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MOISTURE INFILTRATION IN FRACTURES AND CONSEQUENCES ON THE HYGROTHERMAL PERFORMANCE OF BUILDING FACADES

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ABSTRACT

Moisture transfer in porous construction materials carries many causes for their degradation: mould development and freeze-thaw damage are favoured by the accumulation of water, and chemicals such as chloride ions and carbon dioxide may accelerate the fracturing of cementitious composites. 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.

Current simulation codes for heat and moisture transfer modelling in building facades do not allow accounting for the presence of cracks and defects in the material layers. The present work aims at integrating such effects of damage in simulations at the scale of building facades. Experimental measurements of crack patterns were integrated into a newly developed numerical model predicting coupled heat and moisture transfer in multi-layered components. The consequences of fractures on the hygrothermal performance of these components were then investigated by comparing damaged and undamaged materials in a series of simulation cases. Cracks were found to accentuate the amplitude of daily sorption/desorption cycles and moisture accumulation in the walls, particularly in case of impacting rain. Their impact on the overall thermal performance is small, although not negligible in case of water infiltration towards an insulation layer.

Nomenclature

c	Specific heat capacity [J.kg^{-1}.K^{-1}]
$\mathbf{g}$	Moisture flow [kg.m^{-2}.s^{-1}]
$g_{l,r}$	Wind-driven rain [kg.m^{-2}.s^{-1}]
I	Solar irradiance [W.m^{-2}]
K_l	Liquid permeability [s]
$k_{f,l}$	Fracture liquid permeability [s]
L_v	Latent heat of vaporization [J.kg^{-1}]
p_c	Capillary pressure [Pa]
p_v	Vapour pressure [Pa]
$\mathbf{q}$	Heat flow [W.m^{-2}]
RH	Relative humidity
R_h	Horizontal rainfall [mm.m^{-2}]
T	Temperature [K]
U	Wind speed [m.s^{-1}]
u	Crack aperture [m]
w	Moisture content [kg.m^{-3}]
Greek symbols	
α	Heat transfer coefficient [W.m^{-2}.K^{-1}]
β	Moisture transfer coefficient [s.m^{-1}]
δ_p	Vapour permeability [s]
η	Dynamic viscosity [Pa.s]
κ	Absorptivity
λ	Thermal conductivity [W.m^{-1}.K^{-1}]
ρ	Density [kg.m^{-3}]
σ	Solid/water surface tension [N.m^{-1}]
Subscripts	
a/c	Advective/convective
dir/dif	Direct/diffuse
eq	Equivalent
$0/l/v$	Solid/liquid/vapour
l/t	Longitudinal/transverse

INTRODUCTION

Moisture transfer in porous construction materials carries many causes for their degradation: mould development and freeze-thaw damage are favoured by the accumulation of water, and chemicals such as chloride ions and carbon dioxide may accelerate the fracturing of cementitious composites. Moisture may furthermore affect the thermal properties of a building, as well as the health and comfort of its occupants. Hygrothermal simulations of building components are now commonly applied to the evaluation of moisture related concerns and to oriented design (Mukhopadhyaya et al., 2006). Examples include the assessment of mould growth (Sedlbauer, 2002), of moisture buffering in materials (Abadie and Mendonca, 2009), or of moisture related damage (Steeman et al., 2009).

Most of the existing hygrothermal models lie on the assumption that material properties, such as the moisture permeability, are isotropic and constant in time. After several years of service, components are however inevitably altered by both mechanical loading and moisture infiltration: the pore structure of the material may change over time, or present cracks and defects covering a wide range of sizes. Although the numerical implementation of moisture flow in fractured porous media has received a lot of recent contributions (Moonen, 2009; Alfaiate et al., 2010), its applications to the field of building physics remain limited. Indeed, current simulation codes for heat and moisture transfer modelling in building facades do not allow accounting for the presence of cracks and defects in the material

