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Numerical Modeling of Rock Mechanics Tests in Layered Media Using a Finite / Discrete Element Approach

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ABSTRACT: A numerical simulation based on a finite/discrete element approach is used to study the deformation and failure process of standard rock mechanics tests on Opalinus clay samples, when subjected to static loading conditions. The layered structure of the Opalinus clay is considered and the resultant anisotropic behaviour is modelled. Rock heterogeneity is also taken into account, with the main purpose to visualize micro-cracks creation, coalescence and eventually propagation of a single macro-failure plane. Anisotropy is introduced in the model by mesoscopic bedding planes. Uniaxial compression tests have been simulated on samples having a layered structure oriented parallel, perpendicular and inclined at 45° with respect to the axial loading. The results obtained are analyzed in terms of the predicted "global mechanical response" which is compared to that available from experimental tests on Opalinus clay samples (Konietzky et al., 2003). FEM/DEM modeling has been used to simulate the genesis and propagation of fractures, the consequence of rock degradation and its change in behaviour from continuum to discontinuum.

1 Introduction

In this paper a series of numerical analyses have been carried out to assess the suitability of a finite/discrete element (FEM/DEM) approach to properly and efficiently simulate typical rock mechanics tests. To this purpose three standard rock tests carried out on Opalinus clay (Konietzky et al., 2003) have been numerically simulated. The model considers the rock layered structure and the consequent material heterogeneity. The results have been analyzed in terms of the "global mechanical response" obtained by evaluating if the fracturing response is realistically represented.

To investigate the global fracturing response the FEM/DEM code ELFEN (Rockfield Software, 2007) has been used. The FEM/DEM technique provides a unique ability to model fracture initiation and growth, as it simulates the transition of rock 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.

FEM/DEM capability to properly and efficiently simulate typical rock mechanics tests has been verified first by simulating standard laboratory tests such as a standard Brazilian test, an inclined flat crack in a sample under uniaxial compression, uniaxial compression tests and triaxial compression tests (Stefanizzi, 2007). Then, the approach adopted has been used to simulate testing of rock containing bedding planes.

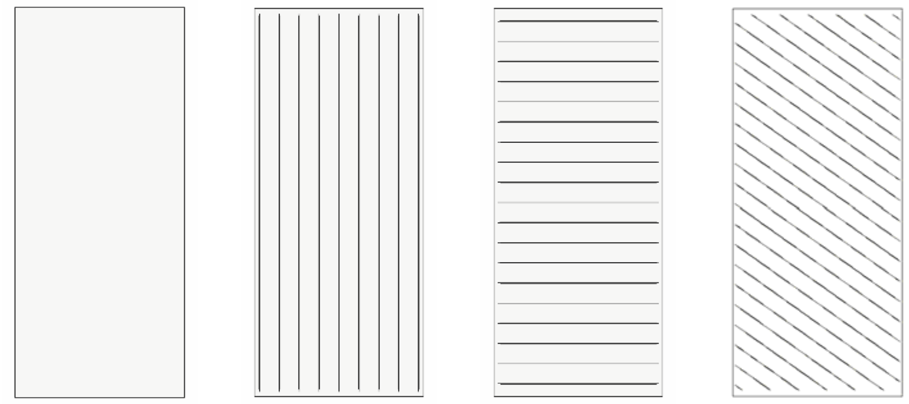
2 Background information on the simulation process

A series of numerical analyses have been carried out by using the FEM/DEM approach as available in the ELFEN code (Rockfield Software, 2007). The results have been analyzed in terms of the “global mechanical response” obtained by evaluating if the fracturing response is realistically represented.

The number of time steps required to bring a structure to failure under quasi-static conditions is such that the simulation time is of the order of weeks. In order not to over increase the simulation time, the smallest element side length that is created in a fracturing analysis is specified to be equal to the original mesh size, so new fractures break from the boundary of the element. This means that fractures will propagate around the element boundaries, avoiding the problem of thin, badly-shaped elements being formed when elements break.
In the “discrete element constraints” window the contact properties to pre-existing cracks and newly generated cracks can be assigned. Results of simulations are strictly influenced by the parameters assigned. Discrete contact data are defined in two ways: 1. Global properties – these apply to all free surfaces, unless specific surface type properties are applied (newly generated cracks); 2. Surface type properties – named sets of contact properties can be defined and applied to specific parts of the model, overriding the global properties (pre-existing cracks).

