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Modeling of Fractured Rock Under Stress for Nuclear Waste Disposal Applications

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INTRODUCTION

Characterization of natural fractured rock for the disposal of high-level nuclear waste in a crystalline host rock is of importance to the investigation of the natural barrier system and transport of radionuclides. Studying the mechanical-hydrological-thermal-chemical response of a single fracture and fracture network under stress also provides better understanding of the behavior of the repository and its surroundings with time.

Fracture network analysis is of importance to the study of migration of radionuclides away from a geological nuclear waste repository in fractured rock. Recent studies included evaluation of the characterization methods Fracture Continuum Model (FCM) and Discrete Fracture Network (DFN) model [1]. The study allowed understanding of different characterization methods suitable for use in geologic disposal of nuclear waste in crystalline host rock. Use of fracture network models in the evaluation of experimental data is documented in [2].

There is also an interest in understanding the mechanical-hydrological-chemical response of single fracture and fracture network under stress. Such work was started in [3]. Currently, Sandia is participating in DECOVALEX 2023 Task G. The main objective is to combine the previous study on fractures with rock mechanics. DECOVALEX 2023, Task G is on: Safety ImplicAtions of Fluid Flow, Shear, Thermal and Reaction Processes within Crystalline Rock Fracture NETworks (SAFENET). The task is to be conducted in steps in order of increasing complexity using benchmark exercises.

In this study we present preliminary results of modeling benchmark exercises for mechanical-only and hydromechanical problems. The mechanical-only benchmark exercise is on fracture mechanics, with the objective of understanding the mechanical response of a single fracture under stress. The problem involves modeling of a single fracture embedded in a rock matrix under constant normal load and direct shear stresses. The hydromechanical benchmark exercise is similar to the mechanical-only problem, with the added condition that the fracture is subject to internal fluid pressure. For the simulations COMSOL Multiphysics™ [4] software was used. Simulation results for the two benchmark exercises were compared to analytical solutions that provide normal and shear displacements along the fracture plane.

STEP 1 AND STEP 2 PROBLEM DEFINITION

Step 1

The Step 1 benchmark problem is on modeling of a single fracture embedded in an elastic matrix. It involves fracture mechanics, with the objective to understand the mechanical response of single fracture under stress. Figure 1 illustrates the definition of the benchmark exercise, with a 2D model domain of size 0.5 m × 0.5 m. The plane fracture has length of 0.17 m and is inclined from the horizontal at specified angles. Table 1 shows experimental mechanical properties obtained from shear tests (DECOVALEX 2023 Task G). Simulation results can be compared to the analytical solution [5], which provides solutions for normal and shear displacements along the fracture plane.

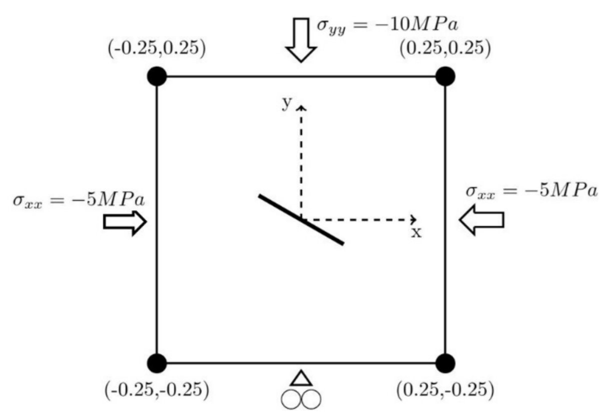

Fig. 1. Benchmark Exercise Step 1: Rock material with a single fracture

Step 2

Step 2 represents a porous sample of very low permeability with an embedded fracture where the fracture is loaded by internal fluid pressure. The fracture is inclined at -30° to the horizontal. The fluid pressure within the fracture is p = 2MPa. Step 2 consists of two cases:

Case 1: Planar fracture with no external loading and an internal fluid pressure of 2MPa. Predicted fracture displacement (fracture opening) can be compared to the analytical solution [6]:

$$u(r) = \frac{2(1-\upsilon)PR}{\pi G}\sqrt{1-\left(\frac{r}{R}\right)^2} \qquad (1)$$

where u is the surface deformation, r is the radial coordinate from the middle of the fracture to the extremity at R, υ is Poisson's ratio, G is the shear modulus and P is the fluid pressure inside the fracture.

