Rock Mech Rock Eng (2014) 47:291–302
DOI 10.1007/s00603-013-0519-z

ISRM SUGGESTED METHOD

ISRM Suggested Method for Laboratory Determination of the Shear Strength of Rock Joints: Revised Version

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Published online: 30 November 2013
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1 Introduction

The term 'discontinuity' refers to any mechanical break in a rock mass with negligible tensile strength (Priest 1993). Discontinuities can be geologic in origin (i.e., faults, bedding, schistosity, cleavage planes, and foliations) or anthropogenic in origin (i.e., blast-induced, stress-induced, or hydraulic-induced fractures).

Regardless of their origin, discontinuities play a significant role in the behavior of rock masses and, consequently, in the behavior of several rock engineering projects involving slopes, surface excavations and underground openings such as tunnels or caverns. Discontinuity-induced failures in rock masses are a major hazard in civil and mining engineering projects as they are responsible for many accidents and costly construction/production delays.

Assessing the risk posed by these blocky systems to a particular project requires the evaluation of the shear strength of the rock discontinuities. Estimates of shear strength can be obtained through shear testing. The best shear strength estimates are obtained from in situ direct shear tests as they inherently account for any possible scale effect (Barla et al. 2011; Alonso et al. 2011). However, due to the duration and cost of such tests, it is common practice to perform laboratory direct shear tests on relatively small discontinuity samples instead.

Conventionally, direct shear testing has been conducted with a constant normal load applied to the discontinuity plane. While this boundary condition is appropriate for a class of engineering problems involving the sliding of rock blocks near the ground surface (e.g., rock slope stability and surface excavation stability), there is class of problems where the normal stress may not remain constant as sliding occurs. Namely, any time the dilation of a discontinuity is constrained while sliding (e.g., around an underground excavation), the normal stress on the sliding surface may vary. For this class of problems, a constant normal stiffness boundary condition is more appropriate for direct shear testing (Johnston and Lam 1989; Leichnitz 1985).

2 Scope

(a) This Suggested Method (SM) is a revision and an upgrade of Part 2. Suggested Method for laboratory determination of direct shear strength, included in the

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Suggested Methods for determining shear strength (ISRM 2007), and was prepared with consideration of the technological advances since its initial publication and other existing standard methods, including ASTM D 5607–08 (ASTM 2008), USACE RTH 203-80 (USACE 1980), and JGS 2541-2008 (JGS 2008).

(b) This SM intends to cover the requirements and laboratory procedures for performing direct shear strength tests of rock discontinuities using constant normal load and constant normal stiffness laboratory apparatuses. This type of test can also be referred to as a sliding friction test.

(c) This SM is limited to the determination of the quasi-static shear strength of discontinuities under monotonic shear loading. Procedures for cyclic and dynamic shear loading are not addressed herein.

(d) Discontinuities may be open or almost closed, and must display negligible tensile strength. This SM is not intended to cover direct shear tests of intact rock or other types of natural or artificial discontinuities that display tensile strength, such as rock–concrete interfaces or concrete lift joints.

(e) Discontinuities may also be partially or completely filled with gouge or clay fillings. This SM is not intended to cover tests of discontinuities with gouge or clay fillings where in situ pore water pressure conditions have to be considered.

(f) This SM proposes to measure peak and ultimate or residual direct shear strength in a selected direction as function of the normal stress applied to the sheared plane. Results can be implemented, for instance, in limit equilibrium analyses of rock blocks in slopes or sidewalls of underground excavations, and as input parameters for 'joint' elements in continuum and discontinuum numerical modeling of blocky rock masses.

(g) Shear strength of rock discontinuities can be determined by tests under constant normal loading conditions (CNL), or under constant normal stiffness loading conditions (CNS). The use of constant normal load shear tests does not really test the joint strength, but the resistance to shear at a certain normal load, which may be appropriate for design purposes under certain boundary conditions. Constant normal stiffness testing procedures can be used to define the ultimate shear strength of a joint. Though they do not consider that the normal stiffness is likely to increase during dilatant shearing, CNS tests should be preferably used to reproduce the natural response to simple shearing of non-planar discontinuities.

(h) Under constant normal loading conditions, shear strength determination usually includes the application of several different magnitudes of constant normal loads or stresses on multiple samples from the same joint or test horizon, and measuring the shear stresses and respective shear and normal displacements resulting from a prescribed rate of shear displacement. At least three, but preferably five, specimens from the same joint or test horizon with similar characteristics must be sampled and tested along the same shear direction.

(i) In cases where it is not possible to sample a large enough number of specimens, alternatively, the same specimen can be tested repeatedly under different constant normal loading conditions. For a single rock joint, at least three, but preferably five, different normal stresses should be used. This multi-stage approach is only applicable when breakage and degradation of joint surface asperities from subsequent shearing stages is minimal (e.g., under low normal stresses). To minimize the influence of damage and wear, each consecutive shear stage should be performed with an increasingly higher normal stress.

(j) Under constant normal stiffness loading conditions, a single shear strength determination usually includes the testing of multiple samples from the same joint or tests horizon under differing initial normal loads and/or constant normal stiffnesses, and measuring the shear and normal stresses and respective displacements resulting from a prescribed rate of shear displacement. At least three, but preferably five, specimens from the same joint or test horizon must be sampled and tested along the same shear direction.

