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Effect of mechanical damage on moisture transport in concrete

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ABSTRACT

This paper is devoted to the influence of mechanical damage on moisture transport in quasi-brittle materials, such as concrete. The mechanical analysis is based on the isotropic damage model with the equivalent strain suitable for concrete. The mechanical model is formulated in the rate form in order to connect it with the nonstationary moisture transport which is modeled by a simple diffusion model derived from convection approach. The moisture transport is based on the volumetric moisture content. Three different formulas are used for description of the change of permeability with respect to growing damage parameter. Numerical approach is tested on an example of four-point shear test.

1. Introduction

Coupling between mechanical analysis of civil engineering structures with transport of moisture is usually assumed in one way only, i.e. the mechanical analysis is influenced by the moisture distribution. Similar situation occurs in coupling of mechanics with heat transfer. The one way coupling is acceptable in the case of elastic, visco-elastic, plastic and visco-plastic behavior [1]. In these cases, material is assumed to be continuous without voids or cracks. On the other hand, if damage or crack mechanics is assumed, the continuity of material is broken. In fracture mechanics, explicit cracks are dealt with while in damage mechanics the discontinuities are smeared and a pseudo-continuous material with reduced material parameters is assumed. The broken continuity of material influences the moisture transport. This is also one way coupling. If the mechanical analysis is based on a damage model which is combined with a model of visco-plasticity, the fully coupled hydro-mechanical model is obtained because the damage influences the moisture transfer and simultaneously the moisture distribution influences the irreversible strains and damage evolution.

Moisture transport is described by many models where different driving forces are assumed. Overview of the models is in book [2]. In this paper, a model of moisture transport is based on a diffusion model derived from convective approach after neglecting the gravity effect. The water diffusivity depends on the hydraulic head and hydraulic conductivity. The hydraulic conductivity is determined with respect to fluid properties and the water permeability which is affected by pore dimensions and distribution [2]. When the solid matrix is damaged by a load, the pore space could be changed and therefore the water permeability is changed too. Effects of temperature and damage on permeability of concrete was experimentally studied e.g. in [3] or [4]. Numerical model of the influence of damage, which is expressed by the damage parameter, on the permeability of concrete was studied in [5].

This paper deals with numerical model where damage mechanics is coupled with moisture transfer. The model of damage is formulated in the rate form and could be therefore simply coupled with nonstationary transport process. This paper

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generalizes models and numerical framework published in [6] and is devoted to concrete. There is lack of experiments dealing with the dependence of permeability on damage for other quasi-brittle materials, such as rocks, and therefore the proposed method cannot be used for them although their damage behavior is described [7].

This model is the first step in the development of a generalized coupled hygro-mechanical model for concrete. At this time, the moisture transport is being accompanied with transport of chemical species, especially salt. Penetration of salt into concrete structures deteriorates their durability. Coupled salt and moisture transport is described e.g. in Ref. [8].

2. Mechanical problem

This section contains description of general framework for isotropic damage response, the mesh dependency is briefly summarized and algorithms for computer implementation are included.

2.1. General framework

Let a structure or its part be modeled by bounded domain $\Omega \subset R^d$, where $d \in \{2, 3\}$ denotes the space dimension. The boundary of the domain is denoted Γ and it satisfies the Lipschitz condition. The boundary is split into part Γ_u where the Dirichlet boundary condition is prescribed (there are prescribed displacements) and part Γ_t with the Neumann boundary condition (there are prescribed surface tractions). It is assumed that $\Gamma_u \cap \Gamma_t = \emptyset$ and $\Gamma = \Gamma_u \cup \Gamma_t$. Small strains are assumed and the strain–displacement relation [9] has the form

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \tag{1}$$

where ε_{ij} are the components of strain tensor $\varepsilon_{ij} \in S^{d\times d}$, $S^{d\times d}$ is the set of symmetric tensors of the second order and u_i are the components of the displacement vector $\boldsymbol{u} : \Omega \to R^d$. Equilibrium equations have the form

$$\frac{\partial \sigma_{ij}}{\partial x_j} + b_i = 0, \tag{2}$$

where $\sigma_{ij} : \Omega \to S^{d\times d}$ is the stress tensor and $b_i \in L_2(\Omega)$ are the body forces. Constitutive relationships are in the form

$$\sigma_{ij} = T_{ij}(\varepsilon_{kl}) = T_{ij}(u_k), \tag{3}$$

where $T_{ij} : R^d \to S^{d\times d}$ is an operator. The problem is to find a displacement vector, $\boldsymbol{u}$, satisfying the following equations and boundary conditions

$$\begin{aligned} \frac{\partial \sigma_{ij}(u_k)}{\partial x_j} + b_i &= 0 \quad \text{in } \Omega, \\ u_i &= 0 \quad \text{on } \Gamma_u, \\ \sigma_{ij}(u_k)n_j &= s_i \quad \text{on } \Gamma_t, \end{aligned} \tag{4}$$

where n_j are the components of the outer unit normal and s_i is the prescribed surface traction.

The stress–strain relation of an elastic material with isotropic damage is derived from the Helmholtz free energy which for damaged material under isothermal conditions has the form

$$\varrho\psi(\varepsilon_{ij}, \omega) = \frac{1}{2}(1-\omega)D_{ijkl}\varepsilon_{ij}\varepsilon_{kl}. \tag{5}$$

D_{ijkl} is the fourth order stiffness tensor of the material and $\omega \in [0, 1]$ is the damage parameter. The damage parameter is equal to 0 for undamaged material while it is equal to 1 for totally damaged material. In some papers the continuity parameter is used. It is defined in opposite way to the damage parameter, i.e. it is equal to 1 for undamaged material and it is equal to 0 for totally damaged one [10]. The stress tensor is obtained

$$\sigma_{ij} = \frac{\partial(\varrho\psi)}{\partial \varepsilon_{ij}} = (1-\omega)D_{ijkl}\varepsilon_{kl} \tag{6}$$

and the effective stress has the form

$$\bar{\sigma}_{ij} = \frac{1}{1-\omega}\sigma_{ij}. \tag{7}$$

The elastic energy release rate has the form

$$Y = \frac{\partial(\varrho\psi)}{\partial \omega} = -\frac{1}{2}D_{ijkl}\varepsilon_{ij}\varepsilon_{kl}. \tag{8}$$

With respect to the second law of thermodynamics, the mechanical dissipation has to satisfy