Case 2: Planar fracture with an external vertical loading of 10MPa and horizontal loading of 5MPa, and internal fluid pressure of 2MPa. Simulation results are to predict the surface deformation of the fracture. The results will be compared to those of Case 1, to understand the effect of external loading.

MODEL SETUP

Preliminary modeling analyses were conducted for Step 1 and Step 2 benchmark exercises, using provided problem specifications and analytical solutions. For the simulations an embedded fracture in an elastic material was assumed. COMSOL Multiphysics™ software was used for both Step 1 and Step 2 simulations.

For Step 1, the embedded fracture is represented as a spring foundation using Hooke's law. Material properties used for the preliminary simulations are shown in Table 1. The geometry includes a matrix domain of size 0.5 m x 0.5 m and a single fracture length of 0.17 m length. Fracture angles from horizontal of -30°, -45°, -60° were considered. The mesh for Step 1 simulation is shown in Figure 2.

TABLE 1. Material Properties used in modeling

Parameter	Granite	Unit
Density	2590	Kg/m^3
Elastic Modulus	4.975×10^{10}	Pa
Poisson's ratio	0.26	-

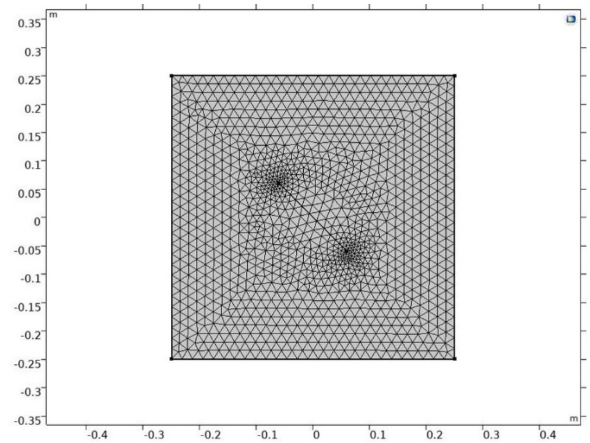

Fig. 2. Meshing for Step 1: Fracture at -45° angle from horizontal

A similar set-up was used for Step 2 simulation. For Step 2 an internal fluid pressure of 2MPa was applied to the fracture, and a fracture angle from horizontal of -30° was used. The external loads and stresses are the same as in Step 1.

RESULTS

COMSOL Multiphysics™ Version 5.6 was run for both Steps 1 and 2.

Step 1

For Step 1 three separate runs were made for the three fracture angles. For the COMSOL™ runs the steady state option was selected. The results are shown in Figures 3 to 6. Figures 3, 4 and 5 show predicted results of surface stress tensors for xy, y and x components, respectively. The results show stress concentration at the fracture tips. Figure 6 shows shear displacement along the length of the fracture for the run with -45° inclination angle. The simulation results were compared to the analytical solution [5], as shown in Figure 6. An excellent match was obtained.

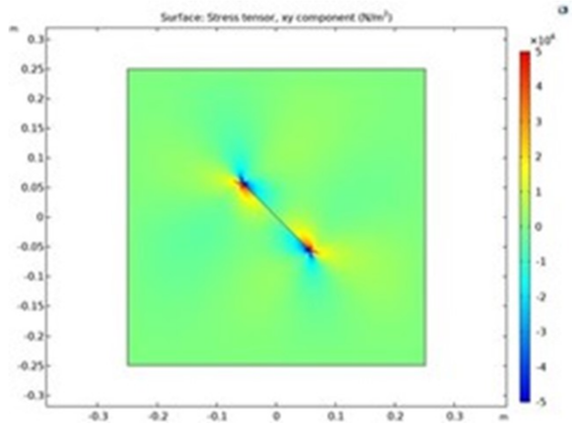

Fig. 3. Results for Step 1: Surface stress tensors: xy component (N/m^2)

