Article no. 32

THE CIVIL ENGINEERING JOURNAL 3-2019

STRAINS OF ROCK DURING UNIAXIAL COMPRESSION TEST

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ABSTRACT

The contribution is focused on investigation of strains in a rock specimen during uniaxial compression test. Three components of strain occur in cylindrical shape specimen: axial, radial and volumetric. Determination of the strains is possible by using of local sensors. Strain gauges fixed on specimen surface were used in this study. Axial and radial components of strain were measured directly, and volumetric strain was calculated. Two types of rock were tested, syenite and sandstone, to illustrate variability of strain behaviour of rocks. Strain measurement is necessary for determination of Young's modulus and Poisson's ratio. Moreover, early states of failure can be identified by volumetric strain which is considerably sensitive to failure states.

KEYWORDS

Rock mechanics, Uniaxial compression test, Strains, Strain gauge

INTRODUCTION

Strain measurement can significantly widespread knowledge obtained from a uniaxial compression test of rock and can contribute to description of deformation characteristic of tested rock. Data from strain measurement is necessary in order to determinate Young's modulus and Poisson's ratio as widely used parameters in geomechanical engineering calculations. Phases of specimen's failure can also be identified according individual components of strains.

Uniaxial compressive strength (UCS) is one of the most common parameters for rock characterisation in rock mechanics. Hence, the testing of this property is well accommodated in rock mechanics laboratories. Cylindrical shape of specimens is typical for UCS testing and the mentioned shape is also required by worldwide accepted American standards (ASTM) [1] and Suggested methods of International Society for Rock Mechanics (ISRM) [2]. Three types of strains can be distinguished: axial, radial (referred as circumferential or lateral, as well) and volumetric. Axial and radial components of strain can be measured directly, while volumetric strain usually has to be calculated afterwards according Equation (1) [2].

$$\varepsilon_{vol} = \varepsilon_{ax} + 2\varepsilon_{rad} \tag{1}$$

Every type of measurement to determine strains should be carried out with local sensors. Other indirect methods are less accurate and can distort results. Two approaches of strain measurement are common in practice according type of sensors: removable or permanently fixed (Figure 1). The former one usually employs linear variable differential transformer (LVDT) sensors based on mechanical movement sensing by induced voltage changes in magnetic field. The second approach employs strain gauge sensors based on measurement of electrical resistance changes caused by changed length and cross-section of conductor in the sensor. Regardless of technology, two sensors are usually applied to measure axial strain. Averaging of readings is performed in order to eliminate potential error caused by bending of a specimen during test. Radial strains can be measured by chain sensors (Figure 1) or by single point measurement of diameter change at one or more points by LVDT sensors. In case of strain gauges, one or more sensors are placed perpendicular to longitudinal axis to measure radial component of strain (Figure 1).

Advantage of strain gauges is low cost in comparison with LVDT sensors. On the other hand, strain gauges are not reusable, and installation takes longer time, then in case of LVDTs. Significant advantage of LVDTs is their robustness and low distortion of measurement by specimen cracking.

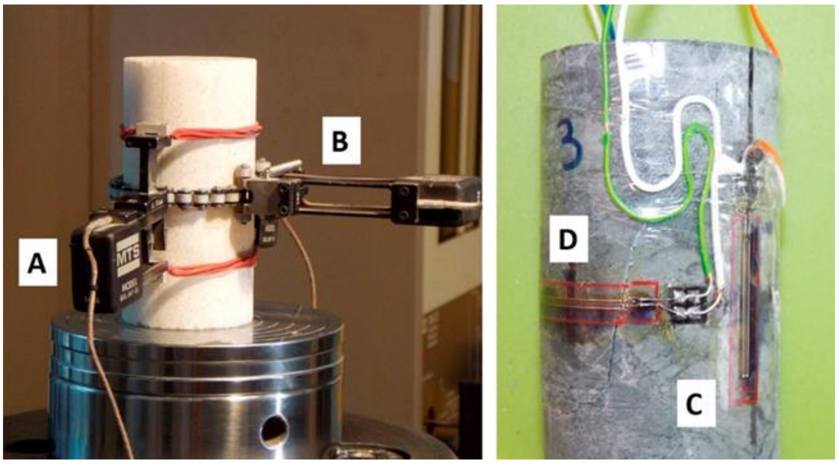

Fig. 1 – Examples of strain measurement sensors: Left – LVDTs; Right – strain gauges. A – axial LVDT; B – circumferential chain LVDT; C – axial strain gauge; D – radial strain gauge.

