Hygrothermal modeling and evaluation of freeze-thaw damage risk of masonry walls retrofitted with internal insulation

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Abstract. For historical buildings with a worth-preserving appearance, internal wall insulation can be the only possible solution to improve the building energy efficiency. However, the application of an internal insulation layer changes significantly the hygrothermal performance of the building envelope. For masonry walls, such intervention may lead to freeze-thaw damage of the brickwork. In this study, a hygrothermal model is developed. The model takes into account moisture and heat transport in porous medium and tracks the occurrence of freezing and thawing in function of pore size distribution and as well as the ice content. Freezing and melting of water in porous medium is implemented based on the theory of freezing point depression, as freezing temperature of water in porous medium depends on pore size, *i.e.* water in the smaller pores freezes at temperatures lower than 0° C. The numerical model results are compared with a porous medium freezing experiment and good agreement is found. Traditional hygrothermal assessment uses the number of zero crossings on a Celsius scale as the number of freeze-thaw cycles. We propose a method that uses the number of actual ice growth and melt cycles as an indicator more accurately accounting for the freeze-thaw process. In addition, we develop an index, called FTDR Index, to assess freeze-thaw damage risk. We perform simulations of uninsulated and internally retrofitted masonry walls using two Swiss climatic conditions. The study clearly shows increase of freeze-thaw cycles and ice content after internal retrofitting in both climates. Thus, FTDR Index increases after internal retrofitting.

1. Introduction

Energy efficiency in buildings can be improved by retrofitting masonry walls with internal or external insulation. For historical buildings with a worth-preserving appearance, internal wall insulation is the main retrofit solution to consider in order to improve building energy efficiency. However, internal thermal insulation changes significantly the hygrothermal performance of the building envelope. In particular, the addition of insulation to the inside of load-bearing masonry walls may cause performance and durability problems of individual components or whole systems, such as the initiation of freeze-thaw damage of the facing brickwork [1]. As the added insulation reduces the heat flux from the interior into the insulation, the wall drying ability decreases, leading to increased moisture levels and decreased temperature in the masonry walls. This is the main cause of freeze-thaw damage problems resulting from internal retrofitting. Professionals and building owners may avoid internal insulation solutions due to the difficulty to assess the increased risks of freeze-thaw damage. Therefore, it is essential to provide a mode of analysis of the eventual risk of freeze-thaw damage in masonry walls subjected to inside internal retrofitting.

The primary mechanism responsible for freeze-thaw damage is the expansion of water when the liquid changes to ice [2]. In porous medium, the volumetric expansion of water by 9 per cent due to freezing exerts tensile stresses on the material matrix and causes damage when the stresses exceed the strength of the material [3-5]. One approach is the use of the number of freeze-thaw cycles to estimate the potential for freeze-thaw damage [6]. However, such studies often use the number of zero crossings on a Celsius scale as the number of freeze-thaw cycles [6-9]. This approach fails to

consider that water in porous medium freezes at temperature below 0 °C, varying in function of the pore size. The water in the smaller pores freezes at much lower temperatures, so that liquid water can be preserved well below 0 °C. From thermodynamic principles, the freezing point is the temperature where the free energy of water in the porous medium is equal to that of ice. The free energy of water in porous medium can be affected by capillarity, adsorption and dissolved salts. The capillary pressure is inversely proportional to the pore size. Therefore, the smaller the pore size, the larger the capillary pressure.

Previous research has shown that freezing is not necessarily damaging to porous medium and the most important factor for freeze-thaw damage is degree of saturation of moisture content at the time of freezing [10-13]. The degree of saturation is defined as the ratio of actual moisture content to moisture content at saturation. The critical degree of saturation is widely used in literature to define a porous material resistance to freeze-thaw damage [13-15]. At moisture contents above critical degree of saturation, the porous material will be seriously damaged by freezing. Prick [15] reported the critical degree of saturation of ten French limestones to be between 0.58 and 1.0. Mensinga et al. [13] reported that the critical degree of saturation for three Canadian bricks is between 0.25 and 0.87. Additionally, the frost durability of porous medium is affected by pore size distribution and porosity. High porosity reduces the frost resistance of bricks while small pores are more dangerous to freeze-thaw damage than bigger pores. Maage [16] developed an empirical mathematical correlation between frost resistance and pore characteristics.

Field observations of freeze-thaw damage in clay masonry structures suggest that the performance of bricks is affected not only by the materials characteristics but also to the microenvironment in which they are exposed [17]. Factors such as geographical location, direction of exposure versus rain or sun, season of the year affect moisture content in the masonry wall. The most likely meteorological condition for freeze-thaw damage is a substantial temperature drop below 0 °C with a significant amount of rainfall in the previous days. Liso et al. [5] developed a frost decay exposure index based on number of freezing events and rainfall sums prior to freezing events to provide a geographically-dependent freeze-thaw damage risk assessment.

Hygrothermal models, simulating coupled heat and moisture transport, have the ability to assess long-term heat and moisture performance of wall assemblies and predict risks of moisture related problems [18-20]. They are suitable to analyze the changes in hygrothermal performance after adding insulation layer to masonry walls. However, traditional hygrothermal models used for investigating the risk of freeze-thaw damage do not model the process of freezing and thawing of moisture in porous medium [7, 8]. It is yet not known whether it is appropriate to apply those models for studying freeze-thaw damage risk problems.

The objective of this paper is to assess the influence of internal insulation retrofitting on freeze-thaw damage risk of masonry wall assemblies. A hygrothermal model which can account for moisture and heat transport in a porous medium and track locally the occurrence of freezing and thawing in function of pore size distribution is developed in this study. The numerical model is validated using a porous medium freezing experiment. A new assessment method is proposed to indicate freeze-thaw cycles. In addition, a new index is proposed to evaluate risk of freeze-thaw damage. We perform simulations of the hygrothermal performance of base and retrofitted masonry walls for two Swiss climatic conditions. The number of ice content and freeze-thaw cycles occurring in the uninsulated and in the retrofitted masonry walls are compared.

