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Modeling of Insulation in 19th Century Metal Framed Structures

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ABSTRACT: In 19th century metal framed construction, load-bearing girders were encased in "jack arch" fire-proofing. Since the masonry arches were filled with "early concrete" or other filling materials (which provided thermal insulation to the metal girders), their thermal properties are necessary in determining the temperature profiles of cast iron/steel beams during fire exposure. This paper will present the results of a detailed sensitivity study to investigate the effects of changing the thermal properties of "early concrete" and masonry within the bounds of variability on the fire resistance of the flooring system. Four sets of 2D thermal finite element analyses will be conducted for a typical geometry of the "jack-arch" flooring system. Results will be presented in terms of time-temperature evolution curves at different representative locations of the metal beam (upper flange, mid-height of the web and lower flange). In each analysis set, the thermal properties (i.e. thermal conductivity and specific heat) of one insulating material (masonry or "early concrete") will be kept constant and those of the other vary. The temperature-dependent thermal properties are selected according to the appropriate upper and lower bound curves derived from relevant experimental data, either found in open literature or in current design codes. In all the analysis cases, the thermal properties of the metals (cast iron, wrought iron and mild steel) are the same as those for modern steel due to close similarities in the chemical compositions of these materials. The results of the sensitivity study demonstrate that the temperatures in the metal beams are not different from those when assuming the insulation has properties similar to those of concrete. It will be concluded that a model of insulation adopting the EN 1992 part 1 - 2 thermal properties of concrete can provide an accurate estimate of the temperature evolution in the steel/cast iron girders.

Keywords: insulation, 19th century metal structures, fire, thermal properties, arch jack floors, masonry, early concrete, cast iron, wrought iron

1 INTRODUCTION

A common way to provide fire protection in 19th century fireproof flooring construction was to enclose the fire-susceptible metal girders, which were the main load-carrying elements of the system, with insulation materials of that era. These were "early concrete" and masonry. "Early concrete" refers to a material different from modern concrete, as it was produced from various out-of-date materials (limestone, crushed tile, broken brick, cinders, ash or rubble). Masonry was typically made out of units (heavyweight or lightweight) and mortars, which in certain occasions were replaced by Portland cement.

In a typical fireproof floor ("arch-jack" configuration-Figure 1(a)), singly-symmetric cast iron girders were partially enclosed by "early concrete" and masonry, with the lower flange remaining unprotected in most cases. The insulation materials were placed between consecutive beams forming arches. In another configuration ("joist-filler" floor-Figure 1(b)), symmetric wrought iron or mild steel beams were totally encased in "early concrete".

This paper investigates the thermal property variation of the insulation materials with temperature. Afterwards, a sensitivity analysis is conducted to investigate the effect of selecting different models for the thermal properties of the insulation on the temperature rise of the metal element.
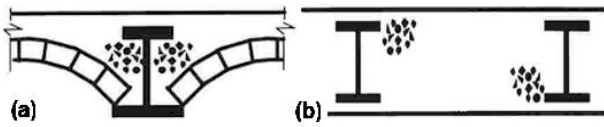
Figure 1. Typical configuration of a typical (a) "jack arch" and (b) "filler joist" 19th century fireproof floor.

2 THERMAL PROPERTIES OF THE INSULATION MATERIALS

The different chemical compositions, in conjunction with the non-standardized manufacturing procedures of the materials used as insulation in 19th century flooring construction, result in thermal properties that vary considerably at ambient as well as elevated temperature conditions. Experimental data collected by Maraveas et al (2013) confirm this statement. These refer to the thermal conductivity and specific heat of heavyweight masonry units (density ρ=1900-2200kg/m^3), lightweight masonry units (density ρ=700-1000kg/m^3), Portland cement, mortars and "early concrete" under elevated temperature effects. Based on this experimental database, upper and lower boundary curves have been derived and are presented in Figure 2 (plot of thermal conductivity variation with temperature) and Figure 3 (plot of specific heat variation with temperature). Relevant expressions for modern concrete per EN1992-1-2 (2004) have also been included in these plots.
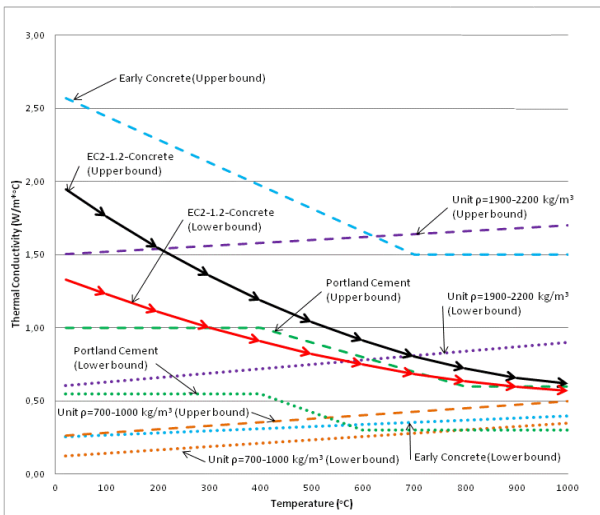

