Direct shear tests on large natural and artificially induced rock fractures in a new laboratory equipment

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ABSTRACT: A direct shear equipment for testing rock fractures up to 400×600 mm size, and up to 5 MN force in both normal and shear loading directions, was developed. Normal loading and direct shear tests under constant normal stiffness (CNS) and constant normal load (CNL) conditions were conducted on 300×500 mm specimens, one planar steel joint and two natural and two tensile induced rock fractures. Design targets, e.g. system to maintain undisturbed fractures up to testing and high system stiffnesses to achieve well-controlled shear tests, were verified by the experiments. A new optical system for local deformation measurements was used to accurately determine fracture displacements besides conventional non-local deformation measurements. The determined normal stiffnesses were similar previous results from the literature on smaller fractures, whereas the shear stiffness data are novel. The results provide a new insight into processes at the onset of fracture slip.

Keywords: Rock fractures, large scale direct shear equipment, local optical deformation measurements, CNL, CNS, fracture stiffness.

1 INTRODUCTION

The mechanics of rock fractures are a key component for the mechanical and hydraulic properties in a rock mass. A correct prediction of the properties of a rock mass is important for several areas in engineering such as infrastructure tunnelling, mining, geological repositories for spent nuclear fuel, hydropower, geothermal energy and carbon dioxide sequestration. There is a knowledge gap on the mechanical behaviour of large fractures (at a meter scale) in a crystalline rock mass at depths of several hundred meters. That is e.g. fracture stiffnesses and shear resistance under a normal stress of 5 to 10 MPa (representing the in-situ stress state) at both constant normal load/stress (CNL) and constant normal stiffness (CNS) loading conditions. 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 (up to 1–2 m) at low normal stresses (up to 1–2 MPa).

This lack of knowledge contributes to the prediction uncertainty of the fracture behaviour in a rock mass. The nuclear waste management companies in Finland (Posiva), Sweden (SKB, Swedish Nuclear Fuel and Waste Management Company) and Canada (NWMO, Nuclear Waste Management

Organization) initiated the first phase of the cooperative POST project, carried out during 2014–2016, to address this uncertainty by focusing on the implementation of field shear testing and numerical modelling of large fractures (Siren et al. 2017). It was concluded that the chosen field testing approach has complications, such as finding representative fracture sets, difficulty in conducting the experiments, large uncertainties of results, and being cost ineffective. Among the recommendations from the project to increase the accuracy of fracture displacement predictions, was to study the mechanical behaviour of large fractures under controlled laboratory conditions, particularly at realistic CNS normal loading boundary conditions which is crucial for the post-peak (after start of slip) shear response. A study of the effect of fracture scale was also recommended to better understand scaling laws. A second phase of the POST project was initiated 2017, this time with the participation of NWMO and SKB and in cooperation with RISE (former SP Technical Research Institute of Sweden) and KTH, Royal Institute of Technology (Sweden) following several of the given recommendations, cf. Jacobsson et al (2021).

A new large direct shear machine for testing fracture specimens of up to 400×600 mm under high normal stresses and stiffness conditions is described in this paper. The equipment is unique due to its high loading capacity of 5 MN in both normal and shear directions and the maximum specimen size. Another novel component for this application is direct measurements of fracture deformation during both normal loading and shear experiments by an optical measurement system. The system performance is validated by normal loading and direct shear tests on a steel specimen and rock specimens containing either a tight natural fracture (N) or a tensile induced fracture (TI) representing a fresh-non-weathered fracture. The importance of a local deformation measurement for determining fracture stiffnesses is demonstrated. An experimental procedure for fracture characterization pre-, syn, and post-shear test was developed and conducted, (Figure 1), although only parts related to mechanical tests are included in this paper. The idea is that a combination of several different parallel measurements will yield an additional understanding of the fracture deformation processes.

