Experimental program on mechanical properties of large rock fractures

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Abstract. Predictions of fracture displacements are required to support the safety assessments of a deep geological repository for nuclear spent fuel. Laboratory and in-situ experiments are used to estimate these properties. Despite significant contributions in the last decades, there is a knowledge gap in terms of the impact of high normal stresses on the mechanical properties of large-scale fractures under Constant Normal Stiffness (CNS) boundary conditions. Within the framework of the POST project, a cooperative effort was made by SKB (Sweden), NWMO (Canada), and Posiva from Finland (in phase 1) to study these questions. In the second phase of the POST project, a first of a kind direct shear testing machine was manufactured and calibrated that can accommodate samples up to 400×600 mm under normal stresses up to 10 MPa, for both CNS and Constant Normal Load (CNL) conditions, with the ability to shear the sample up to 50 mm. Several best practice procedures were developed for fracture characterization pre-, syn-, and post-shear test which utilize high resolution optical scanning, contact pressure measurements, Digital Image Correlation (DIC) measurements, and acoustic emission measurements during the shear test. Natural and tensile-induced fractures of a granitic rock as well as replicas of the hard rock fractures, at three different fracture sizes of 35×60 mm, 70×100 mm, and 300×500 mm, are now being tested. It is hoped that this program will provide a set of high-quality data which will help reduce the knowledge gap in the understanding of fracture behavior.

1. Introduction

Prediction of fracture displacement around a geological repository for spent nuclear fuel is one of the aspects included in the safety assessment of the repository. For example, a hypothetical secondary fracture shear displacement during a post-glacial earthquake in excess of 50 mm along fractures that intersect deposition holes is considered a threat to the integrity of the copper canister in the KBS-3 repository concept [1]. Fracture normal and shear displacement induced by thermal, glacial, or seismic load may also alter the groundwater flow.

The mechanical behavior of rock fractures depends on the rock material properties, the fracture geometry, the loading state, and the scale. Deformation, strength, fracturing, and friction properties of the rock material stem from its microstructure, composition, and degree of alteration; they all contribute to the fracture behavior. Concerning the fracture geometry, the composite fracture topography, that consists of the fracture surface roughness, the degree of matedness (closely related to aperture), and infill material, directly affects the fracture behavior. The local stress state of a fracture in a rock mass is
Difficult and complex to determine since the loads depend on the in-situ stress state and the additional stress that is generated during the shear displacement due to the constraint imposed by the surrounding rock. For this reason, fractures at greater depth are best represented to be under Constant Normal Stiffness conditions (CNS) whereas fractures at shallow depth are under Constant Normal Load (CNL) conditions. Dilatation induced during shear displacement under CNS conditions increases the normal stresses and thus the frictional shear resistance.

When a fracture is subjected to shearing, different local deformation mechanisms could take place at different scales. The effect of fracture scale on shear resistance has previously been observed and studied in laboratory and in-situ experiments. The general observation is that the peak shear strength decreases but the associated shear displacement increases with increasing fracture size for natural rock fractures [2]. However, increasing shear strength with increasing fracture size or no scale effect has also been reported by other authors, see for example the review in [3]. Furthermore, it has been suggested that the degree of fracture matedness in combination with the sample size plays a controlling role on the peak shear strength [4].

Past and present in-situ and laboratory fracture shear experiments, with a few exceptions, are either conducted on small specimens (up to 200 mm) or on larger specimens at low normal stresses (up to 1–2 MPa). To date, limited investigations have been conducted on the scale effects under CNS loading conditions. In addition, there is a knowledge gap about the shear behavior of fractures in hard rock subjected to a normal stress of 5 to 10 MPa (representing the stress state a depth of several hundred meters) under both CNL and CNS loading conditions. Furthermore, recent developments in characterization techniques have increased our ability to obtain an accurate description of the fracture topography before and after the laboratory tests using high resolution optical scanning of the fracture surfaces. These advances have also enabled us to monitor the normal and shear displacements on the fracture plane via local displacement transducers and Digital Image Correlation (DIC), and to use high strength concrete in fracture replicas, which can be used to generate a set of data that is richer and more complete than currently available data.

