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Effect of Applied Weather Data Sets on the Computational Assessment of Hygrothermal Performance of Historical Masonry

Jan Kočí[1], Robert Černý[2]

Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, Prague, Czech Republic
E-mails: [1]jan.koci@fsv.cvut.cz (corresponding author); [2]cernyr@fsv.cvut.cz

Abstract. Several historical wall assemblies together with several weather data sets are investigated in order to study the effect of environmental load on hygrothermal performance of historical buildings. The effect of weather data is assessed using several damage functions with the emphasis placed on frost induced damage. The climatic data are represented by six different weather data sets, namely by the test reference year, positive and critical weather years, together with the meteorological data measured by the autors during the time period of 2013–2015. Special attention is paid to the recent weather data as there is an apparent trend of average temperature increase in the Central Europe in last few years. The results presented in the paper confirm the warming trend which is manifested by virtually no frost induced damage observed for weather years 2014 and 2015 in the analyzed historical building envelopes.

Keywords: climatic data, historical buildings, sandstone, damage function, temperature.

Conference topic: Environmental protection.

Introduction

Historical buildings are considered among the most valuable cultural heritage of a mankind. For that reason those buildings deserve special treatment during their service live, especially when renovation or restoration works are required. Usually any revitalization, preservation or protection is strictly controlled by monument care authorities, who define the permissible actions. Those authorithies often insist on preservation of original treatments, technologies and materials from the period when the building was built. Therefore, the design of renovation works is usually done under supervision of well-trained persons, who work on the basis of their experience. However, sometimes the renovation works are too complex that even best experienced supervisor cannot guarantee that proposed methods, technologies or materials will work efficiently. For example, when the choice of materials is considered, it is necessary to assess service life of a whole building enclosure to ensure as long durability as possible. As it has been showed, e.g., by Kočí J. *et al.* 2010, Maděra *et al.* 2009, Lu *et al.* 1999, or Larbi 2004, a proper material configuration of building envelope may significantly extend its service life. Combination of improperly chosen materials can lead to damage caused by moisture transport through the interface between materials (Mendes, Philippi 2005). For that reason, computational modelling is often used by designers as a helping tool for the prediction of the long-term performance of historical buildings.

When simulating the long-term performance of historical masonry, whether to assess the renovation work efficiency or to plan renovation works in the future, the boundary conditions play crucial role for the simulation accuracy. Those boundary conditions represent weather data and are mostly implemented in the form of Test Reference Years (TRY), which are constructed by averaging real weather data over several decades (Bilbao *et al.* 2004; Kalamees, Kurnitski 2006). Therefore, TRY is suitable for the long-term simulations of building performance. However, there have been made several approaches to define different weather years, such as critical weather year (Kočí J. *et al.* 2014; Salonvaara *et al.* 2010) which is used to simulate the most severe conditions in the studied locality with respect to a particular kind of damage. Critical years are mostly applied for short-term analyses only, as it is unlikely for more such years to occur consecutively. However, during the last several decades a long-term warming trend in the global mean surface temperature, provided supposedly by the continued rise in anthropogenic greenhouse gases in the atmosphere, has been frequently reported. Although the long term global warming trend seems to be persistently evident in surface temperature, there is also evidence of its slowing down in the recent decade as it was observed in several studies (Arora *et al.* 2016; Rosenlof, Reid 2008; Solomon *et al.* 2010). With the awareness of global warming effect some rare approaches for the definition of positive weather year may be registered (Kočí J. *et al.* 2015). The application of positive weather years is not usual in hygrothermal simulations yet although the global warming may lead to their more frequent use in the future.

In this paper, the effect of climatic data selection on simulated moisture and temperature fields in several types of historical building envelopes is analyzed. Six different climatic data sets for the city of Prague are applied, namely the official TRY from the Czech Hydrometeorological Institute, critical and positive weather years generated by a novel approach proposed by the authors, and meteorological data measured by the authors during the last three years. As a typical damage caused by the external environment in Central Europe is due to freeze/thaw cycles in the external surface layers of building structures, the calculated moisture and temperature fields are assessed using damage functions suitable for the cold regions.

