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Hygro Thermal Simulation to Predict the Risk of Frost Damage in Masonry; Effects of Climate Change

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Abstract

According to the Royal Netherlands Meteorological Institute (KNMI) climate change will result in an increase of air temperature and rainfall intensities for the Netherlands in winter in future. In this paper we investigate the effect of the risk of frost damage to masonry. The risk of frost damage to an external building envelope might become less due to the increase in air temperature. However, the risk of frost damage might rise as a construction may be wet for a longer time due to the increase in rainfall intensities. Research has been done on the following topics: (1) which material is sensitive to frost, (2) the conditions under which the material damage occurs, (3) the outside climate conditions (frost damage winters) and (4) the possibility to predicted frost damage with a multi-physical model. Simulations with a hygro thermal model of external building envelopes with the frost-sensitive material calcium silicate brick were able to reproduce so-called frost damage winters in the Netherlands. Using this model to predict future frost behavior indicate a significant reduction of the risk of frost damage in future.

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Keywords: Hygro thermal simulation; Frost damage; Masonry, Climate change

1. Introduction

Future climate scenarios indicate a change in outdoor climate. Major climate changes include changes in temperature, precipitation and extreme weather. According to Sabbioni et al. (2009) [1], cultural heritage is

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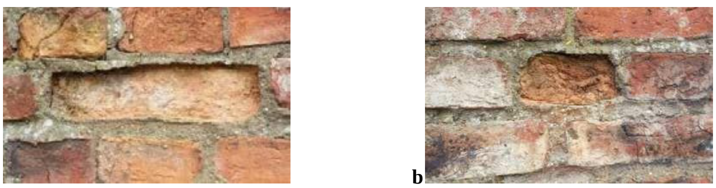
Nomenclature

Heat			Time		
q	density of heat flow rate	W/m^2	t	time	s
θ	temperature	°C	Subscrips		
Moisture			i	interior	
g	density of moisture flow rate	kg/m^{2}s	e	exterior w	
	moisture content	kg/m^3	cap	capillary	
φ	relative humidity (RH=φ.100%)	-	h	horizontal	
R	rainfall intensity	kg/m^{2}s			

vulnerable to climate change, which was investigated in the EU project Noah's Ark (no SSPI-CT-2003-501837) "Global Climate Change Impact on Built Heritage and Cultural Landscapes". In this report maps of Europe were produced where damage potential and the sensitivity of the cultural heritage due to changes in outdoor climate is displayed. Future research on climate change and cultural heritage was recommended under different themes, including modeling of indoor climate behavior. The EU project Climate for Culture (CfC) [2]: "Damage risk assessment, economic impact and mitigation strategies for sustainable preservation of cultural heritage in times of climate change" investigates the impact of global climate change on the indoor climate, interiors and the collection of historical buildings. When the building itself is a monument it is also important to preserve the historic building as much as possible for future generations. Some processes of building deterioration will be accelerated or exacerbated by climate change, while others will be delayed. Cultural heritage is irreplaceable and is even of great economic importance. Changing climate conditions can affect the structure. This study is focused on the possibility of irreversible damage that can be caused by frost damage to an external building envelope of masonry (see Figure 1). To minimize the risk of disintegration of a building envelope due to climate change, it may be necessary to take preventive measures.

The following contradiction can be formulated about frost damage in the future for the Netherlands. As a result of increase in temperature: (a) the number of frost days will be less [3], (b) the number of freeze-thaw cycles will reduce [4] and (c) the frequency of wet-frost events will reduce [4]. From these effects we can deduce a possible risk reduction of frost damage. However, due to the increase in rainfall intensities a construction may be wet for a longer time. This implicates the risk of frost damage might rise [5]. The primary goal is to give an opinion on whether the risk of frost damage increases or decreases in a frost-sensitive external building envelope due to climate change by making use of hygro thermal modeling. The methodology was: (a) literature review on which material is sensitive to frost, conditions under which damage occurs in the material and under which outside climate conditions (frost damage winters); (b) modeling of coupled heat–moisture transfer; (c) simulation of case studies to predict frost damage; (d) drawing of conclusions from literature and case studies. To investigate frost damage climatic conditions (hourly data) are used for the exterior. These climate data are obtained from the Royal Dutch Meteorological Institute (KNMI) and predicted by the REgional atmospheric MOdel (REMO) by the Max Planck Institute [6]: (1) Climate data from KNMI for years 1971 to 2011. Typical frost damage winters may follow from it; (2) Climate data set from the REMO model for climate scenario A1B for the years 1971 to 2011 and (3) Future climate data from 2059 to 2099 are also determined by the REMO model. From the future simulation results should follow if the risk of frost damage relative increases or decreases.

