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Calibration of rock Brazilian test using discrete element method in LS-DYNA

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Abstract. Brazilian test which also known as indirect tensile test is widely used to evaluate the tensile strength of rock. Discrete element method (DEM) together with finite element method (FEM) approach was used to investigate numerically the response of granite material under Brazilian test for indirect measurement of tensile strength of rocks. The calibration analysis performed in this study using the commercial software LS-DYNA. It has been attempted to calibrate the micro-parameters in bonded particle model of granite rock for numerical modelling. In hybrid DEM-FEM simulation, the rock specimen was modelled in DEM while the steel plates were simulated using FEM. This numerical analysis is compared to experimental data of Brazilian test. It shows that the combination of numerical methods simulation could reproduce the trends of experimentally observed stress-strain curve of granite rock under tensile loading. Besides that, the hybrid DEM-FEM simulation also shows the same failure mode of granite specimen. Comparison between experimental data and numerical analyses is presented and discussed.

1. Introduction

Tensile strength of rock is one of the important mechanical parameters because rocks are weaker in tension compared to compression. An indirect measurement of tensile strength of rock known as Brazilian test has been widely adopted in laboratory. Numerous experimental and numerical studies have been performed in the recent years to stimulate high strain rate loading laboratory tests.

The development and applications of Brazilian disc test in rock mechanics have been reviewed by [1]. Based on analytical, experimental and numerical approaches, [1] was classified into three research stages. The early stages of research was focused on 2D stress analysis if the Brazilian disc and comparison with other methods. Stage 2 begins the release of ISRM suggested method for determination of tensile strength of rock materials. The improvement and modifications of the traditional Brazilian test have been extensively studied in stage 3. Moreover, researchers also had reviewed for anisotropic rock of Brazilian tensile strength [2]. Five typical failure modes were classified based on anisotropic rock failure mechanism which are tensile failure across and along the weakness planes, shear failure across and along the weakness planes, and mixed failure.

Discrete element method is a numerical technique for geometry modelling as discontinuum using particles. Potyondy and Cundall [3] mentioned that rock behaves like a cemented granular material of complex-shaped grains which the grains and the cement can deform and break. The mechanical behavior of rock is driven by the formation, growth and existing of microcracks. The mechanical properties of rock are determined by its constituent particles and its structure [4],[5]. These mechanical behaviors can be simulated using DEM.

Discrete element method simulation of Brazilian tensile test has been done by [6] to investigate the effect on clump configuration by varying the clump and ball size. The author found out brittleness can be controlled by changing the ratio of clump size to minimum ball size. In addition, DEM simulation regarding behaviours of anisotropic rock was studied by [7] under Brazilian test. Three different types of anisotropic rocks with different failure process and mechanism are identified.

One of the limitations of the previous model is the transition from continuum to discontinuum and applicability of continuum model to address rock engineering problems which typical of fracturing and fragmentation processes in rock [8]. Munjiza [9] was established an idea of using a new hybrid finite-discrete element method (DEM-FEM) to overcome the limitations. In this hybrid method, DEM used to represent areas of importance and FEM is used for the rest of the model. Each discrete element is discretised into finite elements mesh model. The hybrid method was employed by [8] to reproduce SHPB dynamic testing on Brazilian disc specimens. The simulation results were in good agreement with laboratory observation.

Besides that, combination of Finite/Discrete Element Method also was used to simulate the fracture process in Brazilian test. Difference of this method compared to hybrid DEM-FEM method is both continuous and discontinuous methods can be modelled through FEM and DEM respectively [10]. The Brazilian rock specimen acts as a FEM under low load and when crack is initiated DEM contacts would be broken. This combined method have been implemented by [11], [12] for modelling of rock fracture and to determine tensile strength of rocks.

This study aims to calibrate the micro-parameters in bonded particle model of granite rock for numerical modelling using hybrid DEM-FEM simulation. Several comparisons have been made between numerical and experimental results in the calibration process. The results of the numerical simulations, including tensile strength, tensile strain and failure mode behaviour were compared with the laboratory findings.

