IV.07
Impact of Non-Uniform Distribution of Temperature on the State of Stress of Masonry

Pavel Beran

1 Institute of Theoretical and Applied Mechanics of the Academy of Sciences of the Czech Republic, Czech Republic, beran@itam.cas.cz

Abstract Deterioration of masonry is caused by inordinate loading and by climatic actions. Climatic cyclic thermal stress in structure is incurred by unequal temperature gradient across the thickness of homogenous or heterogeneous masonry. Thermal gradient also causes significant stress close to the interface between stone and mortar in the masonry made of components with different thermal expansion properties. The values of thermal stress increase with higher thermal gradient. Impact of insulation, absorption of solar radiation, air temperature around the structure, heat transfer coefficient, coefficient of heat conduction and heat capacity to the temperature gradient in the wall exposed to the exterior weather conditions were investigated by a numerical model. All of these effects or material properties affect the maximal surface temperatures in masonry during summer. Especially the orientation of surface to the cardinal points, solar absorption and velocity of the wind around structure influences significantly the maximal achieved surface temperature thus the values of stress caused by the temperature.

1 Introduction

1.1 Material compatibility

Masonry of historical structures is a heterogeneous material, created from stone blocks or bricks and mortar. The individual components should have material characteristics that ensure mutual cooperation under loading and climatic action, without defects or damage. This requirement is part of what is referred to as compatibility and is usually fulfilled by a simple requirement for identical or closely similar characteristics of the two materials that compose the masonry.
Durability of masonry is influenced mainly by resistance to load, environmental cyclic thermal stress, freezing cycles, and environmental moisture stress. The influence of the environmental cyclic thermal stress of masonry is described in detail in this paper.

Thermal stress in masonry is influenced by temperature gradient, thermal expansion, and Young modulus of the individual components. Distribution of the temperatures in masonry depends on its environment and “thermal” material characteristics. The main factors of the environment are solar radiation, air temperature around the structure, speed of wind, heat transfer coefficient on the interface between masonry and air, orientation of the surface to the cardinal points, shadowing, and impact of moisture. The “thermal” material characteristics of masonry are heat conduction, heat capacity, and coefficient of heat absorption of solar radiation. Properties mentioned above influence the thermal stress of masonry and consequently its durability. The impact of each material or environmental property will be described in detail in the rest of the paper. Moisture also influenced the temperature gradient but, in this study, is simplified, and therefore this effect is neglected.

1.2 Impact of different thermal expansion of mortar and stone

Masonry consists of mortar, stone, or bricks, which could have different material properties, i.e. Young’s modulus, coefficient of thermal expansion. Masonry is created in a specific moment when both mortar and stone or brick have similar temperature. If both of the masonry materials have different thermal expansion, the increase of temperature causes the increase of stress close to its interface. This phenomena was investigated in a previous study [1], only some conclusions of this study will be presented here.

The state of stress in masonry caused by different thermal expansion of its components is significantly influenced by the value of difference of thermal expansion coefficient between masonry components, Young modulus of its components, and thermal gradient. When both the difference of the thermal expansion coefficient between stone and mortar and the values of stress are higher, these values increase with higher Young’s modulus of stone and mortar.

The previous study [1] was based on a numerical model of a typical masonry section. The section was loaded by the temperature gradient (cooling and heating representing real climatic conditions in Prague, Czech Republic), which generated high stress in the mortar and close to the interface between stone and mortar. The detailed distribution of stress is shown in Fig. 1. One node was chosen from this figure where the relation of stress to the coefficient of thermal expansion of mortar was investigated (Fig. 2). The material characteristics of masonry units were constant in this study, but the coefficient of thermal expansion and Young’s modulus of mortar were variable.
The maximal values of stress were achieved on the surface with the highest temperature gradient. The impact of material characteristics on the thermal gradient was not investigated in detail in the previous study, therefore it is investigated in this paper.

![Fig. 1 Location of the node with maximum effective stress in the mortar.](image1)

**Fig. 1** Location of the node with maximum effective stress in the mortar.

![Fig. 2 History of effective stress depending on the coefficient of thermal expansion and the Young’s modulus of the mortar – this stress is caused by cooling and different thermal expansion of mortar and stone; coefficient of thermal expansion of stone (masonry block) is $18 \times 10^{-6} \, \text{K}^{-1}$; the Young’s modulus of the stone is 15 GPa.](image2)

**Fig. 2** History of effective stress depending on the coefficient of thermal expansion and the Young’s modulus of the mortar – this stress is caused by cooling and different thermal expansion of mortar and stone; coefficient of thermal expansion of stone (masonry block) is $18 \times 10^{-6} \, \text{K}^{-1}$; the Young’s modulus of the stone is 15 GPa.

