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DEVELOPMENT OF AUTOMATIC CONTROL OF MULTI-STAGE TRIAXIAL TESTS AT THE UNIVERSITY OF MISKOLC

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ABSTRACT

During rock mechanical examinations (either in case of the measurements of slope stability or planning of underground cavities and boreholes) one of the most important tasks is to determine the failure curves of rocks. For determining a generalized hyperbolic envelope minimum three parameters are necessary: tensile strength, uniaxial compressive strength and the triaxial compressive strengths with different confining pressure. With the application of the latest measurement system installed in rock mechanical laboratory of University of Miskolc, where multi-stage triaxial tests can be carried out besides conventional triaxial tests to measure triaxial compressive strength.

A series of multi-stage triaxial compression tests were conducted to examine which measurement setup and control mode could most precisely determine the failure points separating the single load stages during the tests because the precise recognition of these is a critical point of the measurement. It was found that brittleness played an important role in choosing the adequate measuring mode (manual or automatic) and control signal (inductive transducer, strain gauge).

1. INTRODUCTION

Three different test types are suggested by ISRM (International Society for Rock Mechanics) for the determination of failure envelope such as individual or single-stage triaxial test, multiple failure state or multi-stage triaxial test (MFS) and continuous failure state (CFS) test. Three single-stage triaxial tests are required to generate a complete failure envelope; consequently three specimens are required at least, while one multi-stage triaxial test may give the complete failure envelope using only one specimen.

The primarily advantage of the multi-stage triaxial test method manifests itself whenever availability is limited and therefore the specimens are expensive. This could be a crucial issue primarily for the rock specimens obtained from deep drilling. Two different methods may be adopted to perform the common multi-stage triaxial test in the practice: the conventional ISRM suggested method [3], and its slightly modified version [1].

1.1. Multi-stage triaxial test according to the recommendation of ISRM

The ISRM recommended testing procedure could be divided into sub- stages as shown below. As a starting step, the axial load and the confining pressure should be increased until both of them reach the value of the confining pressure (p_0 represents this confining pressure value) of the first stage, bringing the specimen into hydrostatic condition.

In the next phase of the test the axial load is then increased keeping confining pressure p_0 constant until the corresponding failure point is observed in the axial stress – axial strain curve (Point A in *Figure 1*). The axial load is being increased while the strain rate is kept constant (displacement controlled test). Failure is defined as the point in the stress–axial strain curve where the curve declines in a given degree from the curve fitted on previously measured $\sigma - \varepsilon$ points, namely when the residual deformation exceeds a threshold value we have preliminary adjusted.

The confining pressure is then increased to the next level in one step, namely from A to A’ in Figure 1. This step is followed by an axial load increase using the procedure described above. Repeatedly increasing the axial load – confining pressure steps we get to the point in the measuring process when the required highest confining pressure is reached (B’ in *Figure 1*). The confining pressure will then be kept constant, while the axial loading is continued till the failure of the specimen (Point C in *Figure 1*). After the failure the axial load will fall back to its residual value (Point D, *Figure 1*). The confining pressure is progressively reduced until the specimen is completely unloaded. During the unloading phase the axial stress as a function of confining pressure curve will follow the residual strength envelope. [3]

