11th International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-11
J. M. Chandra Kishen, A. Ramaswamy, S. Ray and R. Vidyasagar (Eds)
https://doi.org/10.21012/FC11.092334

# A CONTINUOUS APPROACH FOR MODELLING FRACTURE FORMATION IN POROUS, QUASI-BRITTLE MATERIALS AND ITS APPLICATION TO CALLOVO-OXFORDIAN CLAYSTONE.

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**Key words:** hygro-mechanics, damage, porous media, fracture, permeability, self-healing, fracking

**Abstract:**

To study the effects of fracturing in the context of the Callovo-Oxfordian claystone and the proposed use of beds of this rock for a nuclear waste repository (ANDRA) we have developed a model that is implemented in the Cast3m finite elements code. This model couples (poro)elasticity, plastic deformation, damage through cracking at the micro-scale, reversible opening of macro-scale cracks, diffusion of water (and air) with associated changes in degree of saturation (and pore pressure), and swelling of clay minerals in a single, continuous model. Spatial variations in material properties, such as bedding planes, are considered by mapping them onto the mesh. Crack opening is calculated on the basis of previous studies [1], [2].This model is able to account for he effect on induced porous pressure on fracking. The model is compared with experiments carried out in the laboratory for the problem of gas fracturing.

## 1 INTRODUCTION

Callovo-Oxfordian claystone (Cox) possesses similar properties to concrete; it is composed of various proportions of minerals including quartz, calcite, micas, illite and smectite, has a saturation dependent strength under traction of 1-5 MPa and resistance to compression of 30-50 MPa. With values around 5 GPa, the claystone has a lower Young's modulus than most concretes and is more influenced by the degree of hydration owing to the large proportion of clay minerals, changing from a relatively soft and plastic response near saturation to more a brittle response when dried.

This material has very low permeability and is found at great depth (about 600m) on the Bures site in France. This is why Andra has decided to use this site as an experimental laboratory (CIGEO) for storing radioactive waste.

The developed model aims to reproduce the hydromechanical behavior of Cox including the effects of swelling and fracking in order to simulate the behavior of the potential radioactive waste disposal.

## 2 BASIS OF THE MODEL

The quasi-unilateral model of Fichant [3] developed for concrete has been applied within the poromechanics framework [4], [5].

It has demonstrated the capacity of reproducing hydromechanical behavior of Cox [6], [7].

The model normally accounts for the effects of capillary pressure linked to the saturation but for the sake of simplicity, in the case of fracking, the material is supposed to be saturated, and the pore pressure is calculated by a nonlinear diffusion equation.

$$C\frac{\partial P}{\partial t}+\frac{\kappa}{g}div(P-gz)=0$$

where $C$, P, t, κ, ρ, g, z respectively are the water mass capacity, capillary pressure, time, permeability, water density, acceleration of gravity and water level.

The permeability κ is computed by addition of initial permeability $\kappa_0$ and added permeability linked to the crack opening $w$ by a cubic law for an element size of $h$ [8]–[10].

At this point the choice of an isotropic permeability is made even though an anisotropic permeability matrix naturally derives from the method. Then, the anisotropy of permeability simply derives from the crack pattern.

$$\kappa=\kappa_0+\frac{\xi(w)w^3}{12h}$$

A so-called tortuosity coefficient ξ(w) could be applied conforming to [11], [2].

The crack opening is obtained from the state of stress and strain in each Gauss point making the hypothesis of a unique crack at the gauss point [1].

The mechanical damage model uses Hillerborg’s method to avoid spurious mesh size effect [3], [6], [7], [12]. Other regularization techniques could be used but the characteristic length of the Cox is millimetric.

The model is implemented in the Cast3M finite element code with a fully coupled element that is quadratic for displacement and linear for pressure. It is important to note that the integration scheme is implicit and that the equilibrium equations are verified at each time step. The model is implemented in 2D plane stress, plane strain and 3D. Following simulations are performed in 2D.

# 3 APPLICATIONS TO FRACKING

## 3.1 A simple fracking test

The simple fracking KGD test proposed by [13] and used by [14].

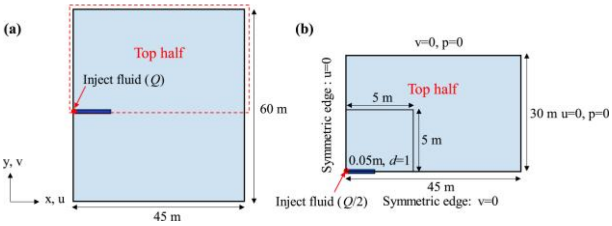

**Figure 1**: Geometry and boundary conditions of the KGD model: (a) the whole reservoir, (b) the modeled top half after [14]

The geometry is illustrated in Fig 1 and due to symmetry only the top half of the problem is modeled. A fluid is injected in a pre-existing crack at a constant fluid injection rate $Q=10^{-4}m^3/s$, the initial permeability of the material is $\kappa_0=10^{-14}m^2$. The modulus of elasticity is $E=17GPa$, the Poisson’s ratio $\nu=0.2$, t the tensile strength $f_t=3MPa$ and the fracture energy $G_f=300N/m$. The initial Biot’s modulus $M_0=6Gpa$ and the Biot’s modulus is updated by the damage $M=M_0(1-D)$ and the Biot's coefficient is $B=0.9$ . The viscosity of the fluid is $\eta_f=0.1Pa\,s$.

The results obtained by our model compared solution proposed by [14] and analytical solution [15] are illustrated Fig 2&3.