This article describes successively: literature on frost damage, coupled heat-moisture model, case studies that may show frost damage, discussion, conclusions and recommendations.



a **b**

Fig. 1. (a) and (b) examples of frost damage.

2. Literature

Frost damage can occur to porous masonry structures by a variety of mechanisms, including the volume increase as a result of the phase change from water to ice [7]. Three conditions must occur simultaneously:

1) The material temperature should be lower than the freezing point of water (0°C);
2) The material should be wet;
3) The material should also be sensitive to frost.

In bricks of calcium silicate freezing occurs if the moisture content is higher than capillary saturation [8]. Capillary saturation in masonry can occur after a long-term rainy period. Severe frost should follow immediately to create frost damage caused by excessive internal mechanical stresses [9]. Winters with these climatic conditions are called frost damage winters. Literature shows that in the Netherlands the winters of 1962/1963, 1978/1979 and 1981/1982 are typical frost damage winters during which a lot of actual frost damages occurred [10].

Bricks of calcium silicate are not the most common stones which are used for external building envelopes. However, it is empirically shown that damage will occur in bricks of calcium silicate after they are being exposed to 25-35 freeze-thaw cycles [11]. Therefore, we conclude that calcium silicate is an appropriate material to test frost damage. The ability to predict frost damage with a heat moisture model is described in the next section.

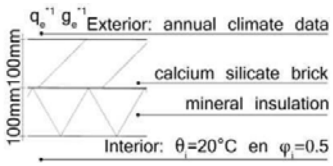
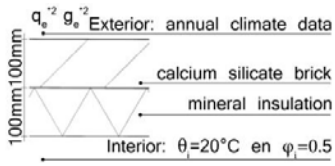
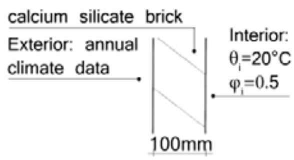
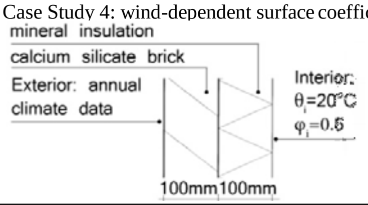
3. Coupled heat – moisture model

Calculated temperatures and moisture contents are an indication for the risk of frost damage, because heat, vapor and liquid transport are simulated without freeze-thaw phenomena. For heat transfer the temperature is the potential. According to Williams Portal et al. (2011) [12], the logarithm of the capillary pressure to base 10, is best suited as potential for vapor and liquid transport. An advantage of the use of the logarithm of the capillary pressure is the continuity at the interface between two materials with different pore sizes. From the capillary pressure, the moisture content of a material can be determined. Heat, vapor and liquid transport through a construction can be described by coupled non-linear partial differential equations (PDEs) [13]. The coefficients in the PDEs are determined from measurable material properties which are moisture-dependent. For solving the PDEs the boundary conditions (BCs) and initial values are necessary. The BCs are given in section 4. To start the simulation with correct initial values, one year has been calculated in advance. A multi-physical model has been developed, because the equations of the non-stationary process are analytically mathematical not solvable. The finite element method is used to solve the PDEs numerically. The model has been verified with benchmark test NEN-EN 15026 [12] and HAMSTAD benchmark no.1 [13]. The model appears to be a valid predictive tool to investigate the impact of a change in climatic conditions on building materials and components. The choice of the moisture potential, the multi-physical modeling, calculation of PDE coefficients from moisture-dependent material properties, the initial and boundary conditions and the verification of the model are described in detail by Aarle (2013) [14]. With the heat-moisture model the occurrence of possible frost damage has been tested using four case studies.

4. Simulation of case studies

Table 1 presents schematically a summary of the case studies. In case study 1 a fictive horizontal construction of calcium silicate bricks with interior mineral insulation is simulated. Horizontal masonry (e.g. soldier course as wall coverings) have extremely high moisture load relative to vertical masonry [15]. The BCs on the interior are assumed constant: temperature 20°C and relative humidity 50%. At the exterior hourly values of weather climate data files are used, which are mentioned in section 1. The boundary conditions consist of (1) density of heat flow rate as a result of a combined constant surface coefficient and the difference between the so called effective temperature and the surface temperature, (2) density of moisture flow rate as a result of a constant surface coefficient of vapor transfer and the difference between the air vapor pressure and the surface vapor pressure and (3) horizontal rainfall intensity, i.e. through a horizontal plane. The density of the heat flow rate is indicated with q_e^{*1} and moisture with g_e^{*1}. Mineral insulation is assumed on the inside of the envelope so that the outer construction is relative cold related to a non-insulated construction. So it is more likely that there is frost damage. In case study 2 various physical processes to the boundary conditions are added: long wave atmospheric radiation, irradiation, latent heat of evaporation/condensation and heating/cooling of the construction due to rain. The density of heat flow rate is indicated with q_e^{*2} and moisture with g_e^{*2}. Case study 3 is based on case study 2, however, the orientation of the building envelope is changed from horizontal to vertical and the construction of calcium silicate brick has no internal insulation. The surface coefficients are wind-dependent. Case study 4 is the same as a case study 3, however, insulation is provided at the inside of the construction of calcium silicate brick.

