resolution displacement. These steps are summarised in Figure 2. For a more detailed description of the method see for example Hall (2012). It is common to complete DIC analysis with calculation of the strains, which is based on standard continuum mechanics approaches starting from the measured displacements.
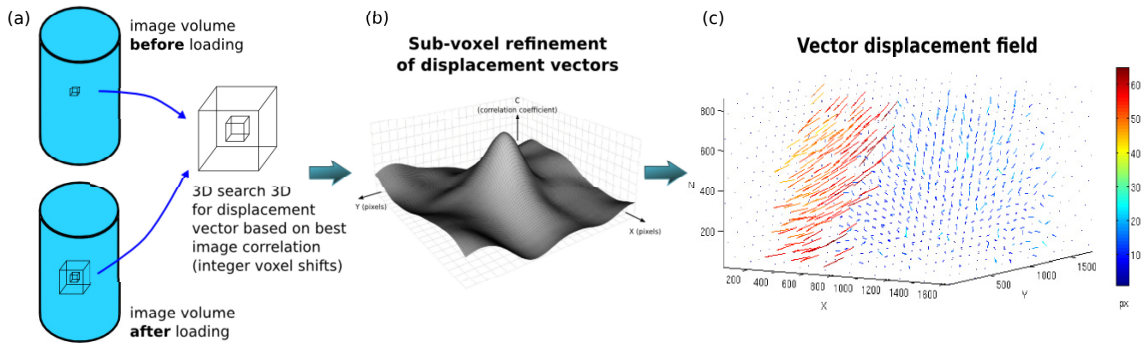

Fig. 2. Schematic of a 3D-volumetric DIC analysis approach: two subset of voxels are correlated, moving one of them inside a search window, to find the integer displacement (a); the subvoxel displacement is given by the maximum of a mathematical function interpolating a set of correlation coefficient (b); repeating this procedure in a grid of points gives the 3D displacement field (c)

The method requires images with sufficient texture that can be tracked uniquely from one image to the next. In the case of 2D- or 3D-surface DIC this texture can be artificially added (*e.g.,* painting the surface of the sample) while in the case of 3D images the texture must, in general, be inherent in the material. Therefore the first part of this work aimed to determine if neutron imaging of rock samples provided sufficient texture for DIC to be used.

4. Results

The procedure described above has been applied to two sets of two 3D images of a Bentheim sandstone sample, acquired before and after triaxial compression test, one set with neutron and the other with x-ray tomography. Figures 3 and 4 show a vertical and few horizontal reconstructed slices after deformation from the neutron and x-ray tomographies and the results of the 3D-DIC analysis in terms of maximum shear strain and volumetric strain. Both neutron and x-ray tomographies reveal that the fracture is not fully developed and that the localised deformation band presents a complex geometry. The comparison between the two slices shows the different sensitivity of neutron and x-rays to the internal structure of the rock sample. In particular, while x-ray absorption is mainly proportional to the density and thus highlights the porosity, neutrons are sensitive to the minerals and reveals inclusions (white spots in the image) that are not visible with x-rays. Nevertheless, the porosity and the formed fracture are visible in both images.

The neutron tomography images appear to contain a sufficient internal character to carry out a 3D-DIC analysis. This is confirmed by the results from the DIC on the neutron images shown in Figure 4. Furthermore, the DIC based on the neutron and x-ray appear to show very consistent results regarding the strain fields, both in terms of the geometry (see also Figure 5) and the magnitudes, which provides a cross-validation of the results, as the two datasets are independent. However, neutron images are slightly noisier than x-ray images which is reflected in the 3D-DIC results.