3 Apparatus

3.1 Testing Machine

(a) Determination of shear strength of rock discontinuities is generally performed using direct shear apparatuses. Although there are many variations in the way specimens are prepared, mounted, and loaded, yet determinations of shear strength are usually similar (Boulon 1995; Blümel and Pötsch 2003; Jiang et al. 2004; Barla et al. 2010). Commonly, direct shear testing machines incorporate (Fig. 1):

i. A stiff testing system, including a stiff frame against which the loading devices can act and a stiff sample holder that is sufficiently rigid to prevent distortion during the test. A stiff system allows the prescribed shear displacement rate to be maintained and allows the post-peak behavior of the joint to be properly recorded.

ii. A specimen holder, such as a shear box, shear rings, or a similar device, where both halves of

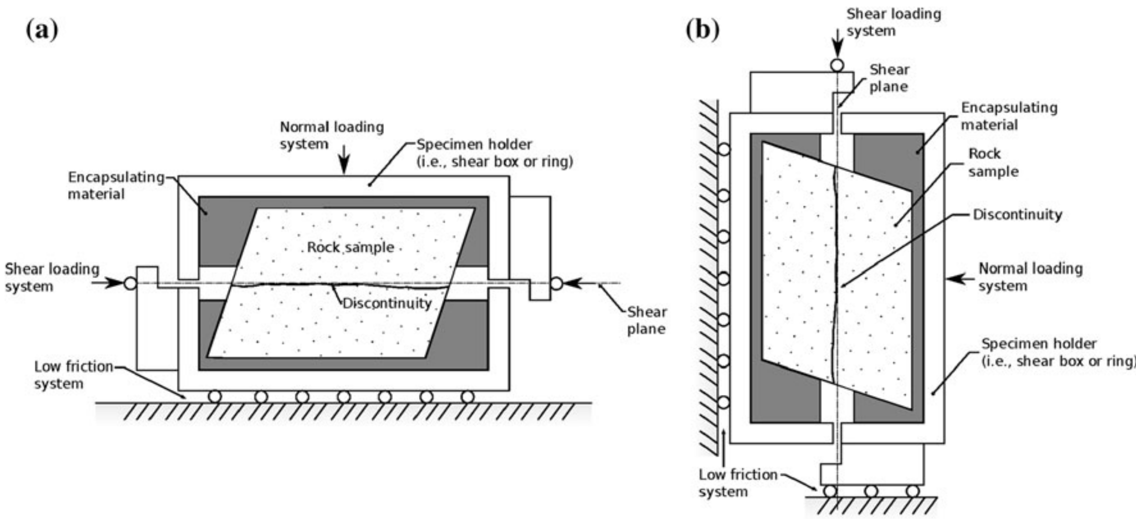

Fig. 1 Schematic illustrating arrangement of laboratory direct shear specimen: **a** conventional horizontal arrangement and **b** alternative vertical arrangement

the specimen are fastened. It must allow relative shear and normal displacements of the two halves of the discontinuity. Frictional forces on the perimeter of the sample holder must be minimized via rollers or other similar low friction devices.

iii. Loading devices to apply the normal and shear loads on the specimens at adequate rates in such way that the resultant of the shear load goes through the centroid of the sheared area to minimize rotation of the specimen.

iv. Devices to measure the normal and shear loads applied to the specimen and the normal and shear displacements throughout the test.

3.2 Loading

(a) The applied shear forces are usually provided by actuators [hydraulic, pneumatic, mechanical (gear-driven), etc.] with or without closed-loop control. Shear force actuators and connecting parts should be designed to ensure that the shear load is uniformly distributed over the discontinuity plane to be tested with the resultant force acting parallel to the shear plane through its centroid.

(b) The applied constant normal load or constant normal stiffness is usually provided by actuators (hydraulic, pneumatic, mechanical, etc.) with or without closed-loop control. Normal force actuators and connecting parts should be designed to ensure that the load is uniformly distributed over the discontinuity plane to be tested. They should accommodate travel greater than the amount of dilation expected in the test and ensure the applied normal load is uniformly distributed over the test horizon with the resultant force acting perpendicular to the shear plane through its centroid.

(c) A cantilever system can also be used to apply a constant normal dead-weight load for CNL tests under low normal stresses and null normal stiffness (Hencher and Richards 1982), while a spring can be used to maintain a constant normal stiffness condition for CNS tests (Indraratna et al. 1999).

(d) Maintenance of the normal load or stiffness is important during shear tests. In accordance, the loading component of the apparatus must be devised to maintain the applied force or stiffness within a specified tolerance (±2 %).

3.3 Recording Load and Displacement

(a) The normal and shear forces are measured with accuracy better than ±2 % directly by load cells, or indirectly by pressure gauges, transducers, or proving rings. Displacement transducers are used to measure the displacements.

(b) A minimum of two transducers are required: one mounted parallel with the shear plane to measure the shear displacement and one mounted vertically at the centre of the specimen to measure normal displacement. Preferably, two transducers should be used to measure shear displacement such that yaw of the specimen is measured, and three to four transducers should be employed to measure horizontal displacement, such that pitch and roll of the test specimen can be evaluated.

(c) It is common practice to perform almost continuous measurements (sampling rate greater than 1 Hz) of these parameters using some kind of computer based data acquisition equipment, which is acceptable for quasi-static loading conditions considered under this SM.
(d) To assure that the loads are effectively being applied to the shear surface, it may be convenient to measure the frictional forces or to perform a dummy test prior to real testing. If corrections are required, they should be reported.

