Sensitivity of fire resistance of 19th century fireproof flooring systems to thermal and mechanical properties of masonry

Sensitivity of Fire Resistance of 19th Century Fire Proof Flooring Systems to Thermal and Mechanical Properties of Masonry

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ABSTRACT: Masonry jack arches are commonly encountered in fire proof flooring systems constructed during the 19th century in Britain and central Europe. Masonry arches provide insulation to the steel girders and the load bearing elements. Because brick and mortar types/classes varied considerably in such historical construction, determining the thermal and mechanical properties of masonry at elevated temperatures is a difficult task. This paper presents the results of a research to resolve the difficulties to researchers when analysing such structures under fire conditions. Firstly, this paper will present collated experimental data reported in the literature for the variations of the thermal (thermal conductivity and specific heat) and mechanical (compressive strength and thermal expansion) properties of burnt clay masonry units and mortars at elevated temperatures. Lower and upper bound temperature dependent curves will be proposed to account for the variability of the material properties based on the collected data. This makes use of the boundary curves of the constituent materials according to expressions found in current design codes (for determination of the compressive strength), the rules of mechanics (applicable for calculating the thermal expansion) or the laws of physics (i.e. the additivity theorem for determining the specific heat of solid multi-component systems). Finally, the boundary curves are used in a series of sensitivity studies to examine the influences of these variations on the fire resistance time of the flooring systems. Results from this sensitivity study will show that even though the thermal and mechanical properties of masonry at elevated temperatures change considerably, with the exception of one case, the variability has little effect on the calculated fire resistance time. As a general rule, the elevated temperature properties of modern brick, given in literature for a similar density, can be used to approximately (but with sufficient accuracy) model masonry in elevated temperature analysis of 19th century jack-arch flooring systems.

Keywords: Fire resistance, 19th cectury fire proof floors, arch jack, thermal properties, mechanical properies, masonry, brick, mortars, elevated temperatures, sensitivity

1 INTRODUCTION

Fireproof floors in 19th century construction comprised of metal load-bearing elements (usually made out of cast iron) protected against fire by masonry "jack arches". Typically, burnt clay bricks were bound together with different types of mortars or, occasionally, with Portland cement and formed the masonry arches which spanned between the metal girders.

To preserve such historic construction, accurate modeling the thermo-mechanical properties of masonry at elevated temperatures is necessary. However, because various types of bricks and connecting pastes were used, determining these properties under elevated temperature conditions is not a simple task. The work presented here will show that the properties of modern brick can be used to accurately model masonry in 19th century fireproof floors, based on a study of experimental data collected from the literature and a thermal sensitivity analysis of a typical "arch-jack" system.

2 PROPERTIES OF BURNT CLAY BRICKS AT ELEVATED TEMPERATURES

2.1 Mechanical properties of bricks at elevated temperatures

Compressive strength at elevated temperatures

Data referring to the compressive strength of masonry units at elevated temperatures are very few. Only the European standard EN1996-1-2 (2005) presents, graphically, the stress-strain relationship of clay masonry units for temperatures ranging from 20^{o}C to 750^{o}C. From the specific graphs (EN1996-1-2, 2005), the reduction in the ultimate compressive strength with temperature can be extrapolated. The authors of this standard suggest a linear decrease, with strength dropping to 70% at 750^{o}C.

Thermal expansion at elevated temperatures

Information regarding the thermal expansion of clay bricks, insulating fire bricks (Harmathy, 1983) and fire bricks (Hu, 1993) suggests a linear increase of the thermal strain with temperature. Figure 1 shows collated experimental data. Also shown in Figure 1 are the EN1996-1-2 (2005) data and the upper and lower boundary curves to be used by the authors.