2. Hygrothermal simulation model

2.1 Coupled moisture and heat transport model for freezing porous medium

The equations are based on the following hypotheses: (1) the porous media are non-deformable and no volume change occurs during freezing and thawing; (2) there is no salt present in the porous medium; (3) there is an analogy between capillary pressure curve (the relationship between capillary pressure and moisture content) and freezing curve (the relationship between subzero temperature

and unfrozen liquid water content). If a solute is considered to be present in the porous medium, the melting point of water in porous medium will be further depressed. The freezing point depression depends also on the concentration of the solutes. In reality, the porous medium is deformable and volume changes occur during freezing and thawing. Since the volume change for bricks is small, the influence of volume change on the freezing process can be neglected.

In a porous medium under freezing, moisture may exist in the form of vapor, liquid and ice. Thus, the conservation equations for moisture transport in freezing and non-freezing porous media can be written for:

Water vapor:

$$\frac{\partial w_v}{\partial t} + \nabla \cdot g_v = -G_{l,v} - G_{i,v} \quad (3)$$

where w_v is the vapor content (kg/m^3); g_v is the vapor flow rate ($\text{kg/m}^2\text{s}$); $G_{l,v}$ is the phase exchange rate between liquid water and vapor ($\text{kg/m}^3\text{s}$); $G_{i,v}$ is the moisture exchange rate between vapor and ice ($\text{kg/m}^3\text{s}$).

Liquid water:

$$\frac{\partial w_l}{\partial t} + \nabla \cdot g_l = G_{l,i} + G_{l,v} \quad (1)$$

where w_l is the liquid water content (kg/m^3); g_l is the liquid flow rate ($\text{kg/m}^2\text{s}$); $G_{l,i}$ is the moisture exchange rate between liquid water and ice ($\text{kg/m}^3\text{s}$); $G_{l,v}$ is the moisture exchange rate between liquid water and vapor ($\text{kg/m}^3\text{s}$).

Ice:

$$\frac{\partial w_i}{\partial t} + \nabla \cdot g_i = -G_{i,l} + G_{i,v} \quad (2)$$

where w_i is the ice content (kg/m^3); g_i is the ice flow rate ($\text{kg/m}^2\text{s}$); $G_{i,l}$ is the moisture exchange rate between ice and water vapor ($\text{kg/m}^3\text{s}$); $G_{i,v}$ is the moisture exchange rate between ice and water vapor ($\text{kg/m}^3\text{s}$).

The ice phase is considered immobile and thus g_i is equal to 0. Summing up Eqs. 1, 2 and 3 leads to the balance equation of the total moisture transport:

$$\frac{\partial w_l}{\partial t} + \frac{\partial w_i}{\partial t} + \frac{\partial w_v}{\partial t} + \nabla \cdot g_l + \nabla \cdot g_v = 0 \quad (4)$$

As $\frac{\partial w_v}{\partial t}$ is much smaller than $\frac{\partial w_l}{\partial t}$ and $\frac{\partial w_i}{\partial t}$, the change in water vapor content is neglected. Eq. 4 can thus be simplified as:

$$\frac{\partial w_t}{\partial t} + \nabla \cdot g_l + \nabla \cdot g_v = 0 \quad (5)$$

where w_t is the total moisture content ($w_t = w_l + w_i$).

Liquid water, ice and vapor coexist in the freezing porous medium for a certain temperature and each phase is in equilibrium with each other. We assume that Kelvin's law, describing the relationship between capillary pressure and relative humidity, is still valid in the freezing porous medium. Capillary pressure is the difference in pressure across the interface between air and liquid water. In addition, we assume that the ice formed in the porous medium has the same properties as bulk ice. The existence of liquid water at temperatures below 0.0°C is due to the melting point depression of water in a porous medium. A thin film of liquid water exists between the ice and the matrix surface in freezing porous media. The equilibrium between ice and liquid water is described by the Clausius-Clapeyron equation. During freezing, water freezes and becomes ice first in the larger pores, while liquid water remains in the smaller pores.

The relationship between liquid water content and capillary pressure and between total moisture content and total water pressure is characterized by the capillary pressure curve is defined as:

$$w_l = \Theta(p_c) \quad (6)$$

$$w_t = \Theta(p_t) \quad (7)$$

where Θ is the predicting function; p_c is the capillary pressure corresponding to liquid water content w_l ; p_t is the total water pressure corresponding to total moisture content w_t .

The relation between capillary pressure and liquid water pressure is the following:

$$p_c = p_a - p_l \quad (8)$$

where p_a is the atmospheric pressure (Pa); p_l is the liquid water pressure (Pa); the value of atmospheric pressure is 0.0 Pa when taking atmospheric pressure as a reference for fluid pressure.

The liquid flow rate g_l is written as:

$$g_l = -K_l(p_c) \nabla p_c \quad (9)$$

where $K_l(p_c)$ is the liquid permeability (s), p_c is the capillary pressure (Pa).

The vapor flow rate g_v is written as:

$$g_v = -\delta_v \cdot \frac{p_v}{\rho_l \cdot R_v \cdot T} \cdot \nabla p_c - \delta_v \cdot \frac{p_v}{\rho_l \cdot R_v \cdot T^2} (\rho_l \cdot L_v) \cdot \nabla T \quad (10)$$

where δ_v is the water vapor permeability (s); p_v is the vapor pressure (Pa); ρ_l is the density of water (kg/m³); R_v is the gas constant of water (461.52 J/kg K); T is the temperature (K); L_v is the latent heat of vaporization (2.256e6 J/kg). For derivation of this equation, we refer to Janssen *et al.* 2007 [21]. The second term at right hand side in equation (10) represents the temperature driven vapor diffusion.

