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Durability of Internally Insulated Historical Solid Masonry under Future Climates: A Stochastic Approach

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Abstract. *Today, it is globally known that climate change needs to be addressed to mitigate its harmful effects on our environment. It is also common knowledge that the contribution of historical buildings to the energy consumption of the existing Canadian building stock is severe. Buildings of historical identity are often poorly thermally insulated. Thus, to increase energy efficiency and occupant comfort in cold climates, the application of thermal insulation on the interior side of solid masonry walls offers a possibility to improve the historic buildings' energy performance, without compromising their identity and cultural heritage values. As a result, the historical masonry will be subjected to lower temperature during the heating season, which can increase the potential for condensation and frost within the wall. A balance must therefore be reached between durability measures and thermal performance objectives. This paper intends to achieve this balance through determining the impact of the interior insulation thickness on the durability of a typical historical masonry wall under the effect of climate change. A stochastic approach is used in hygrothermal simulations to account for the uncertainty in material properties. Results in Ottawa indicate a higher risk to frost damage after interior insulation is added to a brick wall having a moisture critical degree of saturation (Scrit) of 0.25 and 0.35. Moreover, both deterministic and the stochastic results were in good agreement. Also, both methods showed an increase risk to frost damage under a changing climate.*

Keywords: *Historical Buildings, Solid Masonry, Stochastic Approach, Future Climates, Durability.*

1 Introduction

One typical way to reduce a building's heating energy consumption is insulating its envelope. Generally, exterior insulation systems are considered the best alternative to retrofit existing buildings due to their ability to prevent thermal bridges (Straube *et al.,* 2012). However, in the case of historical buildings, exterior insulation is not possible due to architectural and aesthetical reasons. Thus, the only way to retrofit these buildings is through adding interior insulation. Straube *et al.* (2012) suggested spraying an airtight insulating foam directly to the interior side of the existing masonry. However, normally after insulation is installed, the moisture content of the masonry wall increases, which may lead to a higher potential for hygrothermal problems, such as frost damage.

Frost damage is one of the main reasons threatening durability of masonry structures in cold climates. Previous research has shown that under a changing climate, higher rainfall intensity, strong winds, and more frequent storms are expected, which may increase WDR loads on the façade and subsequently, risks for rain penetration (IPCC, 2001). On the other hand, increased solar radiation and air temperature may increase the drying potentials. It is therefore important to assess the effect of climate change on the potential risk to freeze-thaw (FT) damage.

The hygrothermal performance of masonry walls are usually assessed by means of deterministic approach. Though, the hygrothermal responses are influenced by stochastic factors, such as the variability of material properties, boundary conditions and environmental loads. The uncertainties of the input parameters may lead to a deviation between simulation results and the actual performance of the wall assemblies, consequently, leading to faulty designs.

The objective of this paper is to investigate the impact of the interior insulation thickness on the freeze-thaw damage risk of the existing masonry wall assemblies. A masonary basewall and three retrofit options having three different insulation thicknesses were tested. First, a deterministic approach was used to evaluate the hygrothermal performance of wall assemblies using Delphin. Second, a stochastic approach was used to take into account the uncertainties in brick masonry properties under different climate conditions and design configurations.

2 Methods

The methodology includes a deterministic and a stochastic modelling approaches. The latter was developed by Wang and Ge (2018) and applied to investigate the impact of insulation thickness on the FT risk of masonry walls.

2.1 Weather Data

Weather data for Ottawa were provided by the National Research Council of Canada (NRC). A continuous time-series[1] of hourly climate data was prepared for a baseline time-period spanning from 1986-2016 and 31-year long future time-period when global warming of 3.5°C is expected to be reached in the future (Gaur et al., 2019). Future data of 3.5ºC increase, will be reached between 2062-2092 (Environment and Climate Change Canada, 2018). Each data set includes 15 realizations; however, only the median realization based on MI was used.

