Numerical modeling of standard rock mechanics laboratory tests using a finite/discrete element approach

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ABSTRACT: In the present paper, numerical simulations based on a finite/discrete element approach are used to study deformation and failure process during standard rock mechanics. FEM/DEM modeling has been used to explicitly model the transition from continuum to discontinuum. The transition is simulated through a crack nucleation and propagation that obeys to the Griffith's failure criterion. If the fracture criterion within the intact rock (represented by FEM) is met, a new crack (represented by DEM) is initiated. Re-meshing allows the fracture process through the FEM mesh to be tracked and visualized, thus contact properties can be assigned to pre-existing fractures and newly generated fractures. In this study, compressive tests of rock samples are simulated. In this study, compressive tests of rock samples are simulated. The applicability of ELFEN to properly and efficiently simulate typical laboratory rock mechanics tests, with reference to the rock fracture process, is described in detail. In addition, an indirect validation of the extensional strain criterion proposed by Stacey (1981) is given.

1 INTRODUCTION

In this paper a series of numerical analyses have been carried out to assess the suitability of a finite/discrete element approach to properly and efficiently simulate typical rock mechanics tests. To this purpose some standard rock tests have been modeled. The results have been analyzed in terms of the "global mechanical response" obtained by evaluating if the fracturing response is realistically represented.

The rock mechanics tests modeled and described in the following are:

- Brazilian test;
- Uniaxial compression test ;
- Triaxial compression test in a homogeneous rock.

To investigate the global fracturing response the finite/discrete element code ELFEN (Rockfield Software, 2006) has been used. ELFEN provides a unique ability to model fracture initiation and growth, as it simulates the transition from continuum to discontinuum. If the fracture criterion within the intact rock (represented by FEM) is met then a crack (represented by DEM) is initiated.

Re-meshing allows the fracture process through the FEM mesh to be tracked and visualized; thus contact properties can be assigned to pre-existing cracks and newly generated fractures.

2 FRACTURE DEVELOPMENT IN STANDARD ROCK MECHANICS LABORATORY TESTS

2.1 *Brazilian Test*

The Brazilian test involves placing a cylindrical disk diametrically between the platens of a compression testing machine. The platens supply, ideally, a line load, or, more practically, a strip load aligned with the diameter of the sample. The indirect tensile strength of a disk sample of radius R and thickness t, with known load at failure P is given by (Fig.1):

$$\sigma_t = \frac{P}{\pi R t}$$

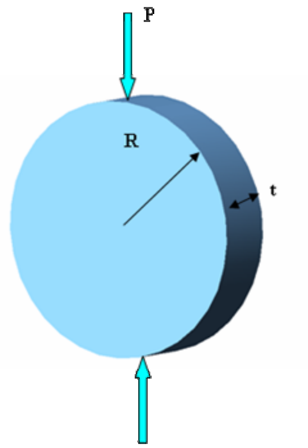


Figure 1. Brazilian test for indirect tensile strength

Correspondence between the results of the direct tensile test and the Brazilian test is governed by the assumption that tensile crack propagation from the centre of the disk will precede shear localization at the loading regions. The zone of high shear potential is small compared with the tensile region in the centre of the disk. Tests which fail through shear at the platen region should be rejected (Cai and Kaiser, 2004).

In the numerical simulation of the Brazilian test using ELFEN the sample has a radius of 50mm. A homogeneous isotropic rock is modelled. The material properties assigned are listed in Table 1. The platen is applied a constant vertical velocity (0.1mm/s) to simulate the applied load. For this model a mesh size of 1mm for the platens and of 0.8mm for the sample is assumed (Fig.2).

Table 1: Material properties

E * [GPa]	ν * [-]	σ_t * [MPa]	G_f * [N/mm]
50	0.25	5	0.05

E=Young’s modulus, ν=Poisson’s ratio, σ_t=tensile strength, G_f=fracture energy

The results obtained in terms of fracture pattern at different time-steps are shown in Fig. 3, which demonstrate that the code is able to simulate well the fracture propagation process during a Brazilian test. In particular, it truly respects the fracture initiation from the disk centre when σ_t>0. The ELFEN code therefore properly simulates fracture in tension.