The conservation equation for heat in non-freezing and freezing porous media can be written as:

$$\begin{aligned} & (C_s \cdot \rho_s + C_l \cdot w_l + C_i \cdot w_i + C_v \cdot w_v) \cdot \frac{\partial T}{\partial t} - L_f \cdot \frac{\partial w_i}{\partial t} + L_v \cdot \frac{\partial w_v}{\partial t} + \\ & \nabla \cdot (C_l \cdot (T - T_{ref}) \cdot g_l + (C_v \cdot (T - T_{ref}) + L_v) \cdot g_v) = -\nabla(\lambda \nabla T) \end{aligned} \quad (11)$$

where C_s , C_l , C_i and C_v are the specific heat capacity of solid matrix, liquid water, ice and vapor (J/kg K); ρ_s is the bulk density of the solid matrix (kg/m³); T_{ref} is 273.15 K, L_f is the latent heat of freezing (3.33e5 J/kg), λ is the thermal conductivity (W/mK).

The thermal conductivity of freezing porous medium is described using the following equation:

$$\lambda = \lambda_{dry} + a_l \cdot w_l + a_i \cdot w_i \quad (12)$$

λ_{dry} is the thermal conductivity of the porous material under dry conditions (W/mK); a_l is the liquid water modification coefficient (Wm²/K kg); a_i is the ice modification coefficient (Wm²/K kg).

As water vapor contributes very little to heat storage, Eq. 11 can be simplified to:

$$\begin{aligned} & (C_s \cdot \rho_s + C_l \cdot w_l + C_i \cdot w_i) \cdot \frac{\partial T}{\partial t} - L_f \cdot \frac{\partial w_i}{\partial t} + \\ & \nabla \cdot (C_l \cdot (T - T_{ref}) \cdot g_l + (C_v \cdot (T - T_{ref}) + L_v) \cdot g_v) = -\nabla(\lambda \nabla T) \end{aligned} \quad (13)$$

In order to account for freezing of water and formation of ice in the porous medium, the concept of freezing point depression is used, where the Gibbs free energy of water and ice must be equal. The differential form of Gibbs free energy is [22]:

$$dG = -sdT + Vdp \quad (14)$$

where G is the Gibbs free energy (J/g); s is entropy (J/K); T is the temperature (K); V is the specific volume (m^3kg^{-1}); p is the pressure (Pa).

As the Gibbs free energy of liquid water and ice is equal at freezing point, the following equation can be written:

$$dG_l = -s_l dT + V_l dp_l = dG_i = -s_i dT + V_i dp_i \quad (15)$$

where l and i refer to water and ice, respectively.

The difference in entropies of the two phases at temperature of freezing is related to the latent heat of freezing:

$$s_l - s_i = \frac{L_f}{T} \quad (16)$$

Rearranging Eqs. 15 and 16 leads to:

$$V_l dp_l - V_i dp_i = \frac{L_f}{T} dT \quad (17)$$

We assume that ice in the porous medium is at atmospheric pressure, although this has been questioned under certain conditions [23], but so far there is little evidence against this assumption [24]. Therefore, dp_i is equal to 0. The Clausius-Clapeyron equation describing the coexistence of liquid water and ice can be written as:

$$\frac{dp_l}{dT} = \frac{L_f}{T} \frac{1}{V_l} \quad (18)$$

By integrating Eq. 18, the relationship between temperature and liquid water pressure in freezing conditions of the porous medium can be expressed as:

$$\int_{T_0}^{T_f} \frac{L_f}{V_l} \frac{dT}{T} = \int_{p_0}^{p_l} dp \quad (19)$$

where T_f is the freezing temperature for specific pores of the porous medium (K); T_0 is the freezing reference temperature (273.15 K); p_l is the liquid water pressure at the freezing temperature T_f ; p_0 is equal to 0 Pa (the liquid water pressure corresponding to freezing temperature of 273.15 K). After integration of Eq. 19, the following equation is obtained:

$$T_f = T_0 \cdot \exp\left(\frac{V_l \cdot p_l}{L_f}\right) = T_0 \cdot \exp\left(\frac{p_l}{\rho_l \cdot L_f}\right) = T_0 \cdot \exp\left(\frac{-p_c}{\rho_l \cdot L_f}\right) \quad (20)$$

Note V_l is the specific volume of water ($0.001 \text{ m}^3/\text{kg}$). The above equation gives us as first approximation that a decrease in temperature by 1°C corresponds to the lowering of the liquid water pressure by 1.2 MPa.

The determination of whether or not a porous medium is at freezing condition is based on the following equation:

$$T^* = T_0 \cdot \exp\left(\frac{-p_l}{\rho_l \cdot L_f}\right) \quad (21)$$

where p_l is the total water pressure corresponding to the total water content. When $T \geq T^*$, the porous medium is unfrozen and no ice exists. When $T < T^*$, the porous medium is at freezing condition and ice exists.

The equation describing the relation between capillary pressure and temperature in a freezing porous medium is:

$$p_c = -\rho_l \cdot L_f \cdot \ln\left(\frac{T}{T_0}\right) \approx -\rho_l \cdot L_f \cdot \frac{T - T_0}{T_0} = -S_f(T - T_0) \quad (22)$$

where $S_f = \frac{\rho_l \cdot L_f}{T_0}$.

The ice content at freezing condition can be written as:

$$w_i = w_t - w_l = \Theta(p_t) - \Theta(p_c) = \Theta(p_t) - \Theta(-S_f(T - T_0)) \quad (23)$$

The relation $\Theta(p_c) = \Theta(-S_f(T - T_0))$ is called the freezing curve, which describes the relation between subzero temperatures and the unfrozen liquid water content.

The capillary pressure for non-freezing and freezing conditions is described using the following equation:

$$\begin{cases} p_c = p_t & \text{if } T \geq T^* \\ p_c = -S_f(T - T_0) & \text{if } T < T^* \end{cases} \quad (24)$$

The equilibrium of the ice-liquid interface with curvature radius r is governed by Young-Laplace law:

$$p_i - p_l = \frac{2\gamma_{il}}{r} \quad (25)$$

where γ_{il} is the ice-liquid interface energy. Combining Eqs. 22 and 25 yields Gibbs-Thomson law:

$$r = \frac{2\gamma_{il}}{S_f(T - T_0)} \quad (26)$$

Eq. (26) indicates that all the pores having radius greater than r freeze at temperature T while water in the smaller pores remains liquid.

