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Determination of the Direct Tensile Strength of Granite Rock by Using a New Dumbbell Shape and its Relationship with Brazilian Tensile Strength

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Abstract. In this study, the determination of the direct and indirect tensile strength of granite rock was carried out in compliance with related standard test methods. In order to analyze rock tensile strength between direct (with using a new dumbbell shape) and indirect (Brazilian tensile strength) test methods were conducted and obtained results were compared between them. A new dumbbell shape samples were used in direct tensile tests and cylindrical specimens, which have different t/D ratios such as 0.5, 0.75, and 1.0, were used in Brazilian tests. Moreover, stress distribution and the stress intensity within the sample were analyzed with Finite Elements Method (FEM) and numerical modeling techniques by using ANSYS R18 software. The direct tensile test yielded lower strength values than the indirect test. For the specimens tested in direct tensile test, failure occurred middle of the dumbbell shape sample due to lower stress intensity factor. Since Brazilian disc test, stress value in the diametrical line of the specimen has been found higher than nominal stress value according to FEM, tensile strength value that should be re-calculated by using any coefficient. Moreover, t / D ratio did not affect the Brazilian test results.

1. Introduction

Tensile strength of rock material is usually defined as the maximum tensile stress which can be endured by such a material [1]. The tensile strength is often the critical mechanical parameter in the engineering practice involving rocks. It governs the failure of rock masses in problems such as the stability of mining roofs, galleries, fracturing, crushing, tunnel boring and in drilling and blasting [2]. Rocks shows lower tensile resistance than compressive and shear resistance. Tension cracks often develop before compression or shear failure [3]. An understanding of the rock behaviour under tension can be beneficial in the analysis that involves either intact rock or rock masses [3]. A number of methods exist to make brittle material fail in tension. In some, specimens are loaded by directly induced tension, as in the direct test for tension; in others, tension is induced indirectly via compression as the most famous is the Brazilian test [4]. The direct testing procedure is carried out on the samples, which require demanding processing conditions. Tensile stress is transferred to the ends of the samples using a cemented or glued steel plate with hooks on it. In order to ensure that the sample breaks at a specific point, it can be manufactured in the form of a dumbbell or dog – bone [1].

Direct tensile strength and deformability of rocks are difficult in the laboratory, and field. Because of the difficulties associated with experimentation in direct tensile tests, several of indirect methods have been suggested for determining the tensile strength of materials such as the Brazilian disc test, ring tests, and bending tests. These indirect methods aim at generating tensile stress in the sample by far-field compression, which is much easier, cheaper and common method for determining the tensile strength of rock in instrumentation than direct pull tests [5]. In general, the experimental results obtained by indirect tensile tests are not strictly comparable with those from direct tensile tests, because of the existence of a compressive component that may be far greater in magnitude than the induced tensile stress, and its influence on failure cannot therefore be ignored [4].

The Brazilian strength test is the most popular one, but the direct tensile strength test gives the most accurate values [6]. Various techniques have also been suggested for forcing the fracture in the central part of the specimen, i.e. away from the stress concentrations, such as shaping the specimen as a dog-bone or machining a notch on the surface. Whilst the first solution is expensive and not always feasible (e.g. for soft rocks), the second introduces stress concentrations which require theoretical interpretation [2].

There is huge amount of work related to determining the direct rock tensile strength and indirect tensile strength properties. Among these are given in below (Table 1), as explained by Briševac et al. [1] , Unlu and Yilmaz [7].

