Influence of shape surface on the actual stress distribution generated along the contact during the uniaxial compressive strength test

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ABSTRACT: Uniaxial compressive strength is one of the key mechanical properties used to characterize rock materials. From international (ISRM) to national (ASTM, UNE) standards have been developed to ensure the trustfulness of testing results. However, they are quite severe with the geometrical tolerances considering the brittleness of rock materials, that provokes the specimens to form chips while machining them during the preparation process. This research analyses the influence of the surface geometrical deviations of the samples during the uniaxial compressive test. The effect of the stress distribution at the contact surface is analyzed using machined metal samples that accurately reproduce controlled flatness deviations. Moreover, pressure films are placed at the contact area to qualitatively record their influence on the actual contact stress distribution. These results are compared to those obtained on rock specimens. Therefore, influence of real contact conditions can be addressed according to the actual machining possibilities of rock materials.

Keywords: uniaxial compressive strength, contact conditions, experimental contact pattern, load distribution.

1 INTRODUCTION

Mechanical characterization of rocks is compulsory to address the design of most mining and civil engineering projects under safety conditions. One of the most important material properties to be determined is the uniaxial compressive strength (UCS). There are different options to obtain its value. For example, it can be determined using indexes obtained from the point load test or the Schmidt hammer test (Goodman, 1981). However, the most reliable test is the uniaxial compression one. It consists of two stiff platens, usually made of steel, that compress the specimen up to its failure. Results can strongly vary depending on the surface finishing properties of the plates as well as the geometry and dimensions of the sample. Many standards agree to use cylindrical samples with a length L to diameter D ratio about L/D=2.5, the diameters being at least around 50 mm, and always 10 times greater than maximum grain size (ASTM D7012-10, Bieniawski & Bernede 1979, UNE 22-950-90). Regarding the platen restriction, proposed values for its hardness, flatness and dimensions are also in good agreement between the standards (ASTM D4543-19, UNE 22-950-90, ISRM 1977).

Nevertheless, there are some relevant differences regarding the geometrical tolerances of the samples, as it is shown in Table 1. A graphical representation of this tolerances is shown in Figure 1a.

Table 1. Summary of the geometrical restrictions proposed by three different standards to determine the UCS in rock materials.

Standard		Flatness (mm)	Side Straightness (mm)	Perpendicularity α (minutes)
UNE	Low deformability	0.020	0.30	10.0
	Medium deformability	0.050	0.40	20.0
	High deformability	0.100	0.50	30.0
ISRM		0.020	0.30	3.5
ASTM		0.050	0.50	15.0

Geometrical tolerances set in the different standards are quite restrictive when it comes to rock materials. In fact, lower flatness deviations are similar to the best results that can be expected from a careful turning of metallic materials. Considering that, obtaining the required quality using rock samples and saw cutting tools is extremely complicated. Furthermore, due to the intrinsic brittleness of most rock materials, chips and partial damage are frequent during the specimen preparation process. Even in those cases where a lapper is used such tolerance levels are almost unreachable and only lead to time and money consuming operations.

In the current article, the effect of the surface geometry is experimentally analysed using pressure films placed between the plate and the specimen. To address this issue accurately, different specimens with controlled generated surfaces have been manufactured and tested using steel and aluminium to simulate the behaviour of a strongly stiff material and high to medium deformability rocks respectively. The shape of the samples has been guaranteed using a coordinate measuring machine, also used to analyse a limestone specimen with high quality finishing treatment. The comparison of the results allows to stablish a guidance on the influence of geometry shape on the stress distribution generated at the contact. This will allow to readdress the recommended values proposed by the different standards.