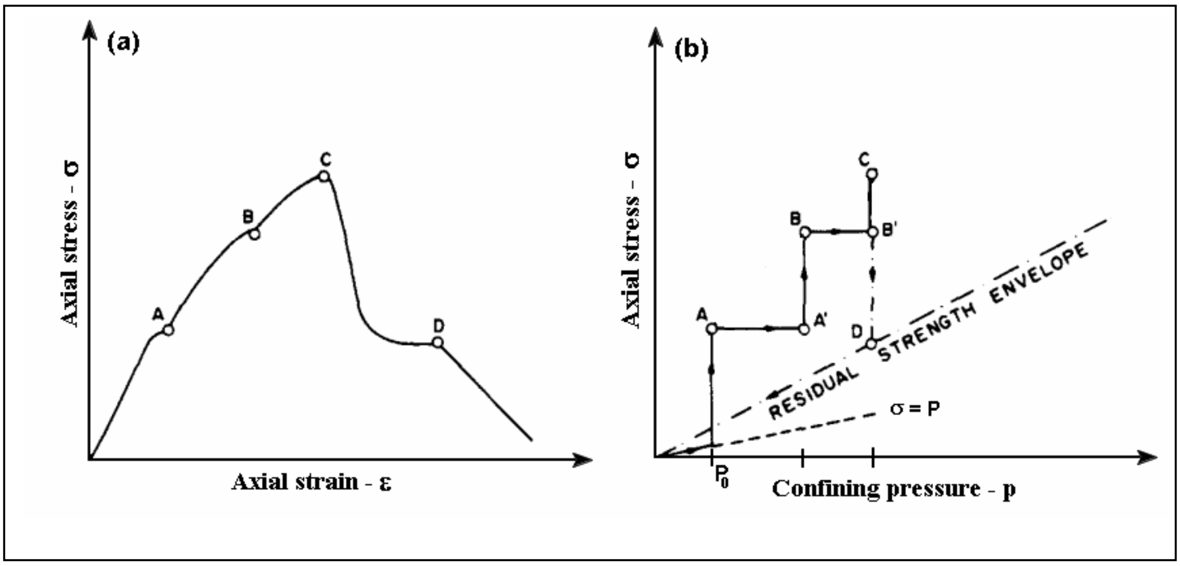

Figure 1.
Multi-stage triaxial test: (a) axial stress – axial strain curve (b) axial stress – confining pressure curve [3]

The authors [3] described the configuration of the testing equipment which is contained by the ISRM recommendation, as well.

1.2. Modified multi-stage triaxial testing method

The modified multi-stage triaxial testing, which is also widely used in practice, is a slight modification of the testing method suggested by the ISRM [2]. The difference between the two methods arises from the fact that after reaching the first imminent failure point, the vertical load is released to the level of the actual confining pressure, developing a hydrostatical state. (*Figure 2*) After this stage, the next desired confining pressure level will be reached while continuously keeping up the hydrostatical state, and then the vertical load is increased till the next failure point. This loading cycle has to repeat starting it from a higher and an even higher hydrostatic phase. According to the developers of the modified testing method, the comparison of the modified multi-stage triaxial method and the single stage triaxial testing results indicates that the modified method is suitable to determine the triaxial strength envelope for brittle rocks. [1]

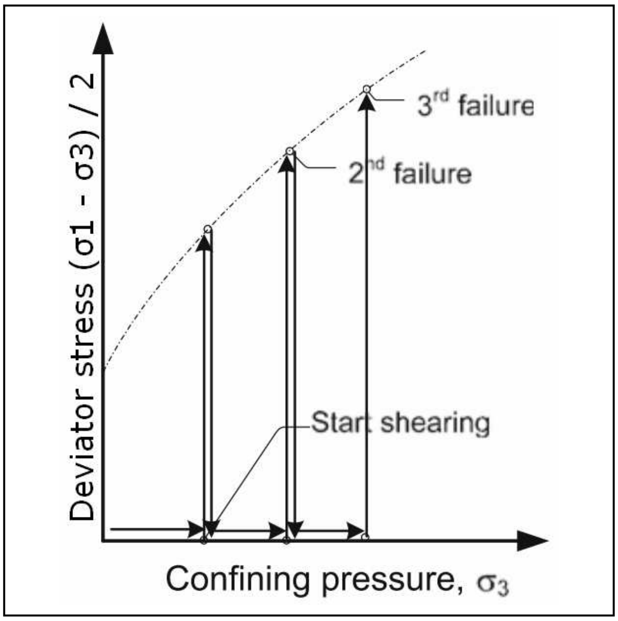

Figure 2.
Stress paths of modified multi-stage triaxial test [2]

According to the literature [1], multi-stage triaxial test has been proven to yield a strong correlation to single stage triaxial test results. The authors highlight that the selection of failure point significantly relies on the experimenter's judgment, since the experimenter should define them during the experiments. The control modes based on real time data processing are suitable for replacing the subjective, individual judgment.

2. MATERIALS AND METHODS

Different rock materials were used in order to gain experiences about the best possible adjustments and set up of the measuring system while testing brittle and ductile rock specimens. Specimens were cut away from andesite, rhyolite and sandstone blocks. Andesite specimens represented the brittle rock type, whereas rhyolite and sandstone specimens represented the transition between brittle and ductile rocks. Two sample groups were defined for the tests.

Table 1

Rock materials used for the tests

Rock type	Quantity [pieces]	Slender ratio	Average uniaxial compressive strength [MPa]
Andesite	3	1.9	170
Rhyolite	4	1.9	73
Sandstone	1	1.9	66

The axial deformations of andesite, rhyolite and sandstone specimens of the first group are measured by inductive transducers in order to control the load. The andesite and rhyolite specimens of the second group are equipped with strain gauges with perpendicular position to the axis of the cylindrical specimens, therefore in this group the load control based on the gauge measuring relative deformation. Relevant reference of the ISRM contains the regulation of sample preparation [1], therefore they are not detailed here.