2.1.1 Selection of reference years

The selection of reference years was made with the intention to test wall assemblies under more representative design weather years in the selected timelines. Annual average of the Moisture Index (MI) (Cornick *et al.,* 2003) and Severity Index (Isev) (ASHRAE, 2010) were computed for the chosen time-periods, and the years were ranked in ascending order. The year corresponding to the 97th percentile (ranked second out of the 31 years) in each time-period was chosen as the MRY. Table 1 summarizes the selection of MRYs under historical and future time-periods.

[1] The full dataset can be accessed from: 10.17605/OSF.IO/UPFXJ.

Table 1. Summary of selected moisture reference year and their values.

City	Data	MI – MRY	Isev_MRY
Ottawa	Historical	2010	2009
	Future	2085	2066

A comparison was then made between the selected MRYs weather data, as shown in Figure 1 for historical and future data. The temperature difference between the MI and Isev MRYs was not as significant as the difference of their rain amount. Monthly rain variation looked relatively uniform throughout the year for MRYs selected by the MI method (2010 and 2085) and considerably less than that found for the years selected using the Isev method (2009 and 2066). MRYs selected using Isev seem to be more severe than years selected by MI; therefore, 2009 and 2066 were selected as the MRYs for this study.

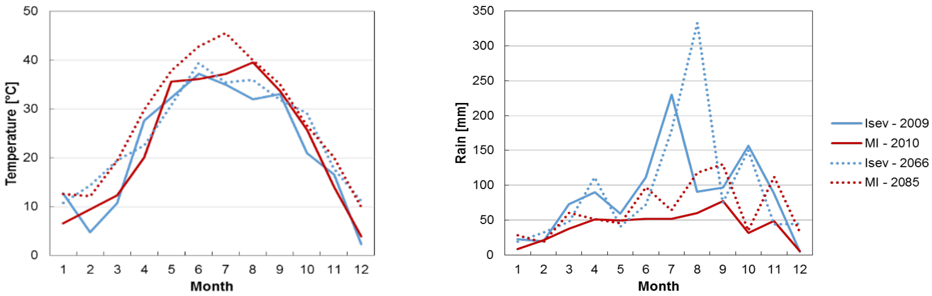
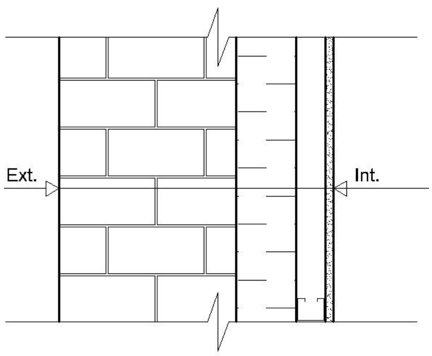


Figure 1. Comparison of monthly temperatures (a) and rain (b) for the years selected in historical data using MI (2010) and Isev (2009) and future data using MI (2085) and Isev (2066) for Ottawa.

2.2 Wall Assemblies

Four wall assemblies were evaluated in this study: a solid masonry wall assembly and three internally retrofitted solid masonry wall assemblies. The first configuration consists of 300mm historical brick (Old Building Brick Rote Kaserne Potsdam – outer brick 1) and 15mm of gypsum plaster. Retrofitted wall assemblies differ only by their insulation thickness: 50 mm (2 inches) and 100mm (4 inches) of polyurethane foam were added as recommended by Straube *et al.* (2012); the insulation thickness was increased to 200mm (8 inches) to satisfy the Passive House requirement (Straube, 2009). Figure 1 shows the configuration of the retrofitted wall assemblies. Material properties are from the Delphin Material Library.



- Existing old brick (300mm)
- Added polyurethane foam
- Added (38mm x 50mm) steel stud
- Added gypsum board (12.7mm)

Figure 2. Solid masonry Wall retrofit solution.

