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# Estimation of Tensile Strength for Granitic Rocks by Using Discrete Element Approach

Aliakbar Golshani, Armin Ramezanzad

***Abstract*****—**Tensile strength which is an important parameter of the rock for engineering applications is difficult to measure directly through physical experiment (i.e. uniaxial tensile test). Therefore, indirect experimental methods such as Brazilian test have been taken into consideration and some relations have been proposed in order to obtain the tensile strength for rocks indirectly. In this research, to calculate numerically the tensile strength for granitic rocks, Particle Flow Code in three-dimension (PFC3D) software were used. First, uniaxial compression tests were simulated and the tensile strength was determined for Inada granite (from a quarry in Kasama, Ibaraki, Japan). Then, by simulating Brazilian test condition for Inada granite, the tensile strength was indirectly calculated again. Results show that the tensile strength calculated numerically agrees well with the experimental results obtained from uniaxial tensile tests on Inada granite samples.

***Keywords*****—**Numerical Simulation, PFC, Tensile Strength, Brazilian Test.

## I. INTRODUCTION

INTACT rock strength is a basic characteristic that needed for predicting the rock and rock mass behavior in geomechanics [1]. Understanding mechanical properties of materials is critical for engineering. By applying uniaxial load to a rock sample in laboratory, we can investigate the rock sample's response to loading (tension or compression). It can be done by applying a controlled tensile or compressive displacement along a single axis and by recording the changes in dimensions and also applying load; we can obtain the stress-strain profile for that rock sample which shall be used in order to investigate the elastic and plastic behavior of the rock. In order to investigate mechanical properties of a rock and its behavior under uniaxial testing condition, we perform compressive and tensile tests on materials, and calculate their mechanical properties such as Young's modulus, yield stress, ultimate tensile strength, and elastic strain energy density.

Because the laboratory experiments and in situ tests are time-consuming and expensive, numerical simulation has proven to be a new avenue for obtaining the mechanical behaviors of geo-materials.

The development of numerical methods and computers has made it possible to analyze these complexities and reach to important rock properties like compressive and/or tensile strength, Young's modulus and Poisson's ratio and also monitoring the cracks growth, etc.

In this research, Particle Flow Code 3-Dimensions software (PFC$^{3D}$) was chosen for simulating rock behavior under two different tensile loading conditions, i.e. uniaxial tensile condition and indirect tensile condition (Brazilian test). PFC$^{3D}$ is a distinct element method (DEM) based in which spherical elements are used to represent particles. DEM method was first introduced by Cundall (1971) and developed for granular material by Cundall and Strack (1979) [2] [3]. In this method, particles are assumed to be rigid which interact based on the Newton's second law. This assumption reduces the time spent on simulation. The particles can also have contact with adjacent particles which is dominated by force – displacement law. Compared with other methods, macro-parameters such as tensile strength are not directly used in the modeling procedure and micro-parameters as input data controls the contacts and should first be calibrated by using macro-parameters for a rock sample and the be used in the simulation. In other words, there is no relationship between synthetic material and model micro mechanical parameters, and therefore, calibration should be performed based on macro mechanical parameters obtained from the experiments which is a complicated procedure due to large number of micro mechanical parameters compared to the available macro mechanical parameters [4]-[6].

## II. PROCEDURE

### *A. Inada Granite*

Inada Granite is a biotite granite sampled from a quarry in Kasama, Ibaraki, Japan.

The color specified by the quantitative measuring by means of scanner indicates high brightness. The light grey color is due mainly to the mineral composition: 34% of quartz, 62% of feldspars, and 4% of biotite. The soft visual impressions are emphasized by the abundance of semi-transparent quartz of slightly pinkish color, which is a notable individuality of the Inada granite. Because of the color, the Inada granite is called in Japan sometimes white granite.

Macro-mechanical properties for Inada granite are brought in Table I.

### *B. Experimental Tests*

In this part, two different tensile loading conditions, i.e. uniaxial tensile condition and indirect tensile condition (Brazilian test) will be explained in order to determine the tensile strength for rocks.

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Aliakbar Golshani and Armin Ramezanzad are with the Geotechnical Engineering, Faculty of Civil and Environmental Engineering, Tarbiat Modares University, Tehran, Iran. (e-mail: golshani@modares.ac.ir, armin.ramzanzad@modares.ac.ir).