layers.
The present paper is part of a recent experimental and numerical project, which aimed at estimating the potential influence of fractures on the long-term hygrothermal performance of the building envelope (Rouchier, 2012). Two previous steps into this project were : the testing of experimental techniques in the prospects of building-scale damage monitoring (Rouchier et al., 2013), and the integration of measured fractures into a finite-element model coupled heat and moisture flow (Rouchier et al., 2012). Digital image correlation was found a reliable technique for monitoring the development of microscopic and macroscopic cracks during mechanical loading of concrete samples. The next step of this procedure, and topic of the present paper, is the application of this simulation code for the estimation of the potential consequences of cracking on the moisture accumulation and thermal performance of a building facade under realistic climatic conditions. This manuscript first describes the numerical implementation of heat and moisture flow in damaged porous media, then describes the simulation settings used to illustrate the target of the study. Simulation results are then displayed and discussed.

MODEL DESCRIPTION

Conservation equations

The conservation equation for heat and moisture in porous materials are written with the following common hypotheses of the building physics field :

- local thermal and mass equilibrium between phases is always assumed,
- moisture storage is temperature-independent,
- hysteresis effects are not considered,
- air movement is neglected.

The present section only briefly introduces these balance equations without extensive explanations. For more information on their derivation, the reader is referred to (Hagentoft et al., 2004) or (Rouchier, 2012).
The mass conservation equation for water relates the temporal variations of its volumetric content w [kg.m^{-3}] to the moisture flow in either vapour or liquid phase, respectively denoted $\mathbf{g}_v$ and $\mathbf{g}_l$:

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

Water vapour transfer is caused by diffusive phenomena described by Fick's law, while liquid transfer is driven by a gradient of capillary pressure, according to Darcy's law:

$$\mathbf{g}_v = -\delta_p \nabla p_v \qquad (2)$$

$$\mathbf{g}_l = -K_l \nabla p_c \qquad (3)$$

where δ_p and K_l respectively denote the water vapour and liquid permeability of the material. The prediction of moisture flow on the basis of Equation 1 requires the material's sorption isotherm $w = f(p_c)$, along with its vapour and liquid moisture permeability.
The energy balance equation, with $T = 0°$ C as the reference temperature, reads:

$$(c_0\rho_0 + c_l w)\frac{\partial T}{\partial t} + c_l T\frac{\partial w}{\partial t} = -\nabla \cdot (\mathbf{q}_c + \mathbf{q}_a) \quad (4)$$

where ρ_0 and c_0 are the density and specific heat capacity of the dry material, and c_l the heat capacity of water. $\mathbf{q}_c$ denotes the convective heat transfer described by Fourier's law, and $\mathbf{q}_a$ denotes the advective transfer caused by moisture flow in both phases:

$$\mathbf{q}_c = -\lambda \nabla T \qquad (5)$$

$$\mathbf{q}_a = c_l T \cdot \mathbf{g}_l + (c_v T + L_v)\,\mathbf{g}_v \qquad (6)$$

The moisture dependency of the thermal conductivity is particularly important in this study, as the impact of the moisture infiltration caused by fractures on the thermal efficiency of the system is to be observed.

$$\lambda = \lambda_0 + \lambda_w \frac{w}{\rho_l} \qquad (7)$$

where λ_0 is the conductivity of the dry material and the parameter λ_w indicates the impact of w on the total conductivity.
The simulations of the present study involve three different material layers, of which thermal and hygric properties have either been measured in the frame of a previous study (Rouchier et al., 2012) or taken from the literature. This matter is addressed in the simulation settings section.

Integration of fracture flow

As opposed to fully predictive approaches, where the position of damage process zones and crack trajectories are computed via coupled hygric and mechanical modelling (Moonen, 2009), the present methodology lies on experimental measurements of crack patterns. Damage is assumed to have occured prior to the heat and moisture transfer simulations.
In a two-dimentional geometry, fractures are discretised in the form of segments (Rouchier et al., 2012), and assigned specific transport properties. The liquid water permeability K_l of these segments is replaced by a permeabiliy tensor $\mathbf{k}_f$ such as:

$$\mathbf{k}_f = \mathbf{R}^T \begin{pmatrix} k_{f,l} & 0 \\ 0 & k_{f,t} \end{pmatrix} \mathbf{R} \qquad (8)$$

