Experimental Study of Shear Behavior of Rock Joints under Two Types of Boundary Conditions: Constant Normal Load and Constant Normal Stiffness

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Abstract. Shear destruction of rock mass along weakened planes is one of the main reasons of the failure of career boards, underground workings and rock slopes. The paper deals with laboratory testing of rock joints under direct shear loading. Special test and measurement complex was created to study deformation and strength characteristics of rock joints. Test specimens were made from single slab of sandstone of homogeneous structure. Shear tests have been conducted under constant normal load (CNL) and constant normal stiffness (CNS) boundary conditions at three values of normal compressive stress: 0.5 MPa, 1.2 MPa and 1.8 MPa. The analysis of test results allowed to reveal patterns of changes of deformation-strength properties of rock joints depending on the level of normal load, boundary conditions and roughness values. The ultimate shear stress is always higher under CNS boundary condition than CNL for the same values of normal compressive stress. Shear stress practically retains constant value after reaching the ultimate stress under CNL boundary conditions and it decreases under CNS conditions. The values of ultimate shear stresses, shear modulus and the length of linear section on "shear stress–shear displacement" curve increases with increasing surface roughness at the equal levels of normal compressive stress.

1. Introduction
Rock joints are the main reason for the destruction of rock mass, the caving of pit edges, inrushes in underground workings, and lead to significant economic losses. The term "joint" refers to any weakening surface in a rock mass having a tensile strength significantly less than that of the solid rock. Joints are of any origin (geological - faults, bedding, cleavage) or man-made, caused by the explosion, pressure, process mining. Joint are the main determinant of geomechanical statement of rocks, underground mining facilities and deep pits. Shear strength of joints can be defined by testing of open cracks under direct shear by field measurements directly in-situ, taking into account the scale factor. Due to the complexity of in-situ tests, laboratory tests are usually carried out on samples from real mining materials, as well as on models from artificial materials. The obtained regularities of the deformation and destruction of geomaterials are further used to predict the destruction of rock massifs.

A number of works devote the studying of behavior of joints on the basis of laboratory modeling on rocks and equivalent materials. The influence of various factors was studied: various model materials, loading speed, type of stress state, humidity, rock structure and patterns of location and orientation of various crack systems relative to the main crack [1-11].
The purpose of this study was to determine the common patterns and the differences of deformation and strength characteristics joints by laboratory modeling of shear loading under two types of boundary conditions: constant normal load (CNL) and constant normal stiffness (CNS) on sandstone specimens of homogeneous structure.

2. Test procedure and equipment
The tests were carried out according to the method of laboratory determination of shear strength of rock joints of International Society for Rock Mechanics - ASTM D 5607-08 [12, 13]. In general, the method includes requirements for testing to determine the strength under direct shear of solid rock samples of low strength and rock samples containing discontinuities. Two types of boundary conditions take into account: 1) CNL - constant normal load acting in a direction perpendicular to the shear force; 2) CNS - constant normal stiffness in the direction perpendicular to the action of the shear force). At the same time, rock joints can be open or almost closed, and should have negligible tensile strength.

The CNL boundary conditions are suitable for situations where the surrounding rock allows joint to move freely without dilatancy constraints, resulting constant normal stress remains during the shear process. The shear test under the CNL boundary condition is only valid for applications such as open rock slopes. However, for non-planar joints, the shear loading leads to dilatancy, since one surface roughness overlaps the other, and if the surrounding rock mass is unable to deform sufficiently, then an increase of normal stress inevitably occurs during the shear. Thus, the shift of rough rock joints under such conditions does not accompanied by constant normal load, but rather normal load is variable, and the stiffness of the surrounding rock mass plays an important role in the shift behavior of rock joints. This mode of shear CNS boundary conditions is correct for describing of deep underground workings or rock entrenched slopes. In many causes, shear tests under constant normal stiffness more accurately match the conditions of failure of rock massif and allow to define the ultimate strength of rock joints.

Laboratory tests were carried out on special testing and measuring complex created on the basis of Instron 8802 servo-hydraulic press. The special equipment for testing of rock joints under CNS boundary conditions (functional layout) is demonstrated in Figure 1. The equipment for testing under CNL boundary conditions and general view of testing and measuring complex are showed in [14].

The normal compressing load (Figure 1) was created by hydraulic cylinder and was controlled by the pressure gauge and the electronic pressure sensor. The mechanism of normal load and connecting elements are designed in such a way that to provide uniform distribution of the normal load on the entire plane of joint. When modeling the CNS boundary condition, the normal load was applied through the set of four springs. The overall stiffness of the springs must be chosen to simulate different stiffness conditions in accordance with the stiffness of the surrounding rock mass, but to allow the possibility of increasing the displacement in the direction perpendicular to the shear plane. The value of stiffness of springs set was chosen equal K=6 kN/mm according to studies [1, 2].