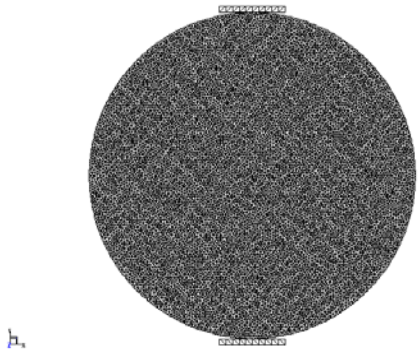
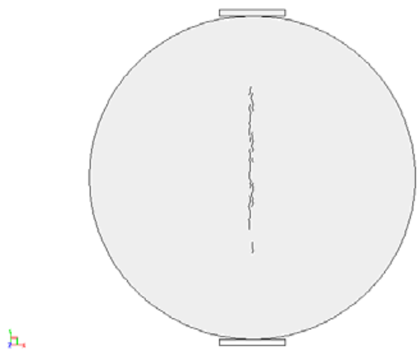
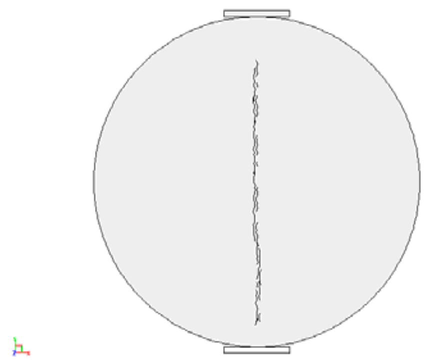


Figure 2. Mesh of the numerical model



Time-step 0.52s



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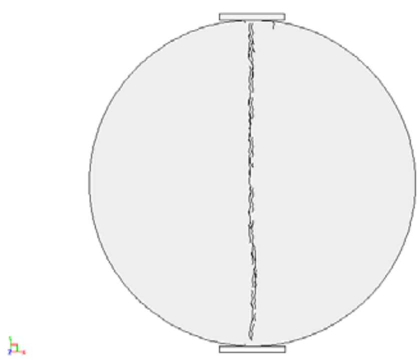
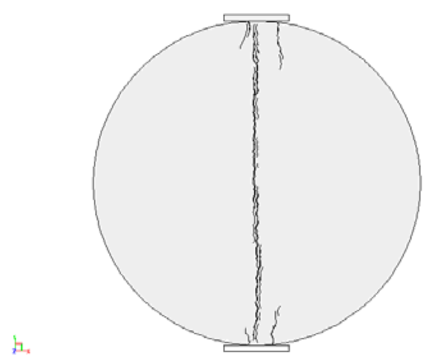


Time-step 0.57s



Time-step 0.76s

Figure 3. Results obtained in the simulation of the Brazilian test

2.2 *Uniaxial Compression Test*

The most common form of direct strength testing for rock is the uniaxial compression test. A uniaxial compression test has been modelled in 2D. The specimen has a width of 50mm and the ratio between the height and the diameter is 2. A homogeneous material is considered, with material properties assigned as listed in Table 2.

Heterogeneity of rock is also introduced by assuming that the mechanical properties of rocks at the mesoscopic level, such as Young's modulus and tensile strength, follow the Gauss distribution. In this way the mechanical parameters of every element in the mesh are specified randomly by using the Monte Carlo method.

Table 2. Material properties

	E [GPa]	ν [-]	σ_t [MPa]	G_f [N/mm]
Rock	50	0.25	5	0.05
Distribution type	Gaussian	Gaussian	Gaussian	Gaussian
Upper variance limit [%]	30	30	50	50
Lower variance limit [%]	30	30	50	50
Initial seed	15	1	1	2

E=Young's modulus, ν=Poisson's ratio, σ_t=tensile strength, G_f=fracture energy

Table 3. Mohr Coulomb parameters

c [MPa]	ϕ [°]	ψ [°]
50	30	0

c=cohesion, ϕ=friction angle, ψ=dilatation angle

The Rankine Rotating crack model coupled with a Mohr-Coulomb failure criterion is used. In this model the applied load is simulated with a constant vertical velocity (1mm/s) applied directly on the specimen (without platens) to avoid stress concentrations and tensile stresses at the ends of the specimen during loading, due to stiffness incompatibilities. For this model a mesh size of 1.2mm for the sample is assumed (Fig.4).