Fig. 1 Inada granite mine

TABLE I
MACRO-MECHANICAL PROPERTIES OF THE INADA GRANITE

| Type of testing | Properties (unit) | Experimental results |
|---|---|---|
| Uniaxial compression test | USC (MPa) | 189 |
| | Elastic modulus (GPa) | 60 |
| | Poisson's ratio | 0.21 |
| Triaxial compression test | Confinement Pressure | |
| | 25 MPa | 480 |
| | 50 MPa | 614 |
| Uniaxial tension test | Tensile strength (MPa) | 11.2 |
| Brazilian test | Tensile strength (MPa) | 8.45 |

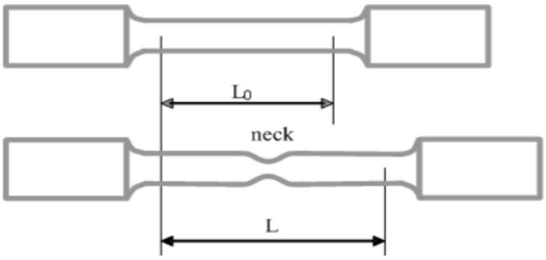

Fig. 2 Typical tensile testing specimen

### C. Uniaxial Tension Test

Tensile strength is the most fundamental parameter involved in considerations of rock fracture, and since it cannot be deduced directly from atomistic considerations of the rock's constituent minerals, it is defined as a bulk property using the uniaxial tensile test as the basis of definition.

For uniaxial tests, applying axial load and resulting axial displacement are recorded continuously. Engineering strain can be calculated as:

$$\varepsilon_e = \frac{\Delta L}{L_0} \tag{1}$$

where ΔL is the displacement parallel to loading axis, and Lo is initial sample length along loading axis. Also, applying stress can be determined as:

$$\sigma_e = \frac{P}{A_0} \tag{2}$$

where P is the applied load and Ao is the initial area of the sample cross section perpendicular to the loading axes. In uniaxial tensile tests, samples have two shoulders and a gauge section in between (Fig. 2).

To avoid torque in tensile tests, various devices have been used. Pulling systems have been fitted with thrust bearings or ball-and-socket joints, and non-twist cable or roller drive chains have been used to apply the loads. In this study, there is no torque effect on specimen.

### D. Brazilian Test

Brazilian test is an experimental approach to measure indirectly tensile strength of rocks. Due to its simplicity and efficiency, it is amongst the most commonly used laboratory testing methods in geotechnical investigation in rocks. This test is also used for other brittle materials such as concrete.

Indirect tensile (Brazilian) testing of rock cores is an easy and common method for determining the tensile strength of rock. Tensile strength is calculated in this test by using (3), which assumes isotropic material properties for rocks. In Brazilian test, a disc shape specimen of the rock is loaded by two opposing normal strip loads at the disc periphery (Figs. 3 and 4).

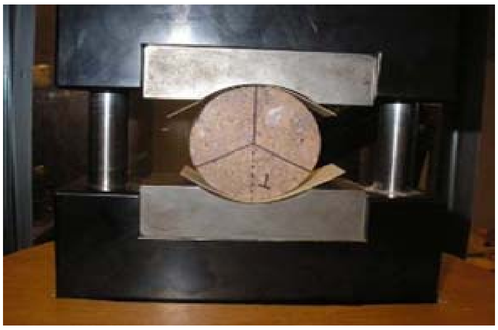

Fig. 3 Brazilian Test in laboratory

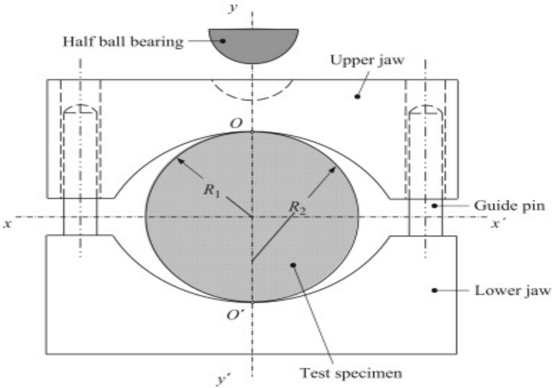

Fig. 4 Brazilian Test model

The specimen diameter shall be at least 10 times the average grain size of the rock sample. The thickness/diameter ratio should be about 0.5 to 0.6. The load is continuously applied at a constant rate to the specimen until failure of the sample occurs. The loading rate depends on the rock properties and changes from 10 to 50 kN/min. The tensile strength of the rock sample is determined at failure point by using (3),

$$\sigma_T = \frac{2F_{max}}{\pi DL} \tag{3}$$

$F_{max}$ is the maximum axial force, D and L are diameter and thickness of the Brazilian disk model, respectively.