1.1. Bonded particle model (BPM)

Bonded particle model (BPM) was defined by Potyondy and Cundall as a model consist of a dense packing of particles either in non-uniform-sized circular or in spherical which the particles are bonded together at their contact points with parallel bond [3]. The mechanical behavior can simulate by DEM using commercialized programs PFC2D, PFC3D [13] and LS-DYNA [14]. Bonded particle model can provide both a scientific tool to investigate micro-mechanisms and an engineering tool to predict macroscopic behaviour. The DEM was introduced by Cundall for analysis of rock mechanics problems and then applied to soils by [15].

The rigid particles interact only at the soft contact which finite normal and shear stiffness. Figure 1 shows the contact bond between particles which the force and moment acting at each contact. Bonded particles in BPM where all of the particles are linked to their neighboring particles through bonds. Bonds represent the complete mechanical behavior of solid mechanics and bonds are independent of the DEM. Every bond between particles is subjected to tension, bending, shearing and twisting [16].

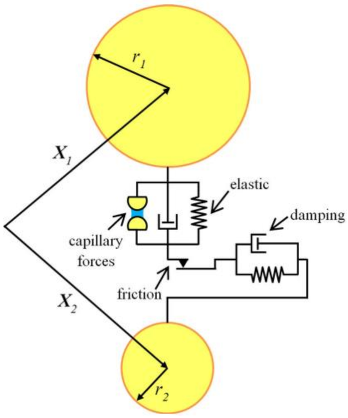


Figure 1. Illustration of contact bond between particles [17].

2. Experimental methods

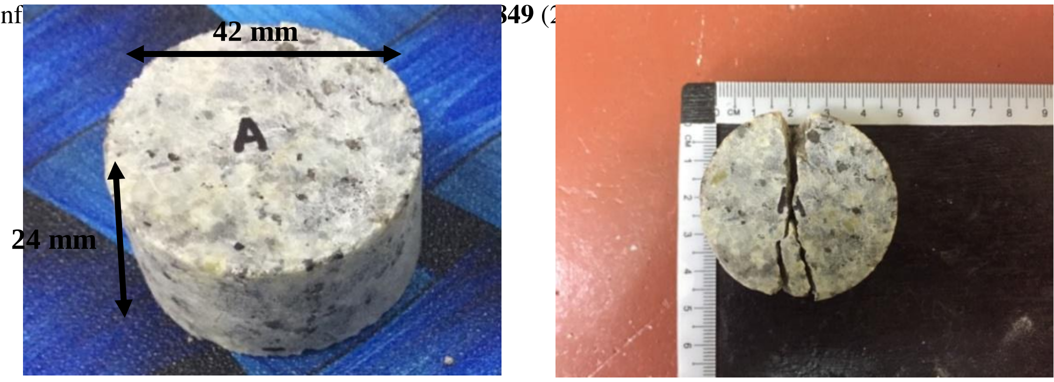
2.1. Laboratory works

Some rock samples from the rock pile were taken from Gemencheh Granite Sdn Bhd (GGSB) quarry which located at Gemencheh, Negeri Sembilan, Malaysia to the laboratory to study the engineering properties of the rock samples. The macro properties of rock specimen such as unconfined compressive strength (UCS), Young's modulus, Poisson's ratio, tensile strength and shear strength were obtained from Uniaxial Compression Test, Triaxial Test, Brazilian Test and Direct Shear Test respectively. Experimentation was conducted based on the International Society for Rock Mechanics (ISRM) standards to achieve consistent results [18], [19]. The intact rock properties obtained from laboratory test are shown in table 1.

Table 1. Intact rock properties selection for analysis in LS-DYNA.

Test type	Parameter	Value
Density test	Density (g/cm3)	2.75
	Uniaxial compression strength, UCS (MPa)	87.96 (AVG: 67.29)
UCT test	Young's modulus, E (GPa)	20.76
	Poisson ratio	0.25
Brazilian test	Tensile strength (MPa)	9.57
Shear test	Shear strength (MPa)	9.52

The collected rock samples were cored and cut into diameter approximately between 42 to 50 mm and height of 21 to 25 mm was used for laboratory test. A total of four rock samples were tested for Brazilian test. Figure 2 (a) shows the granite samples for Brazilian testing and figure 2 (b) shows the rock failure after Brazilian test. According to [20], there are four typical failure mode behaviour of Brazilian test as shown in figure 3 which are central, non-central, central + layer activation and central multiple. It was observed that majority failure mode behaviour of all tested samples is central multiple and was compared to numerical models.



