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Thermal cracking following a blowout in a gas-storage cavern

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ABSTRACT

In this paper, the nucleation and the propagation of thermal cracks following a severe thermal shock in gas storage caverns leached out from a salt formation are studied. This shock is induced by a quick release of the gas stored in the cavern following a rapid gas withdrawal from the cavern. A first model takes into account pressure and temperature changes at the cavern wall to reach critical stress. It also justifies a rate-independent hypothesis in salt formations for rapid loadings. The second model used is the one developed in the variational approach to fracture, which can predict nucleation of cracks as well as their propagation in a single framework, with no *a priori* hypothesis on the topology of the cracks. We illustrate that cracks nucleate on the rock wall with periodic spacing. The geometry of the cavern has little influence. Furthermore, as the heat diffuses, cracks penetrate and their spacing, ruled by Griffith's law, follows a characteristic scale law.

1. Introduction

An abundant literature has been dedicated to the effects of thermal expansion and thermal stresses in such underground openings as mines, tunnels, underground hydrocarbons storage and, above all, underground waste-disposal sites containing heat-producing canisters. In most cases, the rock mass is assumed to behave as a continuum, and no discontinuity is generated. Less attention has been paid to the onset and propagation of "thermal fractures", *i.e.*, fractures generated by thermal stresses.

Complex crack morphogenesis also appears in other engineering fields. The issues to be tackled are always the same, nucleation, path selection and non-regular evolutions, with respect to time and space. Usually, an *ad hoc* criterion is used in addition to the path evolution law. A unified framework addressing these issues has been proposed in the variational approach to fracture of Francfort and Marigo [1]. In the numerical implementation [2,3] the set of cracks is treated through a scalar unknown that can be viewed as a damage variable [4]. In addition, the evolution from diffuse damage to crack onset and growth results from a stability principle with no added ingredient.

In this paper, several examples of "thermal fractures" in a gallery, a mine shaft or a cavern are first presented (Section 2). It is shown that a "simplistic" approach (Section 2.2) allows predicting the onset of fractures. However, this approach is not able to predict fracture depth, spacing or aperture. A more advanced model is proposed (Section 3) in which the brittle behavior of rock and damage propagation are described through minimization of the sum of the elastic (free) energy and the dissipated energy. A non-local damage parameter accounts for both softening and fracture propagation. The evolution of the state of the material is governed by a stability principle. This model is applied to the case of an actual blowout in a salt cavern (Section 3.3) during which both pressure and temperature dropped abruptly. The fracture pattern is discussed in Section 3.4.

2. Thermal fractures in galleries, shafts and caverns

2.1. Field examples

When the fluids (air, water, brine or gaseous hydrocarbons) contained in a mine gallery, a tunnel or a salt cavern experience large temperature changes, the rock at the wall of the underground opening is warmed or cooled. Thermal expansion or contraction of the rock is generated. Because expansion or contraction is partly hindered, "thermal" stresses appear, which may lead to spalling, sloughing or fracturing when temperature changes are large enough. Several examples are described below.

2.1.1. Warming

A case of intense rock warming was described by Lee et al. in [5]. Hot (315 °C) diesel-exhaust gases from an underground power

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plant were circulated in a horizontal drift in a granitic rock formation at a 150 m depth at North Bay, Ontario, Canada, spalls formed at the well drift. After several months, the cross-sectional area of the drift had increased by 100% due to intense spalling from the roof and walls.

"A similar mode of superficial spalling was observed in a smaller test passage (0.76 m by 0.76 m in cross-section and 3 m long) […] excavated for the purpose of experimental study […] Test runs showed that spalling occurred at a surface temperature rise as low as 61 °C. One run was continued for 8–1/2 hours and a mass of spall was produced as shown in [the] Fig. 1" [5, p. 964]

2.1.2. Cooling

Dreyer [6] leached out a small cavern below a mine drift at a 600 m depth. The cavern height and diameter were 2 m and 1 m respectively. The cavern was filled with liquid nitrogen whose temperature was 77 K (−196 °C). At the end of the test, four fractures were observed at right angles, as shown in Fig. 2.

It must be noted that, in sharp contrast with the case of a fracture created by a cold gas at cavern wall, described below, liquid nitrogen is able to enter the fracture and to cool down the fracture itself, fostering fracture propagation (Fig. 3). Wallner and Eickemeier [7] discussed the onset of fractures in an intake air shaft of the Gorleben salt mine:

"During the cold season, temperatures in the shaft decreased by 20 °C [⋯] within a time period of 80 days [⋯] horizontal and vertical fractures were detected by routine inspections in the shaft. Theses fractures had an average spacing of about 2.8 m. The fracture aperture amounted up to several mm." [7, p. 365].

This example was also discussed by Zapf et al. [8] (see also Fig. 3).

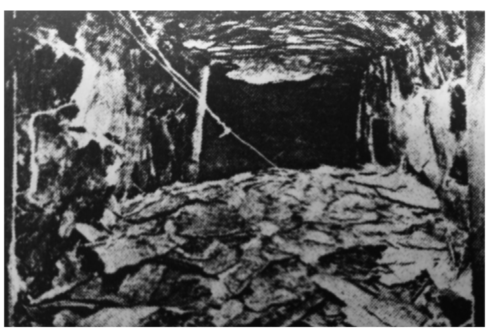

Fig. 1. Test passage at North Bay, Ontario, Canada [5].

