MECHANICAL BEHAVIOUR AND RUPTURE IN CLAYEY ROCKS STUDIED BY X-RAY MICRO-TOMOGRAPHY AND 3D-DIGITAL IMAGE CORRELATION

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ABSTRACT. The mechanical behaviour and the rupture of clayey rocks have been experimentally studied by performing in situ triaxial tests on a synchrotron beamline i.e. performing X-ray micro tomography scans under mechanical loading. The 3D images obtained at different steps of the test were then analysed by 3D-Digital Image Correlation method in order to measure incremental strain fields. The results allow to clearly detect the onset of shear strain localization and to characterize its development in a 3D complex pattern.

1. Introduction

Within the framework of underground nuclear waste disposal, studying the Excavation Damaged Zone (EDZ) created upon the excavation of the host galleries is a crucial issue. The original low permeability of the host rock may be modified in the EDZ by the development of strain localisation. The objective of this PhD work funded by ANDRA (Agence Nationale pour la gestion des Déchets RAdioactifs, French Agency for nuclear waste disposal), was to evaluate the excavation-induced deformation in the rock around a gallery, specifically to investigate strain localisation in clayey rocks using X-ray micro-tomography and 3D-Digital Image Correlation (3D-DIC).

Direct three dimensional (3D) observation of the internal structure of a specimen while it deforms under applied load can provide substantial advances in the understanding of shear banding in geomaterials. In this respect, the recent, rapid development of non destructive 3D imaging techniques such as X-ray tomography offers new experimental possibilities. To perform in-situ tomography, i.e., to load the specimen and to scan it in the same setting and at the same time, it's essential for clayey rocks, to have a "high" resolution due to their fine micro structure, and a also a short scanning time because of the susceptibility of clayey rocks to creep, which makes it difficult to have a stable specimen configuration if the radiation period is too long. The only X-ray source which allows of combining both requirements is the synchrotron due to the very high brilliance of the radiation provided. In this PhD work, a number of original triaxial devices have been realized to characterize damage of clayey rocks, under deviatoric loading, with X-ray micro tomography and a few campaigns of experiments have been performed on a synchrotron beamline at the European Synchrotron Radiation Facility (France), first on a stiff clay soil, the Beaucaire marl and then on a shale, the Callovo-Oxfordian argilite. This paper presents some selected results obtained on the shale.

Another difficulty with experimentally detecting strain localization is associated to the very nature of localized strain. In fact, while localization can sometimes induce large volumetric deformation – either dilatancy (or crack opening) or compaction (compaction bands), depending on the material and loading conditions – in general volumetric strain in a shear band is small compared to the shear strain. Unfortunately, X-ray CT is based on transmission measurement; hence it is sensible to density variations only. Therefore, in the absence of measurable volumetric strain in the region of localized deformation, X-ray CT may fail to detect the phenomenon, especially in its early stage. It has been demonstrated in this study that such a limitation can be overcome by complimenting X-ray CT with digital image correlation (DIC). Through the comparison of couples of reconstructed 3D images of a specimen at two successive steps of loading, this allows to measure an incremental displacement field, from which a strain tensor field can be obtained.

2. Experimental set-up

A number of original triaxial devices have been realized to characterize damage of clayey rocks, under deviatoric loading, with X-ray micro tomography on a synchrotron beamline. The apparatuses include a small triaxial cell and a loading device designed specifically for this study. The triaxial apparatuses are practically the same as a conventional triaxial testing systems, except for their much smaller size and the shape of the confining cell (10 MPa capacity), which has been built in polycarbonate to be as transparent as possible to the X-rays. The axial load and hence the deviator stress is applied in a displacement-controlled manner using a motor-driven screw actuator and the device can be placed in the X-ray beamline without interfering with the tomographic scans. The system has a maximum loading capacity of 7.5 kN, and allows to move the ram at a constant rate in the range of 1 to 100 µm/min. It is worth noting that while in a conventional triaxial system the tensile reaction force is carried by a loading frame, in this case it is carried by the cell walls, which therefore are subjected to traction in the axial direction. This allows a clear path, free of any obstacle (apart from the cell walls), for the X-ray beam within the region to be scanned. Note that theses devices which allow of combining high capacity mechanical test and micro tomography on a synchrotron beamline, are unique and one has been used to study a new material (a metallic glass foam) in collaboration with Caltech (California, USA) [Demetriou et al., 2007]. The specimens are cylinders with height twice the diameter (respectively 20 mm and 10 mm). They have been prepared by cutting from cores provided by ANDRA from their underground research laboratory (500m depth) site at Bure (France) by means of a diamond wire saw, which minimizes material disturbance during preparation. The experiments were carried out at the high energy beamline ID15A at the ESRF in Grenoble. This beamline has been recently equipped with a fast three-dimensional X-ray micro tomography system [Di Michiel et al., 2005]. The X-ray energy used for this study ranged from 50 to 70 keV and the acquisition of an entire specimen of height 20 mm took no more than 15 minutes, with a spatial resolution i.e. a voxel size, of 14x14x14 μm^3.

