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NUMERICAL MODEL FOR HISTORICAL MORTARS EXPOSED TO FREEZING TEMPERATURES

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Abstract: *The present contribution is devoted to modeling of degradation processes in historical mortars exposed to moisture impact during freezing. Internal damage caused by ice crystallization in pores is one of the most important factors limiting the service life of historical structures. Coupling the transport processes with the mechanical part will allow us to address the impact of moisture on the durability, strength and stiffness of mortars. This should be accomplished with the help of a complex thermo-hygro-mechanical model representing one of the prime objectives of this work. The proposed formulation is based on the extension of the classical poroelasticity models with the damage mechanics. The whole concept is demonstrated on a two-dimensional moisture transport in the environment with temperature below freezing point.*

Keywords: Coupled heat and moisture transport, Ice crystallization process, Damage, Historical mortar.

1. Introduction

In the literature, the above described problem is addressed from several perspectives. The first group of publications is focused on the description of the coupled heat and moisture transport reflecting the moisture migration under the conditions of the ice crystal formation in the pores, 2-D and 3-D aspects and different moisture/heat sources, such as wind driven rain, solar short and long wave radiation etc., see (Kong and Wang, 2011; Künzel and Kiessl, 1996; Tan et al., 2011). While models for transport processes have been developed during several decades, the theory of ice crystallization in the pores has emerged only recently, (Scherer, 1993; Scherer 1999; Sun and Scherer, 2010). The authors established relations between physical state of porous system and pore pressures. The physical conditions of ice formation process are described by thermodynamic balance equation between ice, liquid water and solid matrix. Finally, the mechanical response of porous media subjected to the frost action was studied by several authors (Coussy and Monteiro, 2008; Wardeh and Perrin, 2008; Zuber and Marchand, 2000). On the one hand, the poroelasticity formulation based on Biot's continuum model was adopted. It is an efficient method for elastic modeling of porous system, which is subjected to the pressure of the fluid. On the other hand, a novel micromechanics approach was introduced to analyze the creation of micro-cracks in the microstructure during freezing process (Liu et al., 2011). These results predict effective mechanical and transport properties at microscopic level and can be utilized as an input for multi-scale analysis of porous media.

Our goal is to quantify the internal damage caused by the ice crystallization pressure in historical mortars. In particular, a critical point in a restoration works is frequent applications of lime mortars for preserving compatibility with the historical materials. However, lime mortars are very porous, their mechanical strength and durability are mostly very low, thus the development of a lime mortar with improved internal hydrophobicity and associated improved resistance against damage due to the effects of ice crystallization is inevitable. To address this issue with respect to its complexity, an analysis combining both experimental work and numerical simulations has to be done. Nevertheless, the numerical methodology developed within this work can be utilized to simulate the response of any porous material subjected to the frost action.

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2. Material Model

It is impossible to introduce all theoretical derivations due to limited space. Therefore, we briefly describe the concept of proposed material model and focus primarily on the numerical example. The detailed description can be found in (Sýkora, 2014).

The problem of porous system subjected to ice crystallization can be divided into three physical phenomena - heat and moisture transport, ice formation process and evolution of damage caused by pore pressure. Using the thermodynamics, poromechanics and damage mechanics, we propose here the concept of multi-phase constitutive model based on the assumption of the uncoupled system in the sense of numerical analysis. These models are characterized by combining different physical or mechanical models (in space and time) in order to accurately describe structural response of deteriorating infrastructure over time. The general framework of the proposed model was primarily inspired by the work published (Coussy and Monteiro, 2008; Künzel and Kiessl, 1996; Sýkora et al., 2013; Wardeh and Perrin, 2008; Zuber and Marchand, 2000)

In the presented work, the porous material is treated as multi-phase medium consisting of solid matrix, liquid water, water vapor and ice. The mathematical formulation consists of three governing equations representing the conservations of energy, mass and linear momentum. The chosen primary unknowns are temperature θ [°C] moisture φ [-] and displacement of solid matrix $\boldsymbol{u}$ [m].

3. Numerical Example

This section supports through numerical study the proposed methodology. In doing so we consider geometry together with the initial and loading conditions displayed in Fig. 1. Two-dimensional L-shape domain was discretized by an FE mesh into 741 nodes and 1358 triangular elements. The solution of the time-dependent problem also involves a discretization of the time domain into 744 uniform time steps chosen with regard to the convergence criteria of nonlinear solution. The initial conditions were set equal to $\boldsymbol{u}_{\text{in}} = \boldsymbol{0}$ [m], $\theta_{\text{in}} = 14$ [°C] and $\varphi_{in} = 0.5$ [-] in the whole domain. The following Robin boundary conditions were imposed: on the interior side Γ_{int} a constant temperature of 24 [°C] and a constant relative humidity 0.6 [-] were maintained, while on the exterior side Γ_{ext} the real climatic data representing the winter conditions were prescribed, see (Sýkora, 2014). Moreover, the exterior side of the domain Γ_{ext} was loaded by the heat flux from solar short-wave radiation and the driving-rain flux.