As shown in Table I, uniaxial tensile strength and tensile strength obtained indirectly for Inada granite were determined in laboratory as 11.2 MPa and 8.45 MPa, respectively [8].

## III. SIMULATION IN PFC$^{3D}$

In order to simulate rock mass in a discrete environment, calibration process shall be performed. First, to determine mechanical properties of Inada granite, required experimental tests are carried out on Inada granite [7]. Then, the micro mechanical parameters of the particle flow model are calibrated based on the obtained macro mechanical properties (i.e., rock's mechanical properties).

The simulation methods can be placed into two categories: continuum and discrete (discontinuum) methods [8], [9]. The difference between them is that the continuum methods represent the failure in an indirect way, and the latter method represents in a direct way [4]. The discrete methods can be divided into explicit and implicit methods based on the solution algorithm adopted [10]. Particle flow code (PFC) is one branch of explicit discrete element methods (DEMs) that have power of rock mass simulation as well. This algorithm was first proposed by Cundall (1971) and Cundall and Strack (1979) for a granular material that were cohesionless, then by adding and incorporating parallel bond and standard bonded-particle model (BPM) to the software, it could be able to simulate rock mass correctly. After adding a discrete fracture network (DFN), PFC can simulate the mechanics of rock mass [10], [11].

In particle flow code, particles are assumed to be solid, and software algorithm uses three ways for simulating the model contacts that explained here briefly: 1) Contact bond model, 2) Parallel bond model and 3) Flat joint model

There is no linear or quantitative relationships between the micro-parameters and the macro-properties in continuum methods, then using directly input the data obtained from experiments tests is impossible, for solving this problem, the first step is performing calibration until the emerging macro-properties of the model with micro-parameters match those from experiments tests [12].

In this study, Flat Joint model is used for simulating the Inada granite with Micromechanical strength parameters in Table II.

### *E. Simulation of Uniaxial Tension Test*

According to the experimental tests, for further $PFC^{3D}$ modeling of this study, minimum particle diameter for Inada granite were selected, $D_{min} = 2\ mm$ and $D_{max} = 2.5\ mm$ to perform modeling with 50 mm in diameter and 120 mm in height. In result, 25024 particles are produced in the selected sample (Fig. 5).

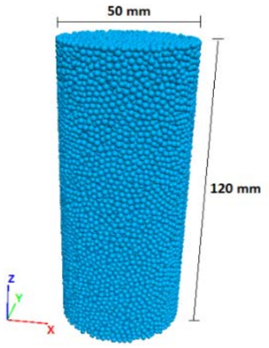

Fig. 5 Sample used in PFC$^{3D}$ simulation for Uniaxial tension test

TABLE II
MODEL PARAMETERS USED IN NUMERICAL SIMULATION FOR INADA GRANITE

| Micro-parameters | Value |
|---|---|
| Minimum grain dimeter, $\boldsymbol{d_{min}}$ (mm) | 2.0 |
| Maximum grain dimeter, $\boldsymbol{d_{max}}$ (mm) | 2.5 |
| Installation gap ration, $\boldsymbol{g_{ratio}}$ | 0.5 |
| Radial elements, $\boldsymbol{N_r}$ | 1 |
| Circumferential elements, $\boldsymbol{N_\alpha}$ | 3 |
| Effective modulus of both particle and bond, $\boldsymbol{E_c} = \overline{\boldsymbol{E_c}}$ (GPa) | 68 |
| Ratio of normal to shear stiffness of both particle and bond, $\boldsymbol{k_n}/\boldsymbol{k_s} = \overline{\boldsymbol{k_n}}/\overline{\boldsymbol{k_s}}$ | 3.5 |
| Mean and standard deviation bond tensile strength, $\boldsymbol{\sigma_b}$ (MPa) | (15.0) |
| Mean and standard deviation bond cohesion strength, $\boldsymbol{c_b}$ (MPa) | (85.0) |
| Friction angle, $\boldsymbol{\varphi_r}$ (degree) | 48 |
| μ | 0.1 |

After packing phase 1, the uniaxial tension mechanism should be simulated in PFC3D. The simulation of uniaxial tension test is performed in $PFC^{3D}$ on cylindrical model with using of two-three row of balls on top and down as a gripped portion. Then, the specimen model is pulled apart (Fig. 6).