in which $k_{f,l}$ and $k_{f,t}$ are the respective values of the longitudinal and transverse fracture permeability, and $\mathbf{R}$ is the rotation matrix for directing the permeability tensor in the direction of the crack. The tensorial form of the liquid permeability in Equation 8 illustrates the anisotropy of fractured porous media. The expression of the longitudinal permeability in a water-saturated crack of aperture u results from the analytical solution of the Navier-Stokes equations for flow between two parallel plates:

$$k_{f,l} = \frac{\rho_l}{\eta_l}\frac{u^2}{12} \quad \text{if} \quad |p_c| \leq \frac{2\sigma}{u} \qquad (9)$$

This saturated permeability applies if the value of the capillary pressure meets an occupancy criterion proposed by (Vandersteen et al., 2003) and derivated from the Young-Laplace equation. Higher values of $|p_c|$ imply that the fracture segment is not filled with water, and this expression is no longer valid. For simplification purposes, the non-saturated longitudinal fracture permeability was set so as to reach a computational value of zero (namely 10^{-17} s) at dry conditions ($|p_c| = 10^9$ Pa).

Finite element implementation

The numerical implementation of Equations 1 and 4 was performed in a newly developed finite-element (FE) simulation code, mainly following the methodology of (Janssen et al., 2007). The Galerkin weighted-residual method was used for the spatial discretisation over a triangular mesh of Lagrange-type quadratic elements. The temporal discretisation follows the first-order implicit scheme. As the storage and transport coefficients of the equations are functions of the field variables p_c and T, the discretised system is strongly non-linear: the solution of each time step is approached iteratively, and a Newton-Raphson iterative scheme was used as to accelerate the convergence. The FE mesh is adapted to the geometry of the cracks, and the permeability tensor shown on Equation 8 is assigned to the corresponding nodes. It is therefore a semi-continuous monolithic approach, in which a discrete fracture network is integrated into the continuous porous medium. This method is simpler than other monolithic approaches, using double- or triple-nodded interface elements (Segura and Carol, 2008). Another alternative for the computation of flow in fractured porous media is a staggered approach, in which transport equations are solved iteratively in the porous material and in the fractures (Roels et al., 2006). This techniques allows reducing computational difficulties and emancipating the FE mesh from the crack geometry via the extended finite element method (Alfaiate et al., 2010). The monolithic approach however allows for a simpler account of the reversibility of moisture infiltration in cracks.

Validation

The validation of the simulation code is twofold. First, the generic modelling of coupled heat and moisture flow in the building envelope (without cracks) was done on the basis of the Hamstad benchmark package (Hagentoft et al., 2004). In the simulation of multi-layered building facades submitted to variable boundary conditions including solar radiation and wind-driven rain, the code achieved the same results than other available softwares (Rouchier, 2012).

The second aspect of the validation concerns moisture flow in fractured porous media. This was the topic of a previous study (Rouchier et al., 2012), in which moisture content profiles were measured in cracked concrete samples by X-ray radiography, and compared to simulation results. The code was found able to accurately predict moisture flow in the porous medium, accounting for the presence of fracures. Validation was however not provided for flow inside the cracks, as it occurs at a smaller time scale. This is not expected to significantly impact the following simulations.

SIMULATION SETTINGS

Geometry and materials

The target of the study is to illustrate the potential consequences of fractures on the hygric and thermal performance of building facades, in order to justify accounting for material degradation in simulations. For this purpose, a specific simulation case was designed, shown on Figure 1.

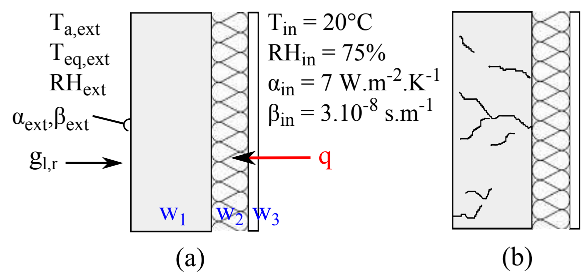

Figure 1: Simulation setup

The simulation setup includes a 20 cm concrete wall as the load-bearing material exposed to the outer surface, a 10 cm layer of hygroscopic fibre board insulation and a 1.25 cm gypsum board as inner finishing material. This setup covers two simulation cases: case (a) is that of a reference wall presenting no signs of damage, while case (b) includes a fracture network in the load-bearing material. The geometry of these fractures comes from a previous measurement performed by digital image correlation during tensile loading of concrete specimen (Rouchier et al., 2012). Although this specific geometry is not expected to be representative of all crack configurations which may arise in real operating conditions, it has been considered fit for justifying the presented methodology.