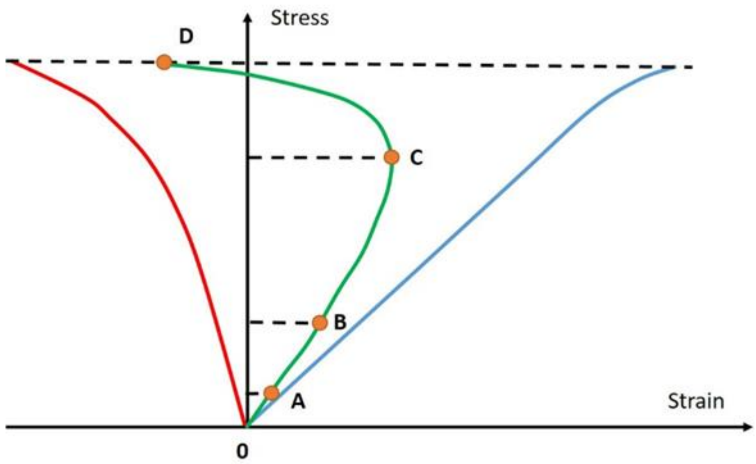

Fig. 2 – Behaviour of strain components: blue – axial strain; red – radial strain; green – volumetric strain (modified from [3], [4]).

Example of typical strain behaviour of rock during UCS test is illustrated in Figure 2. Axial strain (blue curve) performs the lowest sensitivity and the failure can be identified in relatively short advance only. Radial strain (red curve) shows more nonlinear trend than axial one, thus, recognition of approaching failure is earlier. Radial strain has more weight in calculation of volumetric strain (green curve) according to Equation (1). Hence, the sensitivity of failure approach recognition is the highest in case of volumetric strain. Comprehensive study on granites has been carried out, where volumetric strain was investigated in detail and specific stages of failure were described [4]. The failure stages are highlighted in Figure 2: 0-A – pre-existing crack or pore closure in the beginning of loading, which occurs in specific rock types only; A-B – elastic region with linear trend of strains; B – new crack initiation; B-C – stable crack growth; C – minimal absolute volume of the specimen; C- D – unstable crack growth; D – failure at reaching the UCS [3], [4]. Assumptions about crack initiation and propagation influence were validated by further study where acoustic emission was employed [5]. Detailed study of the strain components by Cieslik [6] can be utilized in extensive description of deformability and failure process of various rock types. Sensitivity of rock to water content can be described also by changes in trends of strains as in study by Kwasniewski [7].

Experiments in the presented contribution were focused on acquire of practical experience with strain measuring during uniaxial compression tests of rocks in laboratory. The issue was to evaluate possibility of strain components observation and recognition of early stages of specimen failure by strain gauge sensors. The experiments were carried out on two types of rock in order to study variability of rock strain behaviour. Consequences on methodology of Young's modulus and Poisson's ratio determination based on obtained results are discussed as well.

METHODS

Uniaxial compression tests have been carried out on rock specimens equipped by strain gauges. The cylindrical shaped specimens had diameter of 54 mm (NX) and length to diameter ratio of 2.0. The tests were carried out on two specimens: one of syenite with load control at rate 0.5 MPa/s and one of sandstone with axial deformation control at rate 1.0 μm/s. Different rock types and test control were employed in order to study possible variability of results.

Strain gauges fixed on specimen surface with acrylic resin were used to measure strains. Two of the sensors were placed parallel with axis of the specimen and direction of loading in the middle of specimen height to measure axial strain. Readings from the pair of the sensors were averaged and in further analysis were used only the averaged data. Radial strain was measured by one sensor placed perpendicular to loading direction, similar as in Figure 1 – Right. Period of data acquisition during the tests was 0.5 second.

Obtained data was processed after the tests and volume strain was calculated according Equation (1). Further, Young's modulus and Poisson's ratio were calculated for intervals of each 5 MPa of axial load according Equations (2) and (3) [1] in order to evaluate relevance of the parameters' determination methodology choice.

$$E = \frac{\Delta\sigma}{\Delta\varepsilon_{ax}} = \frac{\sigma_{max} - \sigma_{min}}{\varepsilon_{ax,max} - \varepsilon_{ax,min}} \quad (2)$$

$$\nu = -\frac{E}{\frac{\Delta\sigma}{\Delta\varepsilon_{rad}}} = -\frac{E}{\frac{\sigma_{max} - \sigma_{min}}{\varepsilon_{rad,max} - \varepsilon_{rad,min}}} \quad (3)$$

Where *E* – Young's modulus; *v* – Poisson's ratio; *σ* – axial stress; *ε* – strain with index *ax* – axial, *rad* – radial; indexes *min*, *max* – limit values of each calculated interval.