3. Selected result

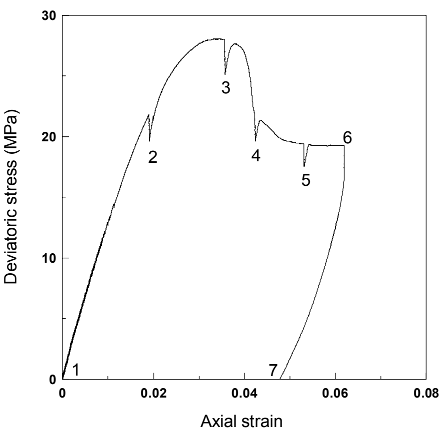

Figure 1.

A preliminary set of tests under drained and undrained conditions has been performed on the Beaucaire marl [Viggiani et al., 2004], and under undrained conditions i.e., no drainage of the pore fluid into, or out of, the specimen was allowed, on the Callovo-Oxfordian argillite [Bésuelle et al., 2006]. Different regimes of behavior were obtained for both material from brittle to ductile. Results from only one test named ESTSYN01 is presented herein. The confining pressure (total mean stress) was equal to 10 MPa. Deviatoric loading was performed under displacement control, by advancing the loading ram at a rate of 3.0 µm/min, which corresponds to a nominal axial strain rate of $2.5.10^{-6}\ s^{-1}$ for a 20 mm specimen height. Deviator stress q is plotted as a function of axial strain ε_a in Fig. 1. The specimen was scanned at different steps: before and right after applying the confining pressure (steps 0 and 1, respectively), and then at different levels of axial strain during deviatoric loading (steps 2-7). One last scan of the specimen was performed at the end of the test, after removal of the confining pressure (step 8). It is worth to note that the ram displacement was stopped at those points of the test when a tomographic scan of the specimen was required. The specimen was scanned while the axial strain was held constant, which unavoidably caused some amount of axial load relaxation during scanning. However, the scanning operations were fast enough for this relaxation to be relatively small. The numbers noted on each curve are the scanning step numbers. A single shear band formed in the specimen during the test, which could be clearly observed by the eye at the end of the test. We focus now on the X-ray CT scans of specimen ESTSYN01 during loading. Fig. 2 shows the reconstruction of a tomographic slice perpendicular to the specimen's axis for each scanning step. Note that the elevation of a given slice decreases from one scan to the next, to take into account the specimen shortening during loading. Strain localization becomes visible at step 4 as a very narrow band in the upper left part of the slice. The band of localized deformation appears as a darker zone (2-3 pixels, i.e., 30-40 mm thick), which means that the material is dilating inside the band (darker indicates lower mass density). In the subsequent scanning steps, the band becomes increasingly visible in term of both length and thickness (about 60 mm at step 7), essentially in the outer region of the slice. A material shift can be observed at the intersection of the band with the external surface of the specimen. The size of such shift increases with specimen shortening, which is due to the relative sliding on the band. When the confining pressure is removed (step 8), the band of localization opens up in the outer region of the specimen and it looks like an open crack. However, no trace of localization is visible in the central region of the slice.