4 Test Specimens

4.1 Sampling, Handling and Storage

(a) The test horizon is selected and dip, dip direction, and other relevant geological characteristics are recorded. If possible, the absolute orientation of the sample relative to the test horizon should be marked on the sample (e.g., oriented core). In doing so, the shear direction in laboratory may be selected to correspond to a particular in situ displacement direction of interest.
(b) Block or core samples containing the test horizon are collected using methods selected to minimize disturbance. The sample dimensions and the location of the test horizon within the block or core should, if possible, allow mounting without further trimming in the laboratory and provide sufficient clearance for adequate encapsulation.
(c) No liquids other than water should come in contact with a test sample prior to testing. Discontinuity samples that appear to have been contaminated with mud produced by drilling or that show unnatural surface wear should be rejected.
(d) Samples should be labeled and packaged to avoid damage in transit to the laboratory. Particular attention should be given to prevent differential movement from occurring along the sampled discontinuity. An option to prevent differential movement includes binding the walls of the discontinuity together with wire or tape, which is to be left in position until immediately before testing. If samples are not immediately transported to the laboratory they should be stored out of the weather to preserve their integrity. Because samples are to be tested near their natural moisture condition, they should be stored and transported in moisture-proof containers. Alternatively, tape, plastic wrap, wax, or other means may be utilized to preserve the in situ moisture content along the test zone. Fragile samples require special treatment, for example packaging in polyurethane foam (Stimpson et al. 1970).
(e) In the laboratory, sample handling and storage should follow the above mentioned measures to avoid any damage to the samples, and to preserve the in situ moisture content if required.

4.2 Size and Shape

(a) Specimens with a regular (rectangular or elliptical) cross-sectional area are preferred. However, specimens may have any shape, such that the cross-sectional areas can be determined with a required accuracy.
(b) The height of specimen shall be greater than the thickness of the shear (test) zone and sufficient to encapsulate the specimen in the specimen holder.
(c) The length of the test plane (measured along the shear direction) should be at least 10 times the maximum asperity height.
(d) The width of the test plane (measured perpendicularly to the shear direction) should have at least 48 mm, corresponding to discontinuities collected from NQ cores.
(e) The width of the test plane should not change significantly over the shearing length. Minimum width should be greater than 75 % of the maximum width.
(f) The sample half that remains fixed during shear tests should have a greater length than the moving half, so that the joint is always supported and the nominal area in contact remains constant. If this procedure is not feasible due to reduced length of the specimen, the nominal area reduction during shear has to be taken into account in the calculations.

4.3 Observations and Measurements on the Sample and Specimen

(a) All characteristics of the discontinuity surface, that may influence its shear strength, including alteration, coatings, fillings, etc., should be assessed according to the methodology described in the ISRM Suggested Method for the quantitative description of discontinuities in rock masses (ISRM 2007).
(b) Both walls of the test specimen should be photographed before and after the test. It is also important to measure the topography of both walls of the test specimen before and after the test to evaluate the

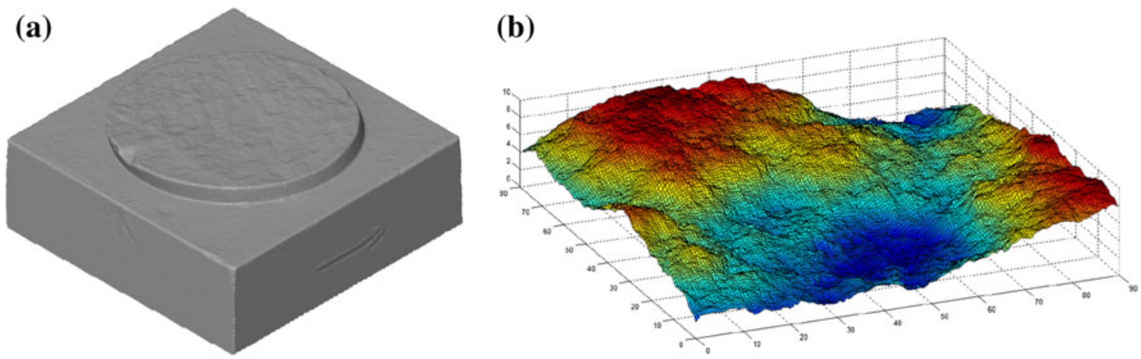

Fig. 2 Examples of the measurement of joint surfaces: **a** circular, **b** rectangular

surface roughness and roughness wear. For this purpose, two types of equipment can be used:

i. Profilometers are simple devices that produce a series of linear roughness profiles of the specimen surface along the shear and the transversal directions. The number of profiles depends on the surface dimension, but at least three along each direction should be mapped (Aydan et al. 1992; Grasselli 2001).
ii. If available, 3D non-contact measurement devices (e.g., laser scanner, slit scanner, photogrammetry or stereo-topometric camera) can be used to digitize the entire discontinuity surface (Fig. 2). Such systems are capable of obtaining point measurements with a nominal spacing <0.5 mm with a precision better than 0.025 mm (Tatone and Grasselli 2009).

(c) Measurement of the nominal cross-sectional area of the specimen shear plane shall be made before each test to the nearest 2.5 mm^2. For regular geometrical shapes, the relevant dimensions required to calculate the nominal cross-sectional area can be measured using a calliper or micrometer. For irregular shapes, the outline of the cross-section can be traced on paper and the area measured using a planimeter or similar device. The area can also be measured using a 3D non-contact measurement device and CAD software.