Table 1. Overview of the four case studies.

Case Study 1: constant surface coefficients	Case Study 2: constant surface coefficients
	
Case study 3: wind-dependent surface coefficients	Case Study 4: wind-dependent surface coefficients
	

Results are discussed with reference to case study 1 for the climate data of the KNMI for January and February of 1979. Calculated temperatures (θ) and moisture contents (w) over the cross section of the construction are presented for one time at January 22nd in 1979 in figure 2. At the outer surface of the construction the temperature is less than 0°C, and at the same time the moisture content is higher than capillary saturation (w_{cap}). Under these conditions: ($\theta<0$°C) and ($w>w_{cap}$), there is a risk of frost damage in the brick of calcium silicate. Frost damage is generated mainly at the outside of the structure [16]. In figure 3, temperature (θ) and moisture content (w) are presented occurring 1 mm underneath the outer surface of the construction. Eleven times there is a risk of frost damage: the temperature is below 0°C and simultaneously the moisture content is higher than capillary saturation. The depth of the risk of frost damage, as seen directed from the outer surface into the interior of the construction as a function of time is presented in figure 4a. The depth range of the risk of frost damage is usually between 3.5 and 7 mm,

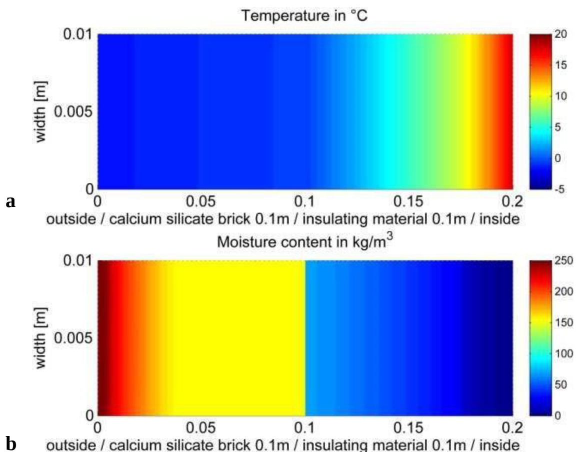


Fig. 2. Temperatures (a) and moisture contents (b) over the cross section of the construction for one time of January 22nd in 1979.

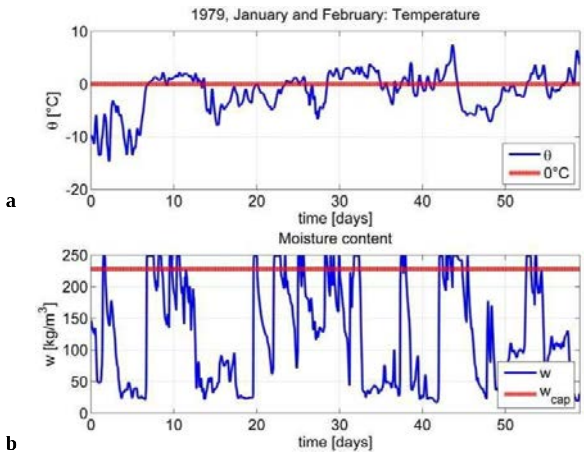


Fig. 3. Temperatures (a) and moisture content (b) occurring at 1 mm underneath the outer surface of the construction for the months of January and February of 1979.

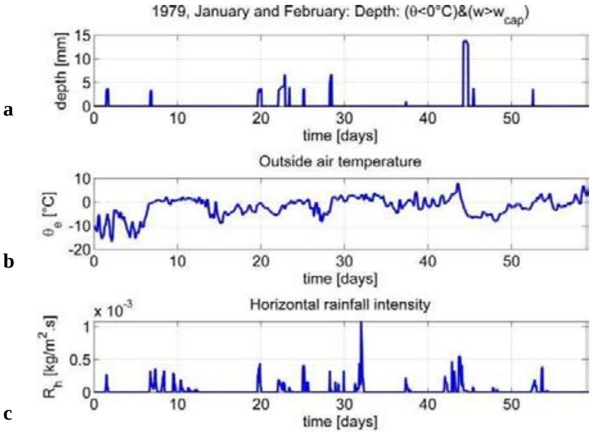


Fig. 4. (a) Depth of the risk of frost damage viewed from the outer surface to the inside of the construction for the months of January and February 1979, (b) Outside air temperature and (c) horizontal rainfall intensity.