Both sets of DIC indicate that the deformation of the rock sample involved a concentration of strain into a narrow dilatant shear band between two blocks that slide past each other, but show little or no internal deformation. This deformation is consistent with the expected deformation for this rock at this confining pressure (see Klein et al., 2001). However, as these results represent the first full-field measurements of the internal deformation for this rock, new insight can be gained into the distribution of the deformation, such as the 3D geometry of the localised deformation
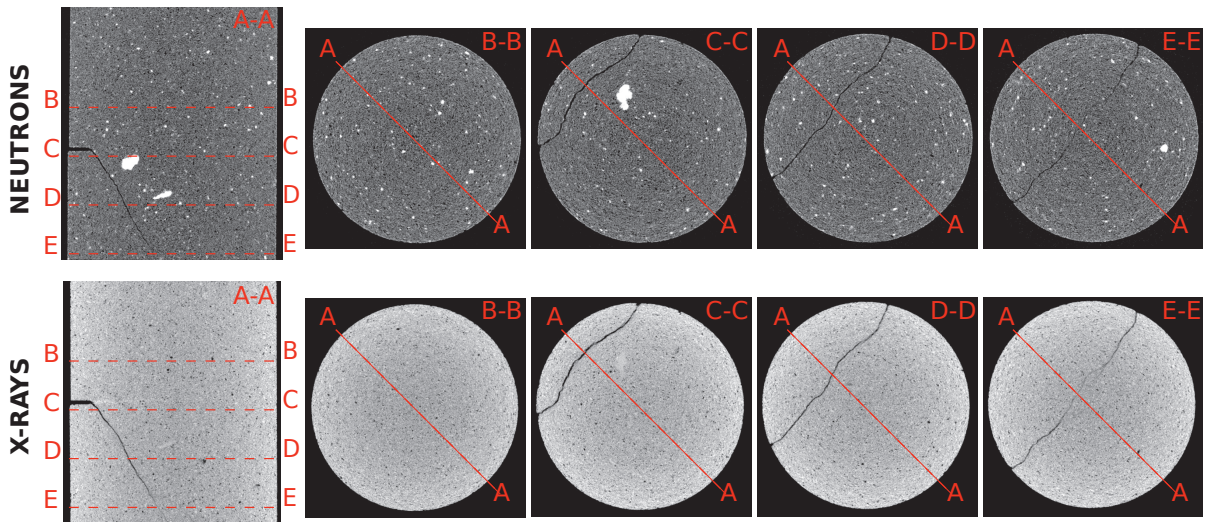
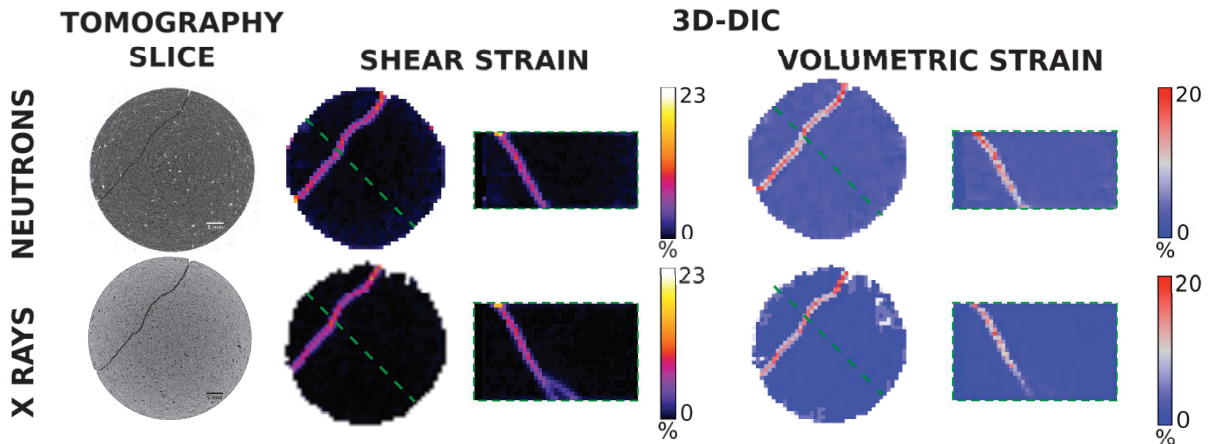Fig. 3. A vertical and four horizontal slices after deformation from the neutron and x-ray tomographies.

Fig. 4. Reconstructed horizontal slices after deformation from the neutron and x-ray tomographies and the results of the 3D-DIC analysis in terms of maximum shear strain and volumetric strain

(see for example Figure 5) and the heterogeneity of the strain inside the band; this will be further investigated in future work.

5. Conclusions and perspectives

Neutron and x-ray tomography of rock samples are complementary techniques that, due to different sensitivities to the constituent materials, give similar images, but contain different information. For example, in the current case, the neutron images allow a better imaging of an inclusion phase in this rock. Furthermore, repeated tomographic imaging, either before and after deformation or during deformation (*in-situ*), can be exploited through 3D-DIC analysis to find 3D deformation fields inside test specimens. This work has investigated the use of neutron tomography for 3D-DIC analysis of the internal deformation field of rock samples (in the example given the Bentheim sandstone). The first important result from this work is that the intrinsic character of the neutron tomography allowed to successfully carry

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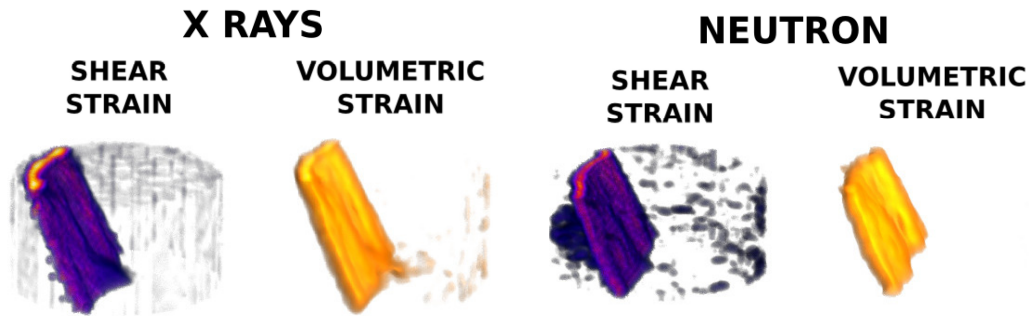# NEUTRON

SHEAR STRAIN ### VOLUMETRIC STRAIN

Fig. 5. Three dimensional view of the localised deformation band obtained by applying a threshold to the shear and volumetric strain fields.

out 3D-DIC analysis.. The results of such analysis have been validated by comparison with equivalent analysis using x-ray tomography images.

The limitations of the use of neutron instead of x-ray tomography to study the mechanical behaviour of rocks through 3D-DIC analysis are the lower resolution for the same voxel size, the lower signal to noise ratio, the lower available flux that implies a longer acquisition time and the reduced accessibility (laboratory sources for the x-ray vs. neutron facilities). However, the better performance of neutrons in presence of denser materials (*e.g.*, metals of confining cells) allows to reach high confining pressure during *in-situ* mechanical tests. After this proof of concept using pre- and post-deformation imaging, the next step is to perform in-situ triaxial testing within a neutron imaging set-up to follow the deformation during triaxial tests at elevated confining pressures.

Acknowledgements

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