2.3 Stochastic Model's Setup

The stochastic models were generated according to the stochastic hygric material properties of brick. The Latin Hypercube Sampling method was applied to generate the stochastic models (Wang and Ge, 2018). The basic material parameters such as effective saturation (θ_{eff}), water vapor diffusion resistance factor at dry state (μ) and liquid water conductivity at effective saturation (k_l) are considered as stochastic variables. Their mean values were based on DELPHIN material properties. Whereas, the standard deviation was calculated as a function of the coefficient of variance (CV). Values of CV were found for a similar type of brick in the literature (Zhao *et al.,* 2015). Descriptive statistics of material properties of the specific old brick material are presented in Tables 2 and 3.

Table 2. Deterministic parameters of brick.

Material property	Unit	Mean
ρ	[kg/m^3]	1842.47
c	[J/kgK]	772.224
λ	[W/mK]	0.7975
θ_{por}	[m^3/m^3]	0.304727
θ_{cap}	[m^3/m^3]	0.255
A_w	[kg/m^{2}s$^{0.5}$]	0.0668929

Table 3. Stochastic parameters of brick.

Material property	Unit	Mean	Std dev	CV (%)
θ_{eff}	[m^3/m^3]	0.28399	0.00954	3.36
μ	[-]	37.5558	9.8734	26.29
k_l	[s]	2E-8	5.248E-09	26.24

2.4 Wall Orientation

This study was carried out for the orientation with the highest amount of annual wind-driven rain calculated according to ASHRAE (ANSI/ASHRAE, 2016). In Ottawa, a wall facing South-South-West (202.5°) was considered. Note that a North-facing wall (receiving least solar radiation) was not included in this analyis; but will be further investigated.

2.5 Boundary Conditions

2.5.1 Indoor boundary conditions

The indoor relative humidity was computed using the ASHRAE 160 simple method (ANSI/ASHRAE, 2016). The indoor temperature was also calculated using the same model for heating only. As for the indoor vapour diffusion and the indoor heat conduction coefficients, they were assumed as $1.52*10^{-8}$ s/m and 8 W/m^{2}K, respectively.

2.5.2 Outdoor boundary conditions

Outdoor boundary conditions include heat conduction, vapor diffusion, wind driven rain, short wave radiation and long wave radiation. To compute the longwave radiation, the boundary layer method was selected in Delphin. The required longwave emission coefficient of the building surface was set to 0.9. And the convective heat transfer coefficient was calculated based on Equation (1):

$$h_{ce} = 4 + 4.v \quad (1)$$

Where, *v* is the wind speed. The reflection coefficient of the surrounding ground (albedo) was 0.2 and the absorptance coefficient of the brick cladding surface was equal to 0.6.

2.5.3 Wind-driven rain

WDR is calculated using ASHRAE method (ANSI/ASHRAE, 2016) for a 3.5 storey building located in the suburban area. Assuming a medium exposure factor, the rain exposure factor (F_E) and the rain deposition factor (F_D) were set to 1.0 and 0.5, respectively.

2.6 Initial Conditions

Initial temperature and relative humidity conditions were selected as constants and set to 21°C and 50%, respectively.

2.7 Performance Indicator for Assessing Wall Performance

One of the most important damage mechanisms in porous materials is caused by the action of freezing and thawing inside materials (K.R. Lisø *et al.,* 2007 G.; Wardeh and B. Perrin, 2008). The onset of freeze-thaw damage in porous materials requires that the value of moisture saturation is exceeded simultaneously with the occurrence of freezing temperatures. According to Straube *et al.* (2006), the critical degree of moisture saturation (Scrit) of masonry can vary considerably among different types of historical brick. For instance, following an experimental study using frost dilatometry, the Scrit of three brick stones found in Canada was found between 0.25 and 0.87 (Straube *et al.,* 2010). In this paper, values of (Scrit) equal to 0.25, 0.35, 0.5 and 0.8 were considered. Also, freezing is considered to occur at temperatures below -5°C within the material (Straube and Schumacher, 2006). The risk of freeze-thaw damage is computed using the critical number of freeze-thaw cycles (FTC). One cycle is counted when temperature decreases below the freezing temperature and moisture content exceeds its critical level.