Table 1. The ratio of tensile strength determined by the direct method and the indirect tensile strength determined by the Brazilian test [1, 7]

Rock type	σ_{UTS} (MPa)	σ_{BTS} (MPa)	$\sigma_{BTS}/\sigma_{UTS}$	References
Bowral trachyte	13.72	12.00	0.87	[8]
Gosford sandstone	3.59	3.72	1.04	
Carrara marble	6.90	8.72	1.26	
Bane granite	13.45	14.34	1.07	[9]
Indiana limestone	5.86	6.21	1.06	
Sandstone	2.96	7.80	2.64	[10]
Vitoshasyenite	20.50	21.05	1.03	[11]
Grey gypsum	1.75	1.99	1.14	
White gypsum	1.42	1.29	0.91	
Aerated Concrete	0.86	0.54	0.63	[2]
Gravinacalcarenite	0.69	0.64	0.93	
Ufalei marble	5.90	6.90	1.17	[12]
Saraburi limestone	9.31	10.9	1.17	[13]
Saraburi marble	6.33	8.02	1.27	
Phu Phan sandstone	6.49	10.68	1.65	
Trachyte	13.7	7.7	0.56	[14]
Marble	7.5	10.1	1.35	
Gneiss	8.2	9.8	1.20	
Quartzite	16.3	13.0	0.80	
Granite	6.3	10.3	1.63	
Schist	13.3	11.8	0.89	
Shale	5.6	5.9	1.05	
Limestone	7.1	6.0	0.85	
Dolomite	5.7	8	1.40	
Sandstone	5.1	9.5	1.86	
Andesite	3.9	7.1	1.82	[7]
Sandstone	6.8	8.9	1.31	

Table 1 (continued)

Concrete	4.2	6.7	1.60
Limestone	11.9	11.8	0.99
Basalt	10.0	13.0	1.30
Artificial rock -A	3.3	6.08	1.84
Artificial rock -B	2.5	6.47	2.59
Artificial rock -C	2.8	5.72	2.04
Artificial rock -D	2.0	4.50	2.25

σ_{UTS}: direct tensile strength; σ_{BTS}: indirect tensile strength determined by the Brazilian test

The Brazilian test is the most common indirect method used to determine the tensile strength of rocks for years. Many researchers in this regard have done a lot of research on the validity of this method, whether it represents direct tensile strength value of materials, and discussed the results obtained.

Firstly, Carneiro [15] proposed the Brazilian test method to determine the tensile strength of concrete. The first application of the Brazilian test in rocks was carried out by [16]. After for a while, ISRM (1978) proposed this method to determine the indirect tensile strength of rocks. After the [17] proposed the Brazilian test method of determining the tensile strength of rocks, this method began to be widely used between1979-1991. In that years, many researchers studied on different subject such as anisotropy, characteristics of nonlinear deformation under compressive and tensile stresses, sample dimension effect [18-22, 10]. Pandey &Singh [10] investigated the characteristics of deformation in tensile stress and they obtained the Brazilian test value two times larger than the direct method values. Aydın and Basu [23] studied the potential of diametral stress-strain behaviour of igneous rocks in the Brazilian test to scale and predict their degree of weathering. Eraslan and Williams [24] given in their studies that the results of laboratory experiments during the investigation of the stress–strain characteristics of Brisbane tuff disc specimens under diametrical compressive cyclic loading. Andreev (1991) revised the current formula by using the ratio between uniaxial compression and tensile stresses to determine the tensile strength of the materials with the Brazilian test. The development of the commonly used Brazilian test method and the modification of the equation used continue from 1992 until the present day. In this regard, many researchers have conducted experimental, analytical and numerical studies. Perras and Diederichs [26] studied the relationship between direct tensile strength and Brazilian tensile strength and the predictability of tensile strength from other methods (such as crack initiation).

Briševac et al. [1] stated that a large number of scientific studies have been conducted on related to the tensile strength of the materials and the Brazilian test, but practical approaches have not been obtained still. For this reason, they suggested that, in order to obtain optimum results for all materials, more accurate correction coefficients should be determined by using the Brazilian test method for estimating the direct tensile strength values of materials.

