C. Maraveas, Y.C. Wang, T. Swailes, Fire resistance of 19th century fireproof flooring systems: A sensitivity analysis, Construction and Building Materials, Volume 55, 31 March 2014, Pages 69-81, ISSN 0950-0618, http://dx.doi.org/10.1016/j.conbuildmat.2014.01.022.

(http://www.sciencedirect.com/science/article/pii/S0950061814000464)

Fire Resistance of 19th Century fireproof flooring systems: A sensitivity analysis

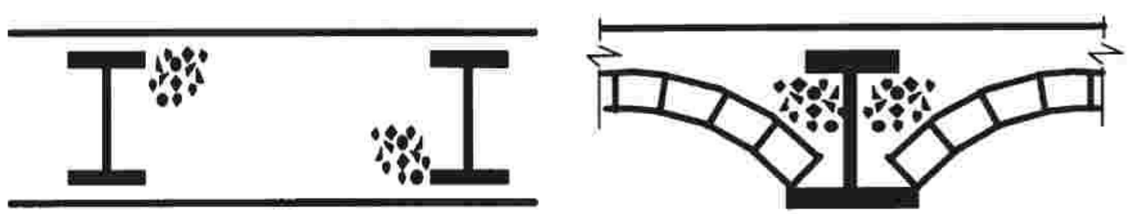
Abstract

Typical fireproof flooring systems of the 19th century comprise of metal beams embedded within insulation materials that span between them, sometimes in the form of arches. The limited or non-existent fire resistance requirement of that era demands a thorough understanding of their structural fire response when dealing with their conservation. This requires suitable material property models. Historical records from different sources contain large variations in the thermal (insulation and metals) and mechanical (for metals) properties of the materials. In this research, the variations were placed within lower and upper boundary curves. A sensitivity study of the thermal behaviour of typical flooring systems was conducted. The results of this study were used to indicate the level of uncertainty in the thermal properties of the metals (cast iron, wrought iron and mild steel) and the "insulation" materials ("early concrete" and masonry) that may be tolerated without introducing large inaccuracy (>10%) in the structural temperature results. To assess the applicability of the proposed boundary curves for the mechanical properties of the metals, the second series of sensitivity analyses of structural performance was performed, using the temperature profiles from the thermal sensitivity study.

Keywords: fireproof flooring; cast iron; wrought iron; mild steel; early concrete; masonry; thermal conductivity; specific heat; mechanical properties; elevated temperatures

1. Introduction

In typical 19th century fireproof flooring systems, metal beams (made out of cast iron, wrought iron or mild steel) were used as the main load-bearing elements. To provide the necessary fire protection, a common practice was to encase the metal members of the floor with insulation materials ("early concrete" or masonry). It should be noted that "early concrete" was made from various constituents (broken brick, crushed tile, cinders, limestone etc.) different from those in modern concrete production. The two predominant types of such flooring systems are the "filler joist" (Figure 1a) and the "arch jack" (Figure 1b) floors. In a typical "filler joist", wrought iron or mild steel girders are completely encased in "early concrete". The "arch jack" floor commonly consists of asymmetric cast iron girders embedded in "early concrete" and masonry in an arch form supported by the lower flanges of the metal beams which remain unprotected.



a) b)

Figure 1: Typical a) "Filler joist" and b) "Arch jack" floor [1].

In order to investigate the behavior of 19th century fireproof flooring systems under fire exposure and evaluate their fire resistance, it is critical to establish the thermal and mechanical properties of the constituent materials (metal beam and insulation) at elevated temperatures. The authors [2] have recently presented the results of a thorough literature review which has yielded an extensive experimental database of the required thermal and mechanical properties. The collected results showed that considerable scatter existed in some cases. However, it can be argued that if the structural performance of the metal beams is not sensitive to the scatter, it would be acceptable to use some nominal (such as the mean) values for the material properties. Whether or not this is the case can be answered by performing a sensitivity study and this is the overall aim of the this paper. Specifically, this research will investigate the sensitivity of the fire resistance performance of the metal beams to variations in the following relevant material properties:

(1) Thermal properties (thermal conductivity, thermal capacitance = specific heat * density) of the metals;

(2) Thermal properties of the insulation materials;

(3) Mechanical properties of the metals.

The variations in the relevant properties collected from literature by the authors [2] are represented by the lower bound and upper bound values fitted to the collected data. These boundary curves (usually straight lines) provide an envelope to the collected experimental data. Because the collected data were from different sources, some dating back a long time ago, they do not always follow a consistent pattern. Hence some boundary curves contain spikes within some specific temperature regions.

The criteria for deciding sensitivity of the fire resistance performance results to variations in the material properties are: for the thermal properties, the fire performance of the metal beams is considered not sensitive to the variations of the properties if the calculated structural temperature does not vary by more than 10% from the mean value; for the mechanical properties of the metals, the fire performance of the metal beams is considered not sensitive to the properties if the load carrying capacity of the metal beam does not vary by more than 10% from the mean value.