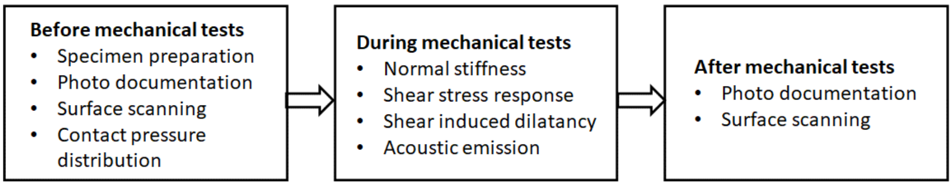

Figure 1. Overall workflow and measurements.

2 SHEAR TEST EQUIPMENT

A direct shear equipment for mechanical and hydro-mechanical tests of rock fractures up to 400×600 mm size was designed and manufactured. The design is based on experience of conducting normal loading and shear tests at RISE (SP) on crystalline rock fractures (e.g. Jacobsson & Flansbjer 2005 and Jacobsson et al. 2012) and ISRM recommendations (Muralha et al. 2014). The existing 20 MN four column testing frame at RISE in Borås (Siren et al. 2017) is used to exert the load in the normal direction via a spherical joint and a shear module containing the specimens and a 5 MN shear loading actuator (Figure 2). The design allows for a 70 mm shear displacement under either CNL or CNS conditions under loads up to 5 MN in both normal and shear directions corresponding to an average stress of 20.8 MPa at the maximum specimen size. The maximum sample size is somewhat smaller than the size 700×700×350 mm recommended in the ISRM (1974) and ASTM (2002) standards for in situ shear tests of rock fractures but still comparable in scale. This was a trade-off needed to be made but judged to be acceptable since previous studies on scale effects, e.g. Bandis et al. (1981), have shown that the main reduction on peak shear strength of fractures occurs within the first few decimeters of the sample size. The specimens could be extracted efficiently from deep tunnels by conventional core drilling (300–400 mm diameter) with the fracture plane oriented along the core as in Jacobsson (2016). An alternative approach would be a more costly wire cutting to extract rock blocks.

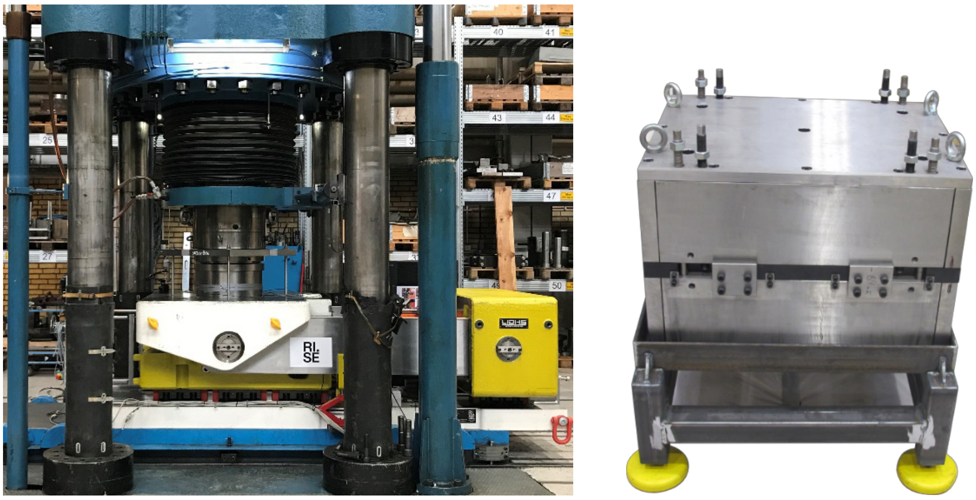

Figure 2. Left: Shear testing module and load frame; Right: Specimen holder with positioning system.

One of the design criteria was to maintain rock fractures undisturbed (i.e., in their original contact position) during grouting specimens in the specimen holders and mounting specimen holders in the shear boxes. This was accomplished by precision made specimens holders and shear boxes and use of linked positioning systems during these stages (Figure 2). Another design criterion was to have a high system stiffness (less stored elastic energy in the test setup) for obtaining good controllability of experiments in the shear direction, i.e. reducing stress variation at the post-peak stick-slip deformation process and maintaining correct value of normal stiffness in the case of CNS loading condition. High-capacity roller bearings are used to obtain low friction in the system during shearing.