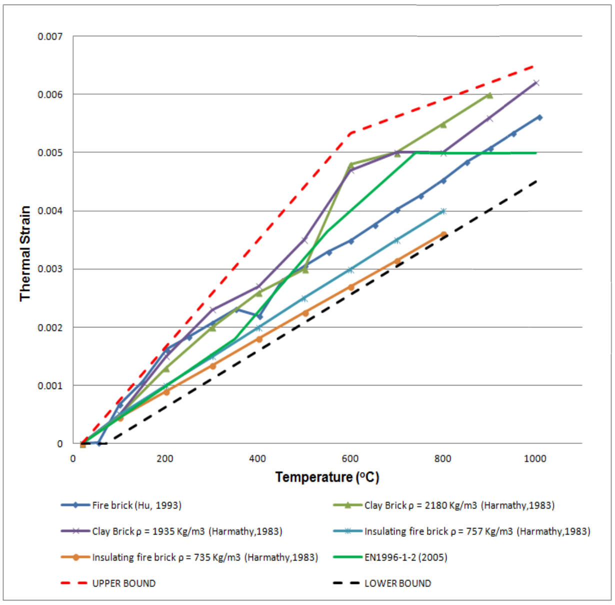

Figure 1. Thermal strain of clay masonry units as a function of temperature.

2.2 Thermal properties of bricks at elevated temperatures

Figures 2 and 3 show the collated experimental data by Maraveas et al (2013) from literature and the upper and lower bound curves, for the thermal conductivity and specific heat respectively, of clay bricks at elevated temperatures, as a function of density for both lightweight (ρ=700-1000 kg/m^3) as well as heavyweight (ρ=1900-2200 kg/m^3) units.

3 PROPERTIES OF MORTARS AT ELEVATED TEMPERATURES

3.1 Mechanical properties of mortars at elevated temperatures

Compressive strength

The research relating to the compressive strength of mortar at elevated temperatures is very recent. These researchers did not focus only on regular mortars, but investigated the behavior of mortars with admixtures, such as expanded perlite aggregate, natural zeolite, waste glass powder, blast furnace slag (Türkmen 2010), graphite powder (Cülfik, 2002), steel fiber and polypropylene fiber (Aydin, 2008) when heated at temperatures higher than ambient. In the absence of data referring to "hot" compressive strength, the residual (after cooling down) strength can be used as an approximation and is studied in this section. Figure 4 presents the collated experimental data and the upper and lower curves.

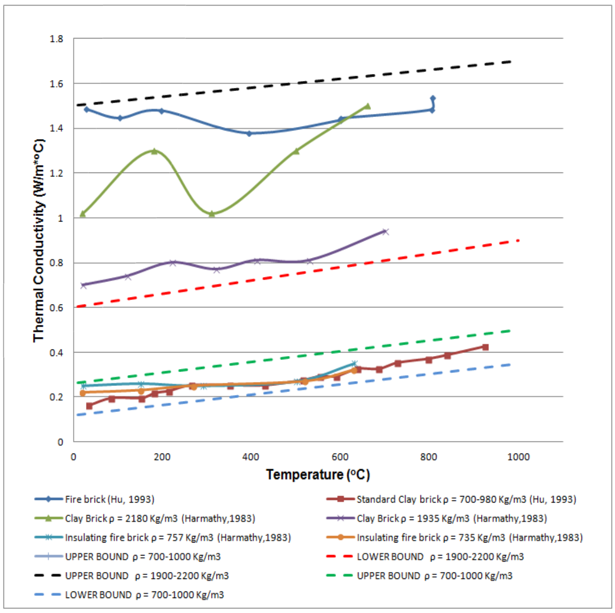

Figure 2. Thermal conductivity variation of burnt clay bricks with temperature: for lightweight (ρ=700-1000 kg/m^3) and heavyweight (ρ=1900-2200 kg/m^3) units.

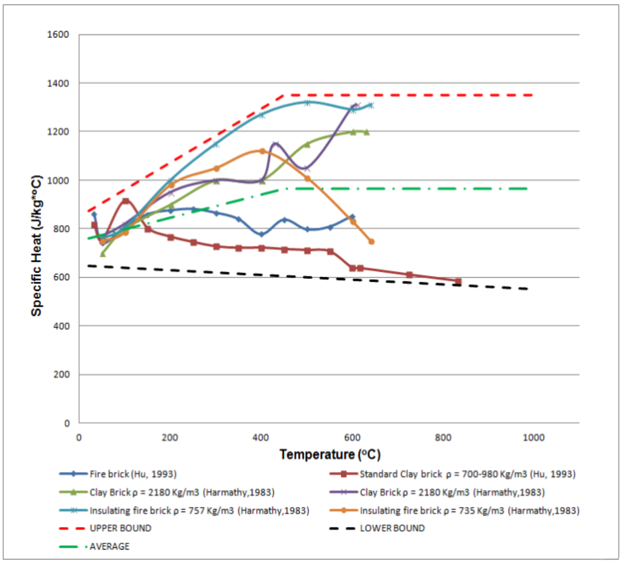

Figure 3. Specific heat variation of clay bricks with temperature.