2. Lower and upper bound values of relevant material properties

2.1 Metals

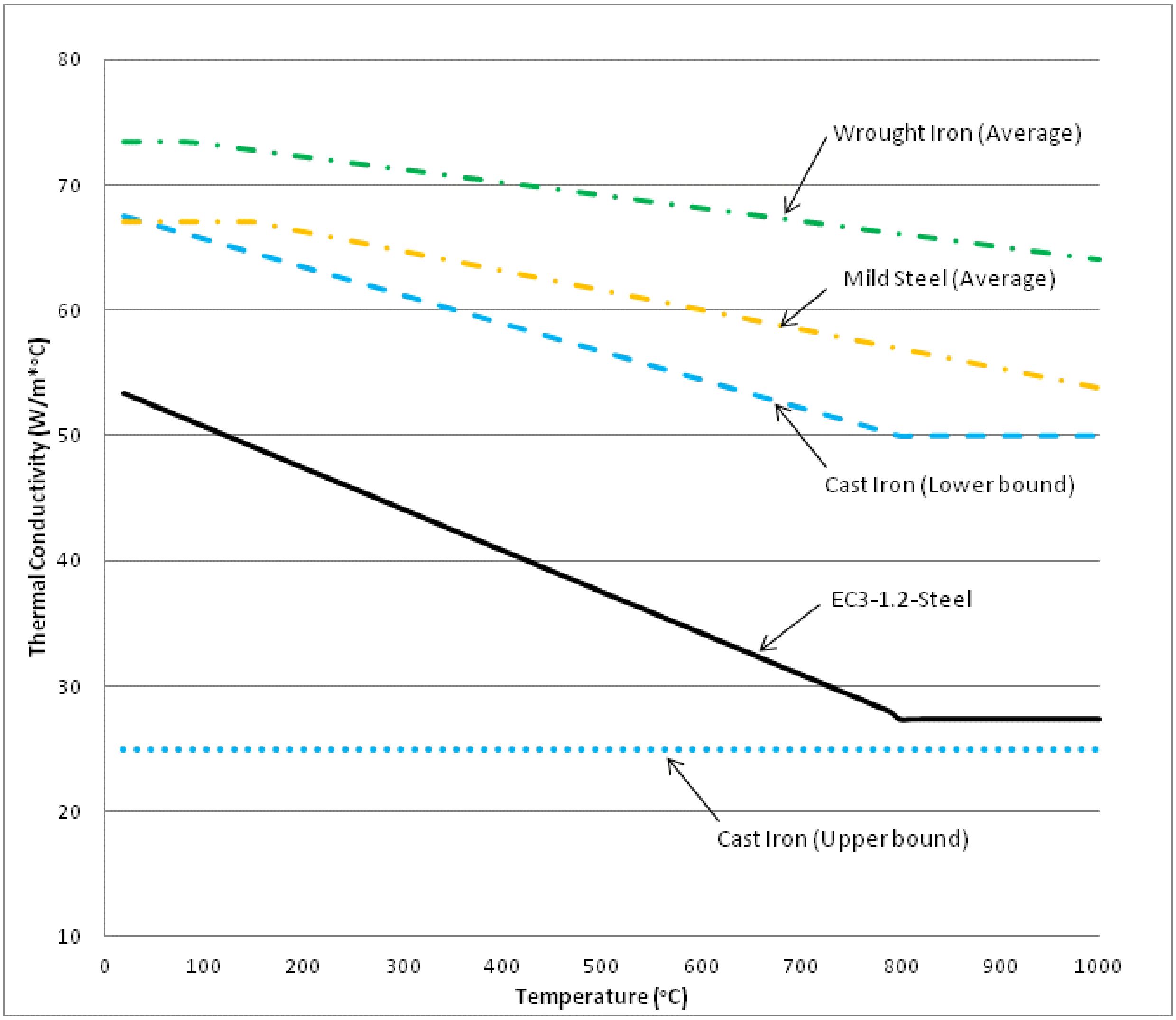
2.1.1 Thermal properties

Figure 2a shows the relevant graphs for thermal conductivity, while Figure 2b is for specific heat. The respective expressions for modern steel, as given in EN1993-1-2 [3], are also included for comparison. It should be noted that the thermal conductivity data for wrought iron and mild steel have negligible scatter so they are described by single "average" curves in Figure 2a. The equations for these boundary curves are presented in Table 1.

Table 1: Equations for thermal property boundary curves

	Thermal Conductivity(W/m*ºC)			Specific Heat(J/kg*ºC)	
Material	**Lower bound**	**Average**	**Upper bound**	**Lower bound**	**Upper bound**
Cast iron	$\lambda = 25$		For $T \leq 800^oC$ $\lambda = 68 - 0.0225 * T$ For $T > 800^oC$ $\lambda = 50$	For $T \leq 850^oC$ $c_p = 185 + 0.3 * T$ For $T > 850^oC$ $c_p = 440$	For $T \leq 670^oC$ $c_p = 550 + 0.6 * T$ For $670 < T \leq 735^oC$ $c_p = 16.12 * T - 9850.5$ For $735 < T \leq 750^oC$ $c_p = 46100 - 60 * T$ For $T > 750^oC$ $c_p = 1100$
Wrought Iron		For $T \leq 85^oC$ $\lambda = 73.5$ For $T > 85^oC$ $\lambda = 74.372 - 0.0103 \times T$			
Mild Steel		For $T \leq 150^oC$ $\lambda = 67$ For $T > 150^oC$ $\lambda = 69.333 - 0.0156 \times T$			
Early Concrete	For $T \leq 1000^oC$ $\lambda = 0.25 + 0.00015 \times T$ For $T > 1000^oC$ $\lambda = 0.40$		For $T \leq 700^oC$ $\lambda = 2.6 - 0.00157 \times T$ For $T > 700^oC$ $\lambda = 1.5$	For $T \leq 800^oC$ $c_p = 750 + 0.25 \times T$ For $T > 800^oC$ $c_p = 950$	For $T \leq 400^oC$ $c_p = 1000 + T$ For $T > 400^oC$ $c_p = 1400$
Masonry units	(HEAVYWEIGHT) $\lambda = 0.6 + 0.0003 \times T$ (LIGHTWEIGHT) $\lambda = 0.12 + 0.00023 \times T$		(HEAVYWEIGHT) $\lambda = 1.5 + 0.0002 \times T$ (LIGHTWEIGHT) $\lambda = 0.26 + 0.00024 \times T$	$c_p = 650 - 0.1 \times T$	For $T \leq 450^oC$ $c_p = 850 + 1.111 \times T$ For $T > 450^oC$ $c_p = 1350$
Portland Cement	For $20^oC \leq T \leq 400^oC$ $\lambda = 0.55$ For $400^oC < T \leq 600^oC$ $\lambda = 1.05 - 0.00125 \times T$ For $T > 600^oC$ $\lambda = 0.3$		For $T \leq 400^oC$ $\lambda = 1$ For $400^oC < T \leq 800^oC$ $\lambda = 1.40 - 0.001 \times T$ For $T > 800^oC$ $\lambda = 0.60$	For $T \leq 120^oC$ $c_p = 584 + 12.63 \times T$ For $120^oC < T \leq 200^oC$ $c_p = 3000 - 7.5 \times T$ For $200^oC < T \leq 400^oC$ $c_p = 1400 + 0.5 \times T$ For $400^oC < T \leq 480^oC$ $c_p = 4100 - 6.25 \times T$ For $T > 480^oC$ $c_p = 1100$	For $T \leq 100^oC$ $c_p = 564.7 + 22.35 \times T$ For $100^oC < T \leq 180^oC$ $c_p = 2800$ For $180^oC < T \leq 220^oC$ $c_p = 5500 - 15 \times T$ For $220^oC < T \leq 400^oC$ $c_p = 2200$ For $400^oC < T \leq 430^oC$ $c_p = -48466.7 + 126.67 \times T$ For $430^oC < T \leq 450^oC$ $c_p = 96300 - 210 \times T$ For $T > 450^oC$ $c_p = 1800$
Mortars				For $T \leq 500^oC$ $c_p = 620 + 0.46 * T$ For $T > 500^oC$ $c_p = 1100 - 0.5 * T$	$c_p = 1250$