4.4 Specimen Encapsulation

(a) To test a discontinuity sample, each half of the sample must be secured in each half of the specimen holder (i.e., shear rings or shear boxes). As discontinuity samples are rarely cut to fit perfectly in the sample holder, they must be encapsulated in some other casting material (e.g., cement, resin, or similar) to ensure a tight fit. Encapsulation also allows the discontinuity plane to be aligned with the shear plane. Specimens can be encapsulated directly inside the specimen holder of the test apparatus or, if several specimens are to be prepared simultaneously, a split mold(s) with identical dimension to the specimen holder can be used. Though some adaptations are allowed, encapsulation of a sample for testing should proceed as follows:

Fig. 3 Encapsulate lower half of a rectangular shaped test specimen

i. Remove sample from packaging.
ii. Position the lower half of the specimen centrally in the lower half of the specimen holder. Ensure that the shear horizon to be tested is secured and that it is parallel with the shear plane and oriented correctly with respect to the shear direction. Ensure the specimen position can be maintained while pouring and curing of the encapsulating material.
iii. Pour the encapsulating material, prepared in accordance with the directions of the manufacturer,

carefully into the space between the lower half of specimen and the lower half of the specimen holder. Stop pouring just below the general plane of the test zone. Ensure a zone of about 5 mm around the sides of the shear plane remains free from encapsulating material. Do not disturb the specimen holding assembly after pouring until the encapsulating material is sufficiently cured.

iv. After the bottom encapsulating material is sufficiently cured, place a split spacer plate of specified thickness on the lower holder such that its cut-out edge encircles the encapsulated lower half of the specimen and encompasses the test zone thickness. Coarse sand or modeling clay can also be used for this purpose. If needed, apply a layer of silicon grease over the surface of the encapsulated material. Place the upper half of the test specimen onto the encapsulated lower half. Ensure a tight fit between the two halves is achieved. Lower the upper half of the specimen holder onto the split spacer plate without disturbing the position of the top half of the specimen. Connect the two halves of the specimen holder. Pour encapsulating compound into the annular space between the top half of the specimen holder and the top half of the specimen. Do not disturb the assembly until the encapsulating compound cures.

v. Remove the spacer plates, sand, or clay to expose the test horizon for shear testing (Fig. 3).

(c) Following encapsulation, the average plane through the test horizon should be verified to be parallel to the top and bottom surface of the specimen holder (i.e., shear plane). Any angular deviation between the average plane and shear plane, measured in the shearing direction, should be measured and reported. This angular deviation should also be accounted for in the shear strength determination.

5 Testing Procedure

5.1 Preliminary Tasks

(a) Prior to any set of tests, the loading conditions and the range of normal loads to be applied during shear have to be defined, according to the normal stresses expected to be acting on the joints in the project under consideration (e.g., slope, dam foundation, underground cavern, or tunnel).

(b) If considered convenient, dummy tests with low deformability specimens, such as steel, with the same dimensions as the real specimens, and encapsulated following the same procedure can be run. Dummy tests of jointed specimens allow one to establish that all devices are operating correctly, and may enable calibration of measuring devices. Dummy tests of intact specimens also allow one to evaluate the normal and shear loading system stiffness, and eventually to correct accordingly (Chryssanthakis 2004).

5.2 Specimen Mounting

(a) Mount and orient the encapsulated specimen within the moving and fixed specimen holders of the testing machine.

(b) Ensure all measuring devices are calibrated according to the laboratory calibration procedures.

(c) Test all monitoring devices to guarantee they are responding correctly and are properly connected to the data acquisition system.

(d) Mount all displacement measuring devices perpendicularly to the shear surface such that they contact the perimeter of the moving half of the specimen holder to measure normal displacement during the test. Generally, four normal displacement measurement devices are used to assess the pitch and roll of the moving half of the specimen during the test. Although not recommended, fewer measurement devices can also be employed. In all cases, these devices must be distributed around the perimeter of the sample shear surface to provide the information necessary to evaluate the normal displacement at the centroid of the shear surface.

(e) Mount displacement devices on the machine in such a manner to measure the shear displacement of the specimen during the test. A pair of devices symmetrically positioned with respect to the specimen cross-section should be used. For some machines, a single device positioned along the shear displacement axis may be sufficient. However, this latter option is not recommended, since eventual yaw movement of the specimen will not be detected.

(f) Ensure all displacement monitoring devices have sufficient travel to accommodate the normal and shear displacements expected in the test. Moreover, ensure these devices maintain contact with specimen holder throughout the test to correctly measure the displacements.

(g) If required, mount and position all other measuring devices, for instance load cells.

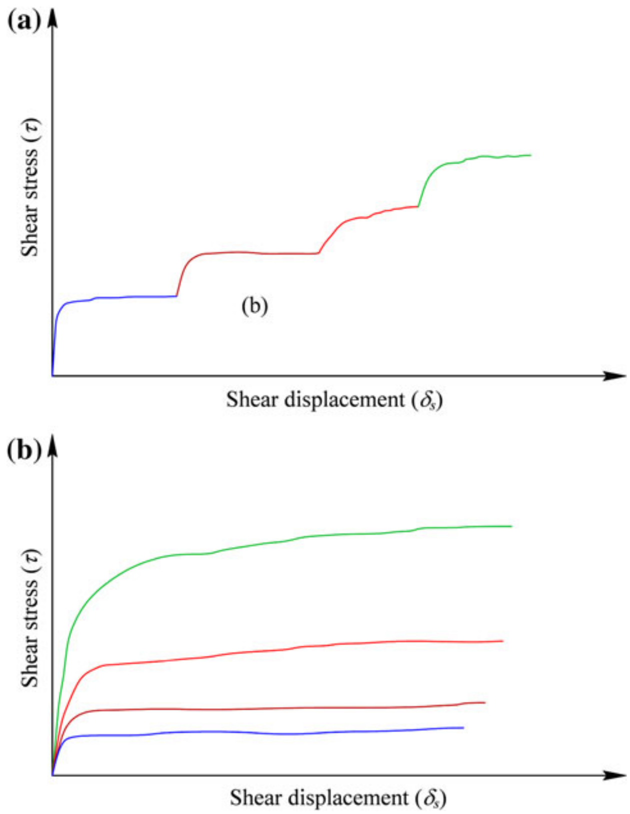

Fig. 4 Example of multi-stage shear tests under different normal loads, **a** without repositioning and **b** with repositioning