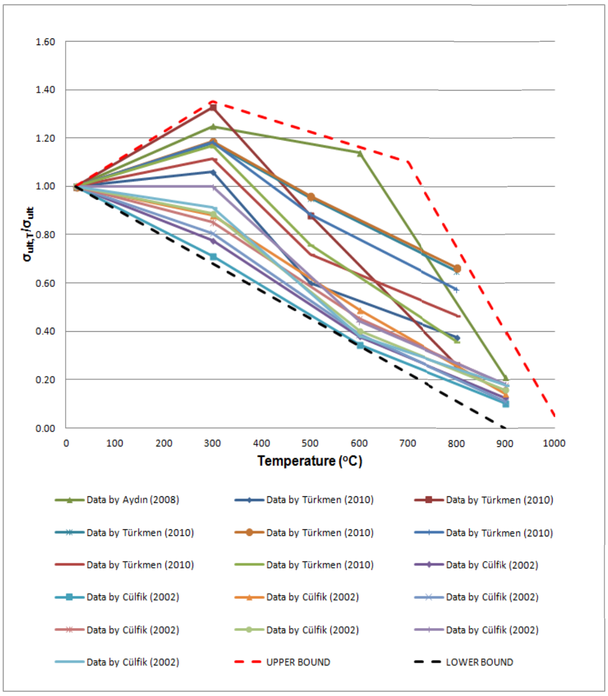

Figure 4. Variation of compressive strength of mortars and with temperature.

Thermal expansion

Figure 5 shows the data from literature and the upper and lower curves. There is a very large variation in this property.

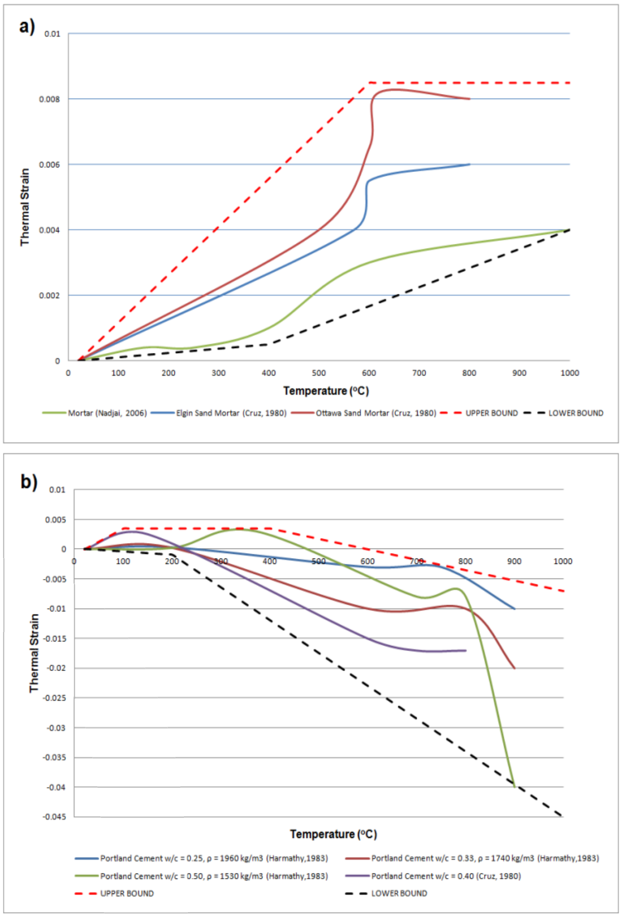

Figure 5. Variation of thermal strain of a) mortars and b) Portland cement with temperature.

3.2 Thermal properties of mortars at elevated temperatures

Figures 6 and 7 show raw data pertaining to the variations of the thermal properties of mortars with temperature, collated by the authors (Maraveas et al, 2013).