2.2 Model implementation

The governing equations for moisture and heat transfer in non-freezing and freezing porous medium are given in Eqs. 5 and 13. These equations are solved using the finite element simulation solver COMSOL.

For non-freezing conditions ($T \geq T^*$), p_t is equal to p_c . The governing equations are the same as those of HAMFEM [21]. The following governing equations are solved in the COMSOL solver:

moisture transfer:

$$\frac{\partial w_t}{\partial p_t} \cdot \frac{p_t}{\partial t} + \nabla \left(-K_l(p_t) - \delta_v \cdot \frac{p_v}{\rho_l \cdot R_v \cdot T} \right) \nabla p_t + \nabla \left(-\delta_v \cdot \frac{p_v}{\rho_l \cdot R_v \cdot T^2} (\rho_l \cdot L_v) \right) \nabla T = 0 \quad (26)$$

heat transfer:

$$\begin{aligned} & (C_s \cdot \rho_s + C_l \cdot w_l) \cdot \frac{\partial T}{\partial t} + \nabla (C_l \cdot (T - T_{ref}) \cdot (-K_l(p_t))) - (C_v \cdot (T - T_{ref}) + L_v) \cdot \delta_v \cdot \frac{p_v}{\rho_l \cdot R_v \cdot T} \nabla p_t \\ & + \nabla \left[(C_v \cdot (T - T_{ref}) + L_v) \cdot (-\delta_v \cdot \frac{p_v}{\rho_l \cdot R_v \cdot T^2} (\rho_l \cdot L_v)) + \lambda \right] \nabla T = 0 \end{aligned} \quad (26)$$

For freezing conditions ($T < T^*$), $p_c = -\rho_l \cdot L_f \cdot \frac{T - T_0}{T_0}$. Therefore, ∇p_c can be approximated

as $-\frac{\rho_l L_f}{T_0} \nabla T$. The following governing equations are solved in the COMSOL solver:

moisture transfer:

$$\frac{\partial w_t}{\partial p_t} \cdot \frac{p_t}{\partial t} + \nabla \left(-K_l(p_c) - \delta_v \cdot \frac{p_v}{\rho_l \cdot R_v \cdot T} \right) \cdot \frac{\rho_l L_f}{T_0} \nabla T + \nabla \left(-\delta_v \cdot \frac{p_v}{\rho_l \cdot R_v \cdot T^2} (\rho_l \cdot L_v) \right) \nabla T = 0 \quad (27)$$

heat transfer:

$$\begin{aligned}
& (C_s \cdot \rho_s + C_l \cdot w_l + C_i \cdot w_i) \cdot \frac{\partial T}{\partial t} - L_f \cdot \frac{\partial w_i}{\partial t} \\
& + \nabla (C_l \cdot (T - T_{ref}) \cdot (-K_l(p_c)) - (C_v \cdot (T - T_{ref}) + L_v) \cdot \delta_v \cdot \frac{p_v}{\rho_l \cdot R_v \cdot T}) \cdot -\frac{\rho_l L_f}{T_0} \nabla T \\
& + \nabla \left[(C_v \cdot (T - T_{ref}) + L_v) \cdot (-\delta_v \cdot \frac{p_v}{\rho_l \cdot R_v \cdot T^2} (\rho_l \cdot L_v)) + \lambda \right] \nabla T = 0
\end{aligned} \quad (28)$$

2.3 Validation of the freezing model algorithm

The difference between models for freezing/thawing or non-freezing porous medium is the consideration not only of freezing of water in porous medium but also of freezing-induced moisture migration. The model described above for freezing-induced moisture migration is validated against the experiment of Zhou *et al.* 2014 [25]. They reported laboratory experiments involving freezing of a partially saturated porous medium (soil). An acrylic glass cylinder of 5.3 cm inner diameter and 23.6 cm length was used to contain the soil (Fig. 1). The soil had a uniform initial moisture content of 160 kg/m³. The capillary pressure curve and permeability curve of the soil are analytically described by the van Genuchten's equation (Fig. 2). The experiment was carried out in a cooling chamber and the periphery of the cylinder was insulated by extruded polystyrene foam. Two Peltier plates were placed at both ends of the soil column to control boundary temperatures. The soil column was initialized at equilibrium at an initial temperature of 3.0 °C by controlling the temperatures of the two Peltier plates. At the start of the experiment, the temperature at the cold end (top) was lowered to -4.7 °C while the temperature at the warm side (bottom) was fixed at 3.5 °C. The two ends of the soil column were tight preventing moisture flux at the boundaries. In the experiment, temperature was measured by platinum resistance thermometers and total moisture content was measured using the gamma-ray absorption technique [26]. For more detail, we refer to Zhou *et al.* 2014 [25].

Fig. 1 Schematic diagram of the setup for freezing experiment (from [25]).

Fig. 1 (a) Liquid permeability, (b) capillary pressure curve and (c) freezing curve of the soil used in the validation experiment [25]

Even though the soil column was placed in a cooling chamber and the lateral sides were insulated, the setup was not able to achieve pure one-dimensional heat transfer in the soil cylinder. To account for the lateral heat transfer, Newton's law of cooling is added on the right hand side of the heat transfer equation as heat source/sink, which can be expressed as follows:

$$Q = \beta \frac{\lambda_f}{d_f} (T_a - T) \frac{1}{d} \quad (27)$$

where λ_f is the thermal conductivity of the extruded polystyrene foam, d_f is the thickness of insulation around the soil cylinder, T_a is the ambient temperature (K), T is the soil temperature (K), d is the radius of the column (m). The thermal conductivity of the extruded polystyrene foam was assumed to be $0.03 \text{ Wm}^{-1}\text{K}^{-1}$ and the foam thickness is 4 cm. For the experiment, the ambient

temperature (T_a) was 0.6 °C. The correction coefficient β was obtained by comparing measured soil temperatures and simulated soil temperatures in the quasi-steady state before the start of the experiment.