Crack development pattern is shown in Fig.5. The fracture process is similar to the observed stress fracturing leading to kinkband and primary shear plane formation. Since element rotation is prevented and further tensile fracturing favoured by the selected low tensile strength σ_t, a secondary shear plane eventually forms and the specimen gradually disintegrates.

The diagram representing the reaction force at the upper boundary of the specimen versus the vertical displacement is shown in Fig.6 and exhibits a linear force-displacement relation before peak. Micro-cracks (crack initiation) appear when the load-displacement curve is linear. When micro-cracks start to coalesce the peak load is reached. With the applied load increasing, cracks gradually develop. After peak, the behaviour is brittle, with the strength dropping rapidly to a residual value.

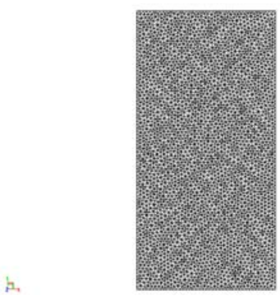


Figure 4. Mesh used for the heterogeneous UCS simulation

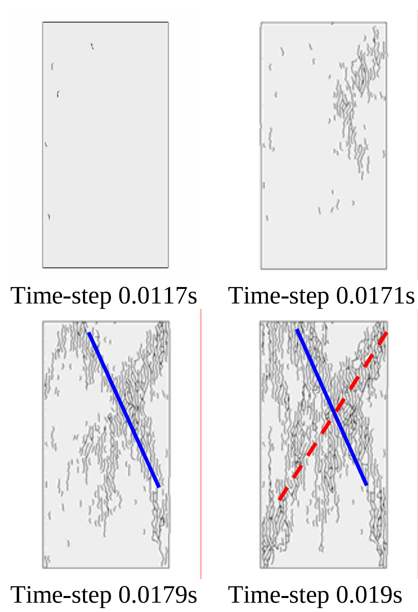


Figure 5. Results for the simulation of a uniaxial compression test with heterogeneity

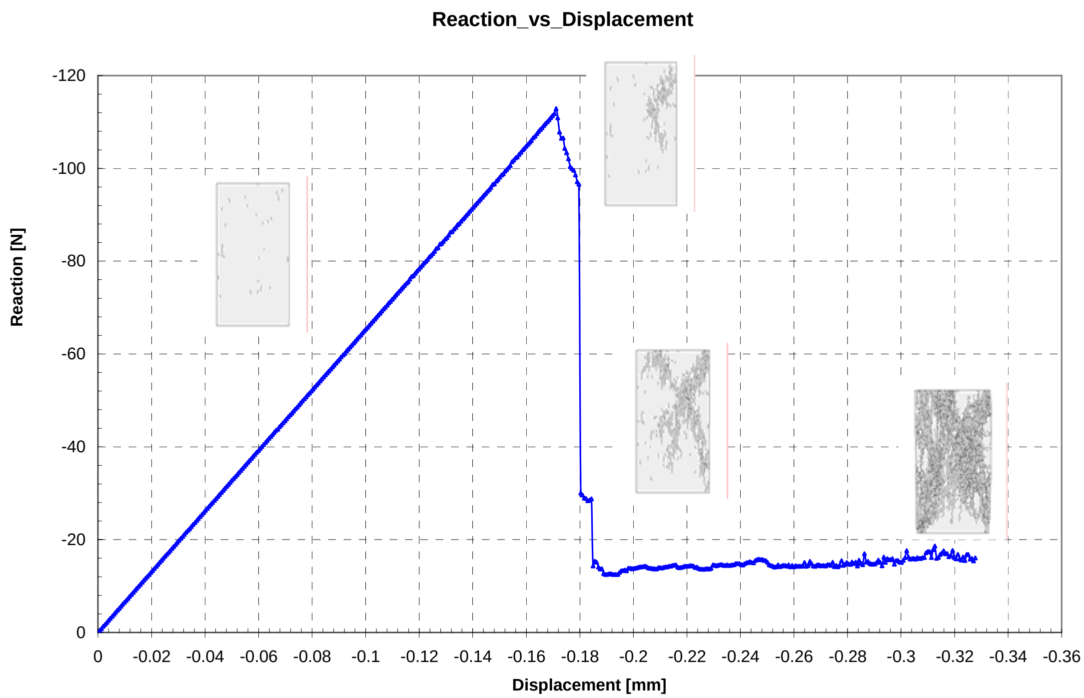


Figure 6. Force and vertical displacement relation of isotropic rock in a uniaxial compression test simulation