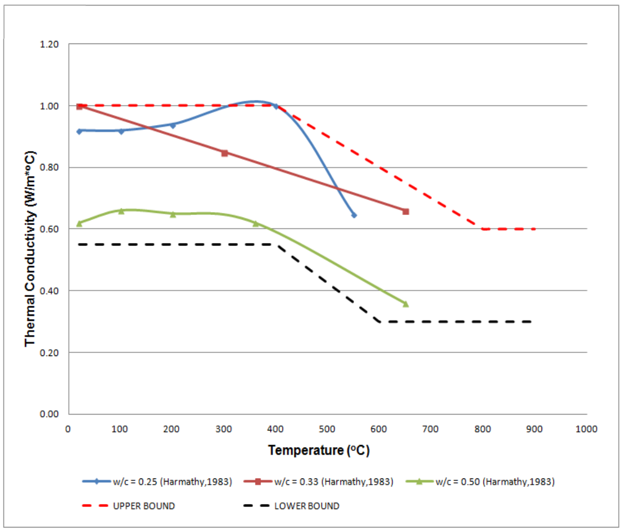

Figure 6. Thermal conductivity variation of mortars with temperature.

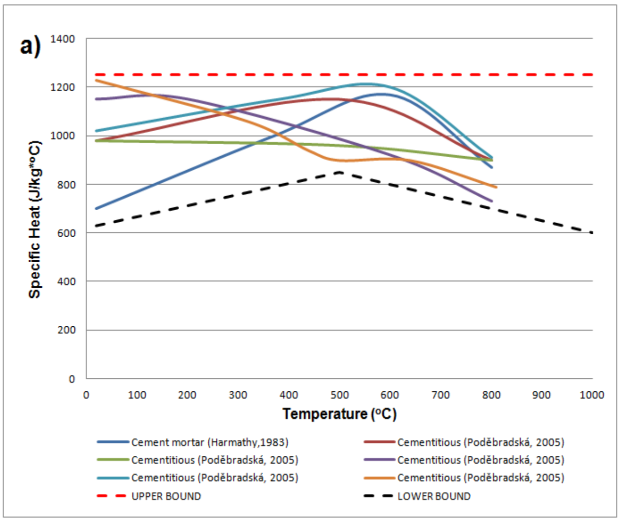

Figure 7. Variation of specific heat of a) mortars and b) Portland cement with temperature.

4 PROPERTIES OF MASONRY AT ELEVATED TEMPERATURES

4.1 Mechanical properties of masonry at elevated temperatures

Compressive strength

The compressive strength of masonry may be obtained based on those of the brick unit and mortar as follows (EN1996-1-1 (2005)):

$$f_k = K * f_b{}^{\alpha} * f_m{}^{\beta} \qquad (1)$$

where f_k is the characteristic compressive strength of the masonry, in N/mm^2, K is a constant depending on the brick and mortar type, α and β are constants (with recommended values α = 0.7 and β = 0.3), f_b is the normalized mean compressive strength of the masonry units (in the direction of the applied action effect), in N/mm^2 and f_m is the compressive strength of the mortar, in N/mm^2.

Thermal expansion

The thermal expansion of masonry can be calculated by combining the thermal strains of the bricks and mortar or cement according to (*Eq. (2)):*

$$\varepsilon_{mas} = \frac{\varepsilon_b \times L_b + \varepsilon_m \times L_m}{L_b + L_m} \qquad (2)$$

where ε_{mas} is the strain of the masonry, ε_b the strain of the bricks, ε_m the strain of mortar/cement respectively, L_b the expansion length of bricks and L_m the expansion length of mortar/cement. For the relevant calculations, a typical thickness of 6cm was assumed for the masonry units and three different thicknesses of the connecting paste (0.5cm, 0.75cm and 1cm) were examined.

