# 4D observation of the formation of rock fractures during rotary shear

*Qi Zhao[1], Nicola Tisato[1,2], Giovanni Grasselli[1]*

*[1]Department of Civil Engineering, University of Toronto*

*[2]Jackson School of Geosciences, University of Texas at Austin*

## Summary

Understanding how grain and powder lubrication affect rock friction and fracture dilation, and how microscopic fractures develop according to fault activation may directly improve our capabilities in exploration and stimulation of oil and gas reservoirs. Using a novel rotary shear testing apparatus specifically designed and assembled to conduct experiments inside an X-ray micro computed tomography machine (μCT) we are able to "see" how rock friction and fracturing process develop during the shearing process, without perturbing the system. Shearing the sample at incremental small steps and recording the variation of normal force and friction during those steps, we are able to shed light on the fracturing and frictional sliding processes.

## Introduction

Conventional techniques measure the physical and mechanical properties of a bulk volume, and assume they are representative properties of the rock. However, many rock properties are intimately related to microscopic features, such as microscopic roughness, grain orientation, pore distribution and fluid saturation. Therefore, in order to improve the understanding of the rock behaviour, one needs to inspect microscopic features in the rock volume.

As part of the Experiential Rock Deformation under μCT project two new high-pressure X-ray transparent vessels were designed, assembled, calibrated and used within the μCT system (Phoenix|X-ray v|tome|x) available at the University of Toronto. The first vessel, ERDμ-Q, is a sub-resonance vessel that allows the measurement of dynamic elastic moduli and seismic wave attenuation in the rock, and simultaneously, link them to saturation variations, or precipitation-dissolution of minerals (Tisato et al., 2014). The second vessel, ERDμ-T, measures friction in the rock, and concurrently link it to the evolution of the frictional surface. In this abstract, we focus on the ERDμ-T apparatus and present a set of experiment results demonstrating 4D observation of the development of fractures.

## Theory and/or Method

### 1. X-ray tomography

X-ray is a form of electromagnetic radiation having wavelength between 0.01 to 10 nm. It can penetrate solid object and undergoes attenuation during such a process. Attenuation can be considered, in first approximation, directly related to the density of the crossed material. Therefore, for instance, the interior of a rock specimen can be "observed" by measuring the incident and transmitted X-ray intensity, by means of the computed tomography (CT) (Vervoort et al., 2004). μCT technology allows discretizing the internal structure of an object with micro-metric resolution, it was initiated in the early 1980s and was quickly adopted by scientists across several fields such as geology, electronics and composite materials (Ritman, 2004). μCT offers a non-destructive method that allows visualization of the entire sample interior, revealing features that are hardly accessible by conventional approaches (Jackson et al., 2008). Since the internal structure of geomaterials is defined by variations in density (i.e. gas, fluid, and solids) and chemical composition (i.e., mineral components), X-ray µCT is particularly well suited to image geomaterials (Ketcham & Carlson, 2001).

**2. Mechanical testing**

To date, it was only possible to study the fracturing process by perturbing the rock sample (i.e. moving it from the testing machine to the CT scan), which introduces uncertainties on the final state of the deformed sample (Tatone & Grasselli, 2015). With our technology, the inspection of the experiment results can be carried out without opening or moving the specimen or disturbing the experiment conditions (e.g. pressure and temperature).

ERDµ-T apparatus performs rotary shear tests inside the X-ray µCT machine (Figure 1a). This setup allows performing rotary shear tests on 12 mm diameter cylindrical samples and image the evolution of the shearing surfaces without introducing any disturbance. In order to reconstruct the 4D evolution of the slipping surfaces and the gauge layer, rotary shear tests are conducted at sub-seismic slip rates (e.g. from 0.8 to 48 mm/s) and for many incremental short sliding steps (e.g. 6 degrees per step). While rotating the specimen, normal stress and torque are acquired by an analog to digital converter with a sampling rate of 2 kHz. The ERDµ-T apparatus also allows the samples to be confined up to 10 MPa and saturated with liquids.

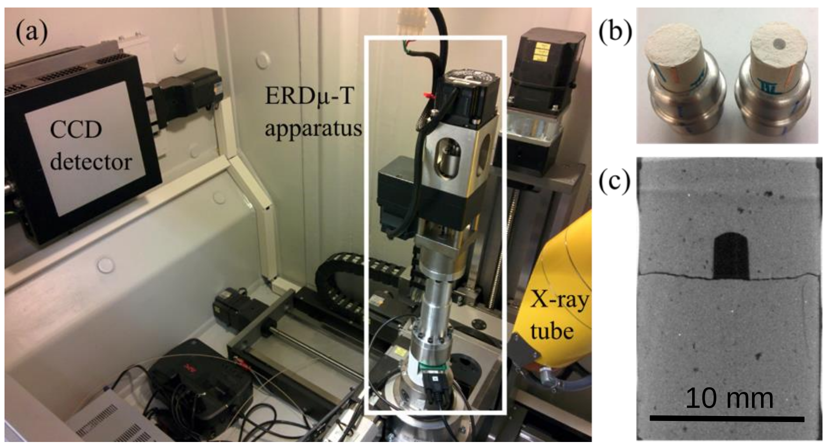


**Figure 1.** (a) ERDµ-T apparatus inside the µCT machine, positioned at its measurement location. (b) A sample set (top and bottom) prepared for the rotary shear test, sitting on the sample holders. (c) A vertical slice of the X-ray image of the initial condition of the shearing surface.

