Fracture Behavior in a Rock Pillar Subjected to Coupled Thermo-mechanical Loading

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Abstract. Using RFPA code, analyses have been carried out to investigate the stability of a rock pillar in a experiment for nuclear waste repositories, the numerically obtained stress field, temperature distribution, failure pattern of the pillar rock and associated AE events are all agree well with the in-situ data. Minor fracture initiation may take place in the vicinity of the boreholes after heating. Heating induces minor spalling at central pillar wall for 0.5 m sections below the tunnel floor, but the area of spalling is found to be limited. The core of the pillar remains intact for stress conditions corresponding to 120 days of heating which not only prove that the proposed technique provides a powerfully alternative and effective approach for the study on thermal-mechanical-damage coupling mechanism but also provide meaningful guides for the experiment design and associated applications.

Introduction

An in-situ experiment has been commenced at Äspö Hard Rock Laboratory to investigate the stability of a pillar between two closely located deposition holes. This full-scale experiment is named the Äspö Pillar Stability Experiment (APSE). The experiment requires a new tunnel that is excavated at the 450 m level. In the tunnel two large holes with a diameter of 1.8 m and a depth of 8.0 m will be bored. The holes will be spaced to create a pillar with the width of 1.0 m between them (Fig.1) [1]. Electric heaters will be used to induce thermal stresses in the pillar that would force the rock in the pillar walls to spall. The experimental stages will be monitored by an acoustic emission (AE) system.

Preliminary modelling was carried out before excavation of the research tunnel. Research with Examine, FLAC, JobFem and FRACOD has been reported by the modelling teams [1].

Fig.1 General layout of APSE experiment [1]

Elastic FLAC, JobFem model gives the stress field and elastic displacements around the tunnel opening and implies damage around holes from elastic stresses and known strength [1]. However, in order to study in detail the damage that might occur another approach has to be taken. One possible and tested tool to model fracturing is based on a micromechanical model that can simulate the failure process of rock [2], called Rock Failure Process Analysis (RFPA). This model possesses the advantage that no a priori assumptions need to be made about where and how fracture and failure will occur. Cracking can occur spontaneously and can exhibit a variety of mechanisms when certain local stress conditions are exceeded. This study summarizes the outcomes of RFPA modeling with updated input parameters.

Model Description

Brief introduction to the Rock Failure Process Analysis, RFPA^{2D}. The Rock Failure Process Analysis (RFPA^{2D}) code based on *FEM*, is a numerical tool capable of handling the fracture initiation, interaction and coalesce process in heterogeneous rocks [2]. A model, implemented with RFPA, of coupling between thermal, mechanical and damage (*TMD*) has been proposed. It can give an effective description to the microscopic damage mechanism and macroscopic failure of rock subjected to thermal and mechanical loading.

Set-up of the model for numerical modeling. The pillar stability modeling was performed in one plane of interest, 0.5 m below the tunnel floor. Plane strain assumption was used in the modeling. The in-situ test area is heated with four heaters. Several thermocouples will be installed in boreholes in the test area to monitor the temperature development during the heating. The layout is shown in Fig2. Fig3 shows the modeling configuration for stability analysis. The model grid zone size is smallest (3.2m * 2.8m) at the pillar area, which is the main area of interest. The model has been discretized into a 192 * 168 (32,256) mesh. The rock mass is planned to be heated 120 days during which time the temperature-induced stresses should have reached high-enough values to initiate fracturing. In numerical modeling, heat flow radiates from four points as shown in Fig3 (four red circles). In thermal modeling, the upper and bottom boundaries are adiabatic i.e. fully insulated, and the right and left boundaries maintain temperature 15°C. The main parameters involved in the numerical modeling are listed in Table 1.

Fig.2 Experiment geometry and instrumentation [1] Fig.3 Pillar model for numerical modeling

Table1 Mechanics Parameters Employed in Numerical Simulation

Parameter	Value	Parameter	Value
Homogeneity index	4	Friction angle [°C]	49
Young's modulus [GPa]	55	Conductivity [W/m,K]	2.6
Uniaxial compressive strength [MPa]	170	Specific heat [J/Kg,K]	775
Poisson's ratio	0.26	Linear exp coeff. [1/°C]	7.0×10^{-6}

Numerical Modeling and Discussion

Temperature field. Fig.4 show the temperatures distribution along A-A' and B-B' during the heating period of 120 days. With the heating, the temperature field move toward the central pillar. After 120 days of heating temperature rises up to 70°C at the central pillar area. The temperature near the vicinity of the right pillar boundary is in around 70°C. The temperature near the mid-pillar is higher which indicate that increasing the stresses will come into being at the pillar area.

Fig.4 Temperature in °C along A-A' and B-B' during the heating period in numerical modeling

Fracture Pattern Associated Stress Field and AE Location. Fig.5a presents the maximum principal stress field in the numerical model. Numerical modeling suggests that most of the pillar area is in uniaxial compressive condition. The highest increase of stress occurs at the central part of pillar. After 120 days of heating the stress increase is near 205 MPa. With the increasing temperature produced by consecutive heating, stresses increase more microcracking starts to appear. Fracture propagation continues successively with stress increase in a limited area close the pillar wall. Possible spalling is restricted to a narrow area at the borehole boundary after 120 days of heating. Fractures may form V-shaped shear spalled zones on both sides on the pillar boundary. In spite of quite extensive fracturing at the pillar wall, the fracture propagation is stable and the pillar core will remain intact. However, if the stresses become higher than expected or the strength of the pillar is lower, damage that may occur is more extensive. Finally, if the situation is favorable, fractures maybe penetrate into the pillar.

Fig.5b represents the associated evolution of AE events during fracturing process. In the figures, each circle represents one AE event and the diameter of the circles represents the relative magnitude of the AE released energy [2]. Red and white circles represent the current active AE events (red circle indicate tension failure, white circle indicate shear failure). AE events are stepwise modelled and the intensity of AE events is proportional to the degree of damage. Due to the heterogeneity of rock, AE events are observed as soon as the two boreholes were excavated. Most of these micro AE events are located in weak element and near the vicinity of the pillar boundary. With the fracturing process, especially after 120 days of heating, AE events become more active within the central part of the pillar. A micro-seismic zone developed quickly along the boundaries of the boreholes which coincides with the early formed V-shaped shear spalled zones. AE events indicate that the failure mode of the pillar is a combination of tension and shear fracturing. Fig.6 is the fracture pattern of pillar in experiment. The numerical results are all agree well with the experimental ones.

(a) maximum principal stress field

(b) AE location

Fig.5 Stress field and AE location in numerical modeling

(a) left

(b) right

Fig.6 Fracture pattern of pillar in experiment

Summary

RFPA successfully reproduced the initiation and propagation of fractures in pillar area during the in-situ test. Calculations suggest that the planned loading geometry will induce stresses that are slightly higher than the limit for fracture initiation with given material properties. Minor fracture initiation may take place in the vicinity of the boreholes after heating. Heating induces minor spalling at central pillar wall for 0.5 m sections below the tunnel floor, but the area of spalling is found to be limited. The core of the pillar remains intact for stress conditions corresponding to 120 days of heating, which not only prove that the proposed technique provides a powerfully alternative and effective approach for the study on thermal-mechanical-damage coupling mechanism but also provide meaningful guides for the experiment design and associated applications. Mathematically, RFPA successfully gives an effective solution to the nonlinear and discontinuum mechanics problems in rock engineering failure using continuum mechanics method.

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