This paper presents the cooperative efforts of SKB (Sweden) and NWMO (Canada) to increase the understanding of fracture behavior within the framework of the POST project. The first phase, with Posiva (Finland) involved, was carried out during 2014–2016 with a focus on the implementation of field shear testing and numerical modelling [5]. Following the recommendations which arose from lessons learned in the first phase, the second phase of the POST project was initiated with the participation of NWMO and SKB and in cooperation with RISE (former SP Technical Research Institute of Sweden) and KTH (Sweden). This paper is the first dissemination of the project which aims at describing the experimental program on characterization of mechanical properties of large fractures, introducing the newly manufactured large direct shear machine capable of testing fracture samples of up to 600 mm in length under high normal stresses and stiffness conditions, multiple parallel characterization methods developed herein, and the types of tests which are underway.

2. Project overview

2.1. Previous results and recommendations - POST project, phase 1 (2014–2016)  
The initial motivation for the POST project was to demonstrate that a 50 mm slip of in situ fractures in a nuclear waste repository at a depth of around 450 m in crystalline rock mass is extremely unlikely. Several in situ experiments at Åspö HRL in Sweden and ONKALO in Finland were planned, designed, and studied via computer simulations [6, 7]. The PUSH Test, which was an in-situ shear test with a CNS boundary condition, was carried out accompanied by back calculations [8]. It was observed that the shear resistance increased as an effect of the rough fractures in combination with a shear displacement induced fracture dilatancy. The results emphasized the importance of characterizing the geometrical properties of the fractures and the CNS loading condition. The other in situ experiments were not realized due to the experimental complexity, uncertainties, and high associated costs. Small scale direct shear experiments were carried out on specimens with Breccia and Calcite infilled fractures.
(100×100 mm) under CNL and CNS conditions. The effect of the soft infill materials in the fracture was that no shear induced dilatancy occurred in the experiments. Consequently, there were no difference in the results between CNL and CNS loading conditions. Moreover, contact pressure distribution measurements prior to shearing showed partly sparse contacts [9]. Surfaces of natural fractures were scanned which produced point clouds by 3D photogrammetry and were used to create realistic models for simulating the shear behavior. Simulations showed that the shear resistance was sensitive to the normal stiffness boundary conditions. This is in line with results from the PUSH Test and from small-scale laboratory experiments reported in the literature, e.g. [10].

The initial part of the POST project revealed that there are several challenges associated with field testing including finding representative fracture sets, difficulties in conducting the experiments, large uncertainties which result in these tests being cost ineffective. It was concluded that to minimize experimental uncertainties, large scale fractures would be better studied under controlled laboratory conditions. Part of the uncertainties lies in the lack of shear test data for larger rock fractures under realistic CNS normal loading boundary conditions and representative normal stress levels to better understand the effects of fracture scale and their incorporation in the models. Therefore, it was recommended that a new laboratory shear testing device be developed with the ability to accommodate shear displacement up to 50 mm under normal stresses of up to 10 MPa and CNS conditions. A second recommendation was to develop a methodology for replicating fractures for studying different loading conditions on specimens with identical fracture surfaces and at different fracture scales [5].

2.2. Current project phase

The current phase of the POST project was initiated in 2017 by SKB and NWMO and the experimental work is currently ongoing. The main driver for this project is conducting high-quality laboratory direct shear testing of large scale rock fractures. The two main objectives of the new phase are: (1) developing a laboratory equipment for conducting well-controlled experiments on large rock fracture specimens and their replicas at relatively large normal stresses under CNL and CNS conditions while allowing a 50 mm shear displacement; and (2) generating a unique set of high quality and well documented laboratory data on the geometries and mechanical behavior of rock fractures and their replicas. The generated data set will serve as the basis for: (a) increasing the fundamental understanding of several aspects of the mechanical behavior of rock fractures such as the behavior of large rock fractures, fracture scale effects, correlation with fracture geometry, the wear of fractures, effect of CNS vs. CNL conditions, etc.; (b) improving existing constitutive models or developing new ones; and (c) further developing and validating detailed numerical models for simulation of fracture behavior.