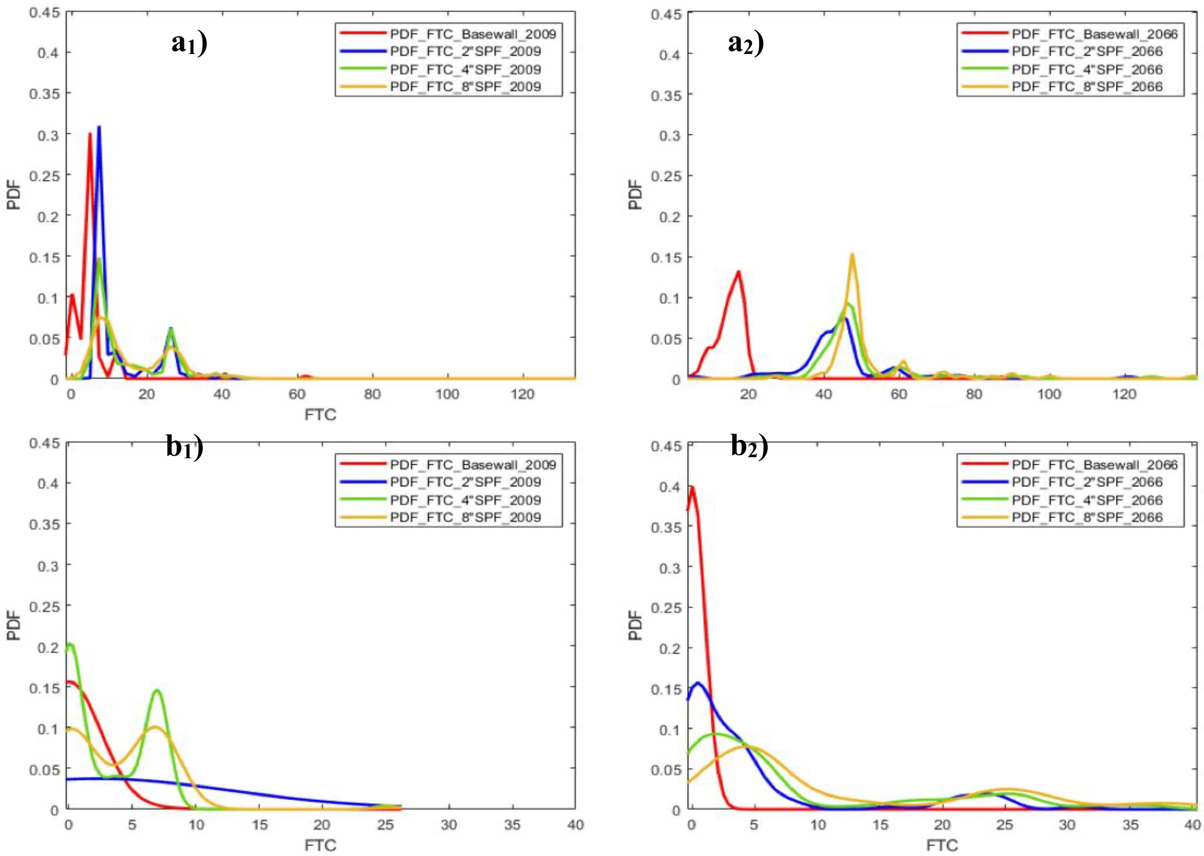
2.8 Simulations

Simulations were performed for the base and retrofitted walls under historical and future loads, using hygrothermal simulation program Delphin 5, v5.9.4. No air and moisture leakage source were assumed. Simulations were executed over a period of five years using the reference year for each time-period; meaning that each selected year is repeated 5 times. However, only the results of the 5th year are evaluated.