3 Uniaxial compressive test in a rock containing bedding planes

The applicability of a FEM/DEM approach to model rock mechanics tests in complex conditions is demonstrated in the following. The influence of the presence of bedding planes in a rock tested under uniaxial compression is analyzed. The selected rock is an Opalinus clay (Konietzky et al., 2003). As shown in Figure 1 the numerical simulation was performed on a homogeneous, isotropic specimen and on specimens loaded parallel (P-specimen), perpendicular (S-specimen) and inclined 45° (Z-specimen) with respect to the bedding planes.



(a) Homogeneous (b) P (c) S (d) Z

Figure 1. P, S, Z specimen used for modeling uniaxial compression tests on Opalinus clay.

The choice to consider specimens P, S and Z was made as the results of laboratory tests were available for these directions of loading. The homogeneous specimen was used for purpose of comparison and in order to highlight the influence of the bedding planes on the failure patterns.

The modelled specimen has a width of 340mm and a height of 770mm. The height/diameter ratio is 2.3. The spacing between the bedding planes is 40mm.

The numerical code ELFEN only considers Mode I fracture initiation and propagation. Therefore, one can see only fractures that are generated by exceeding the tensile strength of the material. The real process is more complex because a shear component is present. Actually, the code is not able to generate fractures due to Mode II (shear mode). It is however possible to modify the material properties to obtain a general behaviour which is more similar to reality, when considering the influence of heterogeneity.

Different approaches have been used in the past to implement heterogeneity effects in numerical models such as:

- randomly assigning different properties, possibly following some kind of distribution, to the elements (Batrouni and Hansen, 1998; Tang, 1997);

- using a mesh with a random geometry, but equal properties for the elements (Garboczi and Day, 1995);
- generating a microstructure and projecting this on regular elements, assigning different properties to the elements depending on their position (Schlangen and Van Mier, 1992; Schlangen and Garboczi, 1997);
- using a combination of random geometry and a generated grain structure (Bazant et al., 1990);
- using a statistical approach with a Weibull distribution (e.g. RFPA code) (Tang, 1997: Tang et al., 2000).

In ELFEN heterogeneity of rock is introduced by assuming that its mechanical properties at the mesoscopic level, such as Young's modulus and tensile strength, conform to the Gauss distribution and the mechanical parameters of every element in the mesh are specified randomly by using the Monte Carlo simulation. Of course, there are an infinite number of parameter combinations that can be encountered in reality. The following is intended to just demonstrate an example of what can be anticipated. The material properties assigned in the following simulation are listed in Table 1 an 2. The Rankine Rotating crack model coupled with a Mohr-Coulomb failure criterion is used for the matrix. Table 3 lists the material properties assigned to the bedding planes.

Table 1. Material properties of the matrix.

	E [GPa]	ν [-]	σ_t [MPa]	G_f [N/mm]
Rock	2.7	0.3	5	0.01
Distribution type	Gaussian	Gaussian	Gaussian	Gaussian
Upper variance limit [%]	30	30	50	50
Lowe variance limit [%]	30	30	50	50
Initial seed	1	1	1	2

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

Table 2. Mohr-Coulomb parameters of the matrix.

c [MPa]	ϕ [°]	ψ [°]
2.6	25	3

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

Table 3. Mohr-Coulomb parameters for the bedding planes.

c [MPa]	ϕ [°]	ψ [°]
2.6	25	3

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

The applied load is simulated with a constant model vertical velocity (15mm/s) applied directly on the model. The model velocity is equivalent to a quasi static loading (0.001 mm/s) for laboratory tests. A mesh size value of 0.8 mm is assumed as compromise between the need of reproducing the rock microstructure and the computational limitations in solving the numerical model. The meshes used for the homogeneous, P, S and Z specimen are shown in Figure 2.