## 2 Temperature analysis

The intention of this paper is investigation by numerical model which material characteristics cause high temperatures in terms of heat conduction. Also, the parameters of the environment were studied.
2.1 Description of numerical model

This study is based on one dimensional finite element model of masonry section. The numerical model represents the cross-section of the wall of 0.45 m thickness. One side of the wall was exposed to solar radiation and outdoor air, while the opposite side was exposed only to the outdoor air.

The transient heat transfer in 3-D, according to [2], is described by equation (1).

\[ \lambda \nabla^2 T = \rho c \frac{\partial T}{\partial t} \pm G' \]

- \( c \) specific heat capacity, J / (kg K)
- \( \rho \) bulk density, kg / m\(^3\)
- \( \lambda \) coefficient of heat conduction, W / (m K)
- \( G' \) source term, in this case is equal to zero, J / m\(^3\)

The 3-D problem of heat transport through the masonry was simplified into the 1-D problem [3]. The equations (1) simplify into formula (2). The heat transport through a wall is basically a 1-D problem.

\[ \lambda \frac{d^2 T}{dx^2} = \rho c \frac{\partial T}{\partial t} \pm G' \]  \hspace{1cm} (2)

- \( x \) coordinate in direction perpendicular to wall surface, m

The equation (2) was completed with formulation of boundary conditions, which represents the effects of heat transfer from air to surface of masonry and absorbed solar radiation [4]. The full description of the formulation of boundary conditions with verification is found in a previous study [5]. The necessary climatic data for the simulations were measured at a meteorological station in Prague Karlov, Czech Republic.

2.2 Material characteristics of the masonry (stone, bricks, mortar)

The material characteristics of the masonry components in terms of heat conduction are influenced mainly by porosity, amount of water in the material, chemical composition, and colour of the surface. Coefficient of heat conduction is significantly influenced by the number of pores in the material and whether or not the pores are filled with water. The heat conduction coefficient has low values when the material has a high quantity of pores that are not filled with water. If the pores are filled with water, the coefficient of heat conduction increases. Also, compact materials without pores usually have a higher heat conduction coefficient.
than materials with pores. The non-porous material usually has a higher bulk density thus also higher volume heat capacity. Specific heat capacity has similar values for all kinds of stone, bricks, and mortars. Colour of the surface affects absorption of solar radiation, and dark-coloured surfaces have higher absorption than light-coloured surfaces [6].

The material characteristics in terms of heat conduction of many types of stones are difficult to find. It is also necessary to note that one type of stone has high natural variation of material properties.

2.3 **The impact of variable material characteristics and orientation of masonry to the cardinal points on the maximal surface temperature of masonry**

On the façade, stones or bricks usually have significantly higher representation than the joint mortar in the masonry. Thus, the final distribution of temperatures in the common masonry is mainly influenced by the material properties of the stones or bricks [7].

The surface temperature of masonry is influenced by several factors: orientation of its surface to the cardinal points, heat absorbability of solar radiation, heat conduction of the masonry components, heat capacity of the masonry, and coefficient of heat transfer between outdoor air and masonry. The wide range of possible (realistic) values of material and environmental properties were used in simulations. The impact of the real climatic situation recorded in July 2006 in Prague, Czech Republic, was used for the simulation. This month included one of the hottest days in the known history of Czech Republic. Maximal surface temperatures of masonry were obtained with the one dimensional numerical model. The 1-D model represents the thickness of vertical wall exposed to incident solar radiation on one side and not the other. Both surfaces are exposed to the outdoor air.

2.3.1 **The impact of the surface orientation to the cardinal points**

The impact of the surface orientation to the cardinal points and heat absorbability of solar radiation is plotted in Fig. 3. The horizontal axis on the chart in Fig. 3 shows the azimuth of the normal of vertical surface exposed to solar radiation, and the maximal temperature achieved in July 2006 is on the vertical axis. These values were determined by numerical model. The maximal temperatures were obtained for the orientation of the surface to the west or south-west. Lower values were obtained for the orientation of the surface to the southeast or the south. The absolute values of the surface temperature significantly depend on its heat absorbability of the solar radiation.
2nd Historic Mortars Conference HMC2010 and RILEM TC 203-RHM Final Workshop  
22-24 September 2010, Prague, Czech Republic

2.3.2 The impact of heat conduction

Fig. 3 Relation of maximal temperature of a vertical surface to the orientation to cardinal points. This graph was computed with coefficient of heat conduction 1.4 W.m⁻¹.K⁻¹, specific heat capacity 840 J.kg⁻¹.K⁻¹, bulk density 2400 kg.m⁻³, and coefficient of heat transfer 15 W.K⁻¹.m⁻².