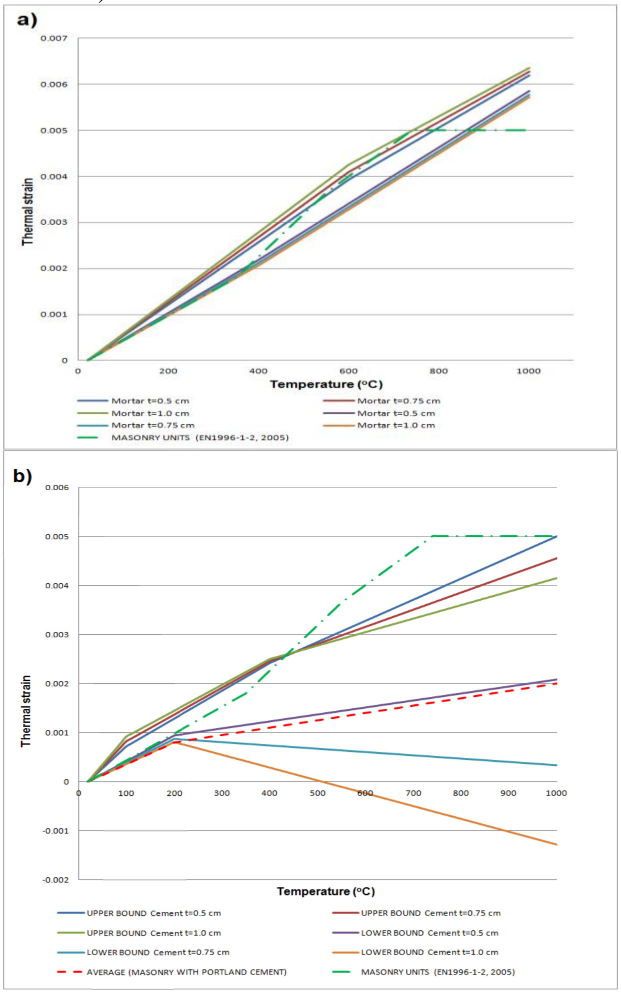

Figure 8. Thermal expansion of masonry with a) mortar b) Portland cement as a function of temperature.

4.2 Thermal properties of masonry at elevated temperatures

Thermal conductivity

According to Brown (1962), the thermal conductivities of masonry walls and bricks tend to be almost identical for units with densities of 1600-2200 kg/m^3. Therefore, the thermal conductivity of masonry at elevated can be sufficiently described by that of the bricks.

Specific heat

The specific heat of solid multi-component systems can be calculated according to the additivity theorem, which can be briefly described by the equation below (*Eq. (3)*):

$$C_p = \sum_{i-1}^{n} F_i \times C_{pi} \qquad (3)$$

where C_p is the overall specific heat capacity of the system, C_{pi} is the specific heat and F_i is the weight fraction of each component, respectively. By applying this theorem to masonry wall systems, the variation of specific heat of masonry with temperature was calculated for three commonly encountered mortar weight fractions (10%, 15% and 20% of the total weight). The results suggest that the specific heat of masonry at elevated temperatures is almost identical to that of the bricks.

5 SENSITIVITY ANALYSIS OF "JACK ARCH" SYSTEM

5.1 Finite Element Model and analysis cases

In order to investigate whether the thermal properties of the bricks (for a given density) can be used to accurately simulate the thermal response of masonry in 19th century fireproof floors, a 2D thermal sensitivity analysis was performed. A typical configuration of the "arch-jack" flooring system was modeled, via the finite element method, in the commercial program ABAQUS. Its geometry as selected to be identical with that described by Swailes (1995).

The simulated floor was subjected to the ISO-834 standard fire (1999) from below for 120min. Eight different analysis cases were carried out. In all of them, the thermal properties of "early" concrete were assumed to be those of modern concrete per EN1992-1-2 (2004), while those of steel per EN1993-1-2 (2005) were selected to model the cast iron girder. The thermal properties of masonry were selected from the various boundary curves derived for the bricks. A summary of these cases is given in Table 1.

Table 1. Thermal analysis cases for the simulated "arch-jack" system.

Analysis Number	Masonry Properties					
	Thermal Conductivity				Specific Heat	
	Upper bound heavy	Lower bound heavy	Upper bound light	Lower bound light	Upper bound	Lower bound
1	*				*	
2		*			*	
3			*		*	
4				*	*	
5	*					*
6		*				*
7			*			*
8				*		*

5.2 Thermal analysis results

The temperature evolution of the simulated floor for the studied analysis cases is depicted at three representative locations (lower flange: Node A, web mid-height: Node B and upper flange: Node C) of the beam. Despite selecting different boundary curves for masonry, the temperature evolution in the cast iron girder shows minor differences (Figure 9).

The temperature contour in the modeled floor after 90 min of exposure to fire (analysis case 1) is shown in Figure 10, which shows that temperature rise is limited to a thin layer in the lower portion of masonry. This is also true for the other analysis cases.

