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Influence of specimen shape deviations on uniaxial compressive strength of limestone and similar rocks

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A B S T R A C T

The results of an experimental research program on ninety intact rock cylindrical test specimens are presented. The main goal is to examine the effect of specimen shape deviations (i.e. "micro" deviations from flatness, parallelism of ends and specimen axis perpendicularity) on uniaxial compressive strength (*UCS*) for limestone and similar rocks. The analysis of the results shows that in the case of the modern testing equipment there are no significant effects on the *UCS* value of neither parallelism nor axis perpendicularity for angle deviations up to 2°. The new proposed tolerance for flatness of specimen end (expressed as total height of the surface profile) is 0.08 mm, to be used with the aim of optimization and control over the aforementioned influences of test specimens in further compressive testing. The experimental research results related to the *UCS* were further re-examined by recently proposed numerical model based on Embedded Discontinuity Finite Element Method (ED-FEM) which proves a reliable interpretation of complex 3D failure mechanisms. We show an excellent correlation between the experiments and our numerical results, as a further confirmation of our findings.

1. Introduction

The present investigation discovers some results that are at first glance unexpected and covers some fundamental aspects of rocks that have already been addressed and even included in the norms, but not yet adequately investigated for some actual cases of intact rock testing. More precisely, we focus on the uniaxial compressive strength (*UCS*) of intact rock and the unavoidable, but insufficiently investigated influences of the test specimen shape deviations on this important mechanical property that appear in testing and can significantly affect the results. The designation *UCS* here has its usual meaning in rock mechanics, which is peak stress sustained by the specimen, i.e., failure load divided by cross-sectional area of the specimen.

It is known, from laboratory work and rare studies on rock[1,2] and other studies on concrete cylinders,[3] that the inaccuracies during preparation of cylindrical specimen in the forms of 'micro' deviations from flatness, perpendicularity and parallelism typically lead to the determination of smaller 'macro' properties – strength and various moduli. That impact can be significant at certain level of inaccuracy of specimen preparing, and should not be ignored. It also means that it should be objectively evaluated and controlled in testing. Influences which are observed are intact specimens shape deviations or deviations of testing objects from the ideal cylinder.

Although laboratory testing topics were much investigated and published, and the 'shape effect' of the specimen is well known in connection with the *UCS*,[4] little data on this specific subject has been published since the 1970s. Some other ('scale') effects of specimen shape and size (length/diameter ratio and diameter size) were described in 5, but on this issue there are no recent state-of-the-art data. On the other hand, by observing the results in an accredited laboratory for a prolonged period a need for further clarification of the effects of specimens shape deviations in following testing became clear, in the case of limestone and similar rocks with uniaxial compressive strength *UCS* about 100–150 MPa. The effects of specimen side straightness, ends flatness, ends parallelism and perpendicularity to the specimen axis on *UCS* and stress–strain curve have been measured in several actual ways and examined on approximately ninety homogeneous specimens in the presented experimental investigations. These investigations were conducted as a part of wider research[6] which also included other mechanical properties, such as Young's modulus of elasticity and Poisson's ratio. Apart from conducting the experiments, we performed the 3D numerical simulations in order to confirm and

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examine the influence of shape deviations to *UCS*. The numerical model is based upon Embedded Discontinuity Finite Element Method (ED-FEM)[7–11] and capable of simulating the complex failure mechanisms in 3D space.

The *UCS* range of approximately 100–150 MPa observed in this work is relatively common (limestones, dolomites, some sandstones), and is located between the two extremes. The first extreme is weak rocks with *UCS* up to 50 MPa, where the influence of small shape deviations is insignificant.[12] The other extreme is rocks with *UCS* even above 300 MPa (e.g. granite), where this influence is unquestionable and regulated by strict requirements.[13–18] Therefore, it can be assumed that for rocks with middle values of mechanical properties the requirements for sample shaping should be somewhere between the extremes (and not necessarily on such a strict level, such as those specified in some applicable standards). Some previous test results (laboratory of Institute IGH in Split, Croatia, period 2006–2012) also indicated that the current specimen requirements for rocks with *UCS* about 100–150 MPa are to some extent overstated and suggested a need for further research.