5.3 Load Application

5.3.1 Normal Load

(a) Before any shear test, normal load application should consist of continuously increasing the load normal to the shear zone at a gradual rate until the specified normal stress is attained, and recording consequent normal displacements.
(b) Normal load application should be applied continuously at selected rate of normal stress assuring that each loading or unloading paths takes about 5 min. In accordance, rates of 0.01 MPa/s or less are required.
(c) Any normal loads imparted on the test horizon by the normal loading system should be accounted for when determining the apparent normal stress on the specimen especially under low normal stresses. For example, if the specimen is held in a horizontal position in the test apparatus, the weight of the upper half of the specimen should be considered.
(d) For CNL tests ensure the testing apparatus maintains the specified constant normal load for the duration of the test. For CNS tests ensure the testing apparatus maintains the specified constant normal stiffness for the duration of the test.
(e) If applicable, allow pore water pressure in the rock and filling material adjacent to the shear plane to dissipate before shearing. Do not apply the shear load until normal displacement has stabilized.

5.3.2 Shear Load

(a) After the normal displacements stabilize under the applied normal load, invoke shear displacement continuously at the selected rate of shear displacement
(b) Shear displacement shall continue at the specified rate until ultimate or residual shear stress is reached. Generally, a shear displacement that ranges between 5 and 10 % of the length of the discontinuity is enough.
(c) Shear displacement rates around 0.1–0.2 mm/min are usually suitable for the whole test, although it can be slightly increased up to values around 0.5 mm/min after peak shear strength. In special cases, such as joints with thin clay coatings, a slower rate (lower than 0.05 mm/min) may be required.

5.4 Alternative Procedures

(a) Rock joint shear strength determination can follow two different types of procedures: single shear procedure and multi-stage shear procedure. Both types of procedures can be performed under CNL or CNS conditions (Muralha 2007; Blümel et al. 2003).
(b) Single shear procedure includes the application of several constant normal stresses on multiple samples from the joint or test horizon and measuring the shear stresses and respective normal displacements resulting from a prescribed rate of shear displacement. At least three, and preferably five, specimens from the same test horizon can be obtained and each tested in the same direction.
(c) Multi-stage shear procedure consists of testing repeatedly under different constant normal stresses the same specimen. For a single rock joint, at least three, and preferably five, different normal stresses should be applied, with shear testing in the same direction. Furthermore, two possible techniques for performing multi-stage shear tests can be followed: without repositioning of the joint in its initial natural position before each shearing stage (Fig. 4a), or with repositioning of the joint in its initial natural position before each shearing stage (Fig. 4b).

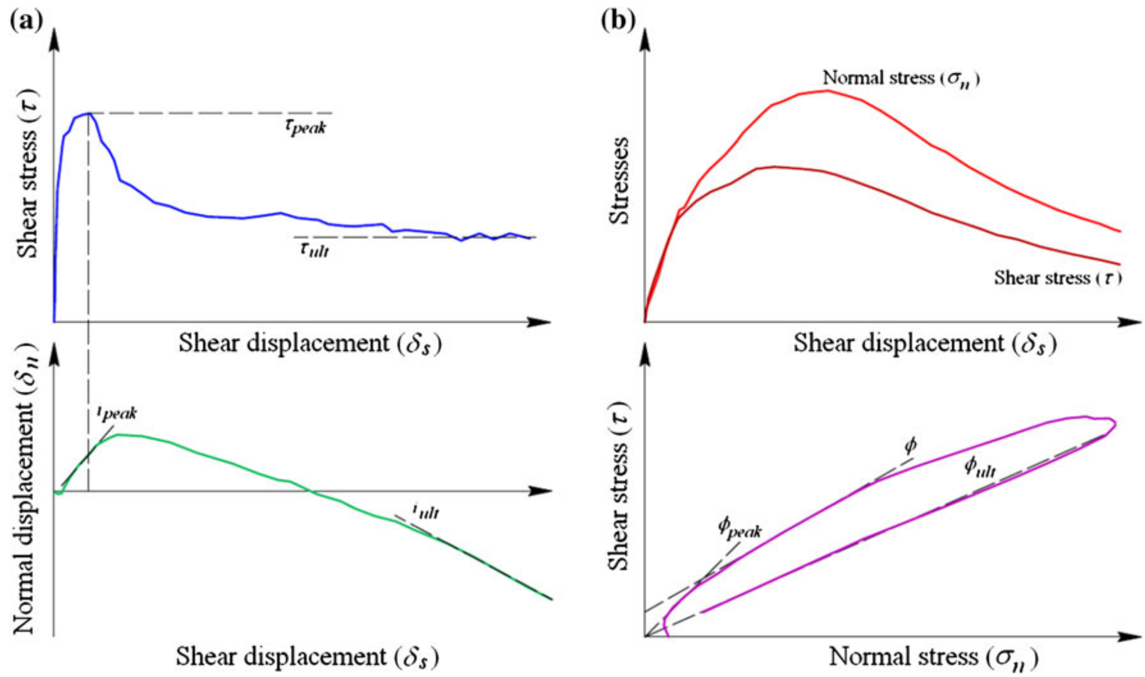

Fig. 5 Typical plots from a rock joint shear test, **a** under constant normal loading conditions (CNL), and **b** under constant normal stiffness conditions (CNS)

5.5 Measurements

5.5.1 *Normal Displacement (δ_n)*

(a) Measure and record normal displacements of the specimen at each load observation to determine the normal displacement of the joint sample as previously defined in Sect. 3.

(b) It is recommended that four measuring devices are used to monitor the pitch and roll of the test sample. Fewer measuring devices can be used, but in all cases they should allow to determine the normal displacement at the centroid of the sample cross-section.