The moisture transport and storage properties of concrete have been characterised in the same study using desiccators and the Boltzmann transformation method applied on transient mass uptake profiles. The hygric and thermal material properties of the fibre board insulation and gypsum board were taken from (Hagentoft, 2002). Accounting for the liquid permeability is particularly important in this study, as some focus will be on the infiltration of wind-driven rain in the fractures.

The output of the simulations is to be displayed in the form of two types of variables, shown on Figure 1: the value of the heat flow from the internal environment towards the inner surface q, and the mean moisture content w of each material layer.

Boundary conditions

The moisture exchange g between the environment and the surface is driven by vapour exchange including evaporation and condensation, and by wind-driven rain impacting the facade:

$$g = \beta\,(p_{v,a} - p_v) + g_{l,r} \quad (10)$$

where β denotes the surface moisture transfer coefficient, $p_{v,a}$ is the ambient vapour pressure and $g_{l,r}$ denotes an incoming liquid flow in the form of rain.
The heat flux q from the environment to the surface includes a term of convective exchange, the sensible heat transfer due to precipitation, and the latent and sensible heat transfer due to vapour exchange:

$$\begin{aligned} q = \quad & \alpha\,(T_{eq} - T) + c_l T_a\, g_{l,r} \\ & + (c_v T_a + L_v)\,\beta\,(p_{v,a} - p_v) \end{aligned} \quad (11)$$

where α denotes the surface heat transfer coefficient and T_{eq} denotes an equivalent external temperature, which combines the temperature of the ambient air T_a, along with the effects of short wave solar radiation and long wave ground radiation.
The exterior boundary conditions of the problem are implemented according to climatic data files measured in Lyon during the year 2011. The following quantities are available as instantaneous measurements recorded with time steps of one minute: altitude and azimuth of the sun, diffuse and direct horizontal irradiance, wind speed and direction, relative humidity, horizontal rainfall intensity and dry bulb temperature. The convective transfer coefficients α and β are functions of the local air velocity on the building surface, determined by its orientation and by the wind speed and direction (Janssen et al., 2007). The effects of solar radiation are then integrated in the expression of an equivalent temperature T_{eq} at which the heat transfer rate due to the temperature across the wall is the same as the rate due to the combined effects of convection, conduction and radiation:

$$\alpha\,(T_{eq} - T) = \alpha\,(T_a - T) + \kappa\,(I_{dir} + I_{dif}) \quad (12)$$

where I_{dir} and I_{dif} denote the direct and diffuse solar irradiance, and κ is the absorptivity of the exposed material. Long-wave radiative exchange between the building surface and its environment is neglected. Wind-driven rain $\mathbf{g}_{l,r}$ is derived from the horizontal rainfall R_h and the wind speed U and direction, using a simplified empirical model (Blocken and Carmeliet, 2004):

$$\mathbf{g}_{l,r} = 0.222\; U\; R_h^{8/9} \quad (13)$$

This expression does not explicitely account for the raindrop size distribution, nor does it include the impact of the building height and of the wind speed, but its description of the rain loads is considered appropriate for the current study.

Climatic data were averaged over time steps of 10 minutes, which is the value of the maximal time step authorised for the calculation. In order to reduce computational costs, simulations were only performed in the case of a westward facade during two separate months: a winter month (february) and a summer month (july). Indeed, the integration of fractures in the geometry involves larger mesh sizes and calculation times. For simplification purposes, the internal boundary conditions and convective transfer coefficients are constant (see Figure 1).

Interface conditions

The interface contact condition between two materials inside the wall are the continuity of the temperature, vapour pressure and capillary pressure distributions. This condition does not ensure the continuity of the moisture content distribution.