Brace (1964) stated that the most suitable sample geometry to be used to determine the direct tensile strength of the materials should be "dog bone (dumbbell)". When the direct tensile strengths sample is not in the form of a "dog bone", the stress intensity can be cause on upper of the cylindrical sample (epoxy or cement connection points or at the point of connection side clamping). Thus, sample could be failed near the upper point and obtained invalid value. In order to prevent the difficulties encountered in the adhesion of the sample (for attachment) in the direct tensile strength test, Komurlu et al. (2016) proposed a new method for dog bone shaped specimens. Tufekci et al. designed a new apparatus with jaw-clutch mechanism to determine the direct tensile strength of rocks and compared the tests results between direct (dumbel-shaped specimens) and Brazilian indirect tensile strength. Unlu and Yilmaz [7] developed a new Push-Pull tensile testing apparatus. which can be used for determining direct tensile strength of cylindrical intact rock specimens and they obtained good correlation between the direct tensile test and the Push-Pull tensile test. Moreover, they proposed a new coefficient for obtained maximum tensile strength of rock. Unlu and Yilmaz [7] stated that push-pull tensile testing apparatus (PPTA) is a practical and reliable tool for determining direct tensile strength of intact rocks.

There is different idea about the value of tensile strength results of materials in literature. Therefore, many readers are confused about which test is best suitable test method or which tensile strength value is real value. In the conclusions or recommendations sections of some studies, it is emphasized that the Brazilian method is not suitable by some scientists and some of them Brazilian test method should be modified and / or the correction coefficients should be determined. In other words, it is understood that there is still no consensus even though it has been about 70 years since the scientific studies.

2. Experimental Method

In order to determine the tensile strength properties of granite using direct and indirect methods some experiments were conducted. The granite rock is mainly composed of alkali feldspar (orthoclase), plagioclase (albite), mica (biotite), quartz and opaque minerals. The rock has all crystalline (holocrystalline) texture.

The tensile strength tests were carried out in accordance with ASTM and ISRM suggested methods. The UTEST model which have electromechanical universal test device, fully automatic, PC controlled and 100 kN capacity was used for direct and indirect tensile testing. In this study, Brazilian tests were carried out at different thickness / diameter ratios (t / D); 0.5, 0.75 and 1.0 respectively. Core samples of 54 mm diameter were prepared from rock in laboratory and at least ten cylindrical samples were prepared in each different thickness (27 mm, 41 mm and 54 mm). The loading speed was chosen as 200 N / s in all experiments.

All specimens were cut and dimensioned according to related standards. At least seven dumbbell shape specimens were tested for direct tensile strength (Figures 1-2). The physical and mechanical rock properties were given in Table 2.

Figure 1. Brazilian test samples in different t/d ratios.

Figure 2. Dumbbell shape specimens for direct tensile test and electromechanical universal test machine

Table 2. Physical and mechanical properties of granite.

Specific Density (g/cm^3)	2.671 ± 0.009
Bulk density (g/cm^3)	2.644 ± 0.004
Apparent porosity (%)	0.484 ± 0.019
P-wave velocity (m/s)	5215 ± 81
Uniaxial compressive strength (MPa)	149.6 ± 18.4
Direct tensile strength (MPa)	5.27 ± 1.11
Brazilian tensile strength (MPa) (with curved loading jaw)	
t/D=0.5	9.54±0.68
t/D=0.75	10.85±0.92
t/D=1.0	10.06±1.20

All samples which were free from cracks were tested on dry conditions. In Brazilian experiments, all rock specimens were failed by axial splitting along the diameter aligned with the axis of loading and, failure occurred in direct tensile test was become in middle of the sample and direction of the crack was perpendicular to direction of the loading axis. Figure 3 shows the dimension of the direct test specimen and assembly of sample and direct tensile test fixture. It is very important that the axis impact of the tensile matches with the axis of the sample without bending or torsion, i.e. other external impacts [1, 33]. In order the sample breaks at a specific point such as middle of sample, specimens were prepared in dumbbell shape. Also, in order to ensure uniform force distributions during the test, the loading plate that consist of two symmetrical parts, were emplaced between sample and jaw. Before the testing, lubricant was used between jaw and loading plate's surfaces to allow transverse direction contract freely.