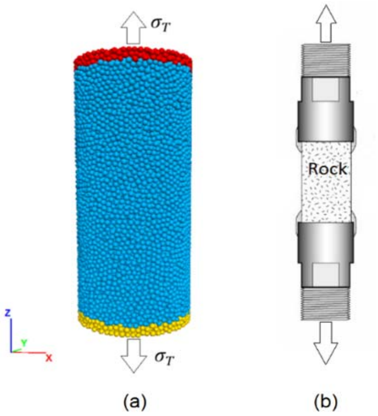

Fig. 6 Uniaxial tension test in (1): PFC$^{3D}$, (2): experimental condition

One of most important outputs from this simulation is the stress-strain curve which is shown in Fig. 7, and the uniaxial tensile strength was determined from this curve as 12.6 MPa.

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[1] First part of making sample in PFC

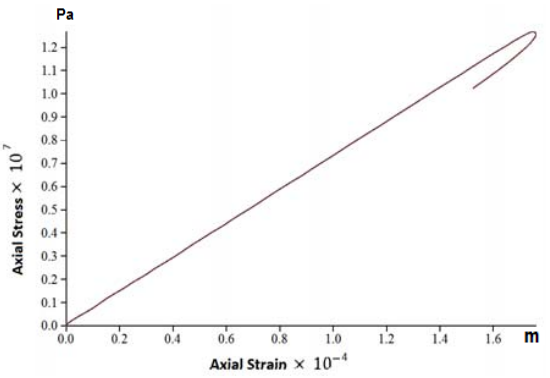

Fig. 7 Stress-strain curve for uniaxial tension test

### *F. Simulation of Brazilian Test*

A sample with 50 mm in diameter and 25 mm in thickness was chosen for simulation of Brazilian Test. Tow plates on top and bottom press the model in order to produce experimental condition (Fig. 8 (a)). At the end, maximum stress was recorded by PFC$^{3D}$ and by using (3), tensile strength for Inada granite was determined. By increasing applying load, tensile cracks initiate and grow mostly parallel to the loading axis (Figs. 9 and 10) and failure plane develops as a result of coalescence of the cracks, parallel to the loading axis at failure point (Fig. 8 (b)) which agrees with the experiment's results.

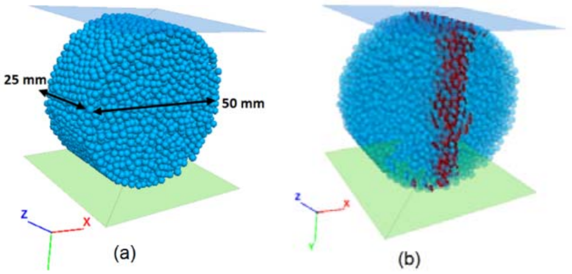

Fig. 8 Brazilian test model in PFC$^{3D}$ (a): dimension of disk, (b): crack propagation after failure

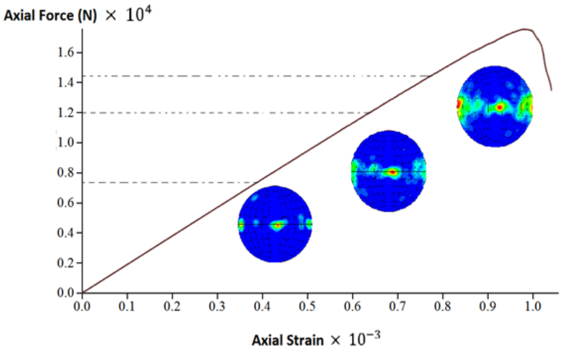

Fig. 9 Stress-strain curve and stereo net projection of cracks under Brazilian test