2.1. Testing equipment

During the tests Hoek triaxial cells were used in which the confining pressure is produced by oil pressure, the axial load is prepared by a high capacity test frame. The Italian Controls testing apparatus were used to make up of the following parts: a 3000 kN loading capacity loading machine is connected to an Advantest 9 servo hydraulic testing unit furthermore a 700 bar confining pressure capacity triaxial unit linked with a Sercomp 7 automatic control console.

The advanced pressure controller capacitates the testing apparatus to perform multi-stage triaxial tests during which the applied load can be regularly reducible or increasable. The whole measurement process can be controlled by the TriaxRocks software developed for multi-stage triaxial tests. To meet our requirements the measuring system had to be able to perform multi-stage tests. The test frame is principally designed for concrete tests, therefore we had to elaborate numerous adjusting modifications for rock materials before the tests.

The manufacturer took into consideration our remarks when programming the TriaxRocks software. It was designed in compliance with our requirements to control specifically multi-stage triaxial tests. We personally took part in the beta test of the software in Milan.

2.2. Applied control methods during the test stages

The test progress forms two stages in terms of controlling. During the first stage load transducer controls the initial confining pressure and the axial loading until confining pressure reaches the value of the first step. The second examination stage starts right after reaching the value of the initial confining pressure. At this stage the experimenter could choose to use the signal of inductive displacement transducers measuring the axial deformation or to use strain gauges sticking on axial as well as perpendicular position to the axis of the cylindrical specimens for controlling the loading stages.

The real-time data processing of the measuring system allows the user to switch in any phase of the test from the subjective manual activation of the pressure step to the automatic recognition of the failure (or residual strength). The pressure step is then, in any case, performed automatically. The system in automatic mode tries to detect the approach of a failure of the sample by monitoring the instantaneous elastic modulus variation. This instantaneous elastic modulus is calculated as a ratio between the load change and deformation change on a time interval, where the time interval is user settable. If this ratio exceeds a settable threshold (different threshold is also to be defined for the residual phase) the software will start a next pressure step in three phases:

- The vertical load is reduced by a given amount, and the control of the test frame switches from displacement/strain control to load control;
- The cell pressure increases (if the test is in the increasing load phase) or decreases (if the test is in the residual – decreasing load – phase);
- The vertical control is switched again to displacement/strain and the test goes on.

3. RESULTS

We concluded that the multi-stage triaxial tests of rhyolite, which represents transition between tough and brittle rocks could be accomplished both in automatic and manual modes. (*Figure 3*)

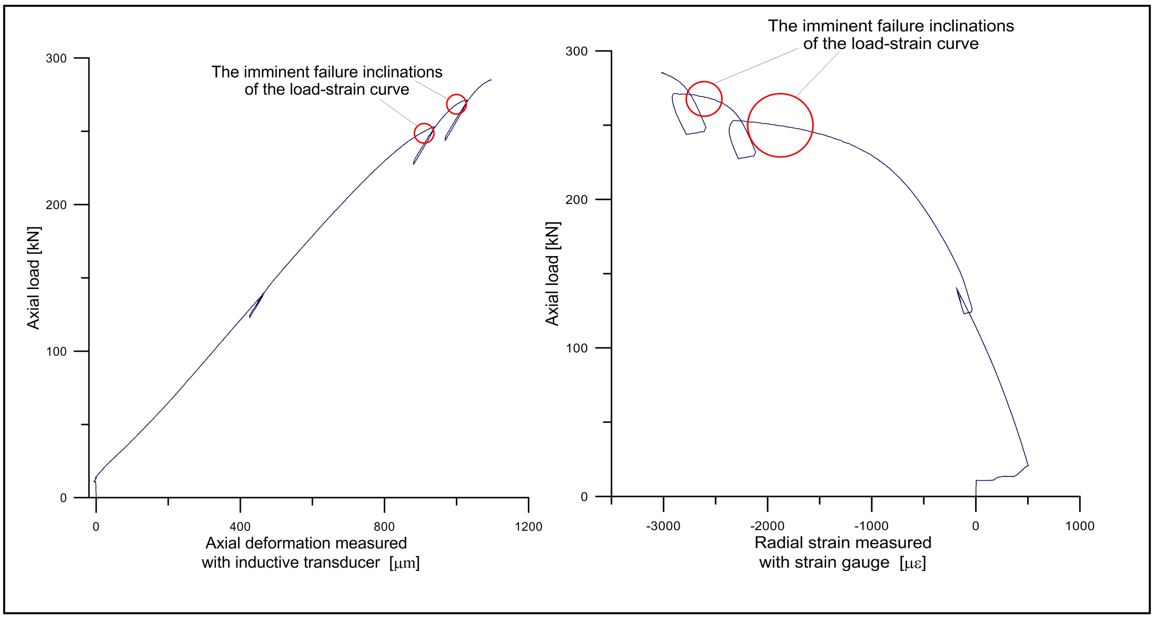

Figure 3. a), b)
a) axial load – axial strain curve of rhyolite sample during the load increasing phases
b) axial load – radial strain of rhyolite sample during the load increasing phases