Fig. 4 Relation of maximal temperature of vertical surface to the coefficient of thermal conduction. This graph was computed with azimuth 262°, specific heat capacity 840 J.kg⁻¹.K⁻¹, bulk density 2400 kg.m⁻³, and coefficient of heat transfer 15 W.K⁻¹.m⁻².

The impact of heat conduction on the maximal surface temperature is plotted in Fig. 4. All parameters were constant in the model except the coefficient of heat conduction. The maximal surface temperature increases as the coefficient of the heat conduction is lowered. The higher coefficient of heat conduction causes faster
transport of absorbed heat into the masonry, and thus, the gradient in masonry is more “linear” and surface temperatures are lower.

### 2.3.3 The impact of heat capacity

The impact of heat capacity on the maximal surface temperature was investigated by numerical model. When the heat capacity is low, the temperatures in whole masonry increase. High heat capacity reduces the temperatures in all masonry and helps to lower temperatures and, consequently, thermal stress. This reduction is lower than the reduction related to the coefficient of heat conduction (Fig. 5).

![Fig. 5 Relation of maximal temperature of vertical surface to the heat capacity. This graph was computed with azimuth 262°, coefficient of heat conduction 1.4 W.m⁻¹.K⁻¹, and coefficient of heat transfer 15 W.K⁻¹.m⁻².](image)

### 2.3.4 The impact of the heat transfer coefficient

The heat transfer coefficient depends on the velocity of the wind, size, and shape of the wall. Descriptions of the relationship of this coefficient to the velocity of the wind and other parameters exist in literature, but are significantly influenced by the specific situation. In general, when the speed of the wind is higher, the heat transfer coefficient also is higher. The value 15 W.K⁻¹.m⁻² defined by the Czech norm in summer time was used in previous chapters [8]. The range of values of coefficient of heat transfer corresponds to the possible values which could be achieved in environment. Coefficient of heat transfer is 23 W.K⁻¹.m⁻² in winter, and 6 - 10 W.K⁻¹.m⁻² at room temperature [8].
When the values of coefficient of heat transfer are low, the increase of temperatures is high (Fig. 6). The surface of the masonry structure exposed to solar radiation is cooled by the heat transfer between air and the wall surface. High velocity of wind causes high coefficient of heat transfer and, consequently, high cooling of the surface of the wall.

![Graph showing relation of maximal temperature of vertical surface to the heat transfer coefficient.](image)

**Fig. 6** Relation of maximal temperature of vertical surface to the heat transfer coefficient. This graph was computed with: coefficient of heat conduction 1.4 W.m\(^{-1}\).K\(^{-1}\), specific heat capacity 840 J.kg\(^{-1}\).K\(^{-1}\), bulk density 2400 kg.m\(^{-3}\), azimuth 262°.

### 3 Conclusion

The parameters that influenced the value of the maximal surface temperature achieved in summer time with exposure to solar radiation could be divided into three categories according to their impact. The first category influences the maximal surface temperature significantly, the second to an intermediary degree, and the third minimally. The parameters of the first category are coefficient of heat absorption of solar radiation, orientation of surface to the cardinal points, and coefficient of heat transfer. The coefficient of heat conduction is the only parameter in the second category. Heat capacity is the parameter of the third category, which has the lowest effect on maximal surface temperature. Each parameter can be combined with any other that can cause an increase or decrease
of surface temperatures into higher or lower values than those mentioned in the paper.

Thermal stress in masonry is caused by the unequal distribution of temperatures across the thickness of masonry, which is considered as homogenous material. The highest stress is implicitly caused by the properties in the first category with a combination of the low coefficient of heat conduction.

Thermal stress in masonry, created by stone units that have different thermal expansion than mortar, is influenced by the extreme temperature in the masonry, which is usually the surface temperature. This stress can be reduced by using mortar that has maximal difference of thermal expansion coefficient between stone and mortar $2 \times 10^{-6} \text{ K}^{-1}$. When the surface is exposed to high temperatures, it is necessary to design the repair mortar very carefully. Ideally, the differences of thermal expansion between stone and mortar should be zero. Stress can be reduced by cleaning the masonry surface. The absorption coefficient of a clean surface is usually lower than the absorption coefficient of a “dirty” surface. This method can be used when the original “clean” surface is light-coloured.

4 Acknowledgment

This paper is based on results and experience acquired with support from the Institutional Research Plan AV0Z20710524 and from Czech Grand Agency grant No. 103/07/1467.

5 References

8. ČSN 73 0540 Tepelná ochrana budov