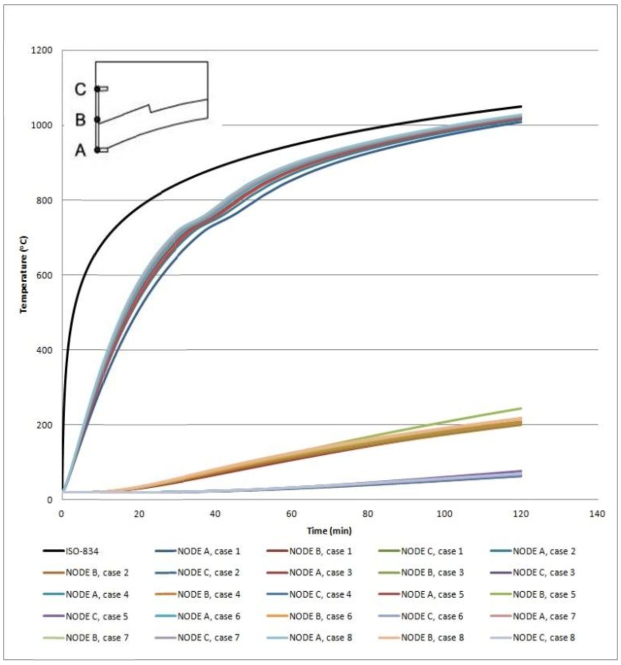

Figure 9. Temperature evolution curves at three representative nodes for the simulated cast iron "arch jack" floor.

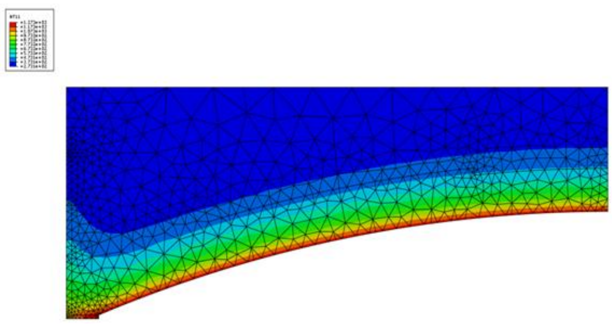

Figure 10. Temperature contour in the simulated "arch-jack" floor (analysis case 1) after 90min of fire exposure.

5.3 Structural response

In order to investigate the effect of the variation in the mechanical properties of masonry with temperature rise on the metal girders of the "jack-arch" floor, one quarter of a such a system (the metal were girders were considered simply supported), with the geometry given by Swailes (1995), was simulated using the finite element method (FEM). The simulation model had been thoroughly validated previously (Maraveas et al 2012). In the simulation, composite action between the steel element and the insulation materials was considered. A uniformly distributed load was applied on top of the system. The mechanical properties of “early concrete” with temperature were assumed to vary per EN1992-1-2 (2004), those of steel per EN1993-1-2 (2005) and those of masonry according to the upper and lower boundaries of Figure 4 and Figure 8. The structural model was coupled with a 3D FEM thermal analysis model, with thermal properties varying as in the 2D model element model (for masonry these were selected according to Analysis 1-Table 1). The results (Figure 11) show that the various simulations produced small deviations (less than 5%). This was expected, because the bearing capacity of the girder is governed by the strength reduction of its lower flange, which is exposed to fire and experiences a severe temperature rise with very small changes when varying the thermal properties of fireproofing materials.

6 CONCLUSIONS

The study presented in this paper shows that the mechanical and thermal properties of masonry (used in 19th century fireproof floors) exposed to fire can be accurately modeled by those of modern brick. Exception to this is the thermal expansion of masonry with Portland cement, in which reduced thermal strain or even contraction is possible. Moreover, in heated “jack-arch” fireproof floors, the temperature evolution in the metal element is not sensitive to the thermal properties of masonry and any of the derived boundary curves for the bricks can be used to accurately model it. The strength reduction in masonry is not significant at low temperatures and is not expected to affect the fire resistance of the system. The thin portion in which high temperature rise is observed is located in the tensile area of the composite cross-section where even vary large variations in the thermal properties of the fireproofing materials have little effect..