Normal displacement (displacement in the direction perpendicular to the shear force) was recorded using four sensors Solartron DP10S located in planes perpendicular to the normal force. The rate of shear load or shear displacement was set by the rate of movement of crosshead of Instron 8802 press and recorded by of Instron sensors. The shear load, shear displacement, normal load and normal displacement were recorded and saved in PC file during experiments with a frequency of 10 Hz.
Figure 1. Functional layout of testing and measuring complex for direct shear tests under the boundary condition CNS.

3. Test specimens and types of tests
The tests were carried out on specimens from sandstone, made from the single slab measuring 1200x400x300 mm. The material had sufficiently uniform structure and good repeatability of properties under uniaxial compression and tensile tests. The average values of compressive strength were 62.9 MPa, tensile strength - 18.6 MPa, Young's module 15.327 GPa, Poisson's ratio 0.132. The variations of the values under uniaxial compression and tensile strength were not more than 7% and 12% respectively. Joints were made by splitting of cylindrical samples into two parts (Brazilian test). The samples with well-mating surfaces were selected for further testing.

The surface roughness coefficient of JRC samples was calculated by the formula widely used in the literature [15]:

\[
JRC = 32.2 + 32.47 \log Z_2
\]

where \( Z_2 \) is square root of the derivative of surface profile, which is calculated by the formula for the case of discrete measurements:

\[
Z_2 = \left[ \frac{1}{L} \int_{x=0}^{L} (\frac{dy}{dx})^2 \, dx \right] = \left[ \frac{1}{L} \sum_{i=1}^{N-1} \frac{(z_{i+1} - y_i)^2}{x_{i+1} - x_i} \right]^{\frac{1}{2}}
\]

where \( L \) is the length of the profile at which the profile is measured, \((x_i, y_i), (x_{i+1}, y_{i+1})\) are the neighbouring coordinates of the profile, \( y_i \) is the roughness amplitude at the point of the profile \( x_i \). The surfaces of joints were digitized using laser 3-D scanner Rangevision PRO 5M with a step scan of 1 mm.

The surface profiles of sandstone joints were digitized and the values of \( JRC \) coefficients were calculated using the formulas (1, 2). Two groups of specimens were completed in accordance with the
values of $JRC$, of six specimens in each group, in the first group values of $JRC_1 \approx 9.5\div11.2$; in the second group $JRC_2 \approx 4.1\div5.3$.

Dental plaster (compression strength 80 MPa) was used for filling the specimens into the shear box. Each half of the specimen was “cemented” directly into the specimen holder. The main requirement is that the entire plane of the joint must be parallel to the upper and lower surfaces of shear box and in the future the plane of the joint must coincide with the plane of shear loading. As an example, the figure 2 shows a shear box with a test specimen placed in it.

![Figure 2](image)

**Figure 2.** Photos of two specimens of sandstone placed in shear box: $JRS = 4.8$ (a) and $JRS = 9.8$ (b).

Sandstone specimens were tested under CNS and CNL boundary conditions at three values of the normal compressive load: 0.5 MPa; 0.9 MPa; 1.2 MPa. The stiffness of the set of springs was $K=6$ kN/mm under CNS boundary condition and $K=0$ under CNL boundary conditions. Each group of six samples were tested under CNS and CNL boundary conditions at three values of normal compressive load 0.5 MPa; 1.2 MPa; 1.8 MPa (sum total twelve tests).

The tests were carried out according to the program stated in [14, 15]. For any shear test (CNL and CNS), a normal load was pre-applied at a rate of 0.01 MPa/s until the fixed value of normal stress was reached and then it held constant during the experiment. After stabilization of normal displacements at fixed value of applied normal load, shear load was applied. Shear displacement was carried out at constant rate 0.2 mm/min and increased until an ultimate or residual shear stress was reached. The shear rate value was chosen of 0.2 mm/min subject to the research conducted in [16], where the conclusion was made about the lack of influence of shear rate on ultimate shear stress at speeds no more than 0.5 mm/min. The effect of the high rates of 0.5 mm/min is to increase the ultimate shear stress for both types of boundary conditions.

4. Test result

Figures 3 and 4 demonstrates the dependences "Shear stress - shear displacement" for the samples of sandstone at three values of normal compressive stresses of 0.5 MPa, 1.2 MPa and 1.8 MPa under the CNS and CNL boundary conditions for specimens with the values of the coefficients $JRC_1 = 4.1\div5.3$ (Figure 3); specimens with values of the coefficients $JRC_2 = 9.5\div11.2$ (Figure 4).

A number of regularities of changes of deformation and strength properties are obtained for joints depending on the level of normal load, boundary conditions and surface roughness coefficient $JRC$ from the analysis of the dependence “Shear stress - shear displacement”.