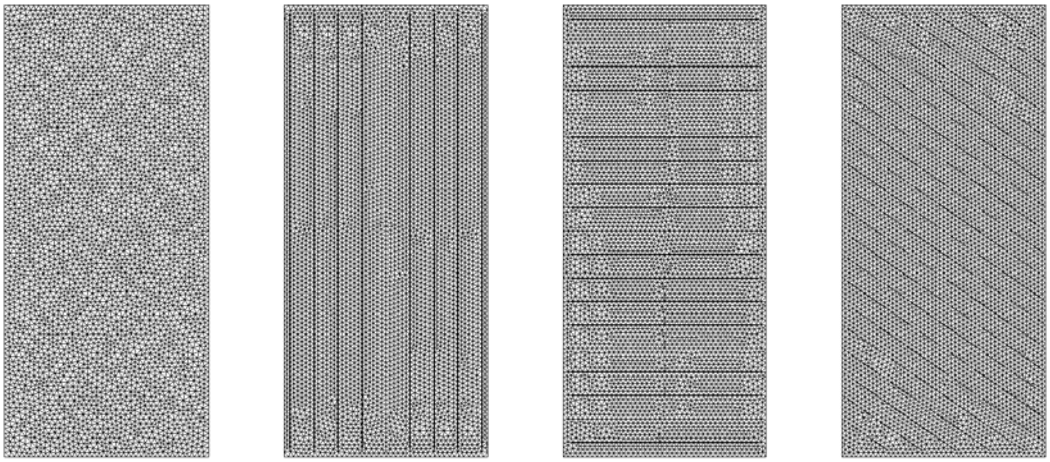
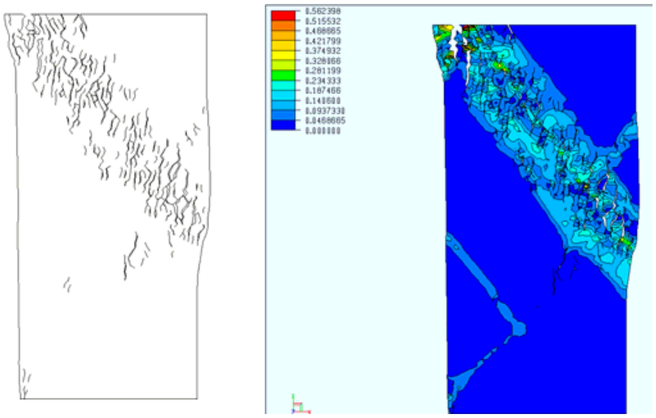

(a) Homogeneous (b) P (c) S (d) Z

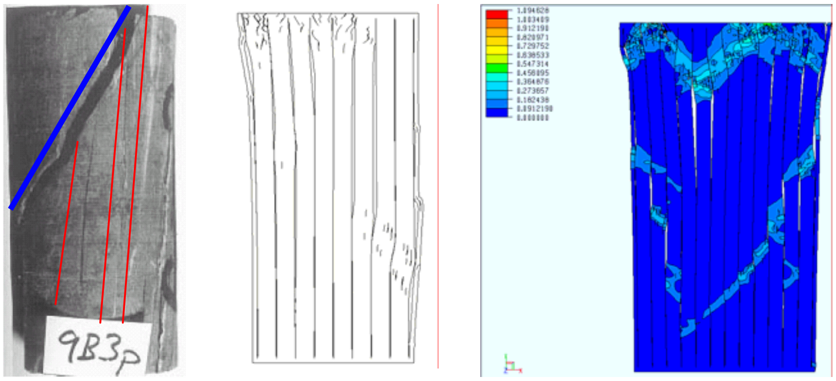
Figure 2. Mesh used for the Opalinus clay tests.

Figures 3, 4, 5, and 6 present the results obtained for each simulation in terms of the fracture pattern (shown on the left) and effective plastic strain distribution (shown on the right). For specimen P, S and Z, selected photographs of the rock failed specimens are also shown.



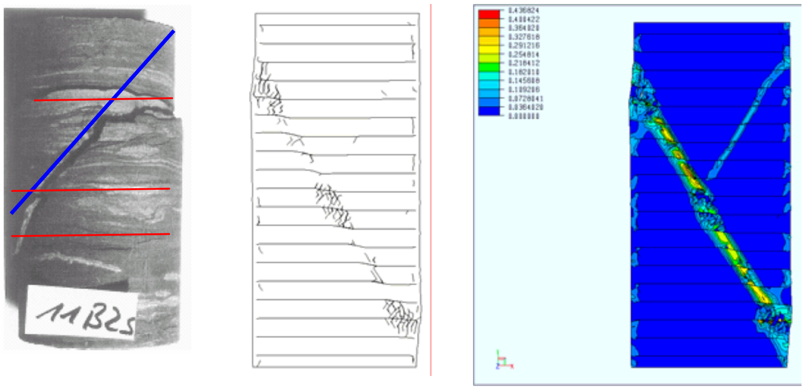
(a) (b)

Figure 3. Fracture pattern (a) and effective plastic strain (b) for homogeneous Opalinus clay simulation.