Direct observation of X-ray micro tomography images allows for immediately detecting volumetric strain, since dilation (contraction) corresponds to a change of mass density, which in turn results in a decrease (increase) of X-ray attenuation. However, as far as shear (deviatoric) strain is concerned, this does not necessarily induce any volume change and therefore it cannot be directly detected by measuring changes in X-ray attenuation. In this study, we have developed a general method for obtaining the distribution of both the volumetric and deviatoric components of strain increment between two reconstructions of a specimen at two different steps of deformation. Tomography images were subsequently analyzed using a Volumetric Digital Image Correlation software developed at the LMS in Palaiseau, France [Lenoir et al., 2007]. Digital Image Correlation (DIC, hereafter) is a mathematical method which essentially consist in recognizing the same material point on a pair of digital images of an object. A material point is assumed to be fully identified by its local pattern (e.g., the gray level distribution around the point in a black and white image). Such a local pattern is assumed to be unique for a given point, i.e., it cannot be found elsewhere on the image. By optimizing an appropriate correlation function, DIC allows for determining for each point/pattern on the first image, the most likely location of such a point/pattern on the second image. Note that from one image to the other, a pattern is in general subject to translation, rotation and distortion. By repeating this procedure for a number of points, a full displacement and deformation field can be obtained for the pair of images. Note that due to the small deformation experienced by the argillite specimens, for this study the transformation between two images was assumed to be a rigid translation, without any rotation and distortion. While such an approximation substantially reduced the computing time, it still provided a fair resolution.

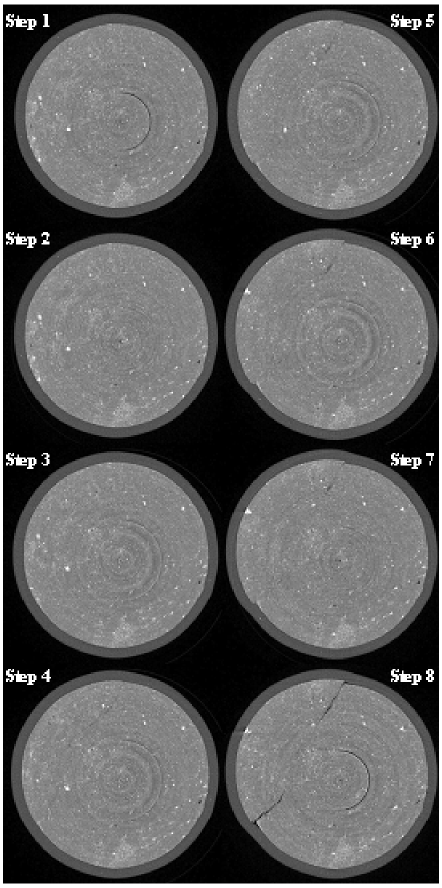

Figure 2.

Hereafter, a few results are presented where DIC was applied to the 3D tomographic images from test ESTSYN01. Only the two increments between steps 2 and 3 and between steps 3 and 4 are discussed herein (see Fig. 1). Hereafter, these two increments will be referred to as the pre-peak and the post-peak increment, respectively. Figures 3 and 4 show the (incremental) strain field as obtained by DIC. More precisely, these fields represent the second invariant of the strain tensor, in the sense of von Mises, which is a measure of shear strain. To better appreciate the computed 3D fields, these are also shown by a few horizontal and vertical cuts (see respectively left and right images on Figure 3). The maximum strain plotted in these figures equals 0.15, which means that the red color indicates shear strain values equal to, or greater than 0.15.Strain localization is distinctly visible already in the pre-peak increment (at left in Fig. 3), close to the bottom edge of the specimen. Such a shear zone appears as a narrow, straight band in the vertical cuts. The shape of the shear zone is circular in the horizontal bottom cut, which suggests that the overall shape of the zone of localized deformation is influenced to some extent by the boundary conditions. In the post-peak increment (at right in Fig. 3), the shear band has entirely propagated through the specimen. As compared to the pre-peak increment, the zone of localized deformation appears straight (planar) both in the vertical and in the horizontal cuts. A second shear band can also be observed, which is characterized by lower values of the (incremental) shear strain. A closer scrutiny of the 3D tomographic images revealed that very close to the intersection of these two bands, in the external part of the specimen, a large inclusion of calcite and pyrite existed in the argillite. This inclusion is in fact also revealed by the green volume (a few subsets in size) which appeared on the “post-peak” 3D strain fields (see top left image). Such an inclusion was most likely stiffer than the matrix, which induced a shear strain concentration. Therefore, it can be concluded that in test ESTSYN01, the pattern of localization was influenced by both the boundary conditions (at the specimen bottom) and natural inclusions in the specimen. Fields of the first invariant of the strain tensor (i.e., the volumetric strain) were also computed for test ESTSYN01, which are not reported herein. These fields indicate that volume changes localized only in the post-peak increment. Just like the simple observation of CT images (without any DIC analysis), the inspection of volumetric strain fields allows to detect shear banding only at a later stage of the test, when dilatancy and/or crack opening induced measurable mass density variations. Volumetric Digital Image Correlation revealed patterns which could not be directly observed from the original tomographic images, because the deformation process in the zones of localized deformation was essentially isochoric (i.e., without volumetric strain), hence not associated to density changes.