A novel direct and a conventional indirect measurement system are used for fracture displacement measurements. The optical direct measurements are made via a 2D digital image correlation (DIC) technique, e.g. Sutton et al. (2009), on images taken by 2448×2048 pixels CCD (machine vision) cameras on surface areas (c 55×45 mm) on the specimen containing the fracture and subjected to a speckle pattern. The displacement field at four areas, two on the left and two on the right side in the front and rear ends in relation to the shear direction, are determined. The local normal and shear displacements were determined by a 2D virtual extensometer, with an equivalent gauge length between 10–15 mm measuring between two subset points (25×25 pixels), positioned at each side of the fracture yielding a resolution of approximately 0.3 µm for both normal and shear displacement components. The relative displacement between the upper and lower shear boxes are measured by linear variable displacement transducers (LVDT), at four locations in the normal direction providing the dilatancy information, and at two locations in the shear direction giving the shear displacement. These are indirect measurements of fracture displacement. The average value of both the direct and indirect measurements for the two directions are presented in the results. The roll and pitch can be determined but are omitted here.

The function of the test system and control of tests were validated by running a normal and shear loading on a steel specimen. The system deformation was measured in the normal direction (Larsson 2021) from which the effective normal stiffness value used during the CNS tests was calculated according to procedure given in Larsson & Flansbjer (2020).

3 EXPERIMENTS

The rock specimens are made from a block of medium-grained granite containing a natural fracture with the orientation along the grain plane collected from the Flivik quarry in Sweden. An artificial tensile induced fracture was made by splitting in parallel to the natural fracture. The material was processed in several stages to obtain the final size of 300×500 mm yielding two types of undisturbed fracture sets, tight natural fractures with small weathering and infill material and tensile induced, fresh and perfectly matching fractures. The measured bulk material properties of the rock are Young’s modulus 72.9 GPa, uniaxial compressive strength 268 MPa, direct tensile strength 10.7 MPa and splitting tensile strength 13.8 MPa (Larsson et al. 2022) and basic friction angle 23.9° (Alejano & Pérez-Ray 2020). Several measurements and documentations were done before, during and after mechanical tests (Figure 1). The normal loading and direct shear tests are presented here. The test starts with perfectly aligned fracture surfaces. The normal loading tests start with a prestress of 0.5 MPa and then by four load cycles 0.5–12 MPa with a loading and unloading rate of 10 MPa/min to gradually consolidate the fracture. The following direct shear tests start with applying a normal prestress (σ_{N0}) of 5 MPa at 5 MPa/min at zero shear displacement. The shear stage was conducted with a constant shear displacement rate of 0.5 mm/min on the shear actuator up to 50 mm shear displacement or up to a normal force of 5 MN (in case of CNS tests) whichever is reached first. An effective normal stiffness of 10 MPa/mm was imposed during the CNS tests, where the method to compensate for machine deformations described in Larsson (2021) was used.

4 RESULTS

4.1 *Normal loading tests*

The results from the normal loading tests are shown in Figure 3. The direct deformation measurements show a joint compression of 0.08–0.28 mm during first loading where a part is an initial compaction which is seen as a residual displacement after unloading. The values measured by indirect measurements by LVDTs display much larger values (0.45–0.60 mm). The fracture reaches almost an elastic shakedown state after four loading cycles. The joint stiffness at the fourth loading (K_N), computed as the secant between 0.5 and 12 MPa, is in the range 100–370 MPa/mm based on local DIC measurements and 32–41 MPa/mm based on indirect LVDT measurements.