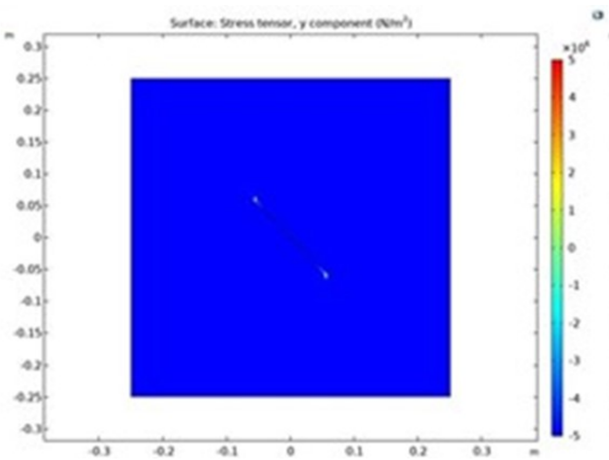

Fig. 4. Results for Step 1: Surface stress tensors: y component (N/m^2)

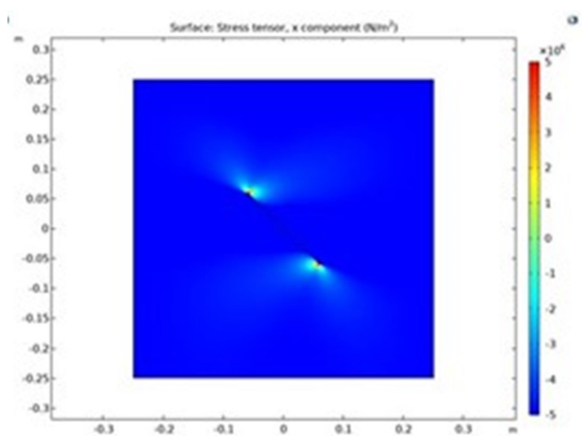

Fig. 5. Results for Step 1: Surface stress tensors: x component (N/m^2)

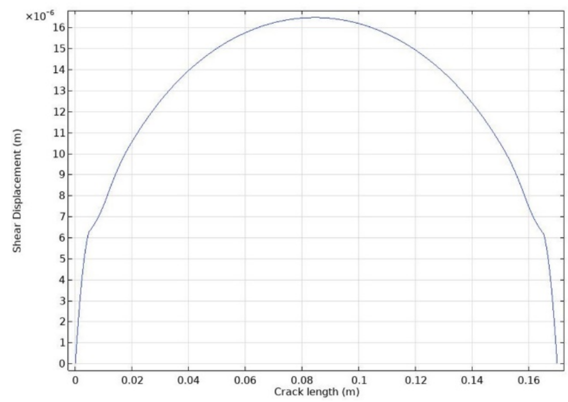

Fig. 6. Results for Step1: Shear displacement along fracture for case with -45^{o} inclination angle

Step 2

For Step 2 two separate runs were made for the two modeling cases (Case 1: no external loading; Case 2: with external loading). For the COMSOL™ runs the steady state option was selected. The results are shown in Figures 7 to 10. Figure 7 shows results for Step 2, Case 1 modeling: The figure shows distribution of normal surface displacement for the case with no external loading and fracture with internal fluid pressure. Figure 8 shows normal displacement along the fracture length for Case 1. As shown in Figure 8, the simulation results were compared to the analytical solution [6]. The simulation results closely match the experimental data. The differences could be related to the selection of the mesh and due to boundary effects related to the domain size. Figure 9 shows results for Step 2, Case 2 modeling. The figure shows distribution of normal surface displacement for the case with external loading and fracture with internal fluid pressure. Figure 10 shows results for Step 2, Case 2 modeling. The figure shows results of normal displacement along the fracture for the case with external loading and fracture with internal fluid pressure. The normal displacement for Case 2 is higher than that of Case 1 because of the added external loads.