RESULTS AND DISCUSSION

The initial conditions of the winter simulations are $T = 10°C$ and $\mathrm{RH} = 75\%$, and those of the summer simulations are $T = 20°C$ and $\mathrm{RH} = 75\%$. Each of the following graphs displays the temporal evolution of w and $\mathbf{q}$ for both simulation cases (reference wall and fractured wall), during one month of simulation. On each graph, the reference wall is shown by the continuous lines, while the wall including a fractured concrete layer is shown by the dotted lines.

Results

The external boundary conditions of the winter month are shown on Figure 2, while the dynamic behaviour of the wall is displayed on Figure 2. The first phase of the simulations (up to $t = 14$ days) shows no noticeable difference between the reference wall and the fractured wall, in terms of moisture content of each material layer ($w_{concrete}$, $w_{insulation}$ and w_{gypsum}). As a consequence of the choice of fracture permeability (Equation 9), cracks exposed to the ambient air have little influence on the moisture diffusion in the gaseous phase. Though the relative humidity is relatively high, the hygric and thermal behaviour of the fractured wall does not differ from that of the reference wall as long as no wind-driven rain is involved.
A rains shower then occurs at $t = 14$ days, as shown by Figure 2. It is followed by a steep increase of $w_{concrete}$, as water quickly infiltrates the cracks of the exposed concrete layer. The value of $w_{concrete}$ then decreases during the drying of the facade, though an important accumulation of moisture remains in this material of low permeability. Some water can be seen to migrate through the load-bearing material and reach the internal insulation layer, as shown by the rise of $w_{insulation}$. As a consequence of this moisture infiltration, a deviation can be seen between the reference and the fractured facade in terms of heat loss q. After the rain shower, the heat flow from the inside is briefly increased in the presence of cracks: this is caused by

a slight cooling of the wall due to water evaporation towards the external air, which is accentuated in the fractured case.

Two additional rain showers occur during this month of simulation: the moisture accumulation is then accentuated in both the concrete and the insulation layers of the fractured facade. As a result, its thermal behaviour progressively deviates from that of the reference wall: as $w_{insulation}$ increases, so does the overall thermal conductivity of the envelope.

Similar observations can be drawn from the simulation of the same facades during the month of July, as seen on Figure 4. Though the effects of fractures on the thermal performances are limited, an important moisture accumulation can be seen to take place in the damaged simulation case, although the moisture content of the reference wall normally decreases slighly during this summer month.

[h]

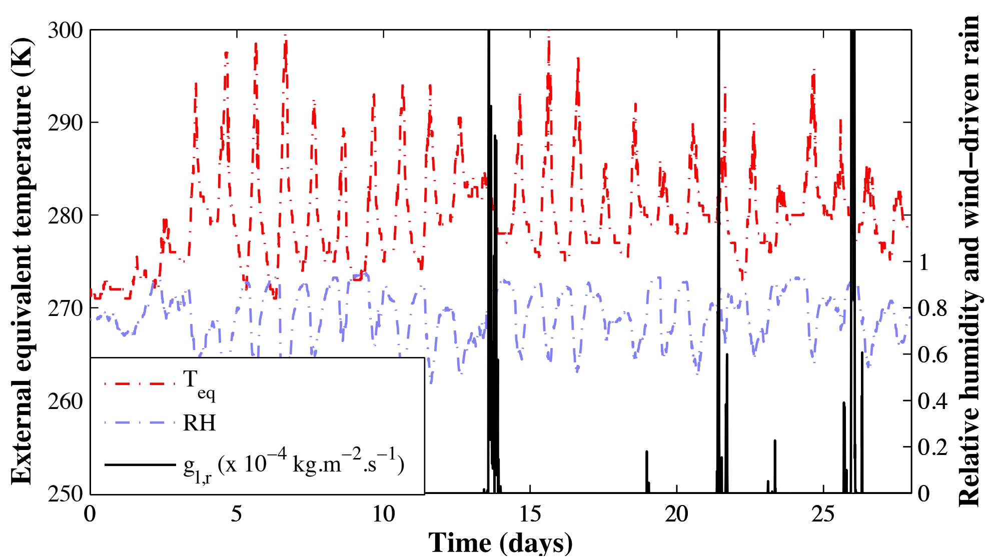

Figure 2: External temperature, relative humidity and wind-driven rain during the month of february