Fig. 2 shows the comparison of the profiles of measured and simulated total moisture content as well as measured and simulated temperature during the freezing experiment. The simulated total moisture content and temperature agree well with the measured ones. The total moisture content on the colder side (top) increases, whereas the total moisture content on the warmer side (bottom) decreases. The moisture migration from above freezing condition to below freezing condition is driven by the temperature gradient. As moisture migrates, the ice content on the colder side grows as the arriving water freezes, modifying locally the amount of total moisture content. The sharp jumps of total moisture content near the freezing front are well represented by the numerical model. The zones below the freezing front have the lowest moisture contents. By comparison, the total moisture contents above the freezing front have much higher values, which are caused by moisture migration from the underlying unfrozen porous medium. When freeze/thaw is not considered, the total moisture content distribution shows almost no change (Figure 2a). Under non-freezing condition, the main mechanism for moisture transport is temperature induced vapor transport, which is very small compared to freezing induced moisture transport. In addition, when freeze/thaw is not considered, there is a rather large difference between measured and simulated temperature at time of 0.5 d.

Fig. 2 (a) Comparison of measured and simulated total moisture content at 0.5, 1.5 and 2.5 days; (b) Comparison of measured and simulated temperature at 0.5, 1.5 and 2.5 days. The measurement results are from [25].

2.4 Material properties and input data

In order to study the influence of adding internal insulation on the freeze-thaw damage risk of a masonry wall, two types of masonry wall structures are selected for hygrothermal modeling (Fig. 3), which are a masonry wall without insulation and an internally insulated masonry wall. The masonry building envelope assemblies consist of the following materials: 3-wythe masonry assembly, aerogel insulation plaster and interior plaster. The material properties of brick, mortar and aerogel insulation plaster are from Guizzardi et al. [27] and the material properties of interior plaster are from HAMFEM database [21]. The capillary pressure curve is described using a bimodal function of the van Genuchten model [28]:

$$w_l = w_{cap} \sum_{i=1}^2 \frac{l_i}{(1 + (a_i p_c)^{n_i})^{m_i}} \quad \text{with } m_i = 1 - 1/n_i \quad (28)$$

where w_{cap} is the capillary moisture content (kg/m^3); a is the inverse of air-entry value ($1/\text{Pa}$); and n is the pore-size distribution index; l is the weight parameter. For freezing curves, the relationship between temperature and capillary pressure is $p_c = -S_f(T - T_0)$. Therefore, the freezing curve that describes the relation between liquid water content and subzero temperature is:

$$w_l = w_{cap} \sum_{i=1}^2 \frac{l_i}{(1 + (a_i \times -S_f(T - T_0))^{n_i})^{m_i}} \quad \text{with } m_i = 1 - 1/n_i \quad (29)$$

The parameters for capillary pressure curve and freezing curve for the different materials are shown in Table 1. Fig. 4 shows the capillary pressure curves and freezing curves of the materials. In the following analysis, the degree of saturation is calculated as the ratio of actual total moisture content or ice content to capillary moisture content. In this study, the influence of temperature on the capillary pressure curve is not considered. Salager *et al.* studied this influence [29] and found only a slight difference between 20 and 80 °C. At lower temperature, a small influence of temperature on the capillary pressure curve may be expected, but this influence is not taken into account in this paper.

The hygrothermal modeling is applied for two locations in Switzerland: Zurich and Davos. Zurich is a city north of the Alps. The climate is characterized by mild winter and warm summer. The annual mean temperature of the city is 9.3 °C and the annual precipitation is 1101 mm. By comparison, Davos is an Alpine town, located at 1560 m above sea level. It has a cold climate with an average annual temperature of 3.9 °C. It receives about 1000 mm of precipitation annually. In winter, due to low air temperature, a large portion of precipitation occurs in the form of snow.

Thirty years of weather data (1981-2010) for the two cities from MeteoSwiss are used for hygrothermal modeling. The meteorological data include hourly horizontal rainfall rate, horizontal solar radiation, air temperature and relative humidity, wind speed and direction. A meteorological year beginning in October and ending in September is most reasonable as the moisture conditions within the building envelope during the winter will affect the moisture conditions during the summer. The hygrothermal behavior of the wall is evaluated for each year separately. For each year, the meteorological data are repeated for four years and the results of the fourth year are used for analysis to ensure independence from the initial condition. In order to select the orientation which gives the most severe moisture problems, the orientation with the largest wind-driven rain load is selected for hygrothermal simulation. The selected wall orientations for Zurich and Davos are 240 and 30 degrees, respectively. The wind-driven rain load for different wall orientations is calculated according to ASHRAE Standard 160 - Criteria for Moisture Control Design Analysis in Buildings [30]. In addition, it is assumed that when the air temperature is below 0.0 °C, precipitation is present in the form of snow and thus wind-driven rain load becomes 0.0. The convective heat transfer coefficient is set according to the European standard EN15026 [31]. The convective vapor transfer coefficient is related to the convective heat transfer using the Lewis analogy. The interior conditions

are determined according to the European standard EN15026 [31], in which indoor temperature and relative humidity depend linearly on the outdoor temperature.