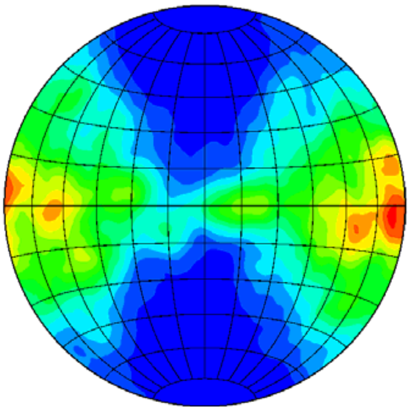

Fig. 10 Stereo net projection of cracks under Brazilian test after failure

Tensile strengths calculated from numerical results (PFC$^{3D}$) together with the values obtained from experiments are brought in Table III.

TABLE.III
TENSILE STRENGTH OF THE INADA GRANITE

| Type of simulations | Strength (MPa) | Experimental results | $PFC^{3D}$ model results |
|---|---|---|---|
| Uniaxial tension test | Tensile strength | 11.2 | 12.6 |
| Brazilian test | Tensile strength | 8.45 | 8.6 |

## III. CONCLUSION

In this paper, the simulation of uniaxial tensile test and Brazilian test has been performed by using Particle Flow Code software in three dimensions (PFC$^{3D}$ ) and the same model parameters obtained from the calibration process (Table II). Then, numerical results compared with the experimental data. The comparison shows that uniaxial tensile strength and Brazilian tensile strength calculated numerically agree well with the experimental results obtained from uniaxial tensile tests on Inada granite samples (about 10% and 2% difference, respectively). Furthermore, the crack initiation and growth during the Brazilian test was simulated which also agrees with the experiment's result.

## REFERENCES

[1] Ewy RT (1999) Wellbore-stability predictions by use of a modified Lade criterion. SPE Drill Complet 14(02):85–91
[2] Cundall PA (1971) A computer model for simulating progressive large scale movements in blocky rock systems. In: Proceedings of the symposium of international society of rock mechanics
[3] Cundall PA, Strack OD (1979) A discrete numerical model for granular assemblies. Geotechnique 29(1):47–65. doi:10. 1680/geot.1979.29.1.47
[4] Potyondy DO, Cundall PA (2004) A bonded-particle model for rock. Int J Rock Mech Min Sci 41(8):1329–1364. doi:10.1016/j.
[5] Scholte`s L, Donze´F-V (2013) A DEM model for soft and hard rocks: role of grain interlocking on strength. J Mech Phys Solids61(2):352–369. doi: 10.1016/j.jmps.2012.10.005
[6] Yang X, Kulatilake PHSW, Jing H, Yang S (2015) Numerical simulation of a jointed rock block mechanical behavior adjacent to an underground excavation and comparison with physical model test results. Tunn Undergr Space Technol 50:129–142. doi: 10.1016/j.tust.2015.07.006
[7] Golshani, A., Y. Okui, M. Oda, and T. Takemura, A micromechanical model for brittle failure of rock and its relation to crack growth observed

in triaxial compression tests of granite. Mechanics of Materials, 2006. 38(4): p. 287-303.

[8] Jing L (2003) A review of techniques, advances and outstanding issues in numerical modelling for rock mechanics and rock engineering. Int J Rock Mech Min Sci 40(3):283–353. doi:10. 1016/s1365-1609(03)00013-3

[9] Jing L, Hudson J (2002) Numerical methods in rock mechanics. Int J Rock Mech Min Sci 39(4):409–427. doi:10.1016/S13651609(02)00065-5

[10] Ivars DM, Pierce ME, Darcel C, Reyes-Montes J, Potyondy DO, Young RP, Cundall PA (2011) The synthetic rock mass approach for jointed rock mass modelling. Int J Rock Mech Min Sci 48(2):219–244. doi:10.1016/j.ijrmms.2010.11.014

[11] Pierce M, Cundall P, Potyondy D, Mas Ivars D (2007) A synthetic rock mass model for jointed rock. In: Rock mechanics: meeting society's challenges and demands, 1st Canada-US rock mechanics symposium, Vancouver, 1:341–349

[12] Yang B, Jiao Y, Lei S (2006) A study on the effects of microparameters on macroproperties for specimens created by bonded particles. Eng Comput 23(6):607–631. doi:10.1108/ 02644400610680333.