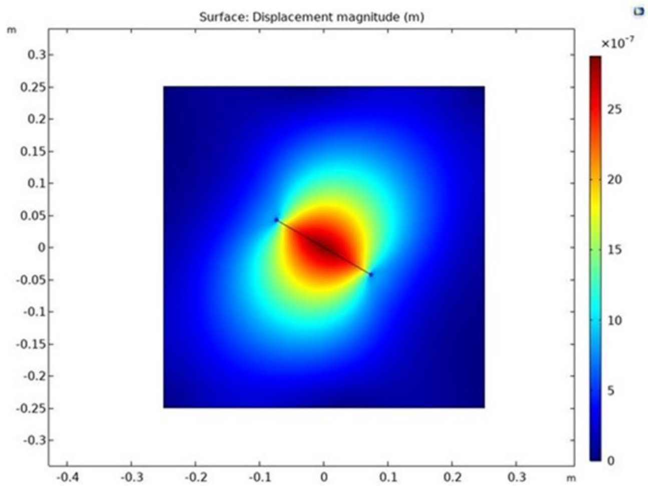

Fig. 7. Results for Step 2, Case 1: Distribution of normal surface displacement

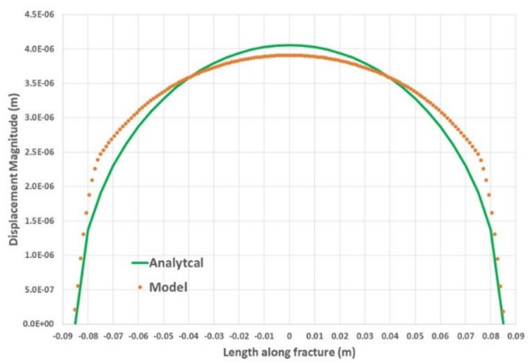

Figure 8. Results for Step 2, Case 1: Normal displacement along fracture

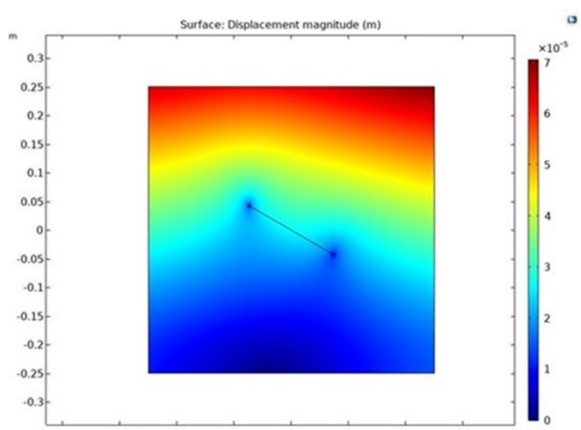

Fig. 9. Results for Step 2, Case 2: Distribution of normal surface displacement

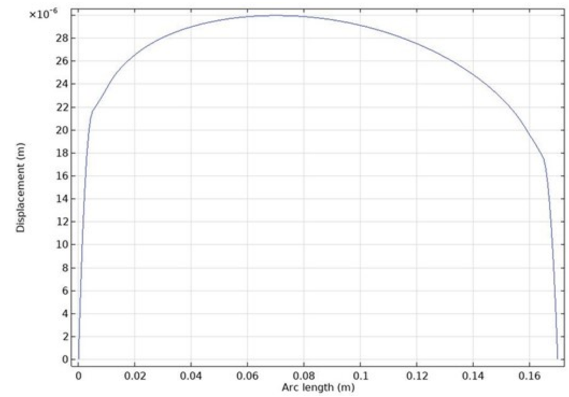

Fig. 10. Results for Step 2, Case 2: Normal displacement along fracture

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