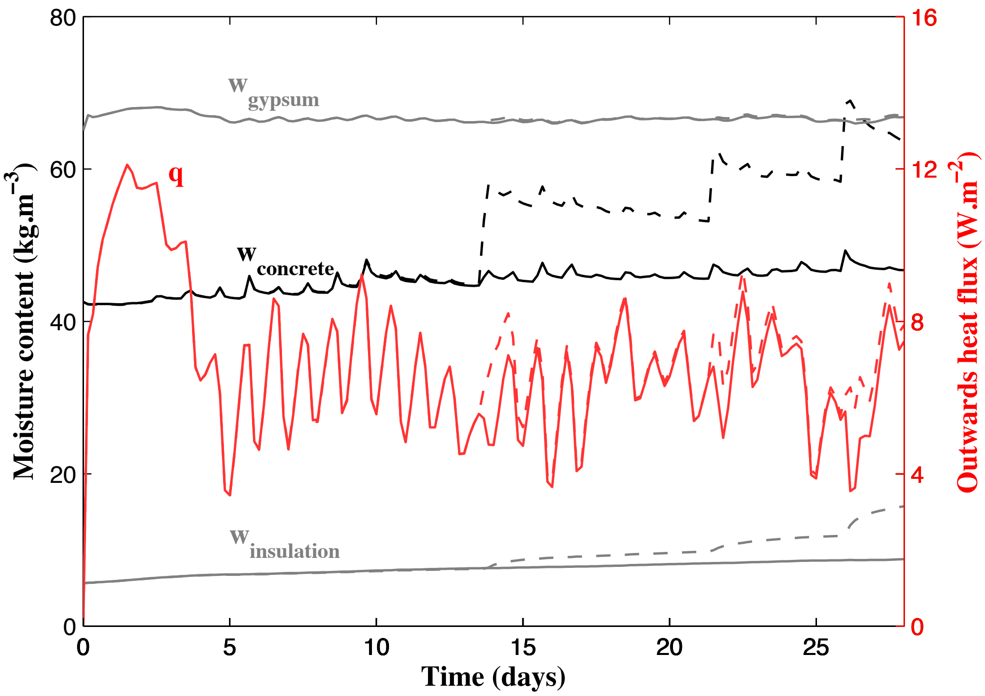

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Figure 3: Winter month simulation results. Continuous lines: reference wall; dotted lines: fractured wall

