Neutron imaging of deformation and fluid flow in sandstones

E. Tudisco[1a], S.A. Hall[1,2], E. Charalampidou[3], H. Sone[4], N. Kardjilov[5] and J. Hovind[6]

[1]Division of Solid Mechanics, Lund University, Lund, Sweden, [2]European Spallation Source AB, Lund, Sweden, [3]Institute of Petroleum Engineering School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, Scotland, UK, [4]GFZ German Research Centre for Geosciences, Potsdam, Germany, [5]HZB, Berlin, Germany, [6]PSI, Villigen, Switzerland

[a] erika.tudisco@solid.lth.se

Abstract. Understanding the mechanisms of deformation and failure in rocks and their implications for fluid flow and storage are key to a number of important industrial/environmental applications, including geologic CO_2 sequestration and hydrocarbon production into/from subsurface rocks. This work aims at developing appropriate tools for full-field investigations of deformation and fluid-flow in rocks under pressure.

Introduction

The traditional approach to study the mechanical behaviour of rocks is to measure forces and displacement at the boundaries of a sample while loaded under triaxial conditions. This implies the assumption of homogeneous deformation when stress and strain are derived. However, this assumption is very rarely valid, as failure in rocks generally occurs through some localised phenomena such as strain localisation or fracture creation. Therefore full-field measurement techniques, which allow the identification of the localised deformation, have been developed in recent years. In particular x-ray and neutron tomography are ideal for this purpose, as they permit visualisation of the interior of bulk specimens and can be coupled with 3D-volumetric Digital Image Correlation (3D-DIC) analysis to retrieve the full strain tensor field. In the same way, traditional tests to measure fluid flow properties, involving monitoring flow rates or fluid pressures at the ends of the test specimen, do not give any information on the pre-existing or induced heterogeneities inside the sample. The focus of this current work is the use of neutron radiography and tomography to characterise both deformation and fluid flow in laboratory-deformed specimens of rocks.

The advantage of using neutron imaging in this contest is two-fold. The first reason is the higher penetration of neutrons in dense materials, such as the metals used in the thick walls of triaxial pressure cells for rock testing, than that of x-rays. This enables *in-situ* (*i.e.*, during loading) 3D imaging of rocks samples deforming at high confining pressures. Secondly neutrons are strongly sensitive to hydrogen allowing the measurement of water distributions and movements in bulk rock samples [1][2].

The experiments described below are part of a larger project that aims to combine in-situ loading of sandstone samples under confining pressure with imaging at different load levels to derive the strain field evolution and also to track the movement of injected fluids as the deformation evolves. The primary purpose of this current work is to prove the concepts using *ex-situ* neutron tomographies (*i.e.*, pre and post deformation) to provide the strain field and neutron radiography to image the fluid flow through the deformed sample. Therefore, two experiments were performed on a Bentheim sandstone sample.

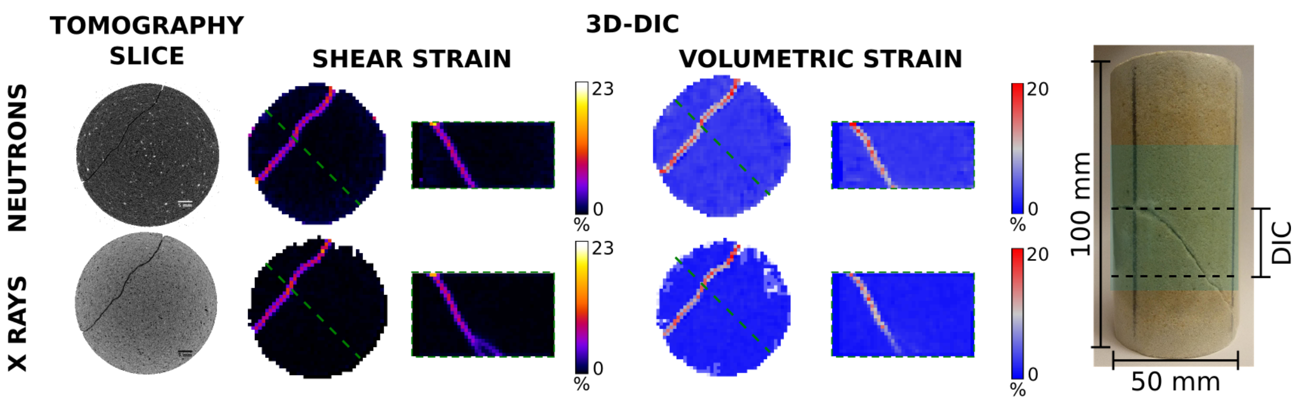

Figure 1 Reconstructed horizontal slices after deformation from the neutron and x-ray tomographies, the results of the 3D-DIC analysis in terms of maximum shear strain and volumetric strain, and a picture of the sample after deformation.