The project comprises several components which contain novel contributions. For example, developing a shear testing machine that can accommodate 400×600 mm large specimens (maximum size not fully used here – the largest sample size in the current program is 300×500 mm), and extracting and manufacturing rock specimens containing natural and tensile-induced fractures at three different fracture sizes of 35×60 mm, 70×100 mm and 300×500 mm. Moreover, the effect of imperfect matching versus perfectly matched fresh fractures on the mechanical behavior of natural fractures will be studied. Replicas of natural rock fractures of a material with a strength comparable to granite are manufactured for load parameter studies on the same fracture geometry. In addition, all fracture surfaces will be 3D-scanned before and after the mechanical testing, the contact pressure distribution will be measured, and acoustic emission measurements will be conducted during the shear experiments. An overview of the different components of the project is shown in figure 1 and are described in more detail in subsequent sections.

The project is generating data which is supporting five on-going parallel projects: (1) PhD project at RISE and KTH on the development of experimental methods, i.e. replica development and validation, scale effects of fractures observed from mechanical tests; (2) another PhD project at KTH on improvement of constitutive criteria for rock fractures; (3) a project at Itasca supported by NWMO on improving numerical simulations of fracture shear behavior using 3DEC; (4) a project at KTH financed
by BeFo and SKB to improve numerical simulation of fracture shear behavior using PFC; and (5) a project at KTH financed by SKB on Hydro-Mechanical (HM) coupled modelling.

RISE has been conducting several experimental projects on the mechanical behavior of rock fractures, e.g. supporting the site investigation programs in Sweden [11] and Finland, and normal loading and direct shear testing of fractures [12]. Direct deformation measurements were used to reduce the measurement uncertainties due to deformations in the testing system. This was further exploited by [13] in conjunction with direct shear tests with CNS boundary conditions. The experience and findings from these studies are carried over to the POST project. The effect of matedness, matching and scale effects of rock fractures were previously explored at KTH in several projects, e.g. [4].

3. Experimental program

3.1. Development of equipment for mechanical testing of large fractures

A review of existing laboratory equipment globally was undertaken during the initial POST project. It was found out that no similar laboratory equipment, with the requested specifications regarding specimen size and forces, and with a possibility to apply CNS loading conditions and area correction during direct shear tests, existed. The design of the new equipment is based on utilizing the existing 20 MN four column testing frame at RISE, cf. [5]. The maximum specimen size of 400×600 mm was chosen to efficiently extract large specimens from deep tunnels by drilling cores up to 300–400 mm diameter using conventional drilling equipment with fracture plane along the core [9]. An alternative approach would be a more costly wire cutting of the required rock blocks.

The development of the equipment, the experimental procedures as well as the testing are mainly carried out at RISE in cooperation with SKB, NWMO, and KTH. According to ISRM recommendations, a high system stiffness (yielding small deformations for the test setup) was an important design parameter [14]. This is important for controllability of experiments in the shear direction (figure 2). The equipment design allows loads up to 5 MN in both normal and shear directions which corresponds to a maximum stress of 20.8 MPa at the maximum specimen size. The equipment has already been manufactured and is currently operational as shown in figure 2. Verification experiments were conducted on a steel specimen which allowed measuring the system stiffness. The results are used to compensate for the system deformations during shear tests under CNS conditions as outlined in [13]. Furthermore, a novel optical system for direct measurements of the fracture displacements in both normal and shear direction was implemented. The importance of the direct deformation measurements for accuracy, over a fracture during normal loading stage, was demonstrated by several researchers, e.g. [12], and is exemplified in figure 2. The design also allows for acoustic emission measurements during the experiments.