(a) (b)

Figure 2. Comparison of granite specimen (a) before and (b) after Brazilian test.

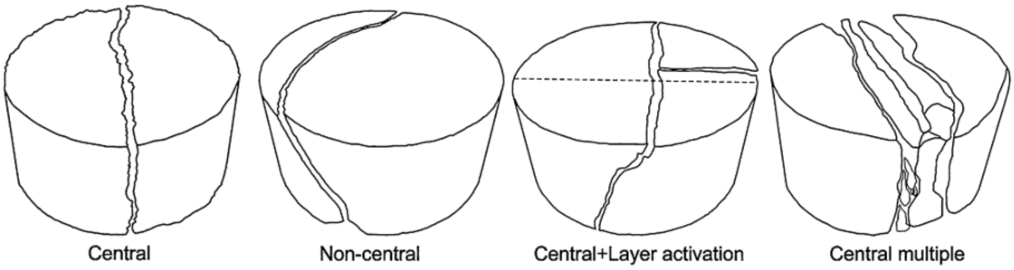


Figure 3. Typical failure mode behaviour of Brazilian test [20].

2.2. Numerical methods

The experimental tests were modelled numerically using the commercial software LS-DYNA. The discrete element method was combined with the finite element method to investigate numerically the response of granite material under tensile loading. The discrete element model has been used to simulate the fracture process in a Brazilian test. Our aim is to calibrate the micro-parameters in bonded particle model of granite rock for numerical modelling. In this hybrid DEM-FEM simulation, the rock specimen was modelled in DEM while the steel plates were simulated using FEM.

Generation of particles is one of the important steps in discrete element modelling. The rock model was meshed first before DEM particles were introduced. In disc sphere generation, there will be three input parameters to generate DEM particles which are minimum and maximum radius and the particle percentage of packing density. Figure 4 shows the flow of input calibration used in this study. In this calibration method, the calibration procedures have to meet the tensile strength and maximum tensile strain tolerance of intact rock specimen from the laboratory test. However, if the model does not meet the tensile strength and maximum tensile strain tolerance, cement volume and micro-parameters need to modify. Finally, comparison of failure mode behaviour between numerical model and experimental model was conducted.

In discrete element modelling process, there are many input parameters of microproperties need to identify to represent the actual granite rock. The input parameters used for this model can be seen in table 2 below. Initial guess of the input parameters value can be made based on laboratory test data in calibration process. Trial and error method are needed to calibrate the model based on the initial guess and also was suggested by [21]. There are four trials calibrated models shown in table 2 and the differences between the models are the value of PBN, PBN_S, PBS_S, SFA and MAXGAP.