a)



80
70
60
50
40
30
20
10
0
100
200
300
400
500
600
700
800
900
1000
Thermal Conductivity (W/m*°C)
Temperature (°C)
Wrought Iron (Average)
Mild Steel (Average)
Cast Iron (Lower bound)
EC3-1.2-Steel
Cast Iron (Upper bound)

b)

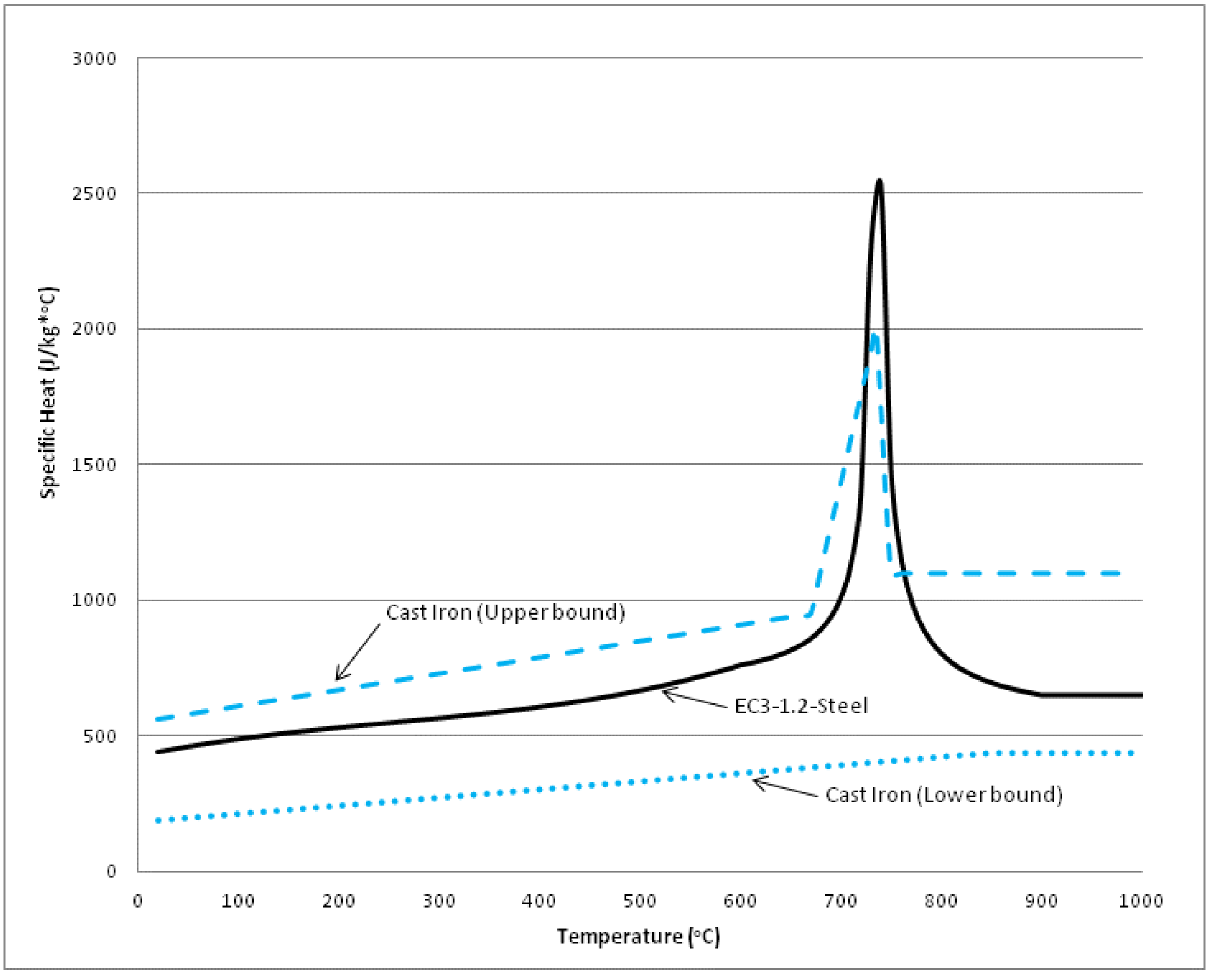


Figure 2: Variations of: a) thermal conductivity and b) specific heat with temperature for the metals of 19th century fireproof floors