Figure 2. Proposed upper and lower boundary curves for the thermal conductivity variation of the insulation materials with temperature.
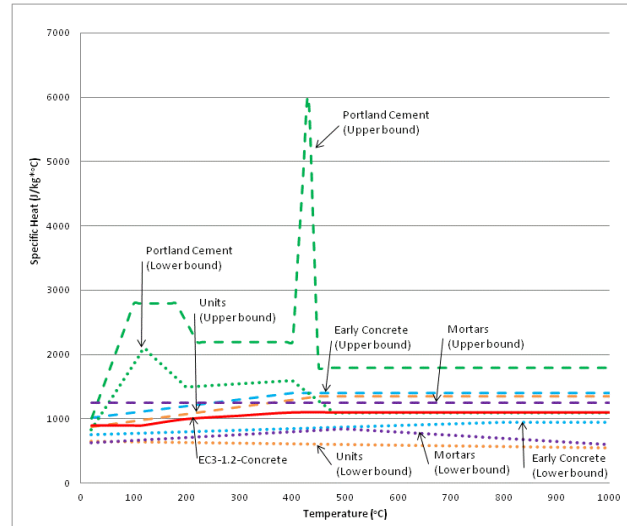

Figure 3. Proposed upper and lower boundary curves for the specific heat variation of the insulation materials with temperature.

Figure 4 compares the thermal conductivity variation of the insulation materials under thermal exposure with that of steel according to EN1993-1-2 (2005). Despite the wide range of the proposed boundaries, due to the scatter of the data, the thermal conductivities of the insulation materials are very small (less than 5% at ambient temperature and approximately 10% above 800°C) compared with that of steel, which is similar to that of the encased metal structural elements. This is a strong indication that the variability of the insulation materials is not expected to affect temperature evolution of the metal beam in a major way and will be confirmed by the subsequent sensitivity analysis. On the contrary, the difference is not so profound for the specific heat (Figure 5).
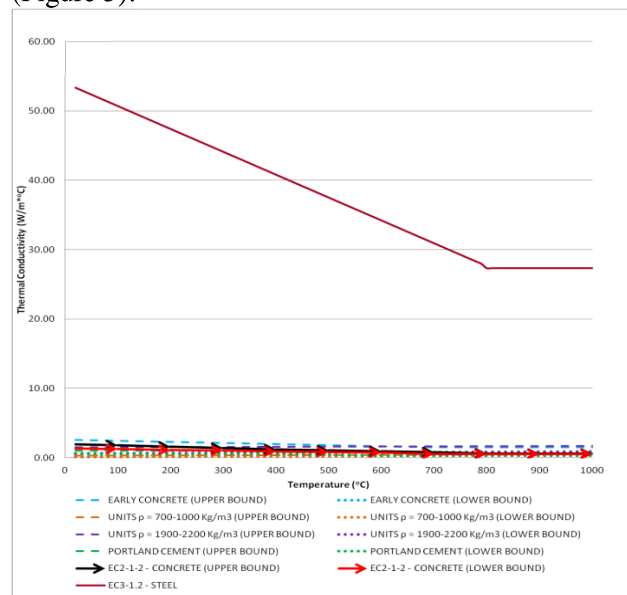

Figure 4. Comparison between thermal conductivity variation of the insulation materials (proposed upper and lower boundaries) and steel (EN1993-1-2, 2005) with temperature.
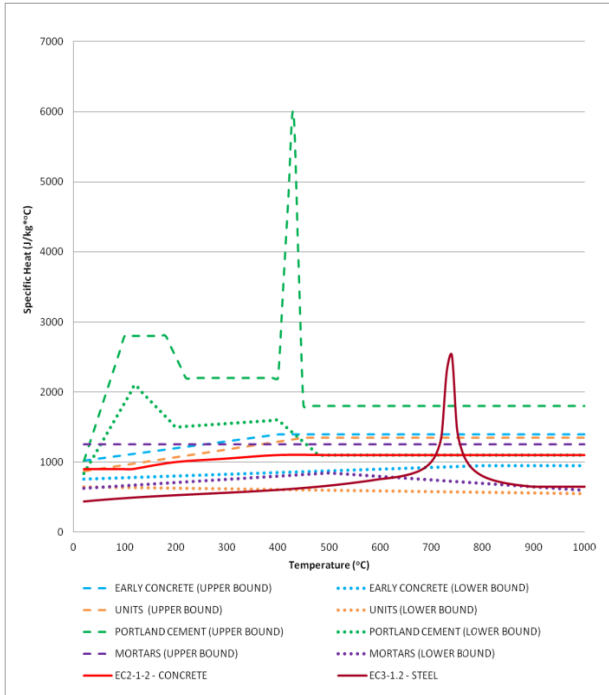
258