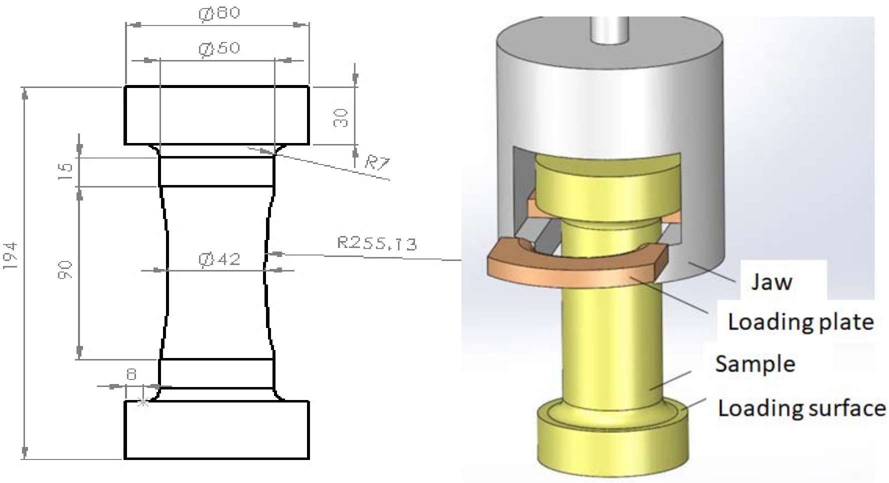

Figure 3. Dimension of the specimen and specimen-fixture assembly

3. Results and discussions

Brazilian and direct methods used to determine tensile properties of granite were analyzed with ANSYS Workbench R18. Curved jaw loading fixtures produced from steel material which has the modulus of elasticity was assumed to be 200 GPa and Poisson ratio is also 0.3 were used in Brazilian test analysis. (Figure 4). The material using in the analysis was assumed homogeneous and linear elastic. The studied Brazilian disc specimen has 54 mm diameter and 27 mm thickness. When the load applied on the upper jaw, the bottom jaw's motion is restricted in all directions. The material properties assigned to the specimen are: Young's modulus (E) = 30 GPa and Poisson's ratio (ν) = 0.3. For the analysis (t / D = 0.5), the load value at which the stress at 1 MPa was produced at the center of the specimen (2P / πDt) was determined to be 2290 MPa. As shown in Figure 4, the load is spread on the upper jaw and the lower jaw is fixed.