## Examples

A synthetic rock material, Flowstone, is utilized in our experiment. Flowstone is mechanically similar to a natural limestone and is a satisfactory material for the creation of joint replicas for the purpose of studying shear-induced asperity degradation (Tatone, 2014). The sample set for rotary sear test consists of top and bottom parts (Figure 1b) characterized by matching rough surfaces created by a four point bending of an intact Flowstone cylinder (32mm x 12mm) (Figure 1b & c).

With the ERDµ-T, it is possible to observe, in time and space, the evolution of the rough surfaces during rotary shear. In this contribution we report the results of a test where 280 N normal force was applied to the sample while the top part was rotated at 6 degrees incremental steps, and the entire sample was x-ray imaged after each step. No confinement was applied.

We were able to extract from the µCT imagery the rock features (e.g. pores and fractures) after each rotation step. We utilize an open source software, MeVisLab (Ritter, 2011), to segment the µCT images and visualize the rock volume. A region grow method is applied for the segmentation, and the segmented rock features are visualized by their surfaces (Figure 2). It is demonstrated by segmented results that (1) at the initial condition, the top and the bottom samples were not in conforming contact due to their slight misalignment between each other (Figure 2b); (2) during the first 6 degrees of rotation, the actual contact area increased, and since the sample was not confined, a vertical fracture appeared (Figure 2c & e); (3) During the second step of 6 degrees of rotation, the first vertical fracture propagated which splits the sample; meanwhile, a second fracture developed (Figure 2d & f).

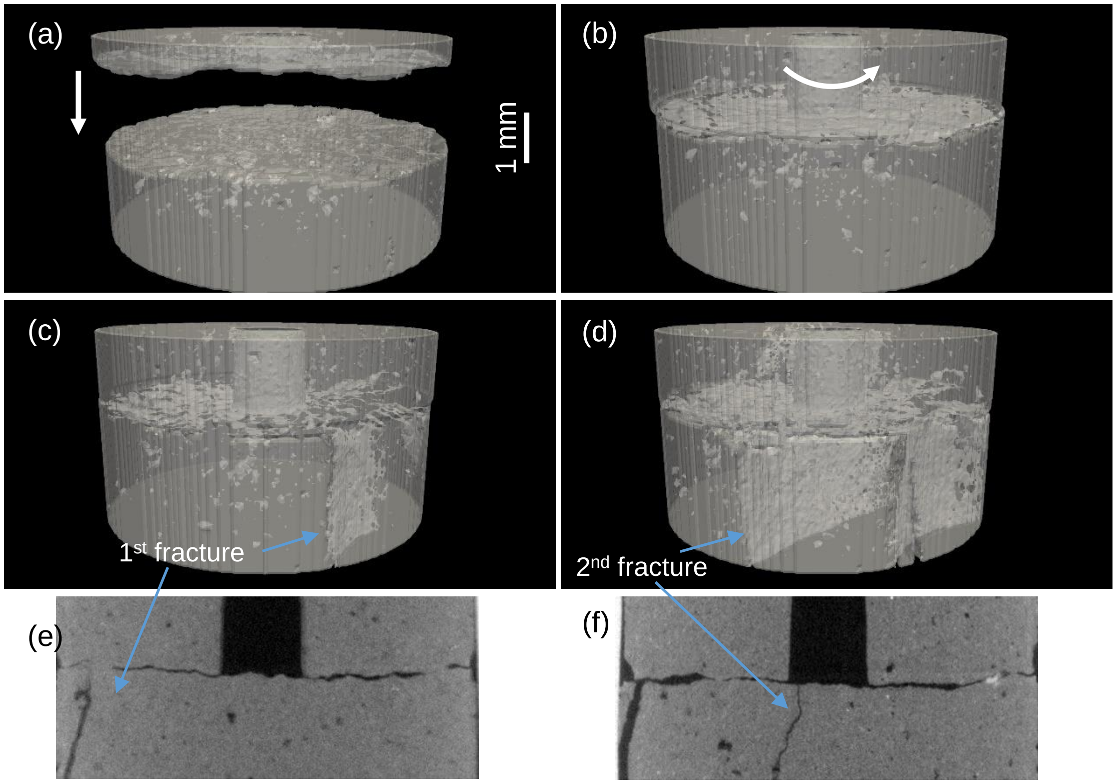


**Figure 2.** Visualization of the reconstructed 3D model of the fractured Flowstone (middle part) at different stages of the experiment. (a) Before the experiment, the top and bottom parts are ~1mm apart from each other, and the top part is moved towards the bottom part to apply normal stress. (b) The initial condition of the rotary shear test, 280 N normal force (~5 MPa) is applied to the sample. (c) Result after the 6 degrees rotation. (d) Result after the 12 degrees rotation. (e) A vertical slice of the µCT image corresponding to (c). (f) A vertical slice of the µCT image corresponding to (d).