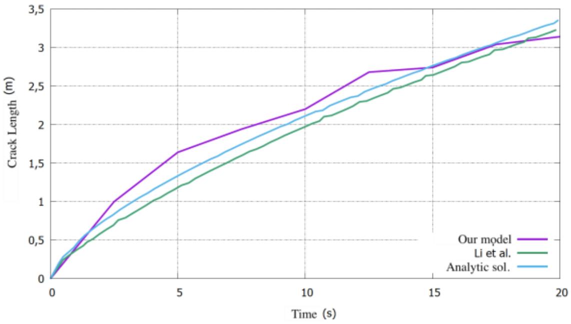

**Figure 2**: evolution of the crack length with time compared to [14] and analytical solution from [15]

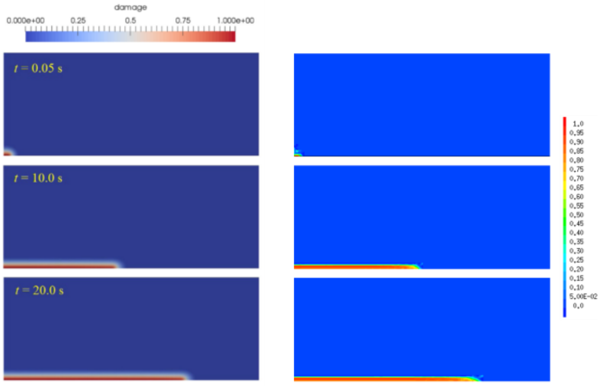

**Figure 3**: Damage filed at different time for the reference model[14] and the proposed model

### 3.2 Effect of an initial defect.

The model must be able to take into account the presence of an eventual initial default. In the case of the CIGEO problem, the Cox exhibits anisotropy of the defects due to the bedding.
The problem of multiple crack interactions posed by [16] is presented in [14] and illustrated Fig 4.

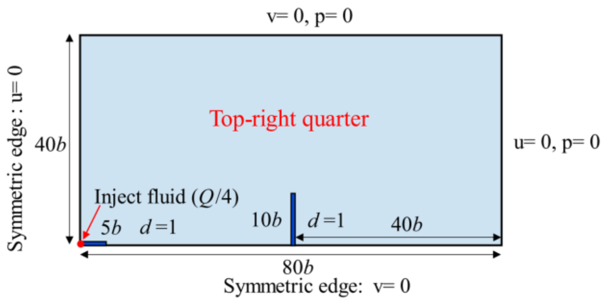

**Figure 4:** Geometry and boundary conditions after [14], b=0,1m.

The fluid is injected in the pre-existing crack at a constant fluid injection rate $Q = 6.45\ 10^{-4} m^3/s$, the initial permeability of the material is $\kappa_0 = 2.5^{-17} m^2$. The modulus of elasticity is $E = 1GPa$, the Poisson's ratio $\nu = 0.2$, the tensile strength $f_t = 0.9MPa$ and the fracture energy $G_f = 12N/m$. The initial Biot's modulus $M_0 = 0.5Gpa$ and the Biot's coefficient is $B = 0.9$ . The viscosity of the fluid is $\eta_f = 0.1Pa\ s$.
The mesh is made of uniform quadrangulars of 0.05m, quadratic in displacements and linear in pressure.

The crack initially propagates along the edge v=0, then a deviation is observed a proximity of the vertical defect. After merging with the initial default the cracks propagates with an angle of about 45 degrees with our model conforming to the simulations reported in [14] and [16].
The angle of the deviated crack depends on the kind of damage/plasticity criteria.

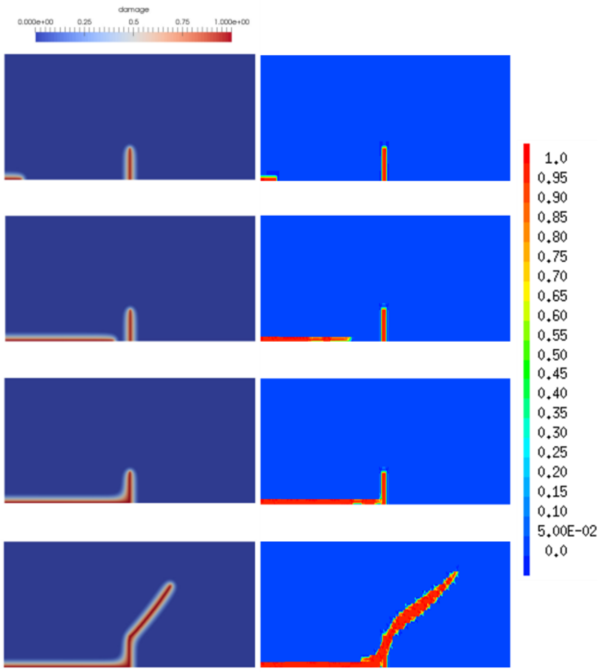

**Figure 5:** crack parten left : after [14], right : our model

## 4 CONCLUSIONS

The quasi-unilateral damage model coupled with plasticity of Fichant was applied within the framework of Biot's theory. This model, initially developed for concrete, has already demonstrated its ability to reproduce the behavior of rocks such as Cox and, in particular, its capacity for self-sealing. In the present study, we have shown that this model is also capable of simulating hydraulic or gas fracturing. The results obtained are comparable to those presented in the literature for test cases.

The model must now be compared to experiments in order to be validated. We need to pay particular attention to the initial conditions and the hydric boundary conditions, which can condition the nature of the solution.

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