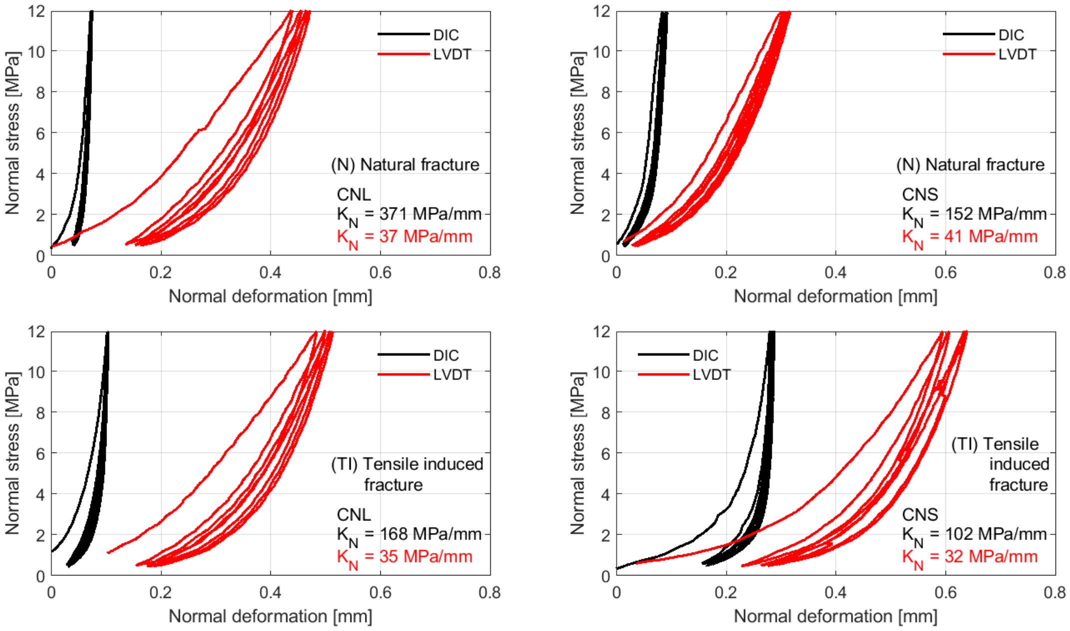

Figure 3. Normal stress vs. normal deformation and fracture stiffnesses.

4.2 *Direct shear tests*

The results from the direct shear tests are shown in Figure 4. The onset of slip is defined as shear displacement that generates dilation, i.e. around 0.1 mm (N) and 0.05 mm (TI) from local measurements (DIC in Figure 4, right). The shear stress at onset of shear slip is around 6 MPa (N) and 10 MPa (TI), respectively. At CNL tests, it is a distinct peak followed by a significantly lower residual stress and progressively continuing dilation throughout the shear distance. The results at

CNS condition show an increasing shear stress due to an increased normal stress caused by dilation. The dilation rate eventually decreases due to the normal stress and is almost zero around 10 mm (N) and 20 mm (TI) shear displacement and is kept almost constant after that. The test of the TI-CNS specimen was stopped as the normal force increased and reached the machine capacity.

The difference between the direct and indirect measurements at the pre-peak state, no slip, is shown in Figure 4 (right). The elastic, pre-peak, secant stiffness is defined as the values between 0.5 and 5 MPa (N) and 0.5 and 9 MPa (TI) and was 12–15 MPa/mm (N+TI) based on LVDTs and 40–70 MPa/mm (N) and 150–220 MPa/mm (TI) for local measurements by DIC.