Studied building enclosures

The effect of climatic data was investigated on several building enclosures made of several historical stones from different quarries, namely Libnava sandstone (SL), Záměl sandstone (SZ) and Kocbeře sandstone (SK). All quarries are located in the Czech Republic. The load-bearing materials were provided with or without the renovation plaster for historical masonry (RPHM) on the exterior side. On the interior side there was lime-cement (LC) plaster for all studied building enclosures. The thermal insulation was not considered in any historical enclosure. In total six different building envelopes were investigated; their list is shown in Table 1.

Table 1. List of studied building enclosures

Building env. #	Int. plaster (10 mm)	Load-bearing material (800 mm)	Ext. plaster (10 mm)
1	LC Plaster	Libnava sandstone	N/A
2	LC Plaster	Libnava sandstone	RPHM
3	LC Plaster	Záměl sandstone	N/A
4	LC Plaster	Záměl sandstone	RPHM
5	LC Plaster	Kocbeře sandstone	N/A
6	LC Plaster	Kocbeře sandstone	RPHM

The material parameters necessary as input data for the computational model were obtained in the laboratories of Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague and can be found in the following literature: sandstones – Kočí V. *et al.* 2014, lime-cement plaster – Vejmelková *et al.* 2010, renovation plaster for historical masonry – Vejmelková *et al.* 2012.

Applied weather data

For the investigation of the effect of climatic data on hygrothermal performance of building enclosures several weather data sets for the location of Prague, Czech Republic were chosen. The data was represented by TRY, critical and positive weather year and 2013–2015 weather years. The critical and positive weather years were selected according to the methodology presented by Kočí J. *et al.* 2014 and Kočí J. *et al.* 2015. TRY was obtained from the Czech Hydrometeorological Institute, which is an official provider of weather data in the Czech Republic. The weather data of the years 2013–2015 were obtained using Davis Vanatage Pro meteorological station. All weather data were implemented in the form of hourly values of temperature, relative humidity, wind speed, wind direction and precipitation. The average yearly values of temperature and relative humidity as well as annual amount of precipitation are provided in Table 2. The monthly averages of temperature and relative humidity of involved weather data are shown in Figs. 1 and 2.

Table 2. Summary of weather data

Parameter/Weather year	TRY	Critical	Positive	2013	2014	2015
Average temperature [° C]	8.67	6.42	9.85	9.97	11.59	11.75
Average relative humidity [%]	74.14	81.67	74.67	76.73	76.72	71.65
Amount of precipitation [mm/m^2]	521.5	513.3	503.4	628.0	214.0	338.4