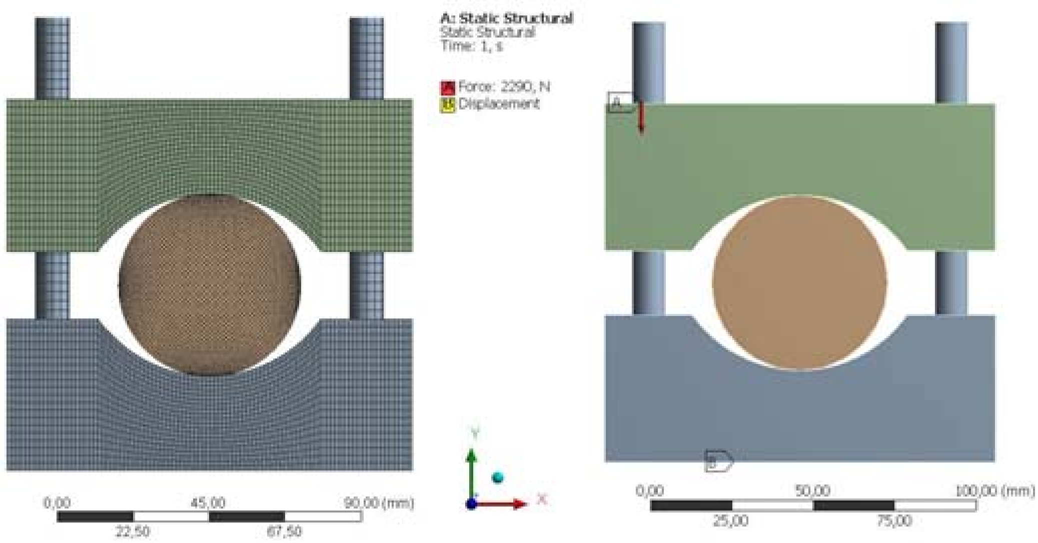

Figure 4. Finite element network structure, loading and supporting state

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The maximum principal stresses at the outer surface of the specimen, the stresses in the direction of the X axis, the stresses in the Y axis direction and the shear stresses are shown in Figures 5.a, b, c, and d respectively. It is seen that the maximum principal stresses in the case of ignoring contact points where force is applied on the sample are higher than tensile stresses in the X direction values in the middle part. Brazilian disk tests usually show that the damage occurs in the middle and to the direction of force effect (vertical line). To be able to see the numerical values of the stresses at these critical points more clearly; Principle stress (Sp), normal stress in the X direction (Sx), normal stress in the Y direction (Sy), and shear stresses in the XY plane (Sxy) are shown in Figure 6.