In order to gain further understanding of the damage process, the computed strain-path is illustrated in Fig. 7. It is shown that the relation between the axial compression strain and the lateral extension strain is linear until fractures start to propagate. Slightly non-linearity is observed when micro-cracks do appear in the specimen. When these micro-cracks coalesce and create multi-cracks fractures, the peak is reached in the reaction versus displacement curve and the corresponding strain-path exhibits a distinct loss of linearity.

2.3 *Triaxial Test*

Since triaxial conditions cannot be simulated in 2D models, the effect of lateral confinement is examined in 2D compression tests. In this section confined compression tests are simulated to study the influence of confinement. The specimen has a width of 50mm and the height to width ratio is equal to 2. The assumed material properties are listed in Table 2.

The Rankine Rotating crack model coupled with the Mohr-Coulomb criterion is used with the Mohr-Coulomb parameters given in Table 3**.**

In this model, the applied load is simulated with a constant vertical velocity (1mm/s) applied directly on the specimen. A mesh size of 1.2mm is used, as in the previous model.

The confinement pressure, taken to be 10MPa and 15MPa respectively, is applied by the "*face load*" option in the ELFEN code. The results obtained in terms of fracture patterns are shown in Fig. 8 with reference to the test with a confinement pressure of 10MPa..

The effect of confining pressure is observed to change the fracture pattern, as expected. Shear bands are now created in the rock specimen due to the coalescence of single micro-cracks. In other words, the predominance of tensile fracturing is reduced by the applied, very high confining pressure σ_3, compared to the UCS.

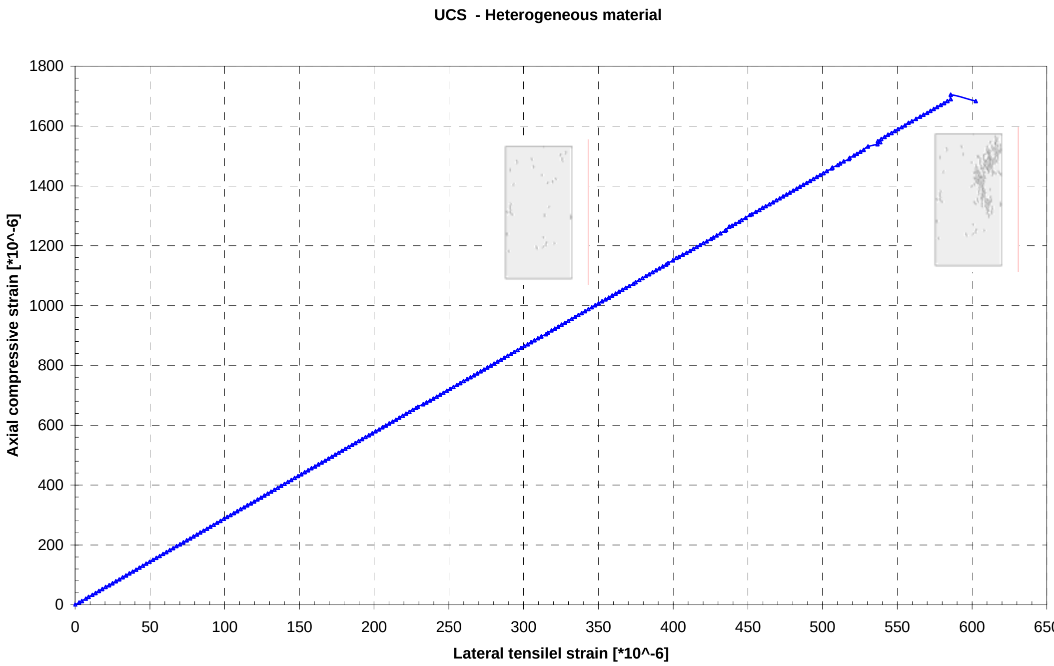
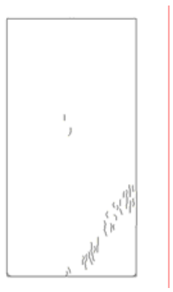
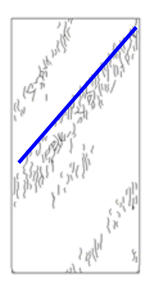