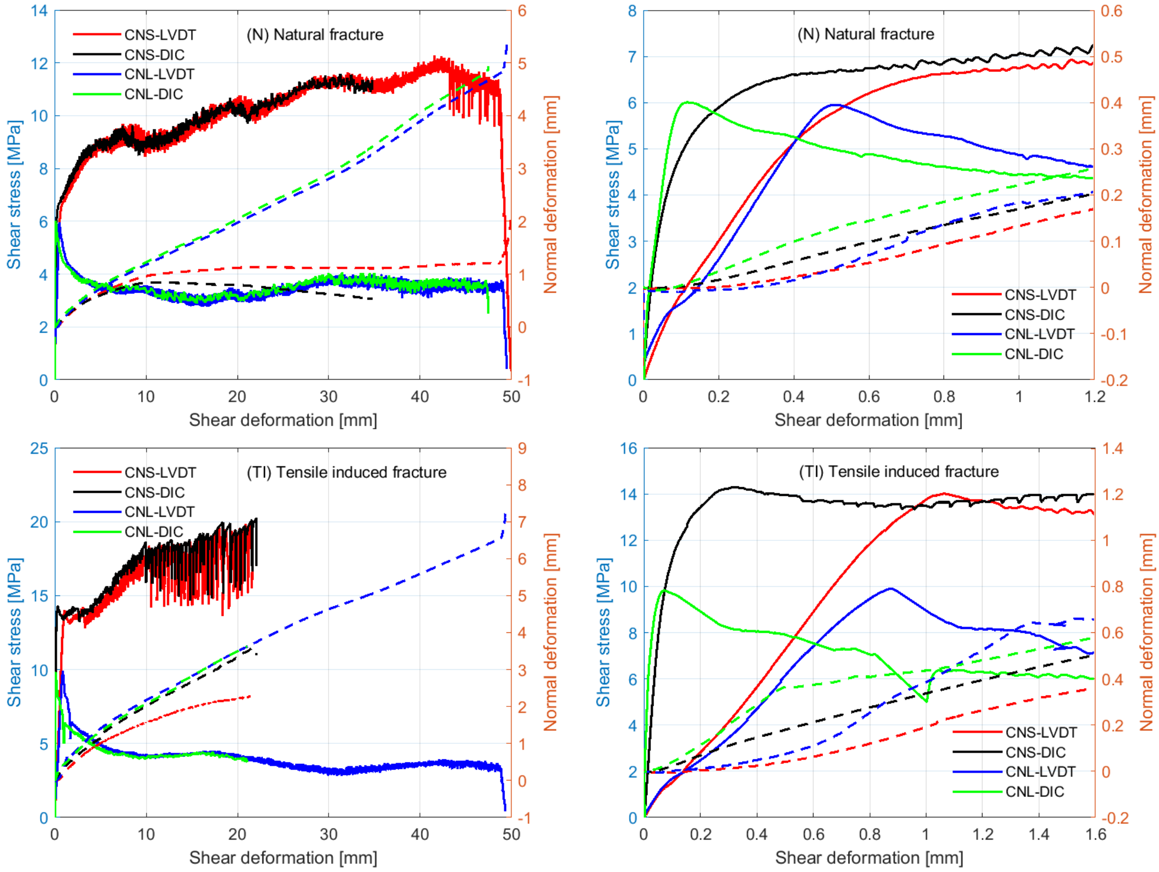

Figure 4. Shear stress and normal displacement (dilatancy) vs. shear displacement for CNS and CNL specimens. Left: Full scale; Right Close up at pre-peak region. Note that the diagrams have different scales.

5 DISCUSSION AND CONCLUSIONS

A new equipment was constructed for testing large specimens under high forces and stiffness which makes it the first of a kind due to its unique capacity. The system performance was demonstrated and evaluated by reference tests on a steel specimen and its function, particularly under CNS loading condition, by tests on hard rock specimens with tight and highly dilatant fractures. The steps to produce large rock specimens with undisturbed fractures, prepare them for experiments and conduct controlled experiments were verified. The system stiffness, based on force-displacement data excluding deformations not belonging to the specimen, was circa 10,000 kN/mm in the normal direction (Larsson 2021) and circa 750 kN/mm in the shear direction (current experiments).

The optical local deformation measurement system is an important component and contribution to achieve more accurate measurements. The data yields a new insight on the deformation process at the onset of shear slip. It is revealed that the onset of slip (accompanied with dilation) takes place at small shear deformations (0.05–0.1 mm). A part of the measured values was elastic deformation of the rock material, but this is negligible since it is estimated to be less than 10% of the measured values. The normal stiffness is in the range of previously measured stiffnesses on natural crystalline rock fractures using direct measurements (e.g. Jacobsson et al. 2012). There are no comparable elastic shear stiffness data in the literature when direct measurements were used. The fracture stiffnesses are much higher from direct measurements compared to the indirect measurements.

Another aim is to provide high quality data from an extensive testing program, by the mechanical tests and the parallel complementary measurements, for research on the remaining questions of fracture behavior, and to be able to improve existing or develop new constitutive relations.

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