RESULTS

Stress-strain diagrams of the tested syenite and sandstone are plotted in Figure 3 as output of the laboratory experiments. Three components of the strain are plotted separately: axial, radial and volumetric strain. Axial strain in both cases indicated approaching the UCS of the specimen by softening (decreasing of Young's modulus – see Table 2) relatively late. Axial strain of the syenite was approximately linear up to ca 80 MPa of axial stress. Vice versa, the sandstone performed increasing of axial stiffness and only short linear trend occurred between 10 and 25 MPa of axial stress. Radial strain performed nonlinear behaviour with permanently decreasing of slope in both cases. Volumetric strain, as linear combination of previously described strain components according Equation (1), appeared as curved increasing until point with the lowest absolute volume of the specimen, and then continuously proceed into the specimen absolute volume increasing. The described trend of the volumetric strain is more considerable in case of sandstone. Sudden change in trend of radial and volumetric strain close to specimen failure was caused by crack which harmed the sensor similar to case showed in Figure 1 – D.

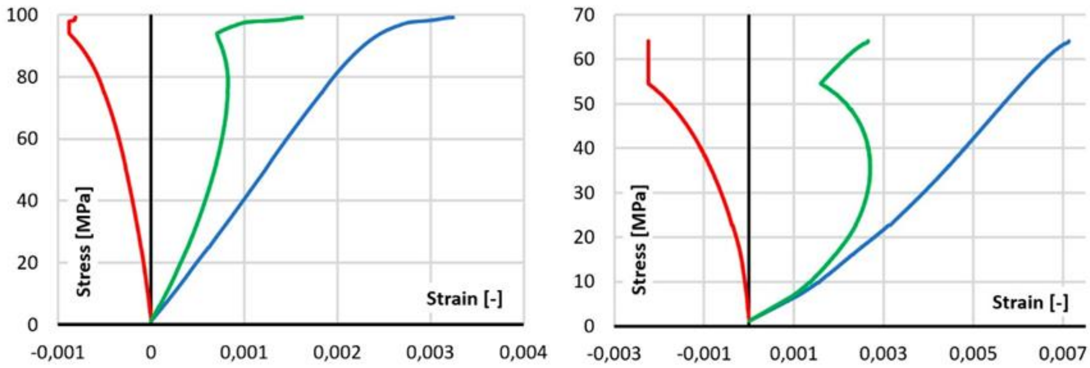

Fig. 3 – Stress-strain diagrams with components of the strains: Left – syenite; Right – sandstone; blue line – axial strain; red line – radial strain; green line – volumetric strain.

UCS values determined by laboratory tests are listed in Table 1. Axial stress at level of minimal absolute volume $\sigma_{vol\ min}$ and its percentage of the UCS are listed in Table 1 also. Young's modulus and Poisson's ratio values calculated for intervals of 5 MPa of axial stress are listed in Table 2. The Young's modulus has the same trend as axial strain curve (blue curves in Figure 3), because it is dependent only on axial component of strain. Values of Poisson's ratio showed steady increasing trend in both cases even over the typically considered maximum 0.5. Explanation is given in the discussion chapter.

Tab. 1 - Comparison of uniaxial compressive strength and stress at minimal volume of the sample

Specimen	UCS [MPa]	$\sigma_{vol\ min}$ - axial stress at minimal absolute volume [MPa]	$\sigma_{vol\ min}$/UCS [%]
Syenite	99.3	78.7	79
Sandstone	64.1	36.1	56

DOI 10.14311/CEJ.2019.03.0032

Tab. 2 - Values of E – Young's modulus and v – Poisson's ratio calculated for certain intervals of axial stress stated in the 1st row of the table (values for sandstone).*