Figure 1. Project content overview.
3.2. Specimens with natural rock fractures and tensile-induced fractures

This testing program is focused on investigating the behavior of strong, single natural fractures with no brecciation and only small amount of infill material originating from mineralization. This will enable establishing a reliable well-controlled procedure for studying the behavior of rock fractures at different scales with reduced number of variables. The rock material was extracted from the Flivik quarry outside Oskarshamn in Sweden, which produces large blocks containing medium-grained granite. This quarry was chosen due to the knowledge from earlier research projects [4, 15]. Quarried granite usually has three main splitting planes, rift plane, grain plane and hardway plane with increasing difficulty to split [16]. Two main blocks, 15.2 and 19.6 metric tons, were extracted in the quarry. The blocks were subdivided in several steps down to final specimen sizes. Two types of specimens were manufactured: specimens containing natural fractures, and those prepared by splitting called tensile induced fractures. All fractures were oriented along the material’s grain plane.

To date, all the 300×500 mm specimens have been extracted, together with most of the 70×100 mm specimens and some of the 35×60 mm specimens. Special procedures were followed for keeping the fractures closed during specimen processing.

3.3. Replica specimens

Replicas of natural rock fractures at the intermediate scale (70×100 mm) were made from an ultra-high strength concrete with a material stiffness and strength comparable to the granite. Imprints of natural rock fractures in silicone rubber were used as a mold for manufacturing the replica specimens. Replicas of natural matching fractures were made by copying both surfaces of the original fractures. In addition, perfectly matched fractures were made by copying one fracture surface from the original fracture. The other fracture surface was made by having the copied surface as a mold for the other opposite surface during casting. The surfaces were scanned to determine the deviations against the original rock fracture surfaces [17] and to improve the replica manufacturing process. Precise replication of the fine fracture geometries is very important in mimicking the mechanical behavior of the original imaged rock fractures. To the best of the authors’ knowledge, no earlier studies on manufacturing replicas of rock fractures from high strength materials was found except in [18] which studied the hydraulic properties in fractures, but not under shear loading.
3.4. Fracture surface geometry, contact pressure distribution and acoustic emission measurements

All fracture surfaces are scanned before and after the direct shear tests using a 3D-scanner. As an example, a blue LED structured light technology with an average point spacing of 0.2 mm is used for scanning the 70×100 mm specimens. With this geometry data, it is possible to characterize the surface topography and determine the spatial fracture aperture. This data can support generation of the mesh for numerical simulation of the fractures under study, or parametrization of the fractures in conjunction with developing models for the mechanical behavior. The data also provides information about the contact areas that were damaged because of the shear test, and the wear can be quantified. The surface areas are also photographed; the images after testing show the wear zones.

The contact pressure distribution is measured by a pressure sensitive film in the same manner as in [9]. The results of the contact pressure measurements are used to determine pressure distribution in the fractures. As a complementary information, the contact pressure data of the replica fractures can be compared with contact pressure data of the original rock fractures, in addition to the geometry data comparisons, to check how the fracture surfaces match. Moreover, the contact pressure distribution measurements can be used to compare the measured aperture distributions and to provide information about the number of active contacts at the initial pre-peak deformation during a shear test. The testing program also employs acoustic emission measurements, with the source location analysis, during the shear tests following the procedure reported by e.g. [19]. This procedure is one of the few methods that allows monitoring evolution of the contacts over the fracture area during the shearing. Moreover, the acoustic emission results may give information on the wear intensity.

3.5. Testing plan overview, workflow and integrated measurements

A summary of the workflow and the different measurements are shown in figure 3. The synthesis of the various measurement and interpretation steps dedicated to studying contact wear zones is also outlined in figure 3 as an example of the integrated measurements.

![Figure 3](image)

**Figure 3.** Top: Workflow and measurements; and Bottom: example integrated measurement and interpretation steps used for studying contact wear zones.