5.5.2 *Shear Displacement (δ_s)*

(a) Measure shear displacements of the specimen at each load observation to determine the shear displacement of the joint sample as previously defined in Sect. 3.

(b) It is recommended that two measuring devices be used to monitor the pitch and roll of the test sample. Fewer measuring devices can be used, but in all cases they should allow to determine the normal displacement at the centroid of the sample cross-section.

5.5.3 *Normal Load (N)*

(a) If the normal loading mechanism is anything other than a dead-weight load (i.e., for CNL testing), measure the applied normal load at every shear load observation with a load measuring device. Normal load must be continuously monitored during testing.

5.5.4 *Shear Load (T)*

(a) Measure the applied shear load with a load measuring device. The selected measurement frequency should be sufficient to fully capture the load displacement response of the specimen. This frequency depends on the nature of the specimen and shear displacement rate. Generally, a measurement every 1 s or less over the test duration should be adequate.

6 Calculations, Plots and Results

6.1 Data

(a) Check the individual data records to check the consistency of all measurements.
(b) If the nominal stresses are not provided directly by the data acquisition system, calculate the normal and shear stresses as:

$$\sigma_n = \frac{N}{A}, \quad (1)$$

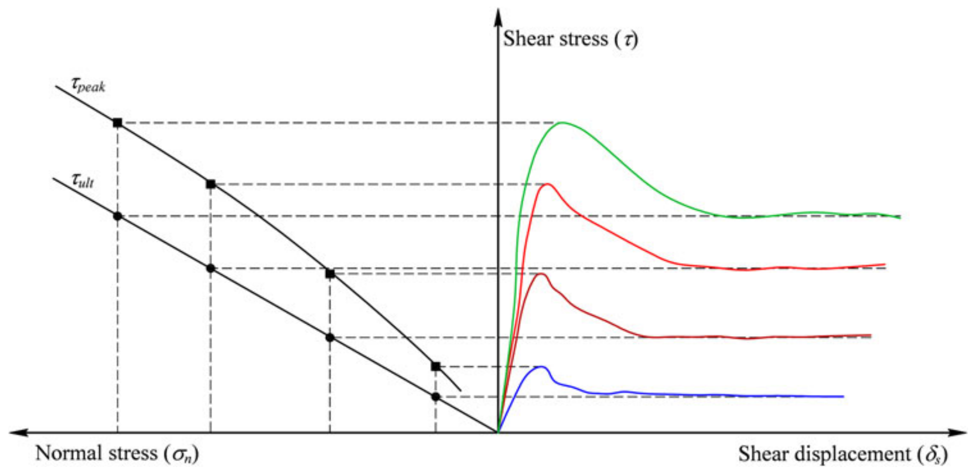

Fig. 6 Evaluation of the peak and ultimate or residual shear stresses

$$\tau = \frac{T}{A}, \quad (2)$$

where N normal load, T shear load, A nominal area, σ_n normal stress, τ shear stress.

(c) As referred in Sect. 4.2(f), if the nominal area decreases during shear displacement, it has to be taken in consideration for the calculation of the nominal stresses.

(d) Calculate the normal and shear displacements if they are not provided directly by the data acquisition system.

6.2 Plots and Calculations

(a) The following plots are required for the determination of the shear strength of the joint specimen (Fig. 5):

i. Shear stress versus shear displacement graphs;
ii. Normal displacement versus shear displacement graphs;
iii. Normal load versus shear displacement graphs, in the case of CNS tests.

(b) Normal load versus normal displacement graphs of the normal load application stages can also be provided.

(c) Using the data records and the shear stress versus shear displacement graphs, evaluate the peak and ultimate or residual shear stresses for each sample of the same rock joint or test horizon in the case of single stage tests, or for all stages of multi-stage tests of the same rock sample (Fig. 6) (Wittke 1990).

(d) Using the data records and the normal displacement versus shear displacement graphs, evaluate the peak and ultimate or residual dilation angles for each sample of the same rock joint or test horizon in the case of single stage tests, or for all stages of multi-stage tests of the same rock sample.

(e) Make plots that depict the relationships of peak shear stress versus normal stress and ultimate or residual shear stress versus normal stress.

(f) Use these plots to evaluate the strength parameters of a prescribed failure criterion. Mohr–Coulomb criteria are usually suitable to adequately model the results of rock joint shear tests. In this case, parameters of this linear failure criterion are defined as follows:

$$\tau = c + \sigma_n \tan \phi \quad (3)$$

where c apparent cohesion, $\tan \phi$ friction coefficient, ϕ friction angle.

(g) Particular care should be paid in using Mohr–Coulomb criterion strength parameters. Results should not be extrapolated beyond the range of the applied normal stresses during the tests, especially for low σ_n values, as illustrated in Fig. 6.

(h) In the case of rough or non-planar joints, a non-linear shear strength envelope may be more representative of the test results. In these cases, it is possible to consider other well-established failure criteria, calculate the respective parameters, and deliver them also as results of the tests. Such criteria include: the i value of Patton (Barton 1976) or the JRC of Barton and Choubey (1977). The latter also allows addressing the issue of sample size effects (Bandis et al. 1981).

(i) In the case of multi-stage tests, the apparent cohesion can be exaggerated due to accumulation of damage with successive shearing of the same joint specimen.

(j) As shear and normal displacement measurements are available, deformability parameters such as normal and shear stiffness of the samples may also be derived from the tests.