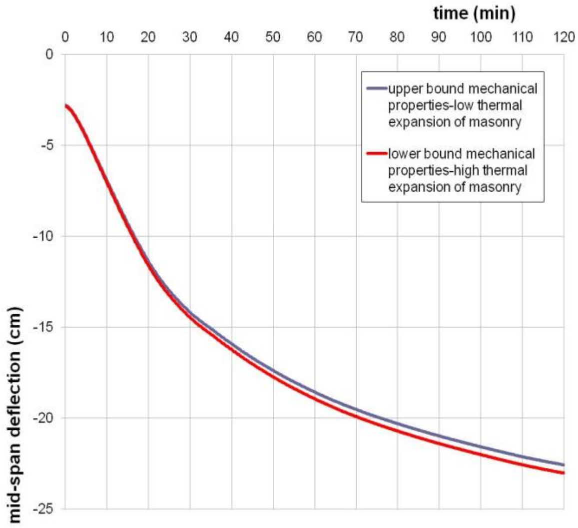

Figure 11. Mid-span deflection of the composite jack arch cast iron beam. .

REFERENCES

Aydin, S., Yazici, H. & Baradan, B., 2008. *High temperature resistance of normal strength and autoclaved high strength mortars incorporated polypropylene and steel fibers.* Construction and Building Materials 22: 504-512.

Brown, W.P. & Wilson, A.G., 1962. *The Thermal Conductivity of Brick Walls - A summary of literature reviewed.* National Research Council of Canada, Division of Building Research. Technical Note No.380.

Cruz, R. & Gillen, M., 1980. *Thermal Expansion of Portland Cement Paste, Mortar, and Concrete at High Temperatures*. Fire and Materials; 4(2).

Cülfik, M.S. & Özturan, T., 2002. *Effect of elevated temperatures on the residual mechanical properties of high-performance mortar.* Cement and Concrete Research 32: 809-816.

European Committee for Standardization, 2004. *Eurocode 2 - Design of concrete structures - Part 1-2: General rules - Structural fire design.* Brussels: European Standard EN 1992-1-2.

European Committee for Standardization, 2005. *Eurocode 3 - Design of steel structures - Part 1-2: General rules - Structural fire design.* Brussels: European Standard EN 1993-1-2.

European Committee for Standardization, 2005. *Eurocode 6 - Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures.* Brussels: European Standard EN 1996-1-1.

European Committee for Standardization, 2005. *Eurocode 6 - Design of masonry structures - Part*

1-2: General rules - Structural fire design. Brussels: European Standard EN 1996-1-2.

Harmathy, T.Z., 1983. *Properties of building materials at elevated temperatures.* National Research Council of Canada, Division of Building Research. DBR Paper No. 1080.

Hu, X.F., Lie, T.T., Polomark, G.M. & MacLaurin J.W., 1993. *Thermal Properties & Building Materials at Elevated Temperatures.* National Research Council of Canada, Division of Building Research. Internal Report No. 643.

ISO 834, 1999. Fire resistance tests-elements of building construction—Part 1: General requirements. International Standard ISO 834-1.

Maraveas,C., Swailes,T., Wang,Y.C. 2012, *A detailed methodology for the finite element analysis of asymmetric slim floor beams in fire*, Steel Construction 5 (3), 191-198

Maraveas, C., Wang, Y.C. & Swailes, T., 2013. *Thermal and Mechanical properties of 19th century fireproof flooring systems at elevated temperatures*, Construction & Building Materials 48: 248-264.

Nadjai, A., O'Gara, M., Ali, F. & Jurgen, R., 2006. *Compartment Masonry Walls in Fire Situations.* Fire Technology 42: 211-231.

Podĕbradská, J., Pavlík, J., Toman, J. & Černý, R., 2005. *Specific heat capacity of cementitious composites in high-temperature range.* In: Proceedings of the Thermophysics 2005 meeting of the Thermophysical Society Working Group of the Slovak Physical Society. Bratislava, Slovakia.

Türkmen, I. & Fındık, S.B., 2010. *Several properties of mineral admixtured lightweight mortars at elevated temperatures.* Fire and Materials. doi: 10.1002/fam.1030.

Swailes, T., 1995. *19th century cast-iron beams: their design, manufacture and reliability.* Civil Engineering 114: 25-35.