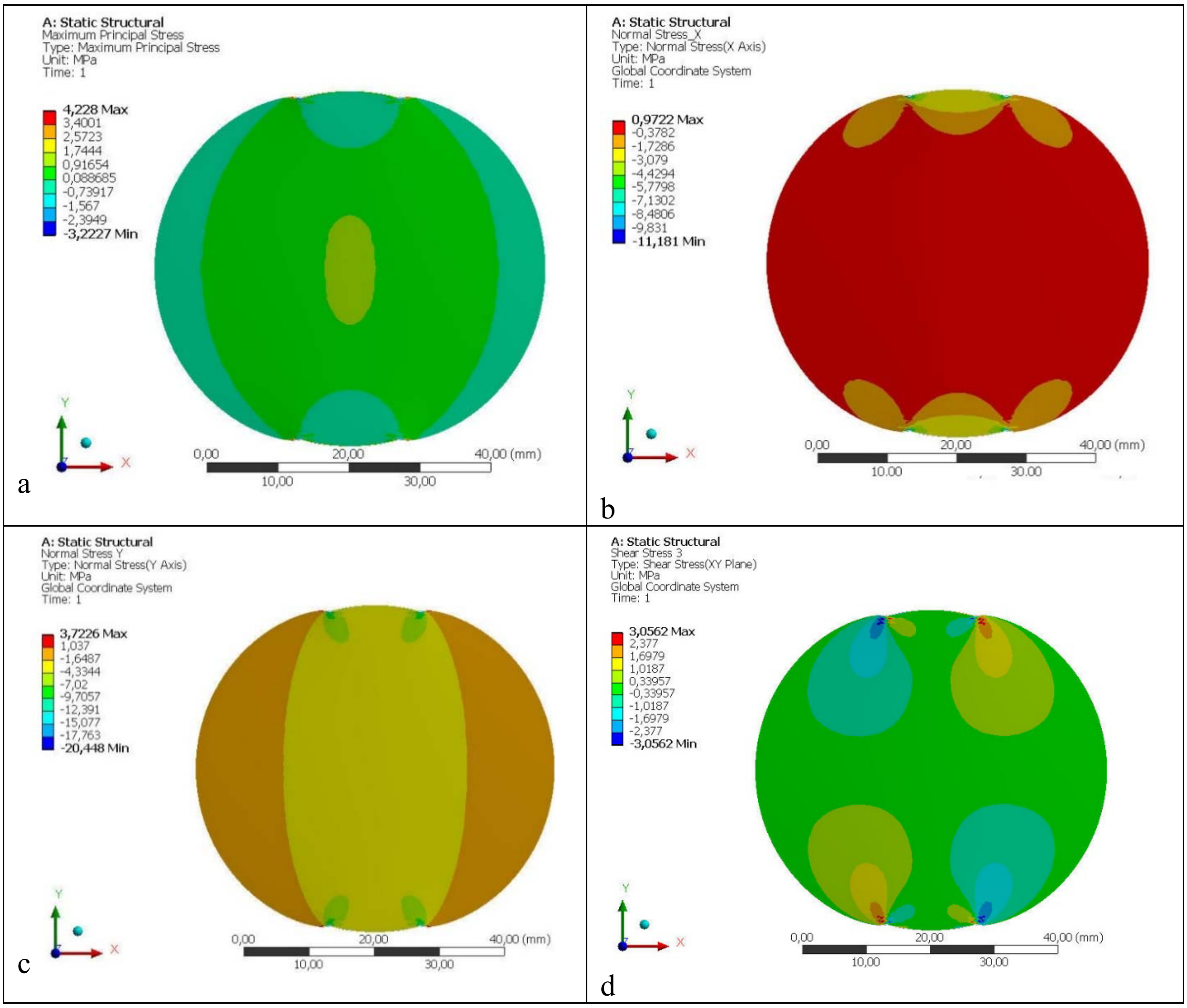

Figure 5. Stress distribution on the Brazilian sample

Similarly, the vertical line and the different stress values on this line are shown in Figure 6. As shown in both Figures, a stress of 1 MPa has been formed in the center of the sample, which is suitable for analytical calculations. It is seen from Figure 6 that the tensile stress in the X direction and the maximum principal stress in the middle of the sample are almost the same. Because; the shear stresses values are very close to, zero in these regions.

When examined is from the horizontal axis (Figure 6), it is seen that the maximum value of the principal stress and the normal stress in the X direction are at the midpoint. When viewed from the vertical axis, it is seen that the maximum principal stress and the normal stress in the X direction are nearly uniform along a distance of about ±15 mm from the center of the sample and compliance with theoretical calculation.

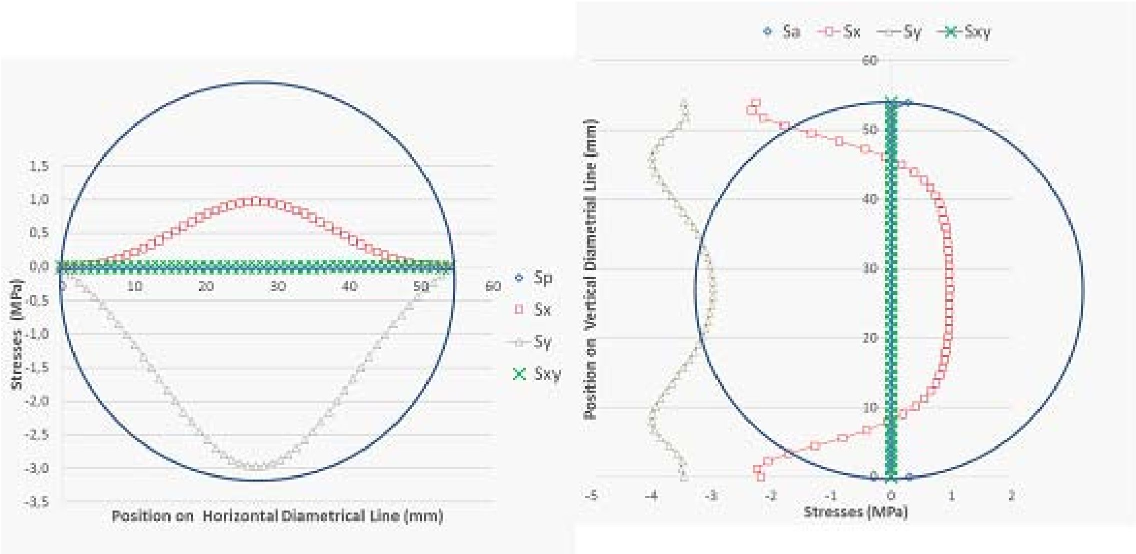

Figure 6. Stress distribution along the horizontal and vertical line

In addition, analyzes were performed for E: 30 GPa, and ν=0.3 for t / D ratio: 0.5, 0.75, and 1.0, respectively. In all analyzes, the finite elements network structure, load and supporting conditions were kept constant. As can be seen from Figure 7, it is understood that the variation of t/D ratios does not make any significant difference in the stress distribution.