It was found that the failure points could be recognized more precisely based on the radial deformation measurements performed by strain gauges in horizontal position to the cylindrical specimen's axis than using inductive displacement transducers measuring the axial deformation in case of andesite specimens, which represented the brittle rocks (*Figure 4*). The plastic limit and breaking limit lie close to each other; therefore the possibility of an accidental failure is less in automatic mode, using a proper threshold.

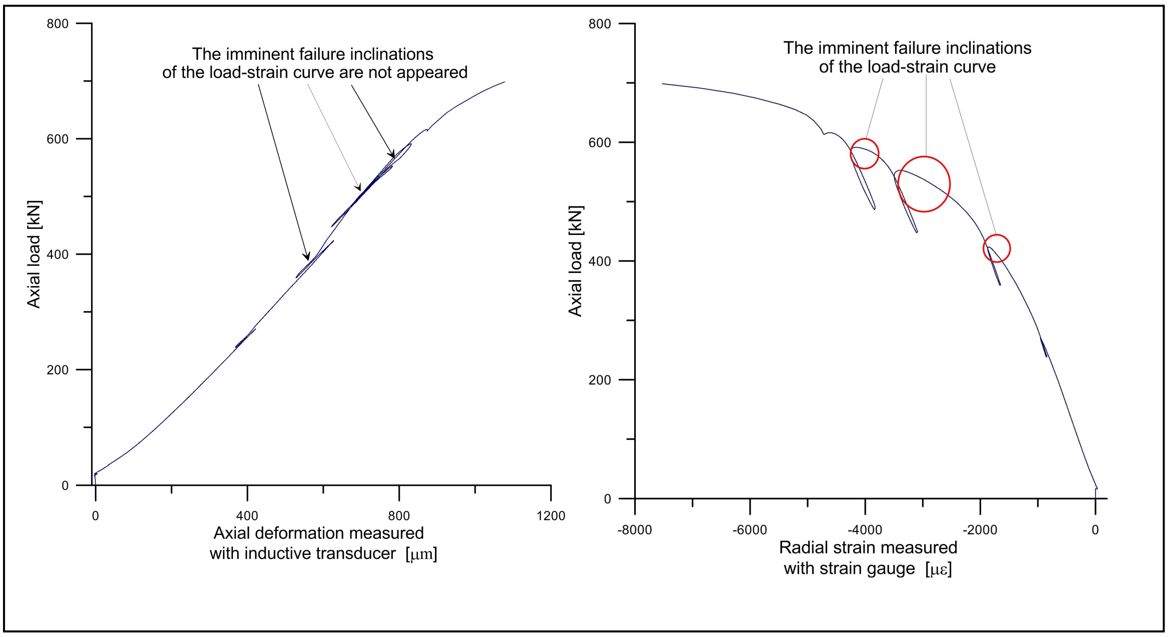

Figure 4. a) b)
a) axial load – axial strain curve of andesite sample during the load increasing phases
b) axial load – radial strain of andesite sample during the load increasing phases

The sandstone specimen was not appropriate for the strain gauge measuring through the discontinuous mantle of the sample, which does not allow the sticking on the strain gauge, therefore its axial strain was measured with inductive transducers. When we test tough rocks, the measurement could be accomplished both in automatic and manual modes because the failure points are uniquely determined by the transducers, as well.

4. CONCLUSIONS

To sum up, we conducted a series of multi-stage triaxial tests using different rock types to define the best adjustments, control method and measuring mode. We concluded that the automatic measuring mode of the multi-stage triaxial tests supported by real-time data processing is suitable for replacing the subjective, individual judgment of the experimenter.

It was found that both the signal of inductive transducers and strain gauges are possible for the experimenter to choose to control the load of the specimen but our experience showed that during the tests of brittle samples an unpredictable failure may damage the strain gauge, making further measurements of that specimen impossible. The adequate selection of the measuring mode (manual or automatic) and control signal (inductive transducer, strain gauge) should depend on the brittleness, homogeneity and mantle property of the specimen.

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