2 METHODOLOGY

In order to address the influence of the surface geometry in the contact load distribution, different and controlled contact surfaces must be generated. There are many possibilities of surface geometry that satisfy the flatness restrictions, as it just imposes the maximum range values in which the final geometry must be contained without referring how those values should be distributed. For example, a saw-tooth final geometry with triangles of height 0.1 mm would verify a 0.1 mm flatness restriction, in the same way as an inclined plane with a maximum height difference of 0.1 mm. However, the load distribution generated all over the contact would be different in these two cases and will influence the final output of the test. Based on this idea, two kinds of metallic specimens have been manufactured: with perfect flat surfaces and with convexity on their top end. In the latter, specimen top ends have been machined to reproduce a spherical surface which maximum height is set at the center of the cylinder in the case of metallic materials. Maximum heights (height difference between π_1 and π_2 planes) were set to 0.033 mm, 0.100 mm and 0.500 mm in order to, not only cover the range of geometrical tolerances recommended by the different standards but also to reproduce the case of clearly deviated specimens.

The rest of the parameters considered in the standards also affect the load distribution generated; but this analysis will consider exclusively the flatness deviations. This parameter has been controlled using a coordinate measuring machine (Figure 1b) to ensure the validity of the results and proving that all machined specimens are well within the standard values.

The rock specimen was obtained from a prismatic sample using a sampler. After that, the specimen was lapped by its both ends to guarantee a flat surface with the highest possible finishing quality.

As the contact is generated between the specimen and the platens these have to be carefully considered. They have been made of steel and their diameters are set to those of the specimens, as all the standards recommend this value within their different proposed ranges.

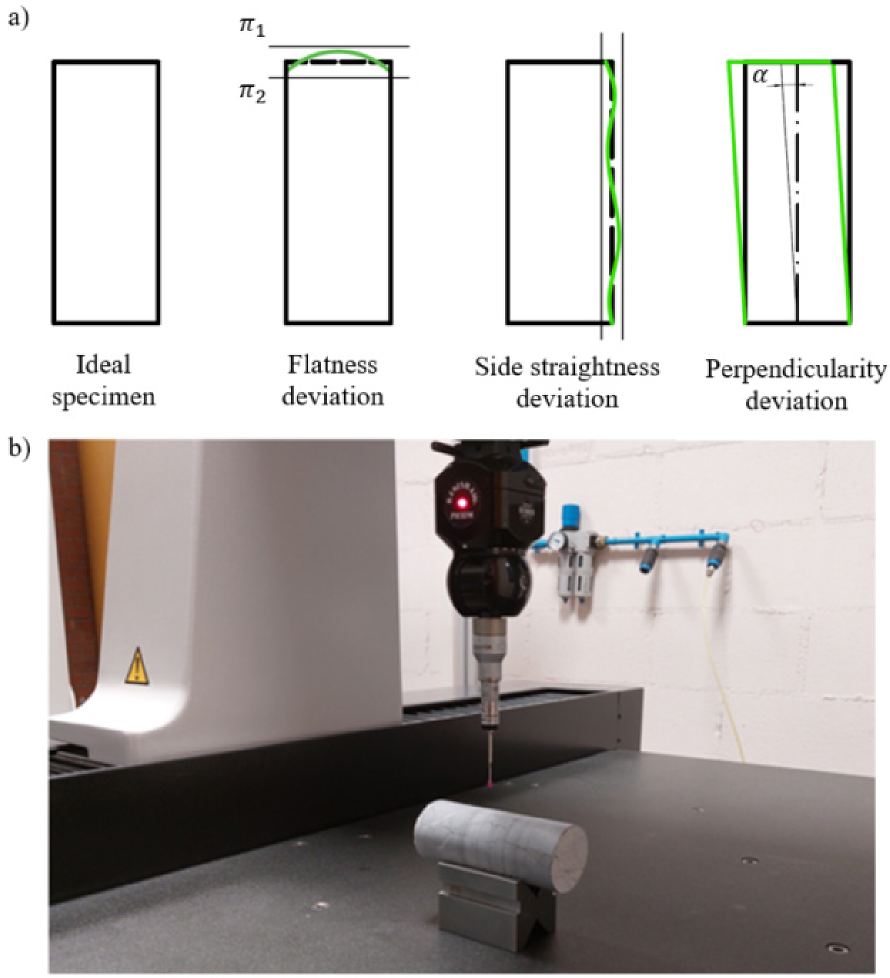


Figure 1. Specimen geometries used (a) and coordinate measuring machine during the geometrical inspection process (b).