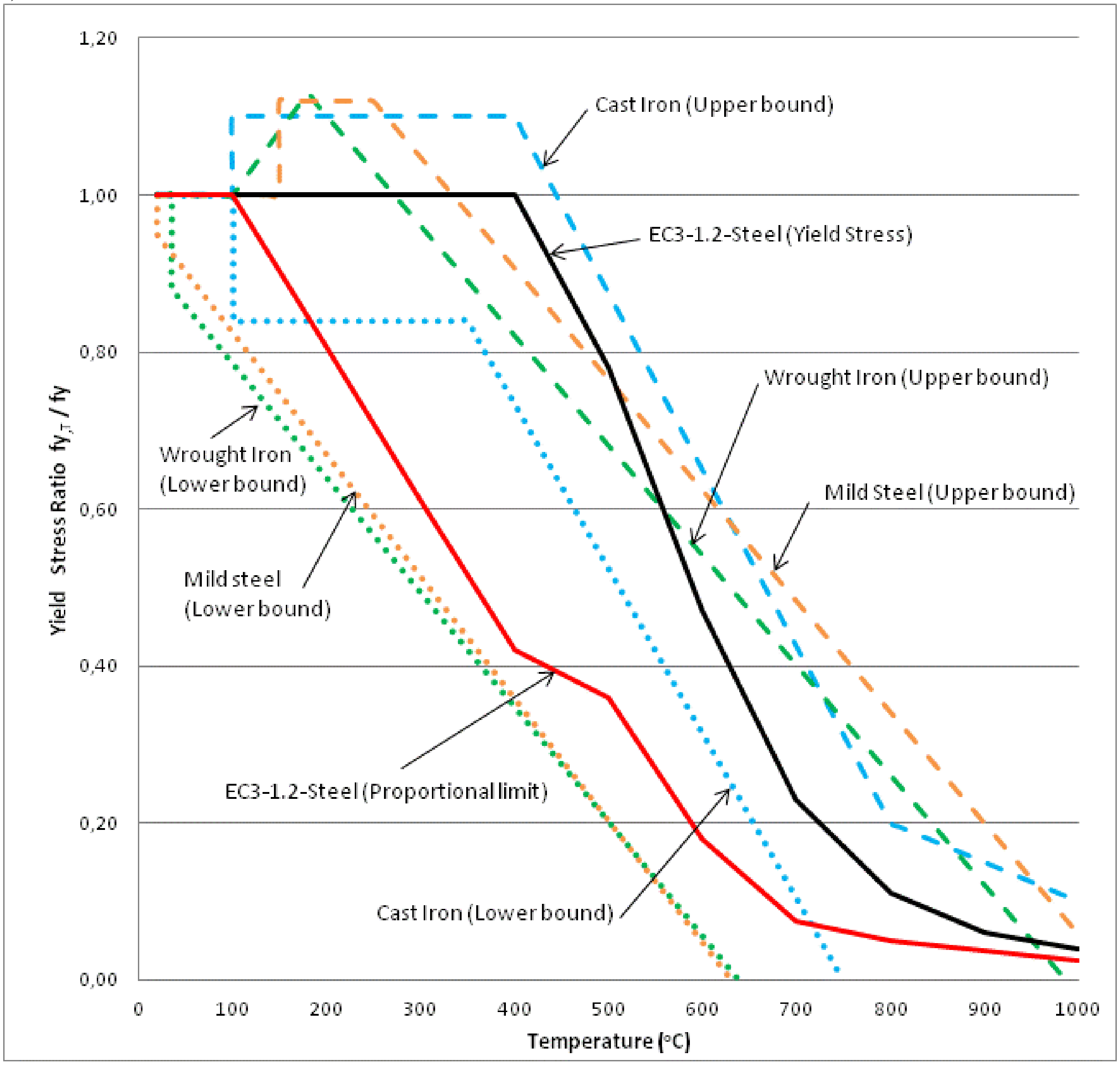
2.2 Mechanical properties

Table 2 presents the lower and upper bound equations for the mechanical properties of cast iron, wrought iron and mild steel. These equations are plotted in Figure 3. For comparison, the data for carbon steel in EN 1993-1-2 [3] are also presented in the figures.

Table 2: Boundary curve equations for mechanical properties and thermal expansion