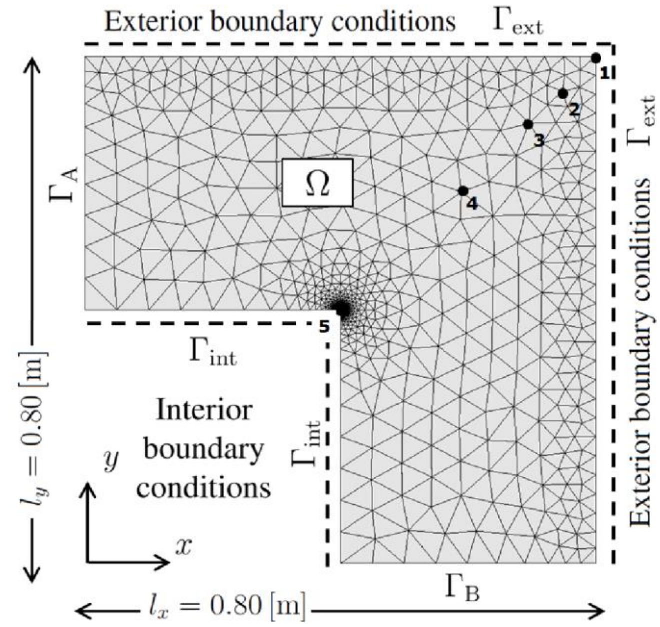
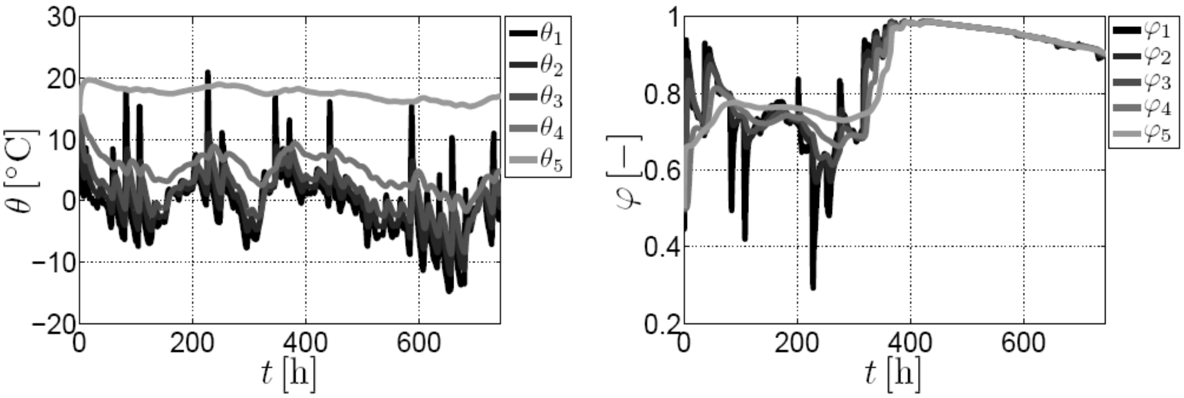


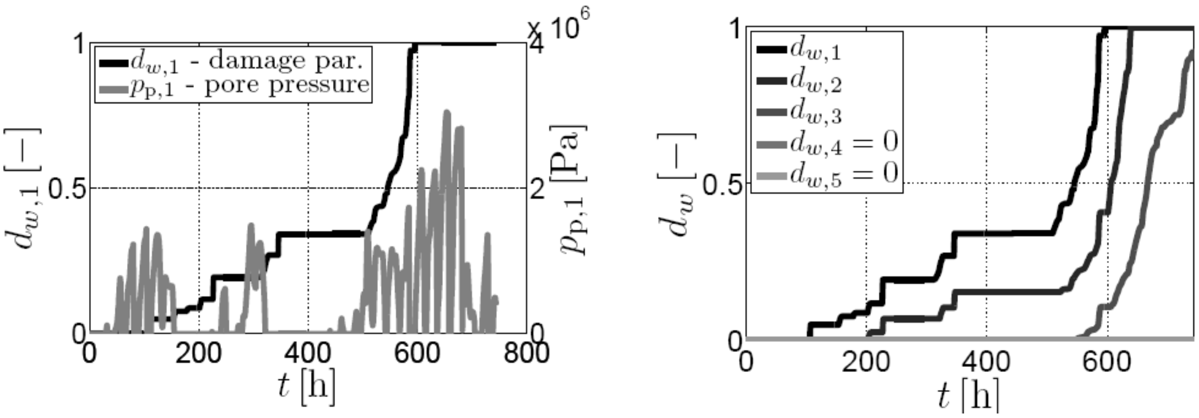
Fig. 1: Heterogeneous structure with boundary conditions (θ is the temperature [°C], q is the heat flux [Wm^{-2}] and l is the length [m]).



a) *b)*

Fig. 2: a) Resulting temperature at selected nodes; b) Resulting moisture at selected nodes.