To experimentally record the stress distribution generated in the contact, two pressure films have been used in each test, one for the top and another for the bottom end. They are made of small bubbles that encapsulate coloured liquid liberated after a certain amount of load is applied over them. There are different types of films, so they must be carefully selected depending on the stress range expected during the test. Due to the stiffness difference between the steel specimen and the rest of them, a different pressure film designed for loading conditions ranging from 50 to 130 MPa has been used for steel whereas films ranging from 10 to 50 MPa were used for the rest. It is worth highlighting that film results show different intensity between the points, allowing that determines where more load has been applied. However, it is not possible to tell, at least by simple eye inspection, whether the reached stress has clearly overpassed the maximum value the film was designed for. Even so, they still allow to determine the areas where the load has been applied and the relation between them in qualitative terms. In the case of convex surfaces, the contact pattern will depend on the matching points generated during the load application process. Thus, similar contact patterns cannot be expected in different materials if they are of different stiffness, that is if they have significantly different Young Modulus values. For that reason, maxim applied load has been varied from 180 kN, 60kN and 40 kN in the case of steel, aluminium and limestone respectively.

As the present analysis aims to study the significance of the specimen shape, it must be carefully determined whether the samples have and adequate geometry or not. Using the coordinate measuring machine shown in Figure 1, the main geometrical tolerances imposed by the different standards are checked and registered in Table 2. Metallic specimens clearly fulfil the requirements stablished in Table 1. The limestone specimen is within the flatness and perpendicular tolerances if considered medium deformability rock. However, some values of its side straightness are clearly out of the allowed limits. Nevertheless, as it will be exposed in section 3, these deviations do not seem to clearly influence the contact pattern.

Table 2. Geometrical tolerances obtained in specimens using the coordinate measuring machine.

Specimen Material	Concavity	Flatness (mm)	Side Straightness (mm) Element 1	Element 2	Element 3	Perpendicularity (minutes)
Aluminium	Flat	0.012	0.048	0.080	0.049	0.8
Aluminium	0.033	0.021	0.028	0.033	0.054	2.0
Aluminium	0.100	0.088	0.093	0.016	0.090	0.5
Aluminium	0.500	0.343	0.142	0.022	0.047	0.7
Steel	Flat	0.011	0.004	0.009	0.073	1.5
Steel	0.033	0.025	0.097	0.028	0.050	0.6
Steel	0.100	0.089	0.052	0.045	0.137	0.6
Steel	0.500	0.380	0.128	0.034	0.102	0.6
Limestone	-	0.021	0.085	0.766	0.786	20.0

3 RESULTS AND DISCUSSION

To ease comparison between different contact patterns, outer end circumferences have been depicted using a solid black line in Table 3 and Table 4, as well as later on Figure 2. After the execution of the planned compression tests, both steel (Table 3) and aluminium (Table 4) specimens show a contact pattern characteristic of convex surfaces with the deviations equal or higher to 0.100 mm, whereas below this value, the patterns are characteristic of flat surfaces. In the latter ones, stress is mainly located on a circular ring placed near the outer boundary, which means that the load is mainly generated in the outer circumference and progresses continuously to the centre. However, when the convexity deviation is higher than 0.100 mm, the contact pattern proves that stresses are initiated at the centre of the top end and increase towards the outer circumference. Therefore, it can be concluded that a change on the contact pattern must occur in the range from 0.033 to 0.100 mm of convexity deviation. The exact point of behaviour change will depend on the material properties of both the specimen and the platen so it will have different values for each tested material. Even so, as steel is clearly stiffer than most rock materials, these results state that higher flatness deviations than those proposed by the different standards will still guarantee successful and valid testing results. Thus, this experimental evidence proves that a debate about softening the value of the requested tolerances can be stated. Furthermore, pressure films turned out to be adequate to record the contact patterns due to convexity.

Table 3. Contact patterns in steel specimens.