4. Concluding remarks

Being able to predict fracture displacements is important to support safety assessments of final repositories for nuclear spent fuel located at a depth of several hundred meters. At the same time, the mechanical properties of fractures are difficult to predict since they are a result of a complex interaction between several factors such as normal stress conditions, the uniaxial compressive strength of the fracture surface, surface roughness, degree of matedness and alteration, infilling materials, and sample size. Even though significant contributions have been made within this research area in the last decades, there is a knowledge gap in the impact of high normal stresses on the mechanical properties, in particular for large sample sizes under CNS conditions. With the aim to reduce this gap and increase the
understanding of fracture behavior, a cooperative effort was made by SKB, NWMO, and Posiva (in Phase 1) within the framework of the POST project. Based on the lessons learned from the first phase, the second phase of the POST project now focuses on the generation of a high quality data set in a laboratory environment for both small and large sample sizes that can be used to investigate the remaining questions about the constitutive understanding of the fracture shear behavior.

To obtain a high quality data set under these conditions in a controlled laboratory environment, a first of a kind direct shear testing machine has been manufactured within the second, now ongoing, phase of the POST project that can accommodate samples up to 400×600 mm under normal stresses of up to 10 MPa for both CNL and CNS conditions with a maximum shear displacement capacity of 50 mm. This maximum sample size is somewhat smaller than the recommended size of 700×700×350 mm in the ISRM [20] and ASTM [21] standards for in situ shear tests of rock fractures [20, 21] but still comparable in scale. This was a trade-off which needed to be made but judged to be acceptable since previous studies on scale effects, e.g. [2], have shown that the main reduction on peak shear strength of fractures occurs within the first few decimeters of the sample size. To provide high quality data for detailed research on the remaining questions of fracture behavior, and to be able to improve existing or develop new constitutive relations, an extensive testing program has been established including both fracture samples and replicas. To be able to perform controlled parameter studies, a manufacturing process for producing high quality replica specimens of fractures using a material with a strength and stiffness comparable to hard rock has also been developed within the current phase of the POST project. This will enable a comparison of the mechanical properties and behavior between real rock fractures and the replicas.

The program contains both natural and tensile-induced fractures at three different fracture sizes of 35×60 mm, 70×100 mm and 300×500 mm. All the fracture and replica samples are also characterized in detail pre-, syn-, and post-shear test utilizing high resolution optical scanning and contact pressure measurements. This will provide unique opportunities for detailed analysis of the influences from most of the factors affecting the fracture behavior. In addition, DIC measurements during the shear test are performed, enabling a reduction of measurement errors related to the sample stiffness. The influence from the system stiffness of the machine is also compensated for by using the methodology developed in [13].

It is our hope that the high quality data generated in this program, within the present and future phases of the POST project, will provide a unique data set which will enable important reduction of the gap in knowledge and a leap forward in the understanding of fracture behavior. The testing program is currently underway and planned to finish during 2022. In future phases of the POST project, upgrading the equipment to conduct coupled hydro-mechanical experiments could be explored. Since this paper is the first dissemination of the ongoing project to demonstrate the newly developed testing capability, the authors look forward to receiving feedback on the project content and suggestions for potential improvements of the ongoing and future studies.