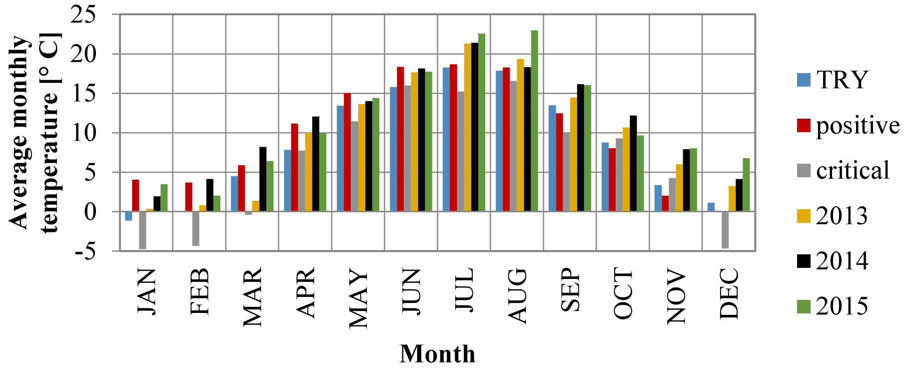

Fig. 1. Average monthly temperature of applied weather data sets

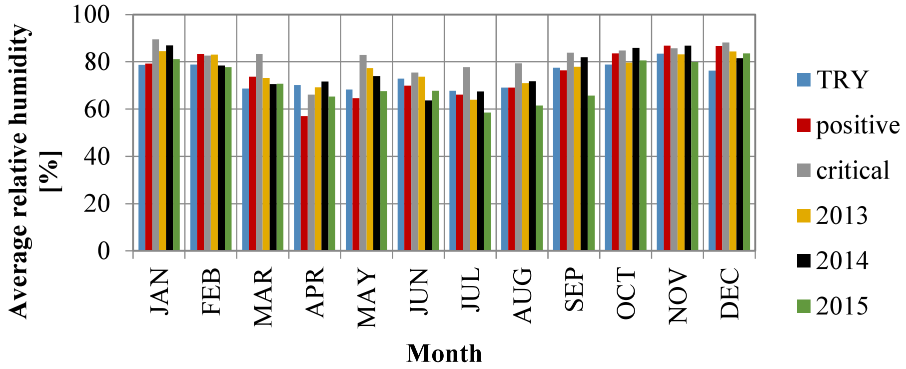

Fig. 2. Average monthly relative humidity of applied weather data sets

Computational model

All studied building envelopes were subjected to the computational simulation using the HEMOT simulation tool (Kočí V. *et al.* 2010). HEMOT is based on the general finite element package SIFEL (Kruis *et al.* 2010) and uses a modified version of Künzel's (Künzel 1995) mathematical model of coupled heat and moisture transport (Ďurana *et al.* 2015). The balance equations are expressed as

$$\frac{d\rho_v}{d\varphi}\frac{\partial\varphi}{\partial t} = div\left[\left(B(D_w\rho_w\frac{dw}{d\varphi}) + A(\delta_p p_s)\right)grad\varphi + \left(\delta_p\varphi\frac{dp_s}{dT}\right)gradT\right], \tag{1}$$

$$\frac{dH}{dT}\frac{\partial T}{\partial t} = div(\lambda gradT) + L_v div[\delta_p grad(\varphi p_s)], \tag{2}$$

where ρ_v is the partial density of moisture, φ is the relative humidity, δ_p is the permeability of water vapor, p_s is the partial pressure of saturated water vapor, H is the enthalpy density, L_v is the heat of evaporation, λ is the thermal conductivity, T is the temperature, D_w is the total capillary transport coefficient, ρ_w is the density of water and w is the moisture content. The transition function assigns the weight to parameters A and B (being within the range of 0–1) with the balance $A + B = 1$ valid for every point of the curve.

The satisfactory combination of power functions reads (Ďurana *et al.* 2015):

$$B = \begin{cases} 1 & (0 \le \varphi \le 0.9) \\ 32\left[\left(\frac{1}{\varphi_2 - \varphi_1}\right)(\varphi - \varphi_1)\right]^6 & (0.9 < \varphi \le 0.938) \\ 1 - 32\left[\left(\frac{1}{\varphi_2 - \varphi_1}\right)(\varphi_2 - \varphi)\right]^6 & (0.938 < \varphi \le 0.976) \\ 0 & (0.976 < \varphi \le 1) \end{cases}, \tag{3}$$

The hygrothermal performance of the particular enclosure was assessed for the 10th year of computational simulation, so that the results are not affected by initial conditions. The hygrothermal performance was assessed in the investigation point placed 5 mm under the exterior surface using several damage functions that were designed for the assessment of frost induced damage (Kočí J. *et al.* 2017). In this particular research two of the proposed damage functions were applied, namely Amount-of-Frozen-Water (AFW) and Time-of-Frost (TOF).

Amount-of-Frozen-Water (AFW) returns the amount of liquid water retained in the investigated point under critical temperature during the year. It is defined as

$$AFW = \sum_{i=1}^{8760} w_i \left[T_i < T_L \wedge w_i > w_L\right], \tag{4}$$

where T_i [° C] and w_i [m^3/m^3] are hourly values of temperature and moisture content, respectively. AFW is calculated only when both $T_i < T_L$ and $w_i > w_L$. Description of the critical values T_L and w_L is provided at the end of this section. AFW works with the assumption that when the temperature drops down below its critical level T_L, and liquid water is present in the material (i.e., $w_i > w_L$), the whole amount of moisture in the investigated point is accounted for ice formation. Although such an assumption is not physically correct due to the fact that there is still some liquid water in the micro- and nanopores that remains unfrozen, the AFW function may serve well for a comparative analysis. The higher value AFW returns, the more severe conditions occur in the investigated point in the wall assembly, which can lead to a faster degradation of the material in terms of frost damage.

The TOF damage function calculates the number of hours during a year when the conditions favorable for ice formation occur in the point of investigation in the building enclosure. TOF is defined as

$$TOF = \sum_{i=1}^{8760} \left[T_i < T_L \wedge w_i > w_L\right], \tag{5}$$

with the same definition of critical values T_L and w_L as in Eq. (1). Similarly to AFW, higher value of TOF indicates higher risk of frost induced damage to the construction.