7 Reporting of Results

(a) The report should include the following:

i. A description of the test specimens, including:

- identification of all samples and specimens;
- the dates of sampling and testing;
- the total number of test specimens;
- the specimen dimensions, including nominal cross-sectional area;
- the source of each specimen, including project name, location, and depth, drill hole number and inclination;
- a geological description of each specimen, including a description of the intact rock, shear surface (e.g., roughness, aperture);
- orientation of the samples and test horizons (dip and dip direction), including the relative angle between the dip direction and the shear direction, or, in the case of borehole samples, the angle between the samples and the borehole axis;
- photographs of the specimens before and after the tests.

ii. A set of plots including shear stress versus shear displacement graphs, normal displacement versus shear displacement graphs, and normal load versus shear displacement graphs, in the case of CNS tests. Normal stress versus normal displacement graphs depicting the normal load application can also be added.

iii. Plots and tabulated values of peak and ultimate or residual shear stress versus normal stress, peak and ultimate or residual dilation angles, together with calculated values for the shear strength parameters.

(b) In the report, the following items may also be included. If not, they should be available upon request.

i. A diagram and description of the test equipment and a description of the methods used for taking, packaging, transporting, storing, mounting and testing the specimen. Reference may be made to this ISRM Suggested Method stating only departures from the prescribed procedures.

ii. Details of any special measuring devices employed to measure roughness, nominal areas or other specimen characteristics. For example, the name, type, resolution, and precision of any non-contact surface measurement device employed should be provided.

iii. Data tables with all values required to plot the graphs presented in the report.

Appendix:Terminology

Aperture distance between discontinuity walls measured perpendicular to the average discontinuity plane.

Apparent stress nominal stress on the discontinuity surface, which is the external normal or shear load applied to the discontinuity per nominal unit area.

Asperity any surface irregularity or deviation with respect to the average discontinuity plane. Irregularities and deviations can range from sharp or angular to smooth or rounded.

Asperities the collection of surface irregularities that comprise the discontinuity surface roughness.

Closed-loop testing system a testing system in which the true response of the loading actuator(s) is continuously compared with the desired response of the loading actuator (i.e., a feedback loop) and corrected if required.

Constant Normal Load (*CNL*) direct shear test methodology whereby the applied normal loading is held constant throughout the test and the normal stiffness may vary.

Constant Normal Stiffness (*CNS*) direct shear test methodology whereby the applied normal stiffness is held constant throughout the test and the applied normal load varies.

Dilation angle arctangent of the ratio of normal displacement to the corresponding shear displacement

i. *Peak dilation angle* (i_{peak}) arctangent of the ratio of the normal displacement at peak shear strength to the corresponding shear displacement.

ii. *Ultimate dilation angle* (i_{ult}) arctangent of the ratio of the normal displacement at ultimate shear strength to the corresponding shear displacement.

iii. *Residual dilation angle* (i_{res}) arctangent of the ratio of the normal displacement at residual shear strength to the corresponding shear displacement (Note that it is usually difficult to reach true residual strength, because of the limited shear displacement, and the term 'ultimate strength' should then be used).

Discontinuity any mechanical break in the integrity or physical properties of rock such as bedding planes, fractures, cleavage, cracks, joints, or faults. Discontinuities can be described as:

i. tight (closed) (i.e., consisting of opposing rock surfaces in intimate and generally continuous contact);

ii. gapped (open) (i.e., consisting of opposing rock surfaces separated by an open space);

iii. partially or totally filled (i.e., consisting of opposing rock surfaces separated by a space, which is partially or totally filled by any type of filling material, such as clay, gouge, breccia, mylonite, thin coatings or veins);

and further characterized as a function of their geometry as:

iv. planar to non-planar (undulating) (i.e., the level of deviation from the average discontinuity plane).
v. Well matched to poorly matched (i.e., the degree of interlocking between the two walls of the discontinuity).

Friction angle arctangent of the ratio of the applied shear stress to the corresponding apparent normal stress (σ_n) which is equivalent to the arctangent of the ratio of applied shear load to the corresponding normal load.

i. *Peak friction angle* (ϕ_{peak}) arctangent of the ratio of the peak shear strength to the corresponding apparent normal stress which is equivalent to the arctangent of the ratio of peak shear load to the corresponding normal load.
ii. *Ultimate friction angle* (ϕ_{ult}) arctangent of the ratio of the ultimate shear strength to the corresponding apparent normal stress which is equivalent to the arctangent of the ratio of ultimate shear load to the corresponding normal load.
iii. *Residual friction angle* (ϕ_{res}) equal to the residual friction angle if the apparatus is able to reach a large enough shear displacement.

Friction coefficient the ratio of the applied shear stress to the corresponding apparent normal stress which is equivalent to the ratio of applied shear load to the corresponding normal load.

i. *Peak friction coefficient* (μ_{peak}) the ratio of the peak shear strength to the corresponding apparent normal stress which is equivalent to the arctangent of the ratio of peak shear load to the corresponding normal load.
ii. *Ultimate friction coefficient* (μ_{ult}) the ratio of the ultimate shear strength to the corresponding apparent normal stress which is equivalent to the arctangent of the ratio of ultimate shear load to the corresponding normal load.
iii. *Residual friction coefficient* (μ_{res}) equal to the residual friction coefficient if the apparatus is able to reach a large enough shear displacement.

Nominal area (A) area obtained by measuring or calculating the cross-sectional area of the projection of the discontinuity surface onto the shear plane.

Normal displacement (δ_n) relative displacement of the joint halves perpendicular to the shear plane.

Open-loop testing system a testing system in which the desired loading response is sent as input to the loading actuator without any feedback of the actual response to facilitate correction.

Peak shear load (T_{peak}) the highest recorded shear load corresponding to a specific initial normal load after which the shear load decreases until ultimate or residual shear loads are reached.

Peak shear strength (τ_{peak}) the highest recorded shear stress corresponding to a specific initial apparent normal stress after which the shear load decreases until ultimate or residual shear loads are reached.

