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Influence of concrete fracture on the rain infiltration and thermal performance of building facades

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ABSTRACT

Water infiltration is known to play an important part in the degradation process of construction materials. Over time, microscopic and macroscopic cracks progressively develop under the effects of mechanical loading and sorption/desorption cycles: their influence is to be accounted for in long-term hygrothermal performance assessments of the building envelope. The present work aims at showing the potential consequences of cracking on the heat and moisture transfer across building facades, in order to justify the need for the identification of damage to prevent durability and thermal issues. Specific simulation cases of insulated and non-insulated building facades were defined, and submitted to atmospheric boundary conditions for simulation times of one month. Some of the simulation geometries included previous measurements of crack patterns in concrete. The comparison of fractured and non-fractured building facades showed the effects of cracks on the moisture accumulation and thermal performance of these wall configurations, thus giving an estimate of what these effects might be in real conditions. A methodology is thus proposed for the identification of renovation needs, which may be applied for the purpose of durability assessments as well.

1. Introduction

Many causes for the degradation of building materials are carried by moisture. Indeed, infiltrated water may transport chemicals, alter mechanical properties and cause freeze thaw damage or mould development. It may also affect thermal properties and overall efficiency, as well as the health and comfort of the occupants. Over time, the pore structure of such materials may however be altered by cracks and defects caused by mechanical loading and aggravated by moisture-induced degradation. All sizes of fractures may have a strong impact on heat and moisture flow in the building envelope, and their influence is to be accounted for in any long-term performance assessment.

Hygrothermal simulations of building components are now commonly applied to oriented design [1] and to the evaluation of moisture related concerns. Examples include the assessment of the risk of mould growth [2], of moisture buffering in construction materials [3], or of moisture related damage [4]. Hygrothermal modelling has also been the target of numerical optimisation [5], and several codes are now commercialy available [6,7]. HAM (Heat, Air and Moisture) simulation codes however often rely on the assumption that material properties are constant over time and do not explicitly allow including the effects of material ageing.

A considerable amount of work has already been performed for the prediction of moisture flow in fractured porous media. Two main approaches can be distinguished. The first method is a fully coupled scheme, in which the same finite-element mesh is used for flow and transport modelling in both the fracture and the porous network. The FE mesh must be adapted to the geometry of the cracks [8], and strategies have been proposed for its automated refinement with crack propagation [9]. Segura and Carol [10] assigned a type of double-nodded, zero-thickness elements to the crack, allowing an explicit formulation of longitudinal and transverse flows, and of exchange terms between the porous medium and the fracture. They later used this formulation for the expression of a fully coupled hydro-mechanical model [11] for the prediction of flow in fracturing geomaterials. The second method is a staggered approach, in which the transport equations for flow and transport are iteratively solved in the porous medium and in the fracture. Between each iteration, the capillary pressure corresponding to the calculated pressure field in the crack is imposed as boundary condition at the matrix-fracture interface. This approach was followed by Roels et al. [12,13], who followed the progress of the moisture front in a fracture by combining a quasi-static pressure equation and a Darcian flux equation. An

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important asset of the staggered approach is the fact that it allows emancipating the FE mesh from the crack geometry: the extended (or generalised) finite element method (XFEM), based on the partition of unity method [14], allows including discontinuities in the problem field by adding degrees of freedom to a set of nodes surrounding the cracks [15,16]. This method allows accounting for crack propagation without modification of the mesh [17]. It was applied in recent studies for the modelling of hygrothermal damage processes [18], moisture uptake [19] and heat transfer [20] in fractured porous media. Both monolithic and staggered approaches allow accounting for moving fractures and including all coupled hydromechanical effects at the interfaces between fractures and matrix. Some authors argue that the staggered approach is more effective in terms of computational costs [12,18,19], although Segura and Carol found the monolithic approach more appropriate in case of strong coupling or non-linear discontinuity behaviour [21].

In the current state of research, long-term simulations of building components do not include the effects of material ageing. Inversely, current applications of full hygro-thermo-mechanical modelling often lie on the manual input of fractures in the problem field [8,12,19–22], which does not reflect the complexity of real crack patterns. Indeed, a numerical simulation of the ageing of a building component over years of service life, including coupled hydromechanical effects and progressive damage modelling, would require an extensive knowledge of all environmental factors which may influence material degradation. The above mentioned cases are suitable for the service life prediction of construction materials. A complementary approach is however preferable for the hygrothermal performance estimation of existing, already damaged building components.