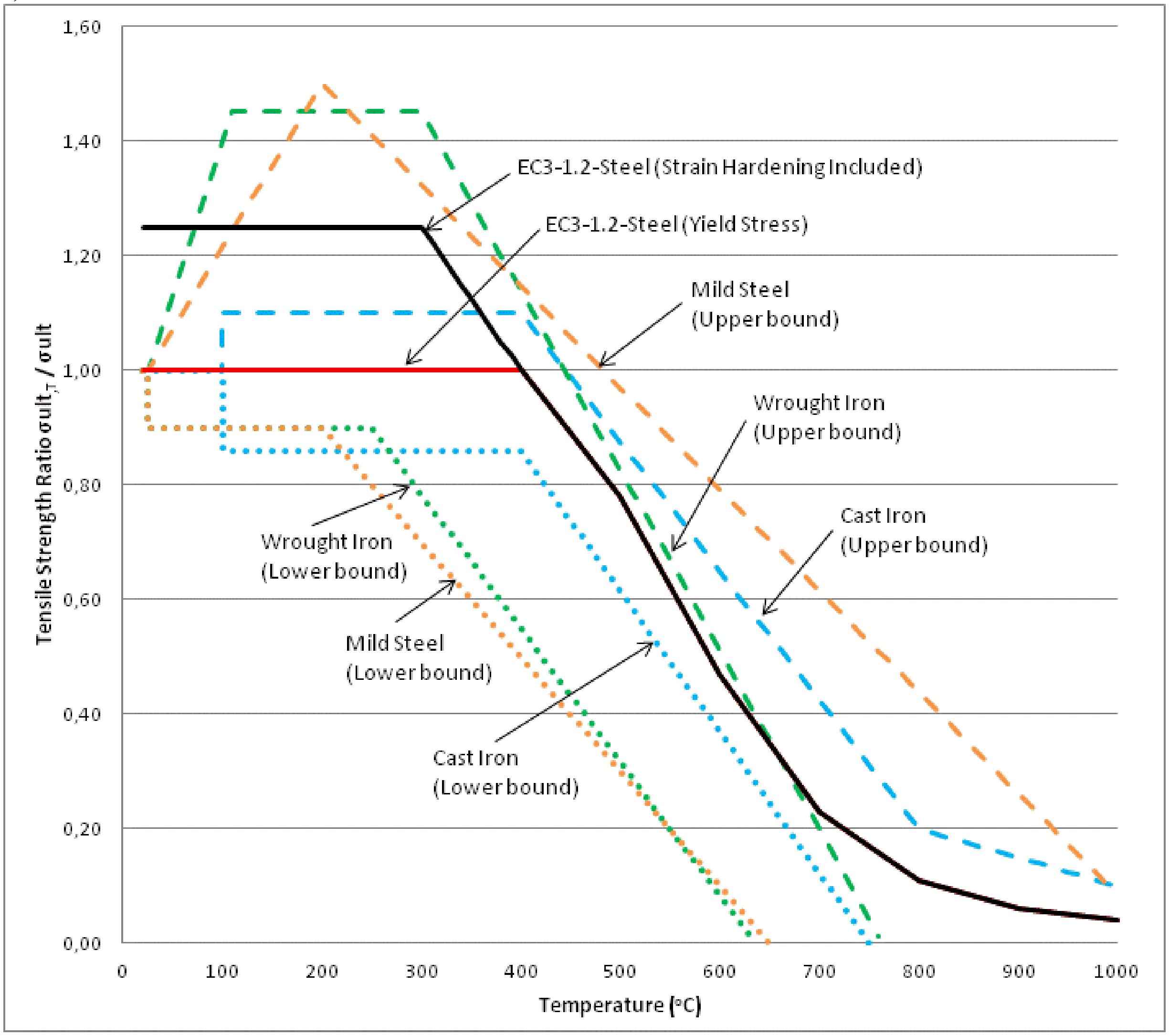
Material	Type of property	Lower bound	Upper bound
Cast iron	Yield strength reduction factor	For $T \le 100^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1$ For $100^oC < T \le 350^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 0.84$ For $T > 350^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1.58 - 0.002 \times T$	For $T \le 100^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1$ For $100^oC < T \le 400^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1.1$ For $400^oC < T \le 800^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 2 - 0.002 \times T$ For $T > 800^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 0.6 - 0.001 \times T$
	Tensile strength reduction factor	For $T \le 100^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1$ For $100^oC < T \le 400^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 0.86$ For $T > 400^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1.84 - 0.00246 \times T$	For $T \le 100^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1$ For $100^oC < T \le 400^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1.1$ For $400^oC < T \le 800^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 2 - 0.0023 \times T$ For $T > 800^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 0.6 - 0.0005 \times T$
	Elongation (%)	For $T \le 400^oC$, $\varepsilon = 0.5$ For $400^oC < T \le 600^oC$, $\varepsilon = -1.5 + 0.005 \times T$ For $T > 600^oC$, $\varepsilon = 1.5$	For $T \le 350^oC$, $\varepsilon = 1.1$ For $350^oC < T \le 600^oC$, $\varepsilon = -0.86 + 0.0056 \times T$ For $T > 600^oC$, $\varepsilon = 2.5$
	Coefficient of thermal expansion (10^{-6} x 1/ºC)	For $T \le 120^oC$, $\alpha = 10.2$ For $T > 120^oC$, $\alpha = 9.72 + 0.004 \times T$	$\alpha = 12.2 + 0.0069 \times T$
Wrought iron	Yield strength reduction factor	For $T \le 35^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1$ For $T > 35^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 0.93 - 0.00146 \times T$	For $T \le 100^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1$ For $100^oC < T \le 180^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 0.84 + 0.00163 \times T$ For $T > 180^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1.38 - 0.0014 \times T$
	Tensile strength reduction factor	For $T \le 25^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1$ For $25^oC < T \le 250^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 0.90$ For $T > 250^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1.48 - 0.00233 \times T$	For $T \le 25^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1$ For $25^oC < T \le 110^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 0.87 + 0.0053 \times T$ For $110^oC < T \le 300^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1.45$ For $T > 300^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 2.39 - 0.00313 \times T$
	Elongation (%)	For $T \le 100^oC$, $\varepsilon = 18 - 0.12 \times T$ For $T > 100^oC$, $\varepsilon = 5.2 + 0.008 \times T$	For $T \le 100^oC$, $\varepsilon = 40 - 0.20 \times T$ For $T > 100^oC$, $\varepsilon = 16 + 0.04 \times T$
	Young's modulus E reduction ratio	For $T \le 20^oC$, $\frac{E_T}{E_{20^oC}} = 1$ For $20^oC < T \le 100^oC$, $\frac{E_T}{E_{20^oC}} = 1.01 - 0.00063 \times T$ For $T > 100^oC$, $\frac{E_T}{E_{20^oC}} = 0.92 - 0.0012 \times T$	For $T \le 300^oC$, $\frac{E_T}{E_{20^oC}} = 1$ For $T > 300^oC$, $\frac{E_T}{E_{20^oC}} = 1.38 - 0.00125 \times T$
Mild Steel	Yield strength reduction factor	For $T \le 20^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1$ For $T > 20^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 0.98 - 0.00156 \times T$	For $T \le 150^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1$ For $150^oC < T \le 250^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1.12$ For $T > 250^oC$, $\frac{f_{y,T}}{f_{y,20^oC}} = 1.47 - 0.0014 \times T$
	Tensile strength reduction factor	For $T \le 25^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1$ For $25^oC < T \le 200^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 0.90$ For $T > 200^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1.3 - 0.002 \times T$	For $T \le 25^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1$ For $25^oC < T \le 200^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 0.93 + 0.003 \times T$ For $T > 200^oC$, $\frac{\sigma_{ult,T}}{\sigma_{ult,20^oC}} = 1.85 - 0.002 \times T$
	Young's modulus E reduction factor	For $T \le 25^oC$, $\frac{E_T}{E_{20^oC}} = 1$ For $25^oC < T \le 200^oC$, $\frac{E_T}{E_{20^oC}} = 0.96$ For $T > 200^oC$, $\frac{E_T}{E_{20^oC}} = 1.30 - 0.002 \times T$	For $T \le 300^oC$, $\frac{E_T}{E_{20^oC}} = 1$ For $T > 300^oC$, $\frac{E_T}{E_{20^oC}} = 1.4 - 0.00133 \times T$

a)