In this paper, the critical level of moisture content w_L corresponds, according to the sorption isotherm, with the moisture content that corresponds to 90% relative humidity of air in the pore space of the material in which the point of investigation is placed. It is assumed that when the critical level of moisture content is exceeded, liquid moisture can appear in the pore space of the material making it susceptible to frost damage when exposed to low temperature. The critical temperature T_L can be a matter of further discussion because T_L obviously depends on the pore size distribution of the analyzed material or the possible concentration of soluble salts. Here, a simple assumption is made that moisture in the pore space of the material primarily fills the pores from the smallest to larger ones. Therefore, when cumulative pore size distribution of the material is known, the radius R of the largest saturated pore can be determined as a function of moisture content, which is subsequently used for the calculation of freezing-point depression in every calculation step. Therefore, the value of T_L is changing in time. The shift of freezing temperature ΔT_f is calculated according to Gibbs-Thomson equation as

$$\Delta T_f(R) = \frac{2T_0 \gamma_{sl} v_l}{\Delta h_b R}, \tag{6}$$

where γ_{sl} is the surface free energy of the water/ice interface, v_l the molar volume of water and Δh_b the melting enthalpy in the unconfined (bulk) state. All the thermodynamic properties are taken for normal water in the bulk state at the normal melting temperature T_0 = 273.15 K. T_L is then calculated as

$$T_L = T_0 - \Delta T_f(R) \tag{7}$$

As far as the point of investigation is placed in 5 mm under the exterior surface, four different materials need to be investigated to obtain the critical values, w_L and T_L. The critical value w_L corresponds to the hygroscopic moisture content which is summarized in Table 3. The value of T_L is calculated using Eqs. (6) and (7) from a known value of moisture content w and the cumulative pore size distribution functions that are shown in Fig. 3.

Table 3. Critical moisture content of investigated materials

Material	w_L [m^3/m^3]
Libnava sandstone	0.01964
Záměl sandstone	0.02721
Kocbeře sandstone	0.00237
Renovation plaster for historical masonry	0.038187

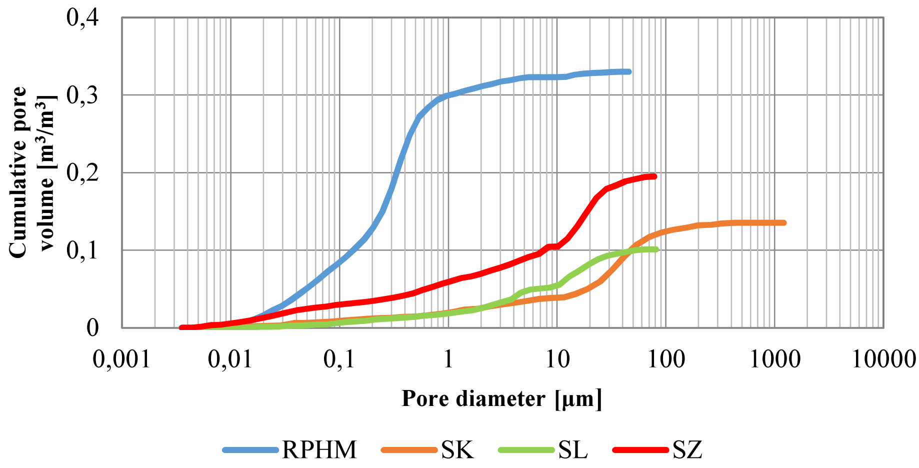

Fig. 3. Cumulative pore volume of investigated materials

Results & Discussion

After the computational simulations were carried out, the time developments of temperature and moisture content during the 10th year of computational simulation were used as input data for the assessment by the proposed damage functions. The outputs of applied damage functions are presented below. In total, six different building enclosures exposed to six different sets of boundary conditions were investigated. The hygrothermal performance was assessed and compared in the point of investigation located 5 mm under the exterior surface. The damage function outputs are shown in Figs. 4 and 5.

The provided damage function values should be understood as a comparative indicator for different weather loads of the construction. The absolute values of those indicators are affected by the pore size distribution function, transport and accumulation parameters of investigated material, thus an inter-constructional comparison does not give a competitive information. Therefore, the highest values of both damage functions were achieved for SZ (building envelope 3) which has highest porosity of studied stones. More to that, both damage functions are in a strong correlation to each other based on their mathematical definitions. Still, some small nuances are apparent, which is given by the materials characterization.