A fine variable discretization, with a minimum element width of 0.5 mm and a stretch factor of 125 was used to set up the meshing of the materials. The point of investigation was placed at a depth of 5mm of the brick surface.

3 Results and Discussion

Figure 3 shows the impact of interior insulation thickness on the estimated number of freeze-thaw cycles (FTC) of an old brick masonry wall located in Ottawa and modelled for historical and future climatic loads. The brick was tested for different critical degree of saturation: 0.25, 0.35, 0.5 and 0.8. However, Figure 3 shows stochastic results for Scrit equals to 0.25 and 0.35 only. For higher saturation degrees, i.e., brick having higher resistance properties, the insulation thickness did not have any influence on the durability of the masonry wall. Estimated FTCs indicated zero; therefore no potential risk to freeze-thaw damage to occur. Therefore, only results for a brick with Scrit equal 0.25 and 0.35 will be discussed.



PDF = Probability density function; SPF = Spray polyurethane foam; [1]Historical year (2009); and [2]Future year (2066).

Figure 3. Stochastic results – the impact of insulation thickness on the estimated number of freeze-thaw cycles (FTC) for brick masonry having a critical degree of saturation of a) Scrit = 0.25; and b) Scrit = 0.35.

In general, after interior insulation was added, the number of FTCs increased, indicating a higher potential of freeze-thaw to occur. For instance, FTC values varied between 0 and 12 for a base wall with Scrit = 0.25. These values increased to range between 5 and 30 FTCs when 2” of insulation was added. When adding a larger insulation thickness of 4” and 8”, the number of FTCs reached a range of [5 – 42] and [5 – 50], respectively (Figure 3-a_1). The probability distribution of FTCs for the same type of brick under future climate denoted a larger difference between the base wall and the retrofitted options. While values of FTC varied between 0 and 22 for a base wall, added insulation has caused the FTC to range between 0 and 100, with a higher probability around 50 cycles (Figure 3-a_2). When the Scrit is 0.35 (Figure 3-b_1 and Figure 3-b_2), adding insulation still has increased the number of FTC; however, with less discrepancies.

Table 4 represents the deterministic results of the predicted number of freeze-thaw cycles. Comparing results obtained by the deterministic and the stochastic methods, they seem in good agreement. Values of FTCs calculated using the deterministic approach corresponds in most of the cases to the FTC number having the highest density within the stochastic results range.

Table 4. Estimated number of FTC results for the deterministic method.

	Basewall			2” added insulation			4” added insulation			8” added insulation		
Scrit	0.25	0.35	0.5 – 0.8	0.25	0.35	0.5 – 0.8	0.25	0.35	0.5 – 0.8	0.25	0.35	0.5 – 0.8
2009	*5*	*0*	*0*	*24*	*2*	*0*	*29*	*6*	*0*	*32*	*7*	*0*
2066	*5*	*0*	*0*	*49*	*2*	*0*	*52*	*9*	*0*	*56*	*21*	*0*

Figure 4 illustrates the impact of climate change on the potential risk to freeze-thaw damage. Stochastic results clearly show that FTC increased in number and spread under future conditions. Deterministic results in Table 4 demonstrated the same as well.