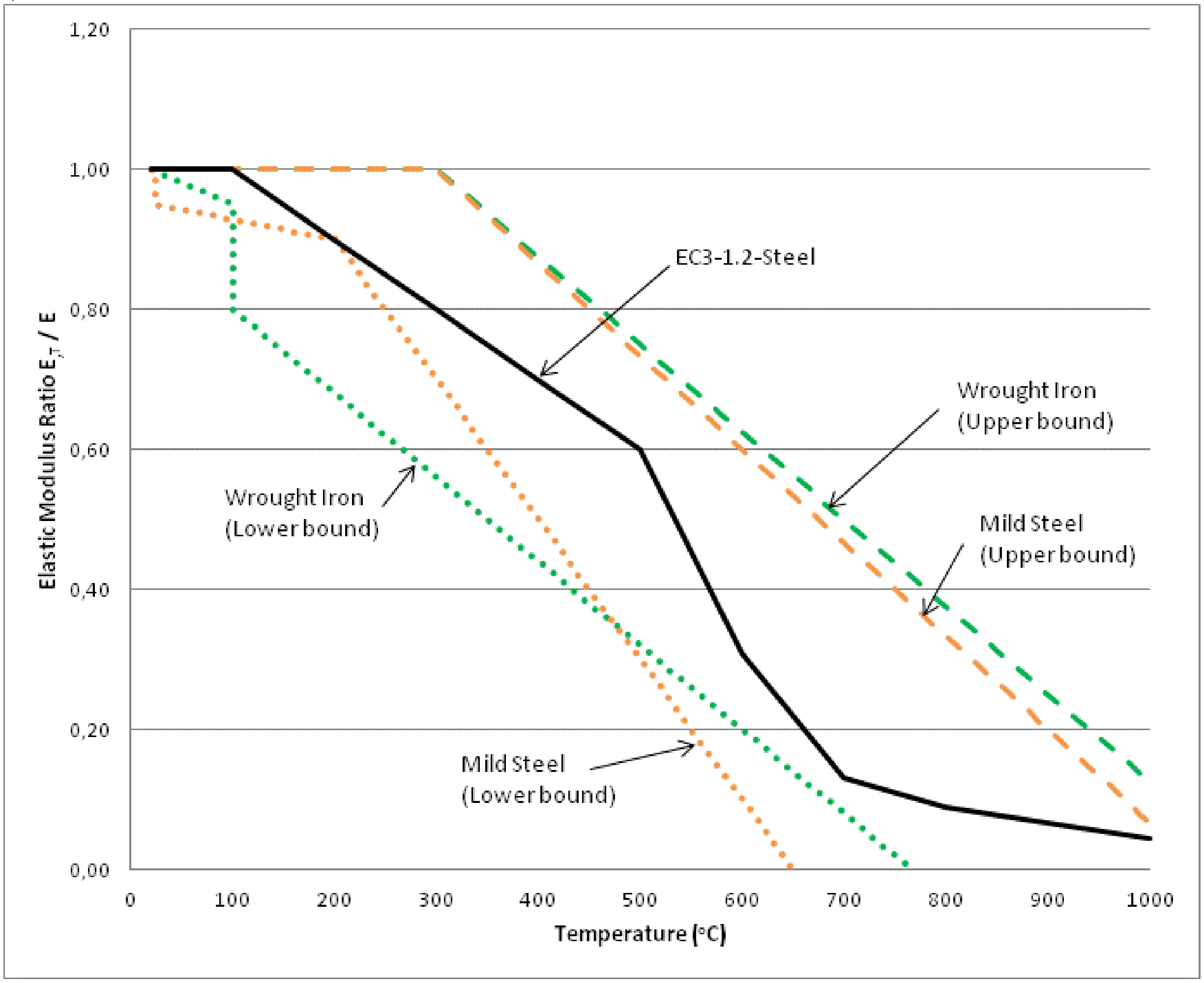
1,20
1,00
0,80
0,60
0,40
0,20
0,00
0
100
200
300
400
500
600
700
800
900
1000
Temperature (°C)
Yield Stress Ratio fy,T / fy
Cast Iron (Upper bound)
EC3-1.2-Steel (Yield Stress)
Wrought Iron (Upper bound)
Mild Steel (Upper bound)
Wrought Iron (Lower bound)
Mild steel (Lower bound)
EC3-1.2-Steel (Proportional limit)
Cast Iron (Lower bound)

b)