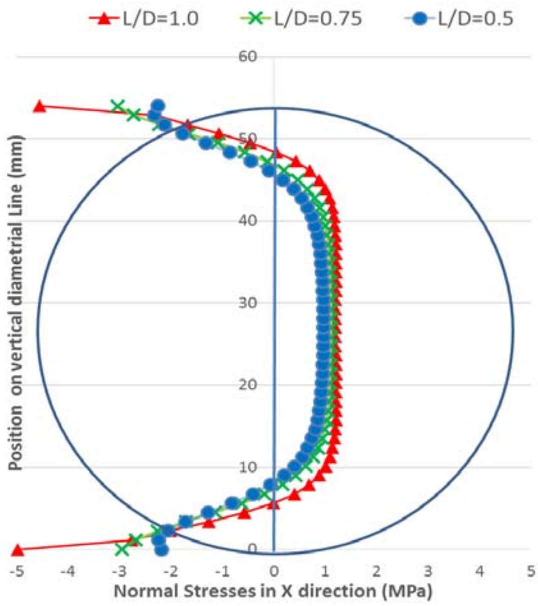

Figure 7. Change of stress distribution by t / D ratio

In order to accurately determine the tensile strength properties of brittle material such as rock, it is important that the fracture location is far away from the cross-section points and within the measurement limits of the extensometer. Although direct tensile strength of brittle materials can be determined by direct methods, stress intensity might be occurring at the points where the sample is connected (using epoxy or cement binder) and damage can be occurring at the same points. Moreover, early failure and bending moments can be occurred during the tensile experiments. In the case of dumbbell-shaped (dog bone) specimens, stress intensity occurs at the diameter change points resulting from the changes in the sections of the specimens. Therefore, in this study, new dumbbell shape model which are define as continuous variable section were developed to reduce stress intensity in dumbbell-shaped specimens to determining direct tensile strengths of the rocks. In addition, in order to perform direct tensile tests, jaw clutch mechanism compatible with this model has been designed and manufactured. It is consisting of a direct pulling jaw and a two-part symmetrical loading plate. These loading plates carried out loading on the specimen. Laboratory tests were carried out by producing samples according to this model. In addition to experimental study, stress distribution and stress intensity on the sample were analyzed by using ANSYS. According to experimental and numerical analysis results; direct tensile strengths of granite rock were determined and this model which are define as continuous variable section is more suitable to determine direct tensile strength of the rocks.

ANSYS R18 program was used for stress analysis with the finite element method of the direct tensile strength sample design. It is aimed to obtain more suitable results by using "quadratic" elements while modelling finite element network structure for analysis. Figure 8 shows the mesh generation for the sample geometry.

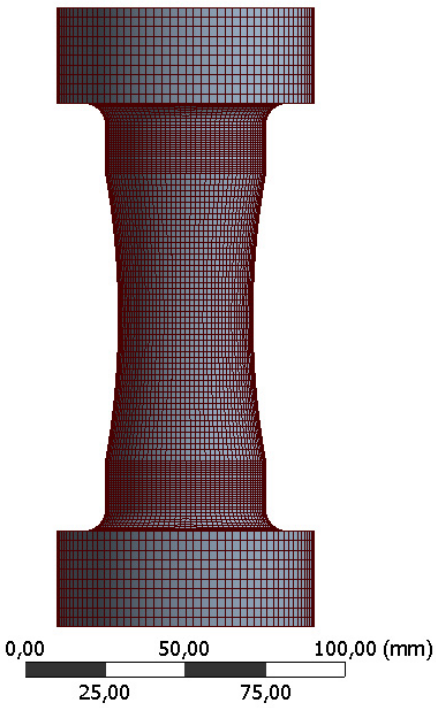

Figure 8. Sample mesh structures

Material properties to be used in finite element stress analysis; modulus of elasticity 30 GPa and Poisson’s ratio 0.3 were determined. The force and support were applied to the surfaces formed at the cross-sectional area just under the head of the sample, in accordance with the actual model. The support condition was defined so that there is no displacement along the Y-axis, which is strongly in the same direction. The force applied to the specimens was determined to produce a stress of 1 MPa in