Pitch angular rotation about an axis perpendicular to the shear direction and parallel to the shear plane.

Residual shear load (T_{res}) equal to the residual shear load if the apparatus is able to reach a large enough shear displacement.

Residual shear strength (τ_{res}) equal to the residual shear strength if the apparatus is able to reach a large enough shear displacement.

Roll angular rotation about an axis parallel to the shear direction.

Roughness a measure of the inherent unevenness and waviness of a discontinuity surface relative to its mean plane.

Shear displacement (δ_s) relative displacement of the joint halves measured along the direction of the shear load.

Shear stiffness the ratio of shear stress to the corresponding shear displacement prior to reaching the peak shear strength.

Ultimate shear load (T_{ult}) the shear load corresponding to a specific initial normal load, for which the shear load remains essentially constant with increasing shear displacement.

Ultimate shear strength (τ_{ult}) the shear stress corresponding to a specific initial apparent normal stress, for which the shear stress remains essentially constant with increasing shear displacement.

Yaw angular rotation about an axis perpendicular to the shear direction and to the shear plane.

References

Alonso EE, Pinyol NM, Pineda JA (2011) Foundation of a gravity dam on layered soft rock. Shear strength of bedding planes in laboratory and large “in situ” tests. In: Anagnostopoulos A et al. (eds) Proc. 15th European Conf. Soil Mechanics and Geotechnical Engineering, Athens, Greece, IOS Press, Amsterdam

ASTM (2008) Standard test method for performing laboratory direct shear strength tests of rock specimens under constant normal force. ASTM International, West Conshohocken, p 12

Aydan Ö, Shimizu Y, Kawamoto T (1992) The anisotropy of surface morphology characteristics of rock discontinuities. Rock Mech Rock Eng 29(1):47–59

Bandis S, Lumsden AC, Barton N (1981) Experimental studies of scale effects on the shear behaviour of rock joints. Int J Rock Mech Min Sci Geomech Abstr 18(1):1–21

Barla G, Barla M, Martinotti ME (2010) Development of a new direct shear testing apparatus. Rock Mech Rock Eng 43:117–122

Barla G, Robotti F, Vai L (2011) Revisiting large size direct shear testing of rock mass foundations. In: Pina C, Portela E, Gomes J (eds), 6th International Conference on Dam Engineering, Lisbon, Portugal. LNEC, Lisbon

Barton N (1976) Shear strength of rock and rock joints. Int J Rock Mech Min Sci Geomech Abstr 13(9):255–279

Barton N, Choubey V (1977) The shear strength of rock joints in theory and practice. Rock Mech Rock Eng 10:1–54

Blümel M, Pötsch M (2003) Direct shear testing system. Geotechnical Measurements and modelling. In: Natau O, Fecker E, Pimentel E (eds), Karlsruhe, Germany, Swets and Zeitlinger, Lisse, pp 327–332

Blümel M, Button EA, Pötsch M (2003) Stiffness controlled shear behavior of rock. 10th ISRM Congress, Technology roadmap for rock mechanics. Johannesburg, South Africa. South African Institute of Mining and Metallurgy, Johannesburg, vol 1, pp 121–124

Boulon M (1995) A 3D direct shear device for testing the mechanical behaviour and the hydraulic conductivity of rock joints. In: Second Int. Conference on Mechanics of Jointed and Faulted Rock MJFR-2, Vienna, Balkema, Rotterdam, pp 407–413

Chryssanthakis P (2004) Oskarshamn site investigation. Drill hole KSH01A. The normal stress and shear tests on joints. SKB Report No. P-04-185. SKB, Stockholm, p 38

Grasselli G (2001) Shear strength of rock joints based on quantified surface description. PhD Dissertation. École Polytechnique Féderale de Lausanne

Hencher SR, Richards LR (1982) The basic frictional resistance of sheeting joints in Hong Kong granite. Hong Kong Engineer, pp 21–25

Indraratna B, Haque A, Aziz N (1999) Shear behaviour of idealized infilled joints under constant normal stiffness. Géotechnique 49(3):331–355

ISRM (2007) The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974–2006. In: Ulusay R Hudson JA (eds), Suggested methods prepared by the Commission on Testing Methods, ISRM, Compilation arranged by the ISRM Turkish National Group, Kozan Ofset, Ankara

JGS (2008) Method for direct shear test on a rock discontinuity. Japanese Geotechnical Society, Tokyo, p 8

Jiang Y, Xiao J, Tanabashi Y, 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(2):275–286

Johnston I, Lam T (1989) Shear behavior of regular triangular concrete/rock joints–analysis. J Geotec Engng 115(5):711–727

Leichnitz W (1985) Mechanical properties of rock joints. Int J Rock Mech Min Sci Geomech Abstr 22(5):313–321

Muralha J (2007) Stress paths in laboratory rock joint shear tests. In: Ribeiro Sousa L, Olalla C, Grossmann N (eds), 11th ISRM Congress The second half century of Rock Mechanics, Lisbon, Portugal, Taylor & Francis, London, vol 1, pp 431–434

Priest SD (1993) Discontinuity analysis for rock engineering, 1st edn. Chapman & Hall, London

Stimpson B, Metcalfe RG, Walton G (1970) A new field technique for sealing and packing rock and soil samples. Q J Eng Geol 3:127–133

Tatone BSA, Grasselli G (2009) A method to evaluate the three-dimensional roughness of fracture surfaces in brittle geomaterials. Rev Sci Instrum 80:125110–125119

USACE (1980) Method of test for direct shear strength of rock core specimens. United States Army Corps of Engineers, Vicksburg, p 9

Wittke W (1990) Rock mechanics: theory and applications with case histories. Springer-Verlag, Berlin