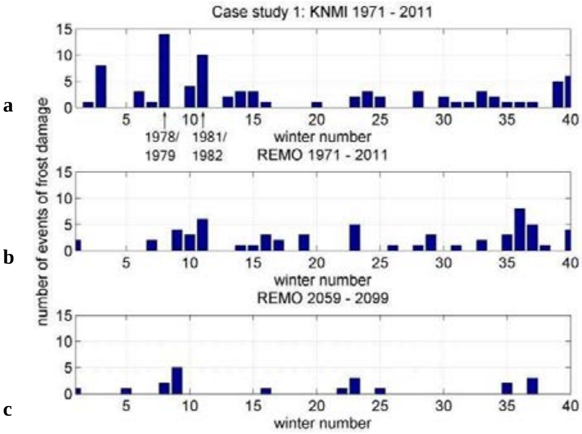


Fig. 5. Number of events of frost damage in case study 1 for the climate data: (a) KNMI 1971-2011, (b) REMO 1971-2011 and REMO 2059-2099 (c).

with a peak to 14 mm. For this period the depth for the risk of frost damage can be explained by analyzing the outdoor climate. Before the peak (14 mm) it rained non-continuously for two days, see figure 4c. Immediately after the rain shower the air temperature dropped to -6.2°C (figure 4b). During the periods of frost, wherein the depth is between 3.5 and 7 mm, the duration of the rainfall intensity in advance was less.

In figure 5 the number of events of frost damage ($\theta<0°C$) and ($w>w_{cap}$) is presented for simulations of case study 1 with hourly climate data from the past to the present, 1971-2011 for KNMI (5a) and REMO (5b) and future climate data, 2059-2099 REMO (5c). Simulations with KNMI climate data show the greatest number of events of frost damage with respectively 14 and 10 times for the winter 1978/1979 and 1981/1982, see figure 5a. Literature shows that these winters are actually identified as typical frost damage winters [10]. The total number of events of frost damage with respectively 84 and 61 times for climate data from KNMI and REMO for the years 1971 to 2011 does not fully correspond. From the simulations with climate data from REMO for the years 1971 to 2011 and for the years 2059 to 2099 follows a decrease in the number of events of frost damage in the future, with respectively 61 and 20 times (figure 5b and 5c). The percentage decrease is equal to: (61-20) / 61 * 100% = 67%.

Case studies 2, 3 and 4 also have been simulated with the same climate data from the KNMI and REMO. Table 2 presents a summary of the four case studies with the total number of events of frost damage for 40 years.

Table 2. Total number of events of frost damage for 40 years: temperature below 0 ° C and simultaneously the moisture content higher than the capillary moisture content.

Case Study no.	KNMI 1971 2011	REMO 1971 2011	REMO 2059 2099	percentage decrease [%]
1	84	61	20	67
2	170	174	47	73
3	1	0	0	0
4	19	14	4	71

Detailed information about the results is given in Aarle (2013) [14]. Case studies 1, 2, and 4 show a reduction in future of the risk of frost damage in order of magnitude of 70%. A non-insulated construction with only calcium silicate brick is not sensitive to frost damage (case study 3). The construction and external climate affect the risk of frost damage.

5. Discussion

Comparison of the total number of events of frost damage with climate data from the past to the present, 1971-2011 for KNMI and REMO does not give exactly the same numbers (see table 2, column 2 and 3), but it gives an indication of the risk of frost damage. The developed hygro thermal model proved to be valid and can be used as a predictive tool to investigate the impact of climate change on building materials and constructions. The comparison for validity between climate data from the KNMI and the predicted with REMO is beyond this study.

6. Conclusions

The results of the simulations of the case studies with former KNMI climate data indicate the same typical frost damage winters as appeared in reality, namely the winters 1978/1979 and 1981/1982. Simulations with a hygro-thermal model of external building envelopes with the frost-sensitive material calcium silicate brick and the climate data determined by Remo, show a reduction in future of the risk of frost damage in order of magnitude of 70% (see table 2). It follows from literature that calcium silicate is a frost sensitive material. For the occurrence of damage caused by frost, the temperature should be lower than the freezing point of water and at the same time the moisture content should be higher than capillary saturation. Frost damage may occur by an outdoor climate if a long term rainy period is immediately followed by severe frost.

7. Recommendations

A research on the correlation between the depth where possible risk of frost damage can occur in brick and the outside air temperature and rainfall intensity just before the occurrence of frost damage is needed.

Our developed heat and moisture model can also be used to investigate possible frost damage in other areas in Europe, by applying other climate data.

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