the sample cross-section relative to the P / A formula. This value was entered into the program by calculating as 1385 N for the sample, which is defined continuous variable cross-section.
The maximum principle stresses of direct tensile test specimen results, which were obtained from FEM analysis, were given in Figure 9 for through sample outer surface and middle cross section area of sample. There is not any stress concentration vicinity of the middle of the specimen where the failure will occur. So that is indicates that obtained experimental results by using this dog bone geometry will accurate.

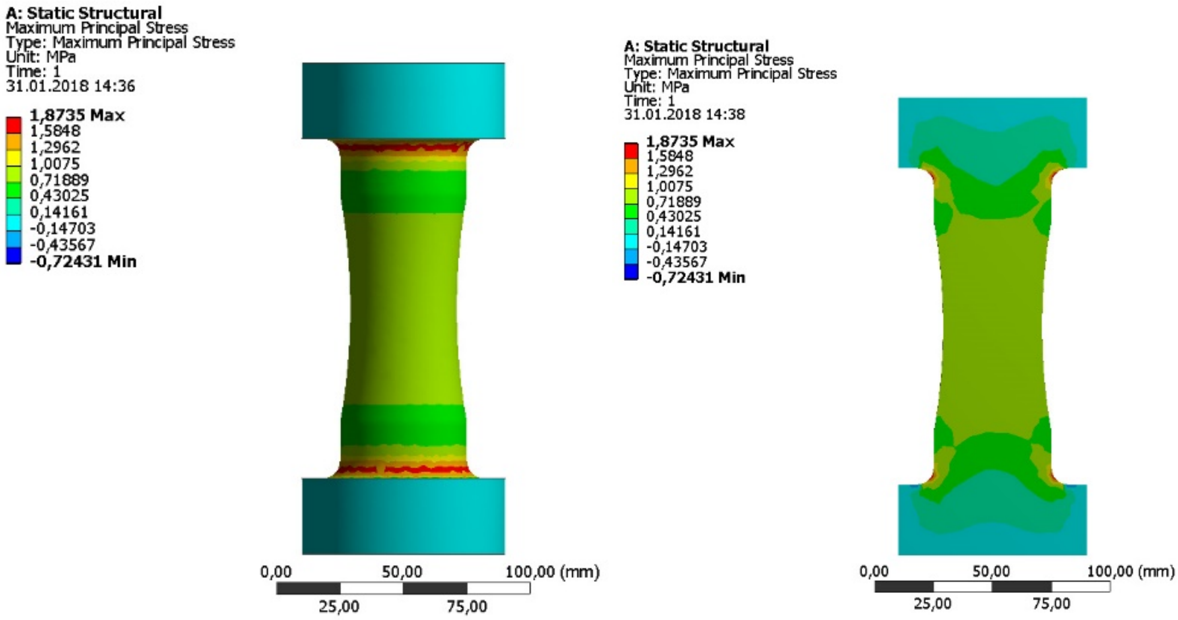

Figure 9. Maximum principle stress distribution whole specimen and cross section area.

4. Conclusions

By using the new dog bone shape, it is possible to get accurate direct tensile strength value because the failure occurs far enough from the high-stress concentration region. The presented Brazilian disk FEM analysis results show that the tensile stress generated within the critical vertical diametrical line complies with the theoretical calculation. On the other hand, when considering experimental results, it can be seen that Brazilian test results indicate high tensile stress value. The Brazilian disk FEM analysis shows that the specimens are under the biaxial (both X and Y direction) stress condition, so the results may differ from the direct tensile test result. The ratio between BTS/UTS was found approximately 1.8 for granite. Our suggestion is that the direct tensile test must be conducted first by using the proposed dog bone geometry and then BTS/UTS ratio should be determined for other kind of rocks. Thus, Brazilian test result may be used by considering this correction factor.

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