Figure 7. Axial compression strain and lateral extension strain relation of isotropic rock in a uniaxial compression test simulation

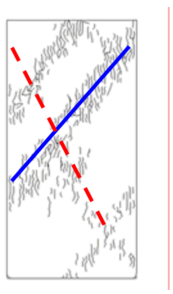
As previously, the reaction force at the upper boundary of the specimen versus the vertical displacement is plotted in Fig. 9 for the tests simulated, with 0, 10 and 15MPa confining pressure. A linear force-displacement relation is seen before peak load. Also, both the peak and residual loads are shown to increase with the confining pressure. Micro-cracks start to appear in the specimen before the peak load is reached with the peak corresponding to the coalescence of micro-cracks to form multi-crack fractures.

It is of interest at this point to consider Stacey's empirical strain criterion (1981), with respect to the simulated behaviours. Stacey's criterion states that "*fracture of the rock will occur in indirect tension, when the tensile strain exceeds a limiting value which is dependent on the properties of the rock*". With this in mind, let us pay attention to the results obtained with the numerical simulation of the unconfined and confined compression tests, by plotting in Fig. 10 the axial compressive strain versus the lateral extension strain as given by the ELFEN code. It is straightforward to note from Fig. 14 that for each test the loss of linearity occurs at approximately the same value of lateral extension strain (at $550x10^{-6}$). Also, initiation of fracture takes place when a small but noticeable increase in lateral strain occurs, i.e. as the extension fractures form in planes normal to the direction of action of the confining pressure (the minimum principal stress direction), the specimen expands more rapidly in the radial direction.





Time-step 0.0221s   Time-step 0.0241s



Time-step 0.0257s   Time-step 0.035s

Figure 8. Results of a triaxial compression test simulation with a confining pressure of 10MPa