When analyzing weather data, it is obvious that the weather years 2013–2015 are very favourable to the studied historical wall assemblies in terms of their frost resistance. This indisputable fact is caused by relatively high temperatures in the first place. As it is shown in Table 2, the average temperature of 2013–2015 is significantly higher than other investigated weather years and, most importantly, 2015 achieves very high temperatures in the winter period when compared to the other weather years. Therefore, the damage function outputs of 2014 and 2015 indicate zero effect of possible frost induced damage. The 2013 weather year indicates a similar effect for almost all of the analyzed constructions except for building envelopes 3 and 5.

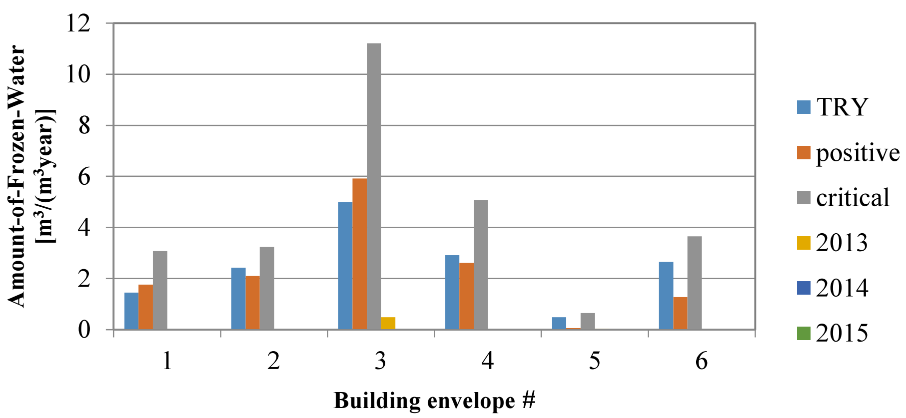

Fig. 4. Amount-of-Frozen-Water damage function outputs

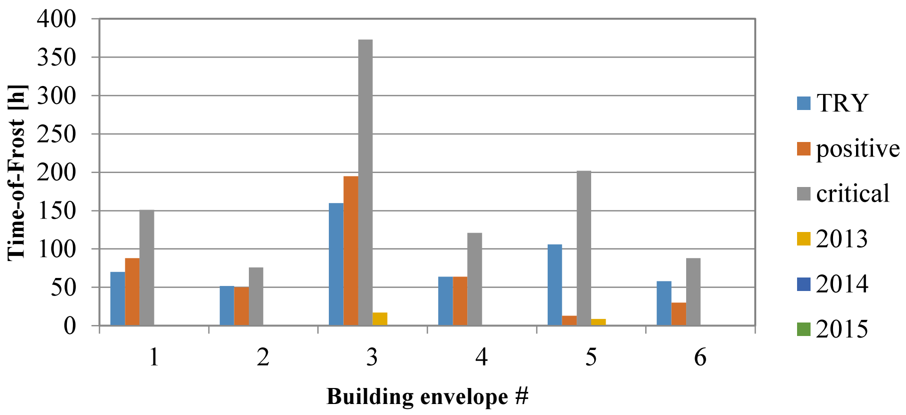

Fig. 5. The Time-of-Frost damage function outputs

Conclusions

Six different weather data sets and their effect on hygrothermal performance of six different historical wall assemblies were investigated in this paper. For the assessment of weather data severity, a damage function approach was chosen allowing quantification of possible frost induced damage of the construction. Before the application of damage functions, a series of computational simulations was carried out in order to obtain temperature and moisture distribution in the studied constructions. As boundary conditions, TRY, critical and positive weather years were used, together with the weather data from the last three years (2013–2015) obtained by the authors.

The results of damage function application proved the last three years to be very positive from the point of view of a possible frost induced damage. Especially the years 2014 and 2015 may be used as a replacement of the positive weather year identified in the previous research when the frost induced damage of sandstone masonry is considered. Based on the observed results, it is recommended to continue with a thorough observation of weather data in the next few years. In the case that the recent trend in warming will be confirmed, redefinition of TRY will be necessary for the long term simulations of hygrothermal performance in particular.

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Disclosure statement

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial, professional, or personal interests from other parties.

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