The first experiment had the objective of testing if neutron tomography can be utilised for full-field strain mapping based on 3D-DIC. Such analysis has been previously demonstrated with x-rays [3]. The sample was imaged using both x-ray and neutron tomographies before and after triaxial testing (triaxial tests were run at GFZ-Potsdam and Laboratoire 3SR, Grenoble). The imaging was performed at the neutron tomography beamline (CONRAD) at the Hemholtz Zentrum Berlin. An example of reconstructed slices and of the results of the 3D-DIC analysis in terms of maximum shear and volumetric strain are presented in Fig. 1. Neutron tomography provides a different set of information to the equivalent x-ray images; whilst the overall structural information is basically the same, the neutron images reveal previously unnoticed features likely relating to more hydrogen rich materials (probably clays). Moreover, the strain measurements based on the neutron and x-ray appear to be very consistent, both in terms of the geometry and the magnitudes, which provides a cross-validation of the results, as the two datasets are independent.

The second experiment investigated the use of neutron imaging to follow fluid flow in the deformed sample. This is achieved tracking the fluid front during pressure driven fluid flow through a dry sample followed by an alternating injection of H_2O and D_2O (heavy water). This test can provide insight into the water permeability of the sample as the H_2O and D_2O flow properties are quite similar. As shown in Fig. 2 the contrast at the air/H_2O and H_2O/D_2O interfaces is strong enough to allow the identification of the fluid front. This experiment was carried out on the NEUTRA beamline at the Paul Scherrer Institute in Villigen, Swtzerland.

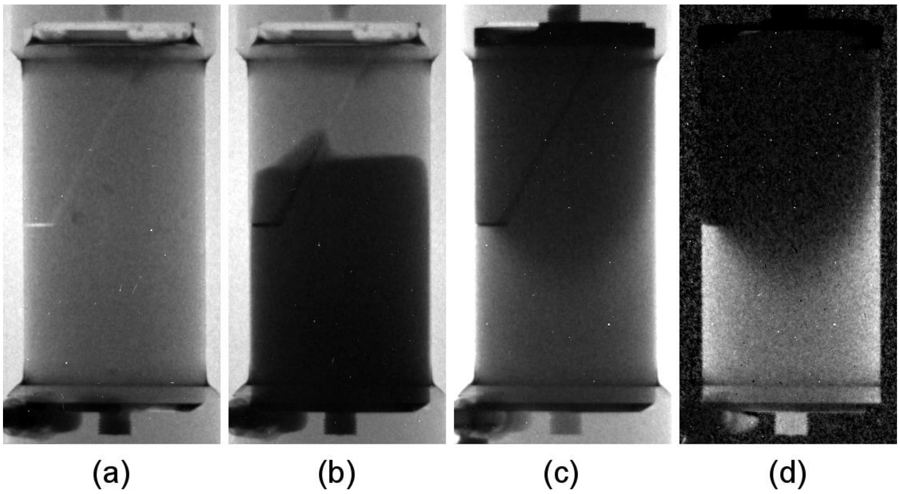

Figure 2 Neutron radiographies of: (a) a dry sample; (b) an H_2O/air flow stage; (c) a D_2O/H_2O flow stage (H_2O is dark, i.e., high attenuation) and (d) difference between (c) and a radiography taken before D_2O entrace to enhance the ontrast between fluid phases (black indicates zero saturation change and white replacement of H_2O by D_2O).

Conclusion

Neutron images have been proven to have the capacity to permit 3D-DIC analysis. The results of this analysis were in good agreement with the analogue analysis performed on x-ray images both qualitatively and quantitatively. Therefore, neutron tomography can be used in much the same way as x-ray tomography for the investigation of the deformation during loading. Neutron radiography allows the tracking of the fluid front during pressure controlled flow. In particular H_2O/D_2O alternating sample floods can provide information on the local permeability of the sample due to the similar flow properties of the two phases.

References

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