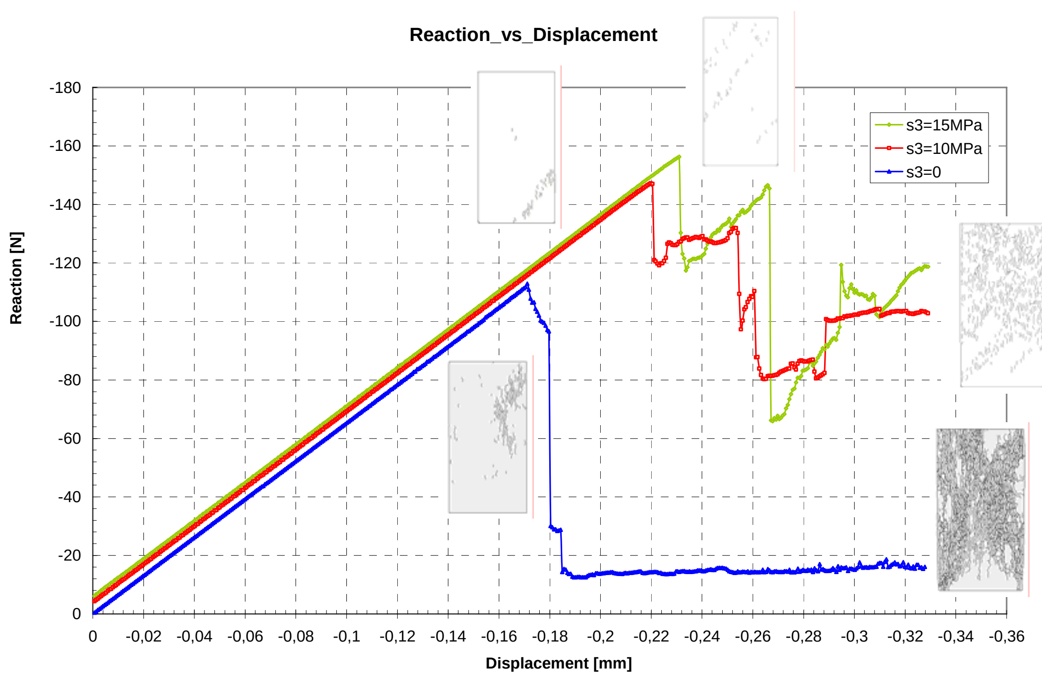


Figure 9. Force and vertical displacement relation in unconfined and confined compression tests simulations

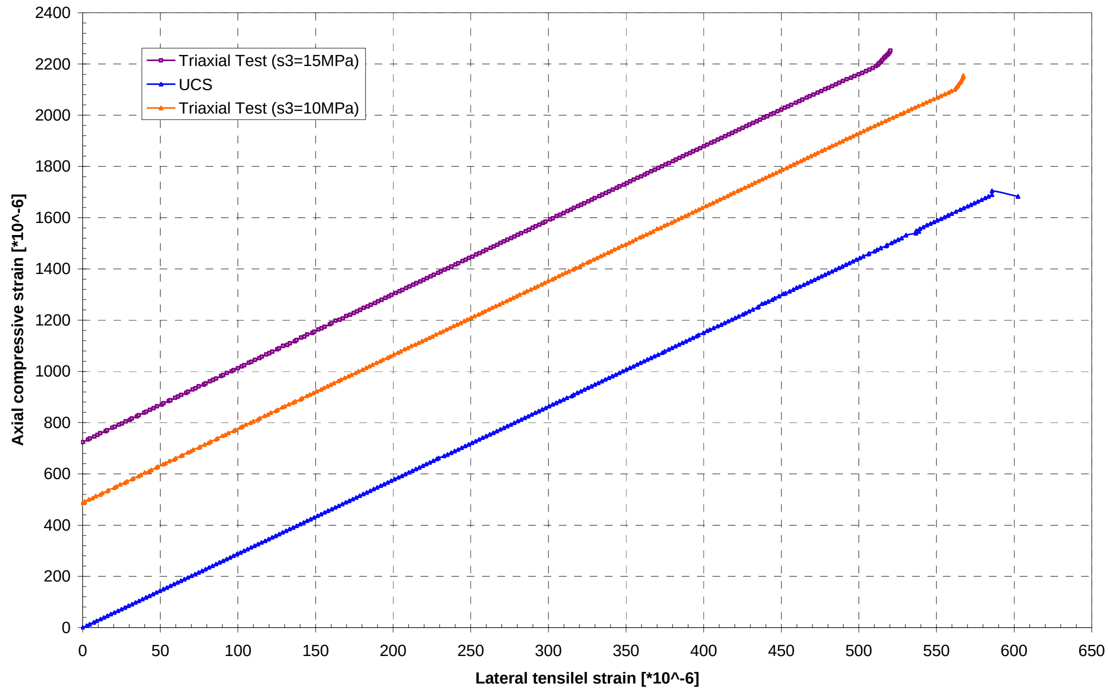


Figure 10. Axial compression strain and lateral extension strain relation for isotropic rock in unconfined and confined test simulations by the ELFEN code.

3 CONCLUSION

In order to model the fracture behaviour of rock under loading, the numerical code ELFEN has been used successfully. Experimentation with rock parameter selection was required to achieve good correspondence. Typical rock mechanics tests have been simulated by showing that the fracture process in rock is represented remarkably well. A notable feature of ELFEN is that no a priori assumptions need be made about where and how fractures will be initiated and develop thus leading to failure. Fracturing can occur spontaneously and exhibit a variety of mechanisms when certain local stress conditions are met.

The entire fracturing process is shown to be simulated during testing, including initiation, propagation and coalescence of fractures. In particular, the analysis of the axial compression strain versus the lateral extension strain diagrams during testing in uniaxial and triaxial compression shows that the Stacey's extension criterion is apparently confirmed.

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