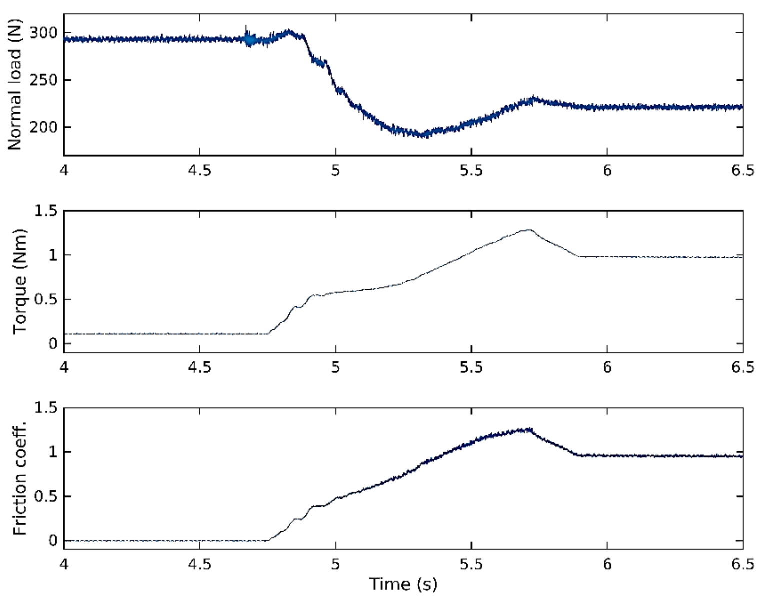


**Figure 3.** Physical parameters recorded during the first 6 degrees of rotation.

During each step of rotation, the normal load and the torque applied to the sliding interface were recorded, and the friction coefficient was calculated (Figure 3). The comparison between mechanical data (i.e. normal load and friction) and CT imagery shows that during the first 6 degree of rotation, the rough interfaces reached a more conforming contact than the initial condition, which resulted in the slight drop in normal load and the increase of actual contact area. On the other hand, the friction coefficient increased to 1.2 because of asperity interlocking. The sudden drop of friction at 5.7 s corresponds with the formation of the first fracture. This explanation was achieved thanks to the observation of the internal structure of the sample, leading to a more comprehensive understanding of the interaction between sliding interfaces and the development of secondary fractures.

## Conclusions

The observation and analysis of experiments on rocks utilizing μCT opens up tantalizing opportunities in exploring the microscopic features encapsulated in the rock material. We demonstrated that we are able to observe the formation and evolution of fractures continuously in time and space. In the coming years, the ERDμ-T will be employed to link the evolution of the physical parameters to the observed changes in the internal structure of the investigated rock sample, which will allow us to understand more fundamental details of the complex frictional behaviour of rock joints and faults.

## Acknowledgements

This work has been supported by the Natural Sciences and Engineering Research Council of Canada through Discovery Grants 341275 (G. Grasselli).

### References

Jackson, M. E., Beuschel, C. A., McAteer, J. A. & Williams, J. C. 2008. *Morphology of major stone types, as shown by micro computed tomography (micro CT).* Paper presented at the RENAL STONE DISEASE 2: 2nd International Urolithiasis Research Symposium.

Ketcham, R. A. & Carlson, W. D., 2001. Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences. *Computers & Geosciences, 27*(4), 381-400.

Ritman, E. L., 2004. Micro-computed tomography-current status and developments. *Annu. Rev. Biomed. Eng., 6*, 185-208.

Ritter, F. a. B., Tobias and Homeyer, Andre and Laue, Hendrik and Schwier, Michael and Link, Florian and Heinz-Otto Peitgen. 2011. Medical Image Analysis: A visual approach. *IEEE Pulse, 2*(6), 60-70.

Tatone, B. A. 2014. *Investigating the evolution of rock discontinuity asperity degradation and void space morphology under direct shear.* (Ph.D.), University of Toronto.

Tatone, B. A. & Grasselli, G., 2015. Characterization of the effect of normal load on the discontinuity morphology in direct shear specimens using X-ray micro-CT. *Acta Geotechnica, 10*(1), 31-54.

Tisato, N., Quintal, B., Chapman, S., Madonna, C., Subramaniyan, S., Frehner, M., et al., 2014. Seismic attenuation in partially saturated rocks: Recent advances and future directions. *The Leading Edge, 33*(6), 640-646.

Vervoort, A., Wevers, M., Swennen, R., Roels, S., Van Geet, M. & Sellers, E., 2004. Recent advances of X-ray CT and its applications for rock material. *X-ray CT for Geomaterials*, 79-91.