Interval of axial stress [MPa]	5-10	10-15	15-20	60-65 20-25*	65-70 25-30*	70-75 30-35*	75-80 35-40*	80-85 45-50*	85-90 50-55*	90-95 55-60*	95-99 60-64*
E – syenite [GPa]	37.6	39.2	41.3	40.7	39.6	38.2	40.0	34.5	29.1	20.2	5,9
v – syenite [-]	0.16	0.18	0.20	0.37	0.42	0.47	0.49	0.58	0.63	0.63	-
E – sandstone [GPa]	6.6	8.4	8.0	8.5	9.9	10.6	11.0	11.7	11.1	10,4	7,7
v – sandstone [-]	0.09	0.12	0.19	0.28	0.34	0.44	0.55	0.88	1.18	-	-

DISCUSSION

Employment of strain gauges to measure strains during UCS tests can be considered as sufficient and inexpensive solution for testing procedures when post-peak analysis is not required. It should be noted from practical point of view, that installation of this type of sensors requires longer time because each sensor is installed separately. Hardening of the resin is time consuming as well. Hence, total time of specimen preparation before testing is several hours, which is significantly longer than employment of LVDT sensors. Installation of the LVDTs requires only several minutes according the author's experience from Rock Mechanics Laboratory at Graz University of Technology. Disadvantage of strain gauges is also potential damage by cracking of the specimen before reaching UCS, as it was demonstrated on the carried out experiments.

Trends of strain behaviour of the tested rocks are in compliance with previous published studies [3], [4]. Considerable variability of obtained results was also noted between syenite and sandstone samples (Figure 3, Table 1). Explanation can be found in dissimilar nature of the tested rocks – relatively high strength compact crystalline igneous syenite and relatively soft sandstone as porous clastic sediment. Load rate applied during the test can also influence the strain response. Load control applied on the syenite was characterized by steeper ramp of stress increasing than deformation control applied on the sandstone. Longer exposition of the specimen to high level of stress close to UCS allows to develop more cracks, thus the value of UCS can be decreased and strain behaviour can be also influenced [3], [5].

Calculated Young's modulus is dependent on considered interval of axial load, as is shown in Table 2. Precariousness can occur if there is not specified stress level for Young's modulus determination. Uncertainty of methodology proceeds constantly in determination of rock deformation characteristics. ISRM methods suggest three approaches for calculation of Young's modulus [2]. Comparison of the approaches was carried out and variation of obtained results was discussed e.g. by study of Malkowski [8]. European standard, established also in the Czech Republic, requires determination of the modulus from unloading-reloading loop at certain level of UCS of the tested rock [9]. The last mentioned approach should overcome problem of nonlinearity of the axial strain, which was also recognized on the sandstone in this study (Figure 3, Table 2).

Appropriate determination of Poisson's ratio is also issue. Variability of Poisson's ratio along whole range of loading can be noticed on the data in Table 2. The parameter is dependent on the radial strain, which performed nonlinear trend (Figure 3). Poisson's ratio was calculated even higher than 0.5 after reaching of stress at the minimal absolute volume of the specimen (Table 1). The minimal absolute volume is represented by reverse of volumetric strain (see point "C" in Figure 2). This point is characterized as beginning of unstable crack growth. The most significant structural changes occur when the stress overcomes this limit and density of micro cracks increases by about sevenfold [4]. Hence, the real failure of specimen can be considered at this point. When cracks propagate through the specimen, total volume can expand even with increasing of the axial stress [3]. The strain measurement considers whole system including the cracks. The formula (3) is valid only within continuum elasticity theory, but the conditions after reaching the point “C” are out of the continuum theory limits. Hence, the Poisson’s ratio should not be determined at stress level higher than the point “C”.

CONCLUSION

UCS tests of rocks with strain measurement were carried out and described in this study. Practical experience and evaluation of advantages and limits of strain gauge sensors have been acquired. Obtained results of the strain components are in accordance with previous studies. Expected variability of the strain behaviour due to material and loading conditions changes was found. Influence of the mentioned aspects is not possible to evaluate, because of currently insufficient amount of the data. Hence, further experiments should be carried out. Progress of failure process was recognized on volumetric strain data in notable advance before approaching UCS of the specimens. Crack development before failure at UCS has significant influence on Young’s modulus and Poisson’s ratio determination. Thus, the research should be widespread in terms of appropriate methodology selection for the mentioned parameters determination.

ACKNOWLEDGEMENTS

This paper has been worked out under the project No. LO1408 "AdMaS UP - Advanced Materials, Structures and Technologies", supported by Ministry of Education, Youth and Sports under the „National Sustainability Programme I".

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