Figure 5. Comparison between specific heat variation of the insulation materials (proposed upper and lower boundaries) and steel (EN1993-1-2, 2005) with temperature.

3 SENSITIVITY ANALYSIS OF 19TH CENTURY FIREPROOF FLOORS

3.1 Geometry of the modeled flooring system

To investigate the variability of the insulation materials on the temperature evaluation of the metal elements, which are the main load bearing elements in 19th century fireproof flooring construction, a thorough sensitivity analysis was performed. A typical "arch-jack" floor, which is described by Swailes (1995), was analyzed using the commercial finite element software ABAQUS.

Detailed information regarding its geometrical characteristics is given in Figure 6. The encased cast iron beam has a singly symmetric cross-section with an overall height of 457.2mm. The web is 30mm thick and the lower flange (which is wider than the upper) has a thickness of 40mm. The underlying masonry has variable depth, which reduces towards the center of the span formed between two consecutive girders. Moreover, the lower flange of the beam is unprotected.
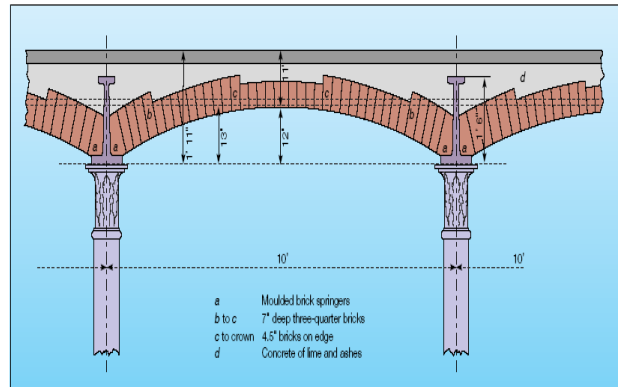

Figure 6. Jack-arch flooring system used in the finite element simulations, as described by Swailes (1995).

3.2 Finite element model

For the "jack arch" flooring system described above, a 2D heat transfer analysis was performed using the commercial finite element program ABAQUS. The created model is depicted in Figure 7. Due to symmetry, only half of the span was modeled. The generated finite element mesh accounts for the geometric characteristics and the different materials of the actual system described by Swailes (1995). The temperature evolution is calculated for three distinct locations of the cast iron girder (Node A: lower flange, Node B: mid-height of the web, Node C: upper flange).
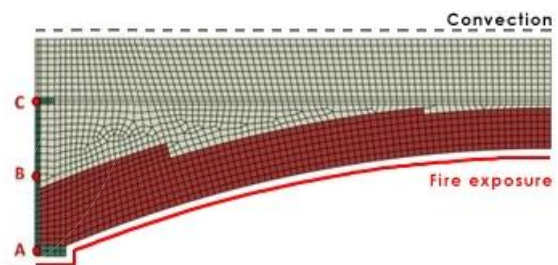
Figure 7. 2D Finite element model generated for the thermal analysis of the jack-arch flooring system. (Node A: Lower Flange, Node B: Web, Node C: Upper Flange).

The model was exposed to the ISO-834 standard fire (1999) from below for a total duration of 120min. The heat transfer boundary conditions followed the regulations of EN1993-1-2 (2005). More specifically, the convective heat transfer coefficient was assumed to be 25 W/m²K at the surface exposed to fire. The value for the resultant emissivity was 0.7. For the unexposed surface, the total heat transfer coefficient was 9W/m²K.