The results are presented in Fig. 2 showing variation of the temperature and moisture at selected nodes labeled in Fig. 1. The obtained results clearly manifesting the influence of exterior boundary conditions on the temperature and moisture fields, especially near the exterior surface of the two-dimensional domain.



a) *b)*

Fig. 3: a) Evolution of damage parameter $d_{w,1}$ [−] and pore pressure $p_{p,1}$ [Pa] at node 1;
b) Evolution of damage parameters d_w [−] at selected nodes.

Several interesting results have been derived within the scope of the calculation of internal damage. Fig. 3a, b display the evolution of damage parameter and its dependence on the average pore pressure. Beside the comparison of the evolution of damage parameter in the time, we also compare growth of damage parameter in the domain, see Fig. 4. Analysis of these results allows better understanding of physical phenomena in porous media subjected to the frost action. A fast moisture increase in the zone close to the exterior surface (Fig. 2b) leads also to the similar trend of the damage parameter, see Fig. 3a. This can be attributed to the lower exterior temperature and higher moisture content in the surface layer caused by the driving-rain flux. The calculated results promote the capability of proposed governing equations to simulate a degradation processes in the building materials exposed to real weather conditions.

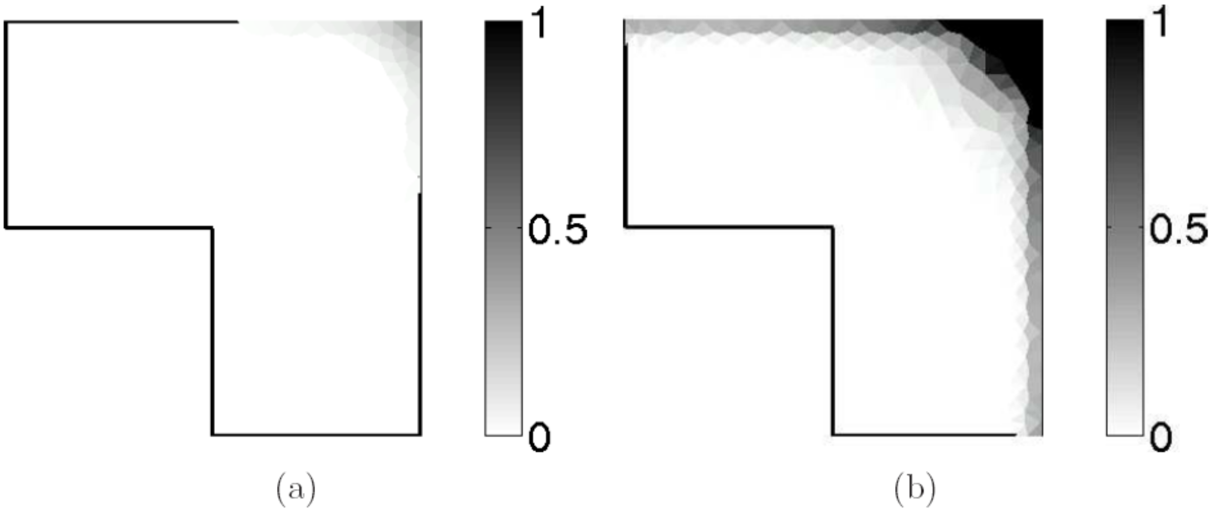


Fig. 3: Evolution of damage parameter d_w [−] *after t = 372* [h], *(b) evolution of damage parameter d_w* [−] *at the end of analyzed time period (t = 744* [h]*).*

4. Conclusions

This paper presents the numerical modeling of damage caused by ice crystallization process in historical mortars. Attention is focused on the thermo-hydro-mechanical model developed here in the framework of uncoupled algorithmic scheme. In particular, we employed coupled heat and moisture model, which is sufficiently robust to describe real-world materials, but which is also highly nonlinear, time-dependent material model. Supported by several successful applications in civil engineering we adopted Biot's model and the nonlocal isotropic damage model in the framework to simulate the frost action on porous media.

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