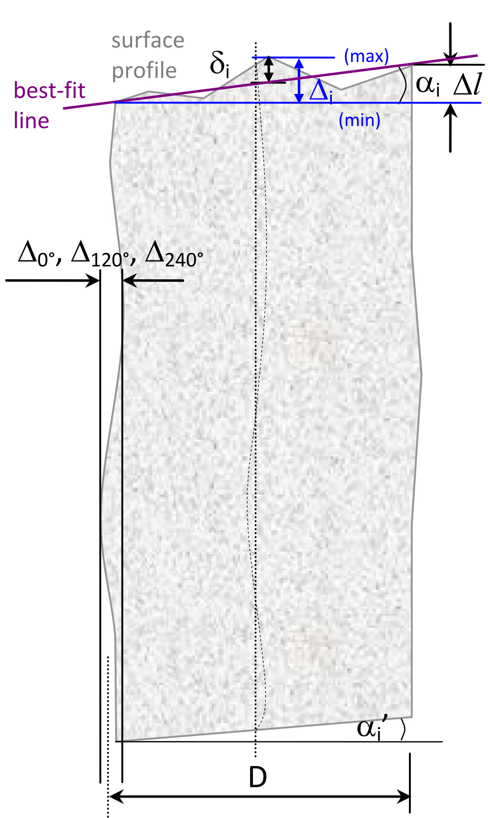
Determination of the input values observed here – shape deviations of intact specimen according to ASTM D4543[17] is shown in Fig. 1. In testing according to ASTM D4543, it is necessary to indicate at least four diameters on the specimen, two mutually perpendicular on the upper end and two opposing on the lower end. Along each diameter points spaced 3 mm shall be marked in which the surface position readings are taken. During measurements, the specimen is in the V-block placed on the flat test surface. From the readings thus obtained the surface profiles can be drawn and shape deviations of the specimen determined as shown in Fig. 1. Side is checked along three straight lines spaced 120°.

Note: These preliminary tests of intact specimens shape deviations and conformance to shape tolerances are demanding regarding sensitivity/accuracy requirements, and if conducted manually, time consuming, tedious and subject to the influence of human factor (they may become a 'bottleneck' for further testing, particularly if the specimen should be returned to the preparation (grinding) due to the strict requirements which are sometimes very difficult to achieve).

Reference investigations which determined the current requirements (shape tolerances) for test specimens shown in Fig. 1 were conducted in the 1970s.[1,2] It is surprising that others, more contemporary have not been found. If we consider the flatness only from reference investigations (Fig. 2), for rocks of interest (limestone, marble, sandstone), the effect of flatness on the *UCS* is clearly less significant than for rocks with high strength (granite). When considering non-parallelism (Fig. 3), if for the mentioned types of rocks only the results that are valid for modern testing machines (spherical head) are isolated, then no *UCS* falls due to non-parallel ends, with a very small number of results. It appears that a critical range of flatness *W* and non-parallelism Δl, where the decrease of *UCS* would occur, at that time were not included in the research.

Fig. 2 shows a weak dependence of *UCS* on *W* for limestone and marble until $W \approx 3000$ μin. = 0.076 mm. The question is at which *W* value the strength will begin to decrease, taking into account statistical variability and risks. In Fig. 3, for the spherical head test the fall of *UCS* is not registered until $\Delta l \approx 34 \times 10^{-3}$ in. (slope of 0.9° for specimen diameter 2.125 in. = 54 mm). Accordingly, update of the results and extended range of flatness and parallelism are needed to examine what is the effect of specimens shape deviations in subsequent testing of *UCS* for the limestones and rocks of similar (medium) strength.

Additional motivation for the research is the fact that the current standards and recommendations that are in use[13–20] specify the requirements for specimens which are of various strictness and sometimes very difficult to achieve. The diversity of requirements in certain documents is confusing, because an agreement of the profession should exist in this issue. Also, some requirements



ASTM tolerances (ASTM D4543-08):

(1) Side flatness (straightness)

$\Delta_{max} = \max(\Delta_{0°}, \Delta_{120°}, \Delta_{240°}) \leq 0.50$ mm

(2) End flatness

$\delta_{max} = \max(\delta_i) \leq 0.025$ mm i=1,…,4 (4 diameters)

(3) Perpendicularity of the ends to the specimen axis

$\max(\Delta_i / D) \leq 1/230 = 0.0043 = \mathrm{tg}\ 0.25°$ i=1,…,4

(4) Parallelism of the ends

max. angular difference between the opposing best-fit straight lines (for spherically seated test machines) ≤ 0.25°

$\max \Delta\alpha_i = \max(\alpha_i - \alpha_i') \leq 0.25°$ i,i'=1,2

Δ_i - difference of the max and min readings on diameter i („W" in preliminary investigation[1], for α_i=0°)

δ_i - max difference of the surface profile and the best-fit straight line along diameter i

α_i - slope of the best-fit straight line along the diameter i

α_i'- slope of the best-fit straight line along the diameter i' opposite (at opposite end) to the diameter i

D - average specimen diameter (measured at mid-height)

Δl - 'nonparallelism' from earlier investigations[1]

Fig. 1. Shape deviations and tolerances of the cylindrical specimen according to ASTM D4543.