3.3 Analysis cases

The sensitivity of the temperature evolution in the metal structural element to the thermal properties of the insulating materials was studied by performing

259

41 analyses in total. In each analysis case, the specific heat and thermal conductivity of the insulation were selected from the various upper and lower boundary curves presented earlier. For all analysis cases, the thermal properties of the cast iron beam were assumed to be those of EN1993-1-2 (2005) for steel, because of the similarities in the chemical compositions of the two materials. The analyses can be categorized in four analysis sets, in which one insulating material was given "fixed" (constant) thermal properties, while those of the other corresponded to different derived boundaries. A summary of the analysis sets and the selection of the "fixed" thermal property are given in Table 1. It should be noted that the thermal properties of the mortars and Portland cement were not included in the sensitivity analysis, because of their minor influence on the thermal response of masonry and the insulation in general.

Table 1. Thermal analysis sets for the studied "arch-jack" system.

Analysis Set	"Fixed" thermal property	Selected curve for "fixed" property	Analysis Cases
1	masonry thermal conductivity	heavyweight unit upper bound	12
	masonry specific heat	heavyweight unit upper bound	
2	masonry thermal conductivity	lightweight unit lower bound	12
	masonry specific heat	lightweight unit lower bound	
3	"early" concrete thermal conductivity	EN1992-1-2 upper bound	8
	"early" concrete specific heat	EN1992-1-2	
4	"early" concrete thermal conductivity	EN1992-1-2 lower bound	8
	"early" concrete specific heat	EN1992-1-2	

Moreover, a separate analysis (which is referred to as "all-concrete" analysis) using the properties of modern concrete per EN1992-1-2 (2004) for the thermal properties of the insulation materials was performed for comparison purposes. In this analysis, the lower bound curve for the thermal conductivity was selected.

3.4 Analysis results

The results of the sensitivity analysis are summarized in Figure 8, which shows the temperature evolution at the lower flange (Node A), the mid-height of the web (Node B) and the upper flange (Node C). The presented temperature curves correspond to the "averaged" results for each analysis set and the "all-concrete" analysis. The time-temperature evolution of the ISO-834 standard fire (1999) is also included. It should be noted that small deviations were observed among the different cases of each analysis set and their "average" curve can be used to represent temperature evolution.
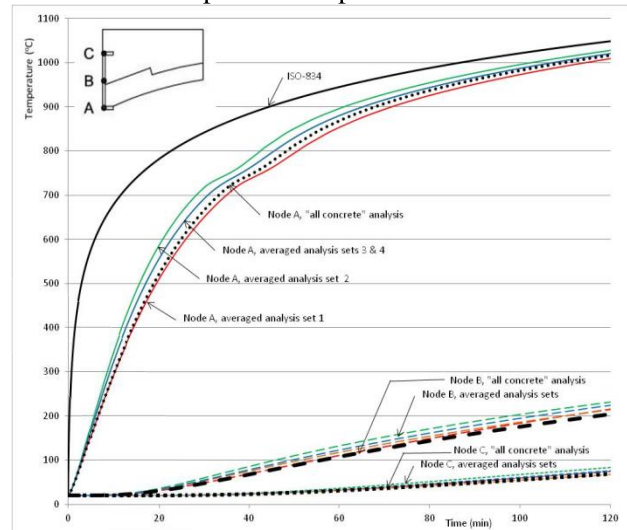

Figure 8. Evolution of temperature at three representative nodes for the studied cast iron "jack arch" floor. The curves refer to the averaged results obtained from the four analysis sets and the "all-concrete" analysis, in which the thermal properties of the insulating materials are modeled according to those of contemporary concrete per EN1992-1-2 (2004).

As expected, the temperature of the unprotected flange rises rapidly and tends to follow the ISO-834 (1999) standard fire curve. On the contrary, the temperature evolution at the other two locations is much slower. Especially at the upper flange, the temperature does not exceed 100°C after 120min of heating. Simulation results also show that temperature at the mid-height of the section reached approximately 200°C to 250°C after the same fire exposure time in all analysis sets. These observations confirm the role of insulation in impeding heat transfer to the load bearing element.

Despite the different models used to simulate the thermal properties of the insulation, minor differences in the temperature evolution curves are observed. Results from all analysis sets are in close agreement. Moreover, the observed variations are not expected to seriously affect the estimation of the load-carrying capacity of the girder, because in the low temperature region (lower than 250°C, i.e. Node B and Node C) its mechanical properties are only affected in a minor way.

4 CONCLUSIONS

The sensitivity analysis presented in this paper showed that the variability in the thermal properties of the insulation materials used in 19th century fireproof flooring construction has little effect on the temperature evolution of the metal load-bearing elements, when such systems are subjected to fire. Additionally, the current formulas for the thermal properties of contemporary concrete given in Eurocode 2 (lower bound specific heat and thermal conductivity) can be used to model the insulation of 19th century fireproof floors in a simple manner and with sufficient accuracy.

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