Steel			
Flat	0.033 mm convexity	0.100 mm convexity	0.500 mm convexity

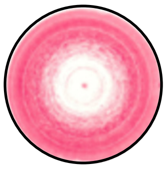
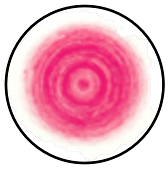
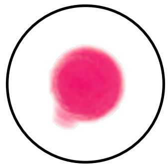
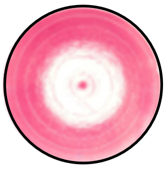
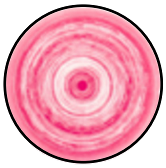
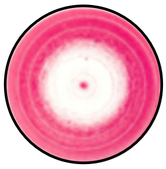
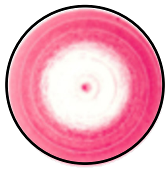
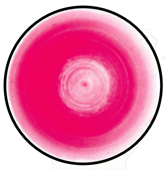
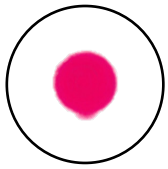
Top End				
Bottom End				

Table 4. Contact patterns in aluminium specimens.

	Aluminium			
	Flat	0.033 mm convexity	0.100 mm convexity	0.500 mm convexity
Top End				
Bottom End				

Despite its side straightness higher than the required by the standards, rock sample has behaved as in the case of flat ends (Figure 2). Thus, it seems reasonable that higher flatness deviations could be allowed in the case of rock materials, especially in the range between 0.033 and 0.100 mm. The patterns also show defined non-contact lines in areas surrounded by high stress values. Some of those are due to the tooling process and is remarkable that they have not been completely removed even after end surface lapping. A previous eye detection of these lines was not possible as they were hardly visible. Other lines are due to the inner characteristic of the limestone which show some weakness planes due to its heterogeneity. Regarding the stress distribution in the contact area, it seems to play a more important role than the own flatness deviation value of this specimen. Nevertheless, the stress has been irregularly distributed around the expected stress ring for flat surfaces in the bottom end. Moreover, the top end shows localized areas with clearly high stresses. These results prove that the contact stress is not always uniformly distributed along the two surface ends. Considering this, it can be concluded that there are remarkable differences from the assumptions made on the theoretical model to determine compression strength.

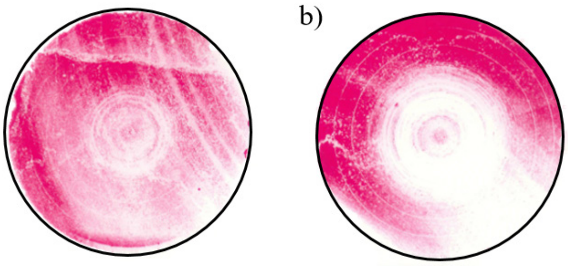


Figure 2. Contact patterns in the top (a) and bottom (b) ends of the rock sample.

4 CONCLUSIONS

Common equipment available for rock testing materials usually struggle to match the severe tolerances recommended by the different standards in the determination of uniaxial compression strength. In the case of flat and almost flat surfaces, maximum stress values are generated close to the outer end boundaries progressing towards their center, so not even in these cases the stress is uniformly distributed at each end. The experimental results of this study prove that a convexity deviation can be detected in contact patterns due to the lack of the aforementioned ring, generating an almost uniform coloured circle. Thus, when convexity deviations play a key role in the contact pattern on a specific test, the evolution of stresses is completely different to the flat case, and this may lead to unexpected failure patterns. In the case of rock materials, discontinuities within the specimen or even the preparation process may significantly affect the contact pattern and thus the stress distribution. Even when these facts can be neglected, the contact pattern shows that stress distribution is significantly higher near the outer boundary instead of uniformly distributed along the whole surface. This may influence the actual stress and lead to the specimen failure. However, this fact has not yet been carefully related in the present work for being beyond its scope and will be presented in future publications. Furthermore, it seems reasonable to readdress the flatness values proposed by the standards as it seems that even significantly stiff materials, as steel, behave as flat surfaces for significant higher deviation values than those proposed by the standards for the case of soft rocks.

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