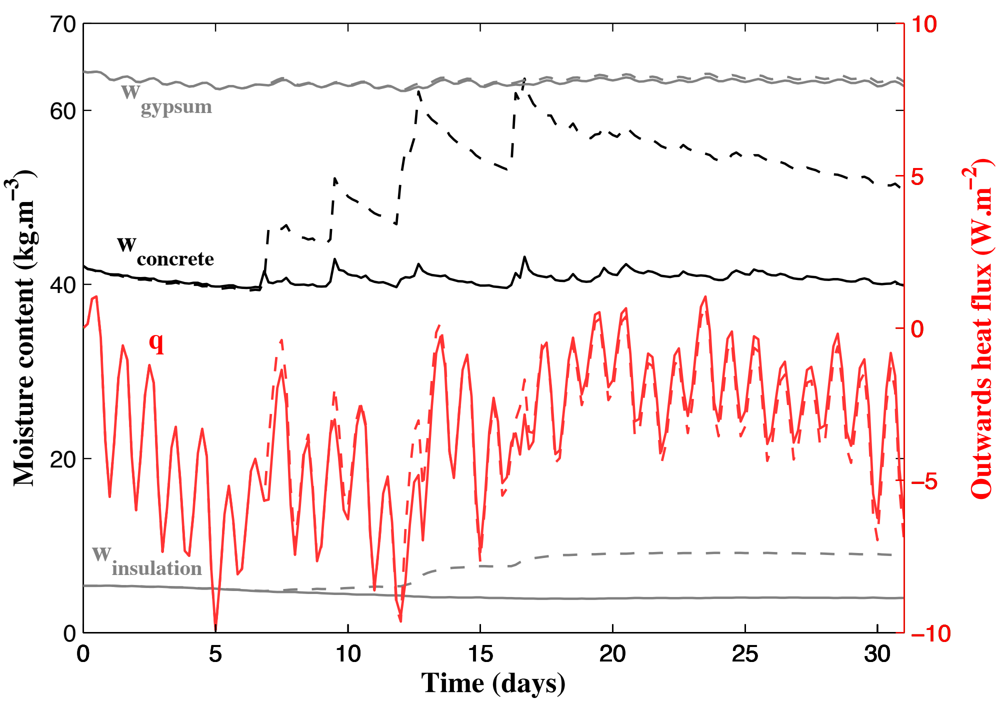

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Figure 4: Summer month simulation results. Continuous lines: reference wall; dotted lines: fractured wall

Discussion

These results illustrate the potential impact of cracks on the hygric and thermal performance of an insulated wall. Specifically, the large increase of moisture permeability caused by fractures may raise two main concerns:

- the aggravation of durability issues and moisture-related pathologies,
- a potential negative impact on the benefits of thermal insulation.

The first of these matters is the most likely to be a serious concern, as moisture carries many causes of material degradation. The calculations have shown an important accumulation of water in the envelope as a consequence of cracks, along with an accentuation of the daily sorption/desorption cycles. Both of these phenomena may contribute to problems of durability. Moreover, this effect is not restricted to the material layer in which the fractures have been placed. The second concern is the impact on the thermal performance of the envelope. Under specific conditions of geometry and choice of material, the fracture-induced rain infiltration can lead to the accumulation of water in a hygroscopic insulation layer, thus impacting its thermal resistance. This impact can be observed by evaluating the total insulation R-value of the wall over time, and comparing it in both intact and fractured walls, as is shown on Fig. 5. The presence of cracks induces successive drops of this value after rain showers. This effect, though of low magnitude in the present results, may become significant in the long-term.

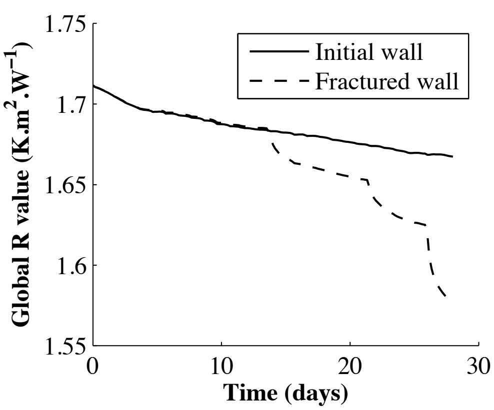

Figure 5: Insulation R-value of the initial and fractured walls during the month of February

It must be noted that the simulation cases of this work have been designed as to illustrate the loss of thermal efficiency. Such results are not to be expected from any material configuration or climatic conditions. The target of this work was however not to display all possible outcomes of fractures in construction materials, but to justify the need for including them in long-term simulations applied to durability or hygrothermal performance assessments.

CONCLUSION

This paper has shown the application of coupled heat and moisture flow simulations to the performance assessment of a building facade including a fractured material.

- A numerical model was presented for including any fracture geometry into a finite-element code for heat and moisture transfer predictions.
- Simulation cases were defined as to demonstrate the potential effects of cracks on the hygrothermal performance of the building envelope.
- Calculations showed that the infiltration of rain, made possible by the presence of cracks in an exposed material layer, may durably affect the sustainability of the structure, and in some cases its thermal performance as well.

Such consequences of water leakage are among the main motivations for the application of hygrothermal modelling tools. Although these results were obtained in the frame of a specific wall configuration and fracture geometry, they show how these tools can be enhanced by accounting for the evolution of material properties and their degradation. The undertaken procedure consists of experimental measurements of fissures integrated into a standard heat and moisture transfer simulation code. The main advantages of this procedure are its applicability to a wide range of facade types, and reasonable computational costs.

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