Fig. 3 Selected masonry wall assemblies for hygrothermal modeling

Table 1. Parameters of capillary pressure curve and freezing curve

	Brick	Mortar	Aerogel plaster	Interior plaster
w_{cap}	303.8	148.0	400.0	209.0
l_1, l_2	0.18, 0.82	0.5, 0.5	0.8, 0.2	0.5, 0.5
a_1, a_2	3.2e-8, 9.5e-7	7.0e-8, 2.0e-7	6.9e-7, 1.8e-6	2.0e-6, 2.0e-6
n_1, n_2	3, 2.2	3, 2.2	2.3, 2.0	1.27, 1.27

Fig. 4 (a) Capillary pressure curves and (b) freezing curves of the materials

3. Results

3.1 Comparison between hygrothermal models with and without freezing

The comparison of the results between the hygrothermal model accounting for freeze/thaw (HM_FT) and the traditional model not accounting for freeze/thaw (HM) is shown in Fig. 5. When there is no freezing of water in the masonry wall (e.g. from October to December and from July to September), the saturation degree of total moisture content and temperature are almost the same in the two models. By comparison, the profiles for saturation degree of total moisture content and temperature for the two models are quite different in the cold periods between mid-December and March where freezing occurs. The difference is due to freezing-induced moisture migration. Meanwhile, the variations in temperatures by HM_FT are smaller than those of HM. The reason for the differences is the latent heat associated with freezing and thawing. Latent heat due to freezing of water delays the cooling of the masonry wall, while latent heat due to thawing of ice delays the warming of the masonry wall.

The effect of freezing-induced moisture migration and latent heat associated with freezing can be seen in Fig. 6. Between the 7th and 8th January 1982, the moisture content simulated by HM changes very slowly while the one simulated by HM_FT decreases first and then increases to saturation. The temperature simulated by HM_FT is very close to that of HM in the beginning. Afterwards, the temperature simulated by HM_FT decreases less than that from HM. The profiles of saturation degree of total moisture content, ice content and temperature in this period from HM_FT are shown in Fig. 7. The region with degree of saturation of ice content of 0.0 is the unfrozen zone. The difference between the total moisture content and the ice content is the amount of liquid water content in the porous medium. Due to the movement of moisture from unfrozen to freezing zones, the total moisture content and the ice content increase in the freezing zone with time. By comparison, the total moisture content decreases with time in the unfrozen zone. When the freezing front penetrates into the previously unfrozen zone, the total moisture content in the previously unfrozen zone starts to increase and reaches saturated condition (at the end of time in Fig. 6). Therefore, the traditional hygrothermal model not accounting for freezing may not be suitable for assessing freeze-thaw damage risk of masonry walls since it will underestimate the risks due to disregarding freezing-caused moisture migration.

Fig. 5 Simulated saturation degree of (a) total moisture content and (b) temperature from HM_FT (heat-moisture transport with freeze/thaw) and HM (only heat and mass transport) as well as saturation degree and temperature difference between HM_FT and HM at 6 cm from the exterior surface for the internally insulated masonry wall for Zurich for the year of 1981.

Fig. 6 Comparison of (a) simulated saturation degree of total moisture content and (b) temperature at 6 cm from the exterior surface from HM_FT and HM model for the wall assemblies with internal insulation for Zurich between 7th and 8th January, 1982.

Fig. 7 Profiles of (a) simulated degree of saturation (S) of total moisture content (TMC), (b) degree of saturation of ice content and (c) temperature in the internally insulated masonry wall for Zurich

between 7th and 8th January, 1982. The left figures are detail of the first 10 cm from the right figure.

3.2 Comparison of two freeze-thaw cycle counting methods

In this study, we propose a new method that uses the number of freeze-thaw cycles, as an indication for the risk of freeze-thaw damage. In the propose method, a freeze-thaw cycle is defined as the process where the ice in the porous medium forms and then totally disappears. The method commonly used in building physics uses the number of crossings below and above 0.0 °C as the number of freeze-thaw cycles. We apply the two methods over the 30 years of climatic data for the 2 cities for the non-insulated masonry wall. The evaluation point is at 0.5 cm from the exterior surface. On one hand, this location is very close to the exterior surface and has a large number of freeze-thaw cycles. On the other hand, unlike the very external location such as 0.1 cm, this location is less sensitive to short time external climatic fluctuations and more representative to evaluate freeze-thaw damage. The HM_FT model is used for the analysis in order to only evaluate the difference in counting method, not considering the influence of different models (HM_FT versus HM).

There are very large differences in the number of freeze-thaw cycles between the newly proposed and traditional methods (Fig. 8). Almost no correlation exists between the number of freeze-thaw cycles between the two methods. For Zurich, the correlation coefficient between the number of freeze-thaw cycles determined by the two methods is 0.079 and, for Davos, the correlation coefficient is 0.069. The traditional method shows a much larger number of freeze-thaw cycles. The yearly average number of freeze-thaw cycles based on temperature is around 44 for Zurich and around 100 for Davos, while the average number of freeze-thaw cycles based on ice content is below 10 for both cities. For a specific year, e.g. 1981, the number of freeze-thaw cycles based on the traditional method is 41 for Zurich, while it is 20 in the same year based on the new method. The distribution of the number of freeze-thaw cycles over the thickness of the first brick shows also very large differences between the two methods (Fig. 9). The traditional method shows larger number of freeze-thaw cycles. For both methods, the number of freeze-thaw cycles decreases with distance from the exterior surface. The high number of freeze-thaw cycles in 1981 for Zurich based on the traditional method is mainly due to the high occurrence of daily temperature variation around 0 °C (Fig. 10). In some periods of November, February and March, temperature drops below 0 °C and returns above 0 °C in short time. Nevertheless the ice content remains at 0 kg/m³ in these periods since the total moisture content is very low in the brick. For example, the total moisture content on 27th February is 51.0 kg/m³ and the temperature is -7.2 °C. The corresponding freezing temperature for the total water content is -18.2 °C. Therefore, the freezing temperature is much lower than the temperature in the brick and no ice is found at this time. By contrast, when the total moisture content is high, the freezing temperature increases. The total moisture content is 254.8 kg/m³ on 3rd February and thus the freezing temperature is -0.63 °C. The temperature of the brick is -2.1 °C, which is lower than the freezing temperature. Therefore, ice is present at this temperature, resulting in an ice content of 118.4 kg/m³ and a liquid water content of 136.4 kg/m³.

The traditional method could be very inaccurate for calculating freeze-thaw cycles, as water in porous medium does not freeze at 0 °C. In some years for the two cities, the number of freeze-thaw cycles is 0 based on ice content, as the water remains in very small pores. Even though a porous medium is at some negative temperature, ice may not be present when the moisture content of porous medium is too low. Therefore, in contrast to the traditional method, the new method captures the physical aspects of freeze-thaw correctly.