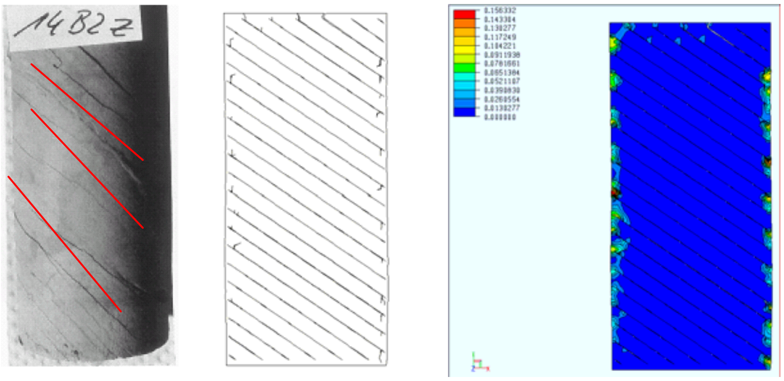
(a) (b) (c)

Figure 4. Real fracture pattern (a), simulated fracture pattern (b) and effective plastic strain (c) for the P-sample. Blue is macroscopic shear failure and red is macroscopic tensile failure (The shear fracture is reproduced by the effective plastic strain and the tensile fracture is reproduced by the fracture pattern).



(a) (b) (c)

Figure 5. Real fracture pattern (a), simulated fracture pattern (b) and effective plastic strain (c) for the S-sample. Blue is macroscopic shear failure and red is macroscopic tensile failure (The shear fracture is reproduced by the effective plastic strain and the tensile fracture is reproduced by the fracture pattern).



(a) (b) (c)

Figure 6. Real fracture pattern (a), simulated fracture pattern (b) and effective plastic strain (c) for the Z-sample. Red is macroscopic tensile failure that is reproduced by the fracture pattern.

4 Discussion

It is noted that for the P-specimen vertical tensile splitting is taking place along the bedding planes, coupled with limited shear band (Figure 4). The splitting (or buckling) process is predominant in the model due to the low material stiffness of the bedding planes and to the fact that the tensile strength at the bedding planes is assumed to be equal to zero. The numerical model reproduces the fracture pattern reasonably well. The effective plastic strain (Figure 4c) indicates the presence of shear bands.

A localized horizontal splitting along the bedding planes was observed in the S-specimen, together with the formation of shear bands (Figure 5). In this case the shear bands develop through the entire specimen and are not inhibited by the splitting process as in the P-specimen.

A clear macroscopic shear failure along the bedding planes takes place in the laboratory Z-specimen as well illustrated in Figure 6.

In summary, one may say that in both the P and S specimens, where the bedding planes are respectively parallel and perpendicular to the direction of loading in uniaxial compression tests, tensile splitting along these planes is accompanied by initiation and development of shear bands.

In contrast, the Z-specimen exhibits essentially shearing along the bedding planes and fails in direct shear mode before the material reaches its strength. In all cases with due consideration given to the complexity of the problem, the experimental results compare satisfactorily with the numerical results, in terms of the phenomena which lead in each case the rock specimen to failure.

5 Conclusions

In order to model the fracture behaviour of rock under loading, a finite/discrete element code has been used successfully. Experimentation with rock parameter selection was required to achieve good correspondence. Typical rock mechanics tests in a layered rock have been simulated by showing that the fracture process in rock is represented remarkably well.

A notable feature of the finite/discrete element code used (ELFEN) is that no a priori assumptions need be made about where and how fractures will be initiated and/or develop thus leading to failure. Fracturing can occur spontaneously and exhibit a variety of mechanisms when certain local stress conditions are met. Thus, the entire fracturing process can be simulated including initiation, propagation, and coalescence of fractures.

Numerical tests conducted on the Opalinus clay demonstrate that the finite/discrete element models are able to reproduce both the fracture and bedding shear processes as those observed during laboratory tests.

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