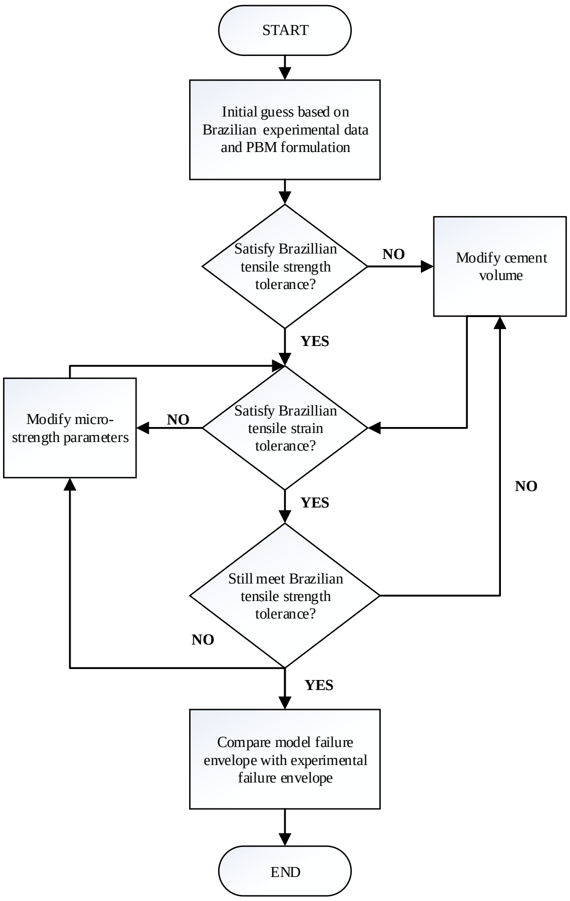


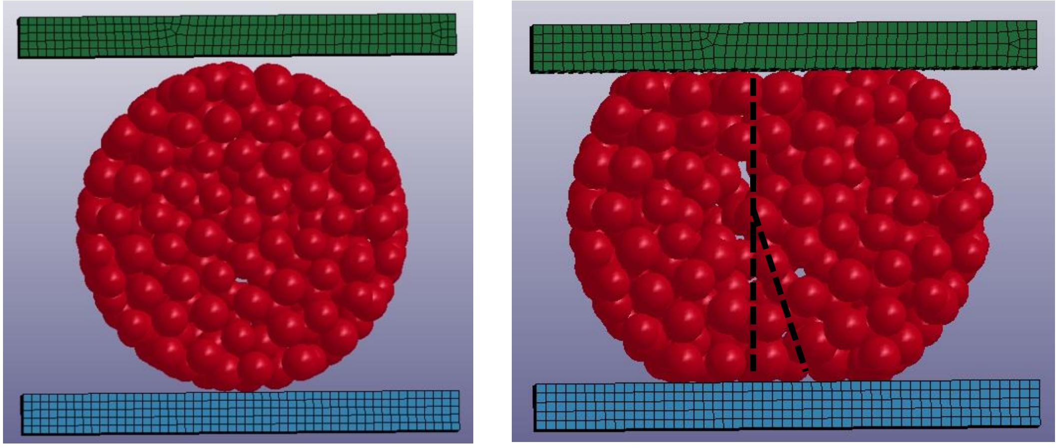
Figure 4. Flow of input calibration.

Table 2. Input parameters of the calibrated model.

Properties	Trial 1	Trial 2	Trial 3	Trial 4
Particle radius/mm	1.75 - 2	1.75 - 2	1.75 - 2	1.75 - 2
Parallel-bond normal stiffness (PBN) / GPa	10.11	20.76	20.76	20.76
Parallel-bond shear stiffness (PBS)	0.25	0.25	0.25	0.25
Parallel-bond maximum normal stress (PBN_S)	30	35	30	30
Parallel-bond maximum shear stress (PBS_S)	20	25	20	20
Bond radius multiplier (SFA)	1.35	1.3	1.35	1.3
Numerical damping (ALPHA)	0.5	0.5	0.5	0.5
Maximum gap between two bonded spheres (MAXGAP)	-1.35	-1.3	-1.35	-1.3
Normal damping coefficient (NDAMP)	0.7	0.7	0.7	0.7
Tangential damping coefficient (TDAMP)	0.01	0.01	0.01	0.01
Friction coefficient (Fric)	0.99	0.99	0.99	0.99
Rolling friction coefficient (FricR)	0.98	0.98	0.98	0.98
Normal spring constant (NormK)	0.1	0.1	0.1	0.1
Shear spring constant (ShearK)	0.4	0.4	0.4	0.4

Figure 5 (a) shows the DEM/BPM numerical model of rock specimen that ready for Brazilian testing. In the models, there are two FEM steel platen was positioned top and bottom of rock specimen. The top steel platen configured to move vertically and fixed in all other direction. Whereas, the bottom steel platen is fixed in all directions. Boundary condition was applied to the top steel plates. The applied boundary condition which related to loading rate was matched with experimental loading force and it is identical for all numerical models which is 0.0067 kN/s. The material of the plates is typical steel, with mass density 7 g/cm^3, Young's modulus 200 GPa and Poisson's ratio 0.3. Material for rock specimen such as density, Young's modulus and Poisson's ratio was assigned as shown in table 1. The friction coefficient between steel plates and rock specimen for both top and bottom plates is 0.39 and 0.5 for damping coefficient.