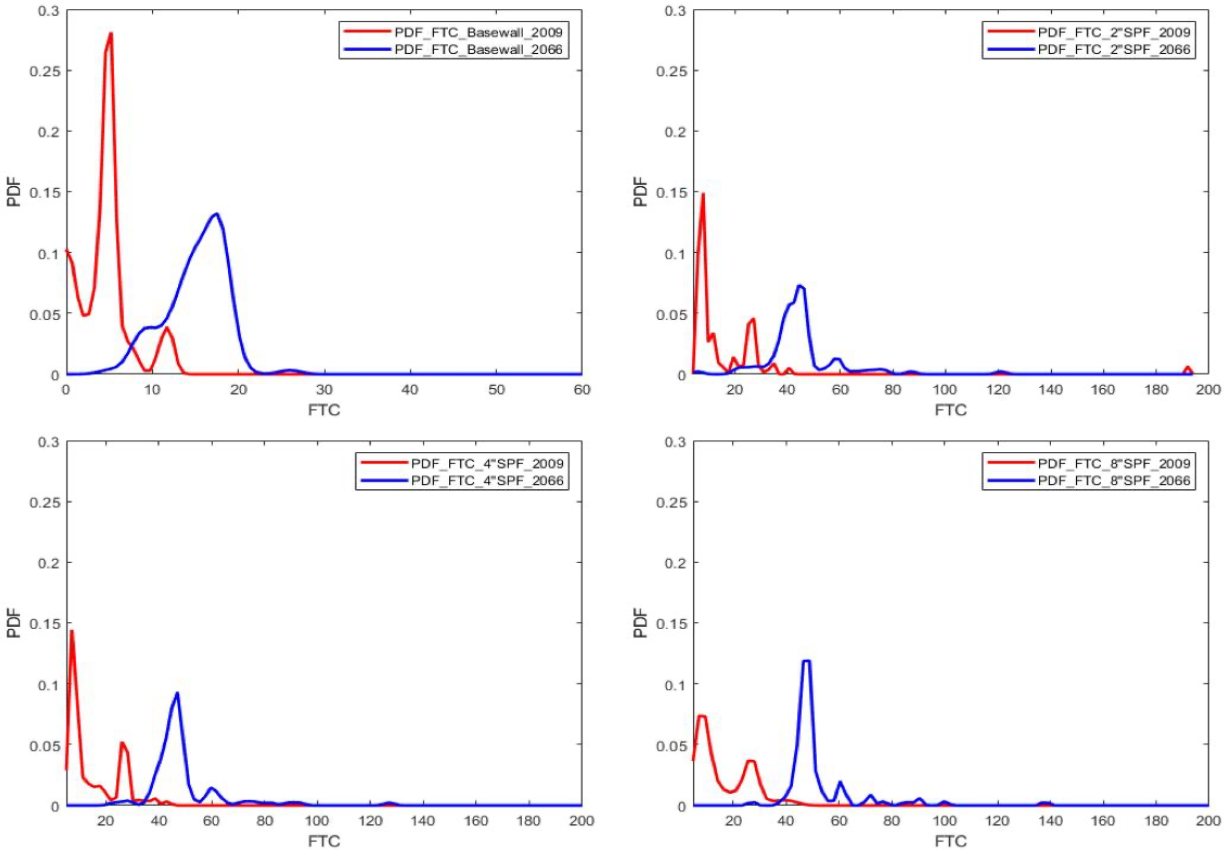


Figure 4. Stochastic results – the climate change effect on the estimated number of FTC for brick masonry having a Scrit of 0.25.

4 Conclusions

The durability performance of a masonary basewall and three retrofit alternatives of the same wall, having three different insulation thicknesses were evaluated using both a deterministic and a stochastic method. This study took into account the uncertainties in brick masonry properties under historical and future climate conditions. The brick was tested for different critical degree of saturation: 0.25, 0.35, 0.5 and 0.8. The insulation thickness did not have any influence on the durability of the masonry brick with better frost resistance, i.e. higher critical degree of saturation of 0.5 and 0.8. However, for a Scrit of 0.25 and 0.35, the number of FTCs increased, indicating a higher potential of freeze-thaw to occur. Results obtained by the deterministic and the stochastic methods were in good agreement, as values of FTCs calculated using the deterministic approach correspond to the number of FTC having the highest probability within the stochastic results range. In addition, both methods showed an increase in FTCs' number and spread under future conditions; thus, a higher risk to frost damage. To provide a safe insulation type and thickness range for the retrofit of masonry walls and to account for the uncertainty of future climate, a study will be carried out later.

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