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References
[1] SKB 2011 Long-term safety for the final repository for spent nuclear fuel at For-smark main report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB, Stockholm.
[2] Bandis S, Lumsden A C and Barton N R 1981 Experimental studies of scale effects on the shear behaviour of rock joints, *Int. J. Rock Mech. Min. Sci. Geom. Abs.* 18 pp 1–21
[3] Bahaaddini M, Hagan P, Mitra R and Hebblewhite B 2014 Scale effect on the shear behaviour of rock joints based on a numerical study. *Eng. geol.* 181 pp 212–23
[4] Johansson F 2016 Influence of scale and matedness on the peak shear strength of fresh, unweathered rock joints *Int. J. Rock Mech. Min. Sci.* 82 pp 36–47
[5] Siren T, Hakala M, Valli J, Christiansson R, Mas Ivars D, Lam T, Mattila J and Suikkanen J 2017 Parametrisation of Fractures - Final Report, Posiva Report 2017-1, Posiva OY, Eurajoki, Finland
[6] Mas Ivars D, Lope Álvarez D, Sánchez Juncal A, Ghazal R and Damjanac B 2015 Parametrisation of Fractures - Estimation of Fracture Shear Displacement due to Excavation of New Slots at The TASQ Tunnel via Numerical Modeling, Workreport 2015-28, Posiva OY, Eurajoki, Finland
[7] Valli J and Hakala M 2016 Parametrisation of Fractures - Model Generation Methodology and Prediction Calculations, Workreport 2016-32, Posiva OY, Eurajoki, Finland
[8] Valli J, Hakala M, Suikkanen J, Mattila J, Heine J and Simelius C 2016 Parametrisation of Fractures – PUSH Test Execution and Back-Analysis, Workreport 2016-52, Posiva OY, Eurajoki, Finland
[9] Jacobsson L 2016 Parametrisation of Fractures - Direct Shear Tests on Calcite and Breccia infilled Rock Joints from Åspö HRL under Constant Normal Stiffness Condition. Workreport 2016-19, Posiva OY, Eurajoki, Finland
[10] Jiang Y, Xiao J, Tanabashi Y and Mizokami T 2004 Development of an automated servo-controlled direct shear apparatus applying a constant normal stiffness condition, *Int. J. Rock Mech. Min. Sci.* 41 pp 275–86
[11] Jacobsson L, Glamheden R, Hakami E and Olofsson I 2012 Rock mechanics laboratory testing in SKB site investigation program. *EUROCK 2012, May 28-30, 2012. Stockholm, Sweden*
[12] Jacobsson L and Flansbjer M 2005 Borehole KFM05A. Normal stress test with direct and indirect deformation measurement together with shear tests on joints. Forsmark site investigation, SKB P-05-141, Svensk Kärnbränslehantering AB, Stockholm, Sweden
[13] Larsson J and Flansbjer M 2020 An Approach to Compensate for the Influence of the System Normal Stiffness in CNS Direct Shear Tests. *Rock Mech Rock Eng* 53 pp 2185–99
[14] Muralha J, Grasselli G, Tatone B, Blümel M, Chryssanthakis P and Yujing J 2014 ISRM Suggested Method for Laboratory Determination of the Shear Strength of Rock Joints: Revised Version *Rock. Mech. Rock. Eng.* 47 pp 291–302
[15] Jacobsson L and Lindqvist J E 2018 Laboratory investigation of crack initiation on hourglass-shaped granite specimens, *Proc. EUROCK 2018, Saint Petersburg, Russia 22-26 May 2018*, pp 633-8
[16] Nadan B J and Engelder T 2009 Microcracks in New England granitoids: A record of thermoelastic relaxation during exhumation of intracontinental crust. *Geol. Soc. Am. Bull.* 121 pp 80–99
[17] Larsson J, Flansbjer M, Williams Portal N, Johnson E, Johansson F and Mas Ivars D 2020 Geometrical quality assurance of rock joint replicas in shear tests – introductory analysis. *Proc. EUROCK 2020, Trondheim, Norway*
[18] Olsson R 1998. Mechanical and Hydromechanical Behaviour of Hard Rock Joints. A laboratory study. PhD Thesis, Chalmers University of Technology, Göteborg, Sweden
[19] Moradian Z., Ballivy G and Rivard P 2012 Correlating acoustic emission sources with damaged zones during direct shear test of rock joints. *Can. Geotech. J.* 49, pp 710–8
[20] ISRM 1974 Suggested method for shear strength, Part 1, Suggested method for in situ shear determination of direct shear strength. Committee on Field tests, Document No 1, Final draft.
[21] ASTM 2002 D 4554–02 Standard test method for in situ determination of direct shear strength of rock discontinuities, ASTM International, West Conshohocken, USA