The cumulative distribution function of freeze-thaw cycles and mean ice content in the brick (0.5 cm from the exterior surface) during the freezing period for the two cities over 30 years is shown in Fig. 11. The cumulative distribution function (cdf) is the probability that a variable takes a value less than or equal to the argument of the function. Compared to Davos, the number of freeze-thaw

cycles and average ice content in Zurich are larger. The relatively low number of freeze-thaw cycles and low mean ice content in Davos is due to the fact that the air temperature in winter in Davos is mostly much lower than $0.0\text{ }^{\circ}\text{C}$ and, at the same time, the wind-driven rain load is quite small in winter, since precipitation mainly occurs in the form of snow. Consequently, the moisture content of the brick stays at a low level and the risk of ice formation remains very low.

Fig. 8 Comparison of number of freeze-thaw cycles based on two methods for the external part of the brick (0.5 cm from the exterior surface) for the uninsulated masonry wall in (a) Zurich and (b) Davos.

Fig. 9 Distributions of number of freeze-thaw cycles based on two methods for the external brick for the uninsulated masonry wall in Zurich for 1981.

Fig. 10 (a) Total moisture content (TMC), (b) ice content and (c) temperature variation for the external part of the brick (0.5 cm from the exterior surface) in the cold period of 1981 for Zurich

Fig. 11 Cumulative distribution function (cdf) of (a) freeze-thaw cycle and (b) mean ice content for Zurich and Davos from 1981-2010 at 0.5 cm from the exterior surface.

3.3 Comparison among wall assemblies with and without internal insulation

The number of freeze-thaw cycles does not necessarily mean a high risk of freeze-thaw damage. However, a high number of freeze-thaw cycles together with high ice content tends to lead to a high risk of freeze-thaw damage. Therefore, a year with substantially high number of freeze-thaw cycles and high ice content is selected for studying the influence of internal insulation on freeze-thaw damage risk. The selected years for Zurich and Davos are 1981 and 1989, respectively.

The comparison of number of freeze-thaw cycles in the 3 wythes of the wall assemblies with and without internal insulation for Zurich in 1981 is shown in Fig. 12. The number of freeze-thaw cycles increases after adding internal insulation, depending on the location in the wall. In general, the difference of the number of freeze-thaw cycles between the two masonry walls is larger at the exterior part of the wall. For the uninsulated masonry wall, the number of freeze-thaw cycles becomes 0 at 19.5 cm from the exterior surface, whereas, for the internally-insulated masonry wall, the number of freeze-thaw cycles becomes 0 at 37.0 cm from the exterior surface. At certain locations, the number of freeze-thaw cycles increases at larger distance from the exterior surface. For example, the number of freeze-thaw cycles is 3 at the location of 19.5 cm from the exterior surface, going to 4 at 20.0 cm (Figs. 12). This difference is due to time evolution of ice content for these two locations (Fig. 13). There is only one freeze-thaw cycle at the location of 19.5 cm from the exterior surface between 8th and 12th January. By comparison, two freeze-thaw cycles exist in the same period at 20.0 cm, whereas, around 11 January, the ice content decreases to 0.0 kg/m^3 and then increases again. By contrast, the ice content at 19.5 cm from the exterior surface decreases to 16.0 kg/m^3 and then increase again.

Fig. 14 compares the saturation degree of ice content at different locations for wall assemblies with and without internal insulation for Zurich. In general, adding internal insulation to the masonry wall increases the ice content in the brick. The ice content difference between the uninsulated masonry wall and the internally insulated wall becomes larger inwards from the exterior surface. However, the internal insulation has a quite different influence on maximum saturation degree of ice content for the two cities. For the uninsulated masonry wall in Zurich, the maximum saturation degree of ice content at 2, 8, 14 and 20 cm from the exterior surface is 0.72, 0.46, 0.37 and 0.0, respectively. By comparison, for the internally insulated masonry wall, the same indicator at the same locations yields 0.72, 0.71, 0.69 and 0.42, respectively. The difference of saturation degree of ice content between the two wall assemblies is very small at 2 cm from the exterior surface, while it is up to 0.32 at 14 cm and 0.42 at 20 cm from the exterior surface. The brick at 20 cm from the exterior surface suffers from freeze-thaw cycling after retrofitted with internal insulation while it undergoes no freezing in the uninsulated masonry wall. The internal insulation reduces the temperature and also the drying potential of the inner wall, which leads to freezing of moisture in the brick wall in cold periods. For Zurich, the number of freeze-thaw cycles at 2 cm from the exterior surface is 14 for the uninsulated masonry wall, while it is 25 for the internally insulated masonry wall (Fig. 12). However, the difference of the number of freeze-thaw cycles at deeper depth such as 14 and 20 cm is much smaller between the uninsulated and internally insulated masonry walls.

Fig. 12 Comparison of number of freeze-thaw cycles in the 3 wythes for the wall assemblies with and without internal insulation for Zurich in 1981

Fig. 13 Ice content at 19.5 and 20.0 cm in the second wythe, from the exterior surface for the wall assembly with internal insulation for Zurich in 1981.

The ice content and the number of freeze-thaw cycles are much lower in Davos than in Zurich (Fig. 15). For Davos, the maximum saturation degree of ice content is 0.4 at 2 cm from the exterior surface for the internally insulated masonry wall. The ice content difference between the uninsulated and internally insulated walls is also much smaller in Davos. The maximum difference of degree of saturation of ice content between the two walls with and without internal insulation is only 0.09. The main reason for the low ice content in Davos is the low air temperature, which leads to precipitation occurring in the form of snow in the cold period and thus low wind-driven rain load on the masonry wall.

Fig. 14 Comparison of saturation degree of ice content (S) at 2 (a), 8 (b), 14 (c) and 20 (d) cm from the exterior surface for the wall assemblies with and without internal insulation for Zurich in 1981.