The present paper is part of a recently undertaken project, aimed at integrating the effects of damage in heat and moisture transfer simulations at the scale of building components. A mixed approach is followed to this aim, using experimental measurements of crack patterns as an input for a numerical model for coupled heat and moisture flow. In a recent study [23], digital image correlation and acoustic emission monitoring were found reliable for the quantification and localisation of all scales of fissures, from micro-cracks to macroscopic fractures. A numerical code was then developed [24], that may include these measurements into a finite-element frame for the prediction of coupled heat and moisture flow. The next step of this procedure, and topic of the present paper, is the application of this simulation code in order to estimate the consequences of cracking on the moisture accumulation and thermal performance of building facades, subjected to realistic climatic conditions during long periods of time. Specific simulation cases of insulated and non-insulated building facades were defined, and submitted to atmospheric boundary conditions for simulation times of one month. Some of the simulation geometries included previous measurements of crack patterns in concrete. The comparison of fractured and non-fractured building facades aim at showing the potential effects of cracks on the moisture accumulation and thermal performance of these wall configurations, thus giving an estimate of what these effects might be in real conditions.

The model for heat and moisture transfer in fractured porous media is first described in Section 2: the balance equations are written on the basis on simplifying hypotheses, and the conditions of their implementation into a finite-element frame are explained. This initial model was validated on the basis of the Hamstad benchmark package. We then describe how fractures are integrated into the geometry of the problem and how their influence on the flow is accounted for. Then, Section 3 clarifies the questioning of the study and shows which simulation cases were defined in order to answer it. These simulation settings are entirely defined in terms of geometry, boundary conditions and time resolution of the problems. The results of this procedure are then exposed in Section 4.

2. Model description and validation

2.1. Initial model

2.1.1. Conservation equations

The general form of the conservation equations for heat and moisture in porous building materials is briefly recalled here. It follows common notations and simplifying hypotheses used in the field of building physics [25,5,26]:

- local thermal and mass equilibrium between phases is assumed,
- air movement is not considered,
- thermodiffusion, hysteresis effects and chemical reactions are not considered,
- the temperature-dependency of the moisture storage is neglected.

2.1.1.1. Moisture. The mass conservation equation for water relates the temporal variations of the moisture content per unit volume w [kg m^{-3}] to the moisture flow in either vapour or liquid phase, respectively denoted $\mathbf{g}_v$ and $\mathbf{g}_l$:

$$\frac{\partial w}{\partial p_c}\frac{\partial p_c}{\partial t} = -\nabla\cdot(\mathbf{g}) = -\nabla\cdot(\mathbf{g}_v + \mathbf{g}_l) \tag{1}$$

Under the aforementioned assumptions (air flow is neglected), water vapour transfer is only caused by diffusive phenomena, described by Fick's law and driven by a gradient of vapour pressure p_v. Liquid transport is driven by a gradient of capillary pressure p_c, according to Darcy's law.

$$\mathbf{g}_v = -\delta_p \nabla p_v \tag{2}$$

$$\mathbf{g}_l = -K_l \nabla p_c \tag{3}$$

where δ_p and K_l respectively denote the water vapour and liquid permeability of the material. In practical applications, only one pressure variable is used as a potential for moisture transfer. In order to guarantee the applicability of Eq. (1), the equivalence between ∇p_v and ∇p_c must be established. This equivalence can be formulated thanks to the Young–Laplace, Kelvin and Clausius–Clapeyron laws:

$$\nabla p_v = \frac{p_v}{\rho_l R_v T}\nabla p_c + \frac{p_v}{\rho_l R_v T^2}[\rho_l L_v - p_c]\nabla T \tag{4}$$

where ρ_l, R_v and L_v are the density, the specific mass constant and the latent heat of vaporisation of water, and T is the temperature.

Using Eq. (1) for the prediction of moisture flow requires the knowledge of the material's equilibrium moisture content $w = f(p_c)$, as well as its unsaturated moisture permeability. Simulations performed in the present work involve five different materials, two of which have undergone hygric characterisation in previous papers [24,27], while the properties of the three other materials have been extracted from the literature. The geometries of the simulation cases, along with the corresponding references for material properties, are defined in Section 3.1.

2.1.1.2. Heat. Under the aforementioned hypotheses (no air transfer and no heat source term), the conservation equation for the total energy, expressed in terms of enthalpy, reads [26]:

$$\frac{\partial \rho h}{\partial t} = -\nabla\cdot(\mathbf{q}_c + \mathbf{q}_a) \tag{5}$$

The first term of this equation, the mixture enthalpy of the system (liquid water, humid air and solid material), is:

$$\rho h = (\rho_0 c_0 + c_l w_l + c_v \rho_v)(T - T_{ref}) + \rho_v L_v \tag{6}$$