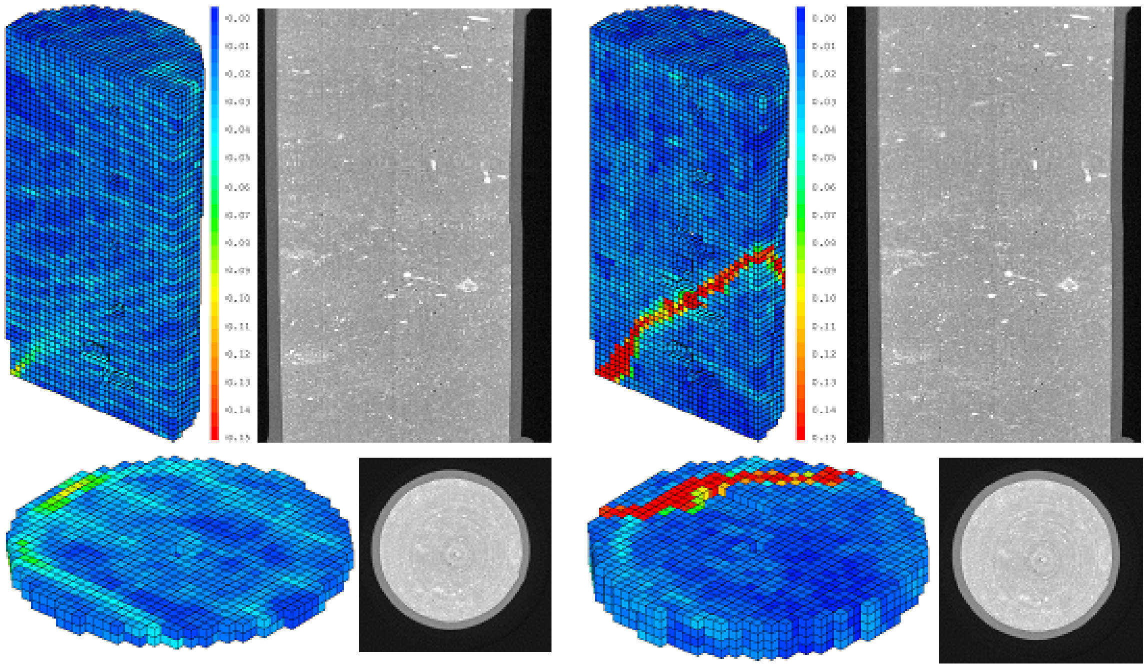

Figure 3. Shear strain incremental fields. "Pre-peak" at left, "post-peak" at right.Conclusions

In order to investigate strain localisation in clayey rocks, a set of original experimental devices has been developed for performing triaxial test on a synchrotron beamline, which allows for X-ray micro tomography observation of the specimen under deviatoric loading. Different regimes of behavior were obtained from brittle to ductile.

X-ray tomography essentially measures material density distribution. During a test, changes of X-ray attenuation are therefore due to volumetric deformation. If the material in a zone of localized deformation is essentially strained in shear, without significant volumetric strain, then the phenomenon can be hard to detect. However, it has been shown in this study that X-ray 3D imaging can be effectively complimented with 3D digital image correlation, which allows to measure a 3D displacement field in a specimen. Full-field incremental strain measurements were obtained from the displacement field, which allow to detect the onset of shear strain localization and to characterize its development in a 3D complex pattern. In the author's opinion, the application of Volumetric Digital Image Correlation to images obtained through X-ray tomography will certainly become a major tool for material science and experimental mechanics in the near future.

According to the results obtained on both materials, a common scenario is proposed. The localized deformation initiates just before the peak of the deviatoric stress with a concentration of intense shear strain in a narrow zone of the specimen. Then, the localized zone develops to be complete at the deviatoric stress peak. Finally, with the increase of the axial strain, some zones of open crack are created and develop (in length and width) along zones previously dilating.

4. References

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