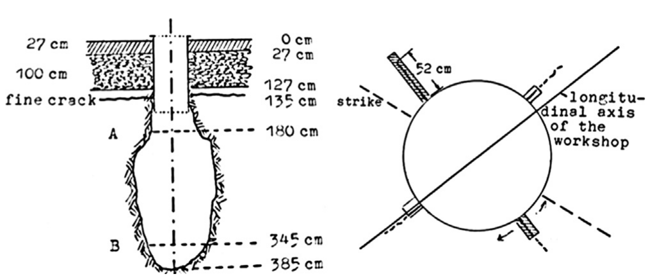

Fig. 2. Fracture development in a small cavern leached out below a salt mine drift [6].

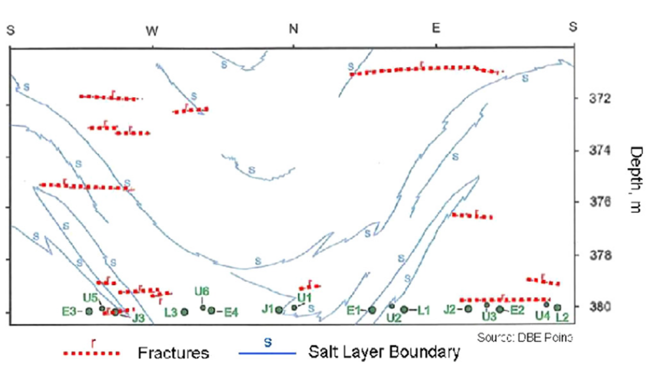

Fig. 3. Gorleben mine: thermal fractures at the wall of a ventilation shaft. Fractures are horizontal; fractures average spacing is 2.8 m [8].

2.2. A simple model

These examples (in which no fluid pressure changes are involved) prove that rock temperature changes can generate significant mechanical consequences in the rock mass. Intense warming generates spall; intense cooling generates fractures that are perpendicular to the cavern wall.

In fact, tests performed on blocks of ceramics or glass (a brittle material, as are rocks and salt under rapid mechanical loading) prove that, when block cooling starts, a large number of shallow fractures, more or less perpendicular to the block face, are first generated [9,10]. When low temperatures penetrate deeper into the rock mass, only a small number of fractures keep growing, and a correlation can be observed among the depth, spacing and opening of fractures.

A simple model can explain the onset of thermal spalls and fractures. Consider the case of an idealized vertical circular shaft (or a horizontal circular gallery) excavated in a rock mass, with radius a. Let P_∞ be the geostatic pressure at shaft depth and P_c be the shaft fluid pressure. Rock geothermal temperature is T_0, and fluid temperature is T_c. As $T_c \neq T_0$, heat is transferred to or from the rock mass through conduction, and rock temperature is a function of time and distance to the shaft axis:

$$T = T_0 + \Delta T(r,t), \quad \Delta T(a,t) = \Delta T_a = T_c - T_0$$

and $\Delta T(\infty, t) = 0$. The effects of temperature changes on the mechanical behavior or the rock mass are two-fold: (i) The values of the parameters that describe rock behavior (say, for elastic behavior, its Young's modulus E and Poisson's ratio ν) are temperature sensitive. (ii) Temperature changes generate rock expansion or contraction.

In the following, we consider only this second effect (rock expansion or contraction). The constitutive behavior of the rock mass can be written as

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{el} + \dot{\boldsymbol{\varepsilon}}^{anel} + \dot{\boldsymbol{\varepsilon}}^{th},$$

where $\dot{\boldsymbol{\varepsilon}}^{el}$ is the elastic strain rate, $\dot{\boldsymbol{\varepsilon}}^{anel}$ is the anelastic strain rate, and $\dot{\boldsymbol{\varepsilon}}^{th}$ is the thermo-elastic strain rate. As we are mainly interested in the behavior of a salt rock mass, the anelastic strain rate can be described by the Norton–Hoff power law $\dot{\boldsymbol{\varepsilon}}^{anel} = A^\star \sigma^n$, where the exponent n of the power law may range from 3 to 6. Although the coefficient $A^\star$ depends on temperature, the effects of temperature on the parameters of the constitutive law are disregarded and $A^\star$ will be considered a constant. More precisely, the constitutive law can be written as

$$\dot{\varepsilon}_{ij} = \frac{1+\nu}{E}\dot{\sigma}_{ij} - \frac{\nu}{E}\dot{\sigma}_{kk}\delta_{ij} + \frac{3A^\star}{2}(\sqrt{3J_2})^{n-1}s_{ij} + a^{th}\dot{T}\delta_{ij}$$

where $s_{ij} = \sigma_{ij} - \sigma_{kk}\delta_{ij}/3$ is the deviatoric stress tensor, and J_2 is the second invariant of the deviatoric stress tensor. The salt thermal expansion coefficient is a^{th}. Plane strains are assumed. It is assumed that the shaft or the gallery was left idle for a long period such that a steady-state behavior has been reached. Steady-state stress distribution in the rock mass at the end of such an idle