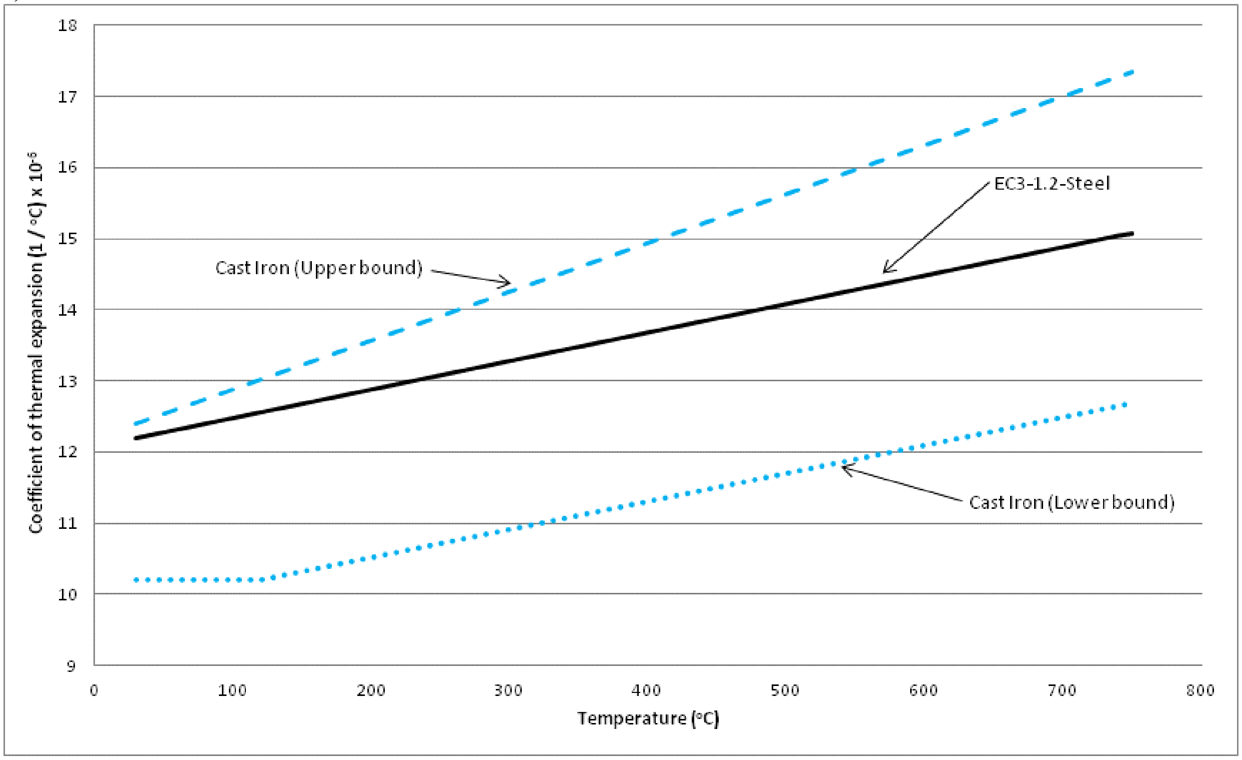
1,60
1,40
1,20
1,00
0,80
0,60
0,40
0,20
0,00
0
100
200
300
400
500
600
700
800
900
1000
Temperature (°C)
Tensile Strength Ratio σult,T / σult
EC3-1.2-Steel (Strain Hardening Included)
EC3-1.2-Steel (Yield Stress)
Mild Steel (Upper bound)
Wrought Iron (Upper bound)
Cast Iron (Upper bound)
Wrought Iron (Lower bound)
Mild Steel (Lower bound)
Cast Iron (Lower bound)

c)



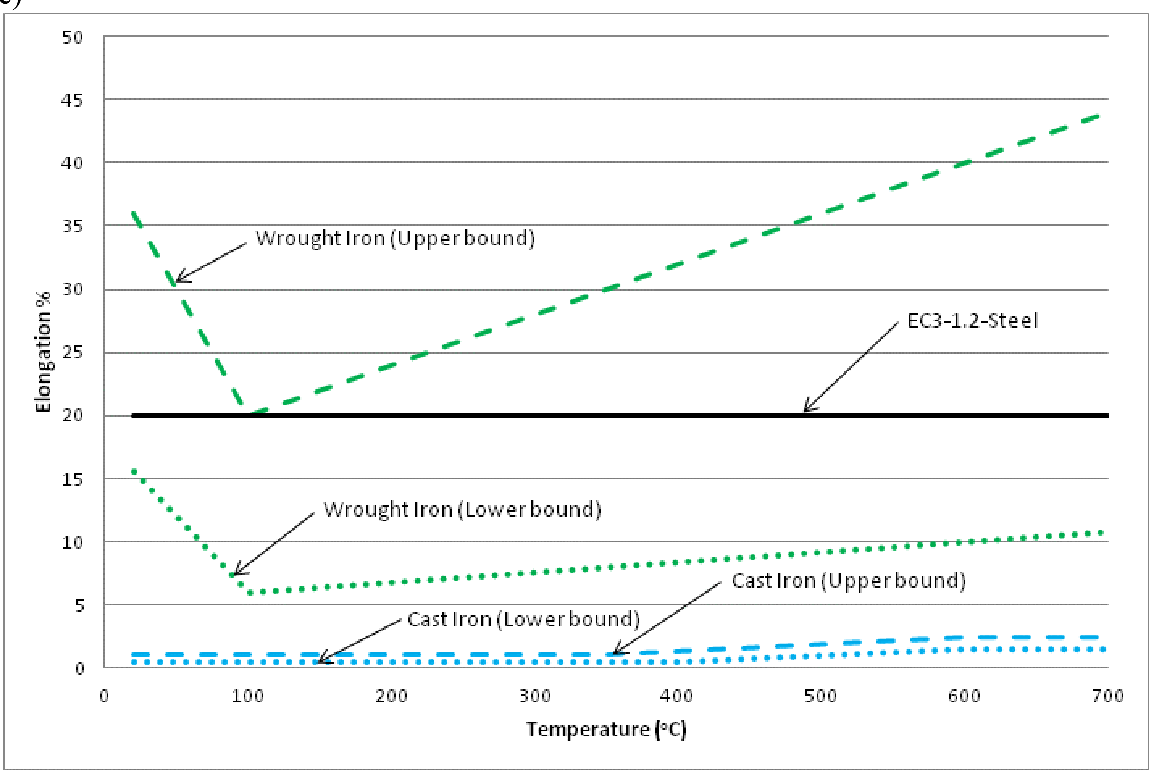
1,20
1,00
0,80
0,60
0,40
0,20
0,00
Elastic Modulus Ratio $E_{,T}$ / E
0
100
200
300
400
500
600
700
800
900
1000
Temperature (°C)
EC3-1.2-Steel
Wrought Iron (Upper bound)
Mild Steel (Upper bound)
Wrought Iron (Lower bound)
Mild Steel (Lower bound)

d)