Fig. 15 Comparison of saturation degree of ice content (S) at 2 (a), 8 (b), 14 (c) and 20 (d) cm from the exterior surface for the wall assemblies with and without internal insulation for Davos in 1989.

3.4 New freeze-thaw damage risk index

In reality, incomplete freeze-thaw cycles, where the freezing process restarts before the thawing process is completely finished, are very common. For example, the saturation degree of ice content at 14.0 cm for the internally insulated masonry wall decreases first from 0.50 to 0.20 and then increases again to 0.47 around the 10th January (Fig. 14c). Such incomplete freeze-thaw cycle is expected to increase also the risk of freeze-thaw damage. Therefore, we propose a new freeze-thaw damage risk index called the FTDR Index. The FTDR Index is defined as the accumulation of the difference between highest and lowest saturation degree of ice content in each complete or incomplete freeze-thaw cycle:

$$FTDR\ Index = \sum_{cycle} (S_{ice,max} - S_{ice,min}) \quad (28)$$

for $S_{ice,max} - S_{ice,min} > 0.05$. A threshold difference value of 0.05 is introduced to disregard the influence of freeze-thaw cycles with very small variation of ice content. The FTDR Index considers both the effect of ice content difference over the freeze-thaw cycle and the number of freeze-thaw cycles. Fig. 16 shows the FTDR Index in the 3 wythes for the wall assemblies with and without internal insulation for Zurich in 1981. In general, the FTDR Index decreases with distance from the exterior surface. The FTDR Indices in the second and third wythes are much smaller than those in the first wythe. In contrast to FTDR Indices for the wall assembly without internal insulation, FTDR Indices for the wall assembly with internal insulation present much larger values. The largest value for the wall assembly with internal insulation is 11.7, whereas the largest value for the wall assembly without internal insulation is 7.4. The FTDR Index becomes 0 at around 19 cm from the exterior surface for the wall assembly without internal insulation, whereas it becomes 0 at around 37 cm from the exterior surface for the wall assembly with internal insulation.

It is noted that the FTDR Index increases at the interface between brick and mortar. The increase of FTDR at the interface between brick and mortar is due to higher ice content close to the interface as shown in Fig.17 at four locations in the second wythe of brick, where the brick and mortar interface is situated at 25.0 cm. The higher ice content at the interface is due to higher liquid permeability at the time of freezing in mortar, combined with higher moisture content and temperature in the mortar, inducing mass flow outwards. As a result, more moisture accumulates in the brick, close to mortar/brick interface, leading to the observed higher ice content.

Fig. 16 FTDR Index in the 3 wythes for the wall assemblies with and without internal insulation for Zurich in 1981.

Fig. 17 Saturation degree of ice content at 4 locations in the second wythe of brick for Zurich in 1981.

Discussion and Conclusion

A hygrothermal model, accounting for moisture and heat transport in porous medium and tracking the occurrence of freezing and thawing in function of pore size distribution is developed in this study. Physical processes such as freezing-induced moisture migration and latent heat associated with freezing and thawing are considered and integrated in the hygrothermal model. The

study indicates that traditional hygrothermal models may not be suitable for assessing appropriately freeze-thaw damage risk of masonry wall since such models do not take into account the migration of moisture during freezing and may underestimate the risks due to disregarding freezing-caused moisture migration. Compared to the traditional model which is based on zero temperature crossing, we propose a new method that uses the number of actual ice growth and melting cycles as a more accurate indicator of the freeze-thaw loading. A new index, called FTDR Index, is proposed to assess freeze-thaw damage risk. The study shows that the number of freeze-thaw cycles and ice content increases after internal retrofitting of a masonry wall.

For the masonry system considered here, for cold regions like Davos, retrofitting with internal insulation will have a rather small influence on the freeze-thaw damage risk. By comparison, for wet and moderate climate regions like Zurich, retrofitting with internal insulation increases considerably the freeze-thaw damage risk of the masonry wall. Although internal insulation added to masonry wall assembly increases slightly the ice content in its most exterior part, such retrofit increases the number of freeze-thaw cycles. Consequently, the FTDR Index increases significantly. Even in the case where the exterior part of the masonry wall does not show signs of freeze-thaw damage before retrofitting with internal insulation, the exterior part could undergo freeze-thaw damage after retrofitting due to the increased number of freeze-thaw cycles. Internal insulation leads to significant increase of ice content in the middle part of the wall. For a multi-wythe brick wall assembly built of all the same brick, the inner wythe will have lower risk of freeze-thaw damage than the external one. The reason is that the inner wythe has much lower ice content and undergoes less freeze-thaw cycles compared to the exterior wythe. However, if the frost resistance of the inner masonry wythe is much lower than the outer wythe as frequently found in historical buildings, that layer could be exposed to risk of freeze-thaw damage after retrofitting with internal insulation.

The occurrence of freeze-thaw damage depends on the mechanical properties of the brick, like stiffness and tensile strength. The critical FTDR index can be determined by performing freeze-thaw experiments. The calculated FTDR index from hygrothermal simulation could then be compared with the critical FTDR index to determine whether there is risk of damage. If the calculated FTDR index is significantly larger than the critical FTDR, a high risk of damage is expected. It has been documented that bricks that are not damaged in standard freeze-thaw tests may fail in service in walls [13]. Ritchie [32] indicated that discrepancies between the performance of bricks in a standard test, e.g. *ASTM Standard C67-07* [33], and in service in a wall are in part due to differences in the way bricks are frozen, in particular, the manner in which the freezing plane passes into the brick. Bricks in service are frozen by the passage of a freezing plane through the exposed face of the brick (unidirectional), whereas, in a standard test, the freezing of the brick occurs through several of its surfaces (omnidirectional). Consequently, the distribution of total moisture content in bricks under unidirectional and omnidirectional freezing conditions may be very different due to freezing induced moisture migration, even though all other conditions are the same. Therefore, it is important to design freeze-thaw tests that represent the environmental conditions to which bricks are actually exposed to.

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