From DEM/BPM numerical modelling results, it was observed that the failure mode behaviour after Brazilian test was similar to the experimental test (figure 2). The DEM bond was detached at the centre of rock specimen and failed central multiple as shown in figure 5 (b).



(a) (b)

Figure 5. Simulation of (a) before and (b) after Brazilian test using DEM/BPM.

3. Comparison of numerical and experimental results

This is the important part to make sure the calibration process was successful. There are several comparison have been made throughout the calibration process in this study. The hybrid DEM-FEM model should satisfy the range of tensile strength of intact rock from experimental results. Based on table 3 below, trial 3 and 4 was satisfied the range of experimental tensile strength results which between 8.71 - 10.42 MPa. In addition, other comparison such maximum tensile strain need to considered in calibration. The range of maximum tensile strain is between 0.95 – 1.18 mm where only trial 3 is within the accepted range.

Besides failure mode behaviour, graph trend of axial stress versus vertical displacement also was compared for calibration. Figure 6 shows graph comparison of Brazilian DEM/BPM model with experimental results. Sample 1 to 3 indicates samples from laboratory test data and trial 1 to 4 indicate numerical simulation results. The graph trend for trial 3 seems similar to sample 2 and 3 of laboratory test results. It was observed that trial 3 satisfied all of the comparison requirements have been made. In conclusion, from trial 3 results shows the calibration was successful and was chosen as the best model in this study.

Table 3. Comparison of tensile strength and maximum tensile strain value between Brazilian DEM/BPM model and laboratory test.

	Laboratory test	Trial 1	Trial 2	Trial 3	Trial 4
Tensile strength (MPa)	8.71 - 10.42	10.66	12.05	10.01	9.33
Maximum tensile strain (mm)	0.95 – 1.18	0.92	0.88	1.18	0.84

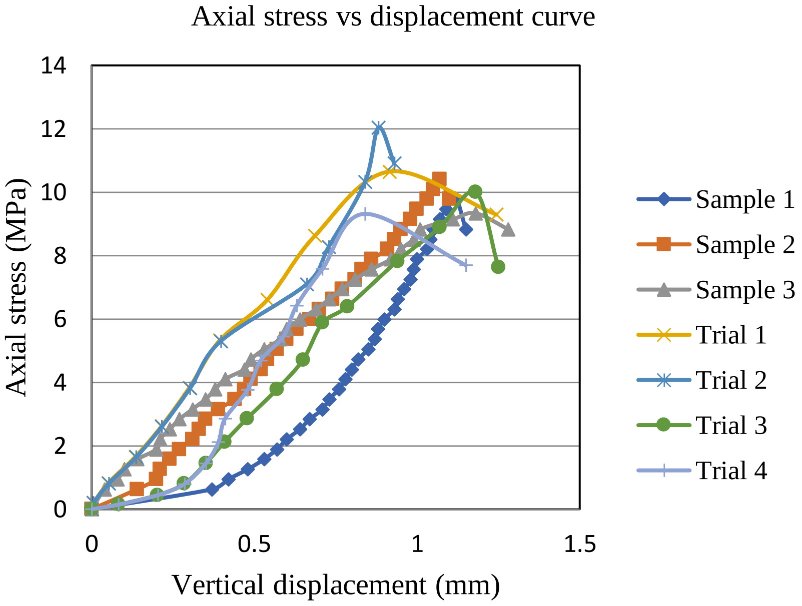


Figure 6. Comparison Brazilian DEM/BPM model with experimental data of granite specimens.

4. Conclusion

The DEM/ BPM numerical simulation was used in this study to calibrate intact granite rock specimen. Several comparisons have been made between numerical and experimental results in the calibration process. The results of the numerical simulations, including tensile strength, tensile strain and failure mode behaviour, are in agreement with the laboratory findings. Trial 3 was chosen as the best calibrated hybrid DEM-FEM model in this study as it meets all of the comparison criteria. It was observed that hybrid DEM-FEM simulation could reproduce the trends of stress-displacement curve of granite rock under tensile loading. In conclusion, hybrid DEM-FEM numerical approach can be used for further study related to indirect measurement of rocks tensile strength.

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