The ultimate shear stress increases as the normal compressive load increases, as expected. At equal values of the normal compressive stress, the ultimate shear stress is always higher under the boundary condition CNS than under the condition CNL. The comparison of curves 1 and 2, 3 and 4, 5 and 6 in figures 3 and 4 demonstrates it. When normal compressive stress increases this difference decreases. Apparently, this pattern can be explained by the fact that the differences between the two boundary conditions are "smoothed" under the influence of higher normal stresses.
Figure 3. Dependences “Shear stress - shear displacement” for the samples of sandstone with the values of the coefficients $JRC_1=4.1\div5.3$ under CNS and CNL boundary conditions at three values of normal compressive stress of 1.8 MPa (curves 1 and 2); 1.2 MPa (curves 3 and 4); 0.5 MPa (curves 5 and 6).

Figure 4. Dependences “Shear stress - shear displacement” for the samples of sandstone with the values of the coefficients $JRC_2=9.5\div11.2$ under CNS and CNL boundary conditions at three values of normal compressive stress of 1.8 MPa (curves 1 and 2); 1.2 MPa (curves 3 and 4); 0.5 MPa (curves 5 and 6).
Under the CNL boundary condition, shear stress practically remains constant after reaching the peak value (curves 4 and 6 in figure 3, curves 2, 4 and 6 in figure 4). Under CNS conditions, shear stress decreases (curves 1 and 3 in figures 3 and 4). The "shear stress–shear displacement" dependences are gently sloping character under the CNL boundary condition.

The values of ultimate shear stresses increase with increasing of surface roughness at the equal values of normal compressive stress. At the same time, the "shear stress–shear displacement" curves become smoother without a distinct stress drop area at the post-peak deformation stage at lower values of JRC. An unstable character of shear deformation is observed at high values of JRC, specifically stress drop, sawtooth type of curves (curves 1, 2, 3 and 4 in figure 4).

The length of the linear section on "shear stress–shear displacement" curve, shear modulus of this curve and values of ultimate shear stress increases with increasing surface roughness value. The value of relative growth of normal stress and the value of normal displacement also increase with increasing of roughness value, i.e., the expansion of rock joint occurs in the direction perpendicular to the shear plane.

5. Conclusion
The test and measurement complex was created to study of rock joints under direct shear loading under two types of boundary conditions: constant normal load and constant normal stiffness. Direct shear loading tests were carried out on specimens from sandstone of homogeneous structure and sufficiently good repeatability of deformation and strength characteristics under preliminary uniaxial compression and tension tests.

Analysis of test results under CNS and CNL boundary conditions at values of normal compressive stress 0.5 MPa, 1.2 MPa and 1.8 MPa allowed to obtained given below regularities of changes of deformation-strength properties of joints depending on the level of normal load, boundary conditions and surface roughness values. The ultimate shear stress increases as normal compressive load increases. The ultimate shear stress is always higher under CNS boundary condition than under CNL condition at equal values of normal compressive stress. Shear stress practically retains constant value after reaching the ultimate stress under CNL boundary conditions and it decreases under CNS conditions. The values of ultimate shear stresses, the length of linear section on and shear modulus of "shear stress–shear displacement" curve increases too with increasing surface roughness.

References
[1] Indraratna B, Haque A and Aziz N 1999 Shear behavior of idealized infilled joints under constant normal stiffness Geotechnique 49(3) 331–55
[2] 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. of Rock Mech. and Min. Sci. 41(2) 275–86
[3] Gao Y and Wong L 2015 A Modified Correlation between Roughness Parameter Z2 and the JRC Rock Mech. and Rock Eng. 48(1) 387–96
[4] Hencher S R and Richards L R 2015 Assessing the Shear Strength of Rock Discontinuities at Laboratory and Field Scales Rock Mech. and Rock Eng. 48(3) 883–905
[5] Indraratna B, Thirukumaran S, Brown E T and Zhu S P 2015 Modelling the Shear Behavior of Rock Joints with Asperity Damage under Constant Normal Stiffness Rock Mech. and Rock Eng. 48(1) 179–95
[6] Jang H S and Jang B A 2015 New Method for Shear Strength Determination of Unfilled, Unweathered Rock Joints Rock Mech. and Rock Eng. 48(4) 1515–34
[7] Mirzaghorbanali A, Nemcik J and Aziz N 2014 Effects of Cyclic Loading on the Shear Behavior of Infilled Rock Joints under Constant Normal Stiffness Conditions Rock Mech. and Rock Eng. 47(4) 1373–91
[8] Mohd–Nordin M M, Song K I, Cho G C and Mohamed Z 2014 Long–Wavelength Elastic Wave Propagation Across Naturally Fractured Rock Masses Rock Mech. and Rock Eng. 47(2) 561–73
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