Coefficient of thermal expansion (1 / °C) x 10⁻⁶
Temperature (°C)
EC3-1.2-Steel
Cast Iron (Upper bound)
Cast Iron (Lower bound)

e)



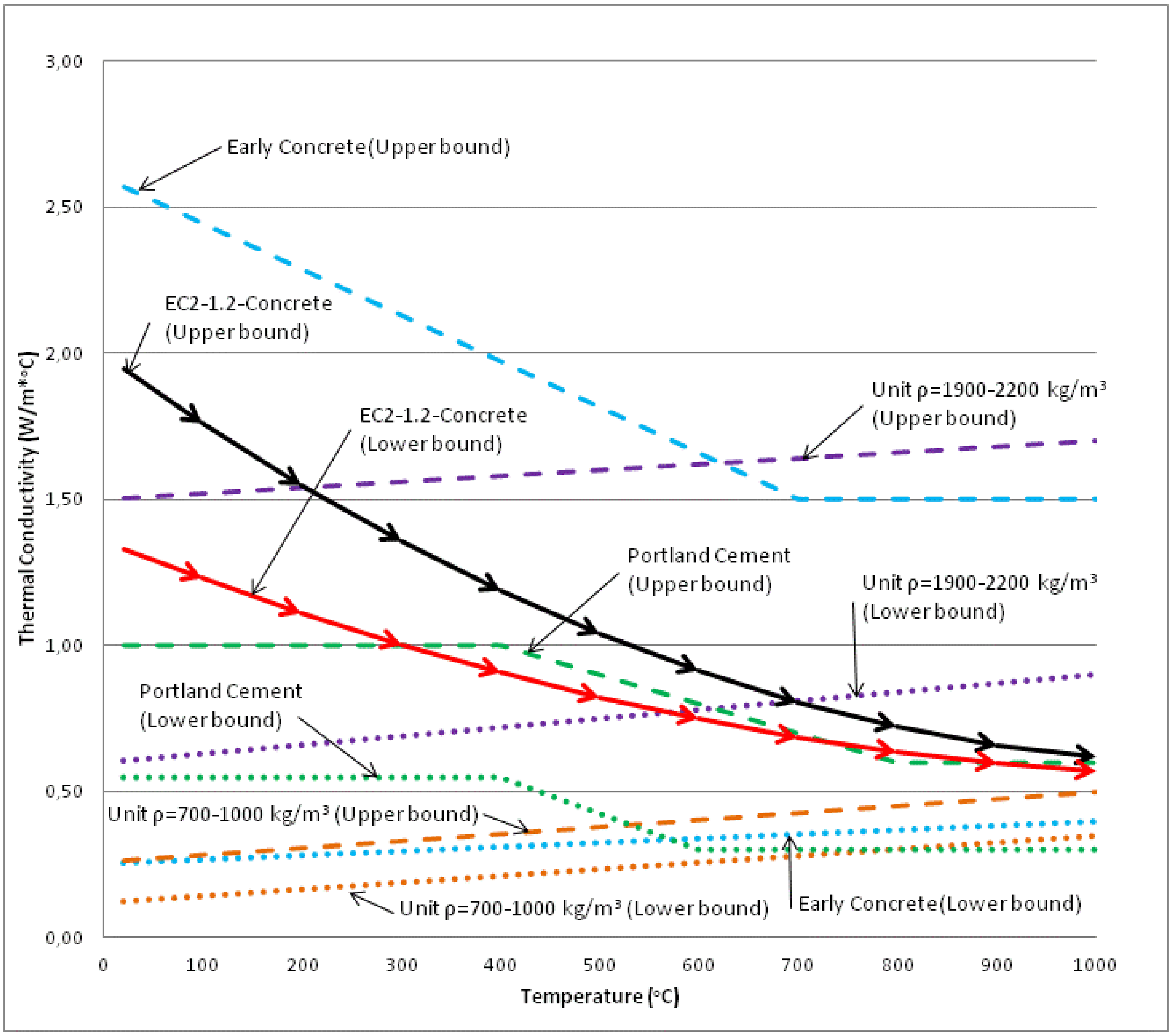
Elongation %
Temperature (°C)
Wrought Iron (Upper bound)
EC3-1.2-Steel
Wrought Iron (Lower bound)
Cast Iron (Upper bound)
Cast Iron (Lower bound)

Figure 3: Variations of: a) yield stress b) ultimate tensile strength c) Young's modulus d) coefficient of thermal expansion and e) elongation with temperature for the metals of 19th century fireproof floors

2.2 Insulation materials

The role of the insulating materials is to limit the temperature increase of the load-bearing metal elements [2]. For this reason, determining the thermal properties (thermal conductivity and specific heat) of these materials at elevated temperatures is of the utmost importance. Figure 4 shows relevant plots of the derived lower and upper bound curves based on the collated data by the authors [2]. The mathematical expressions for these boundary curves are given in Table 1.

a)



Thermal Conductivity [W/m*°C]
Temperature (°C)
3,00
2,50
2,00
1,50
1,00
0,50
0,00
0
100
200
300
400
500
600
700
800
900
1000
Early Concrete(Upper bound)
EC2-1.2-Concrete (Upper bound)
EC2-1.2-Concrete (Lower bound)
Unit ρ=1900-2200 kg/m³ (Upper bound)
Portland Cement (Upper bound)
Unit ρ=1900-2200 kg/m³ (Lower bound)
Portland Cement (Lower bound)
Unit ρ=700-1000 kg/m³ (Upper bound)
Unit ρ=700-1000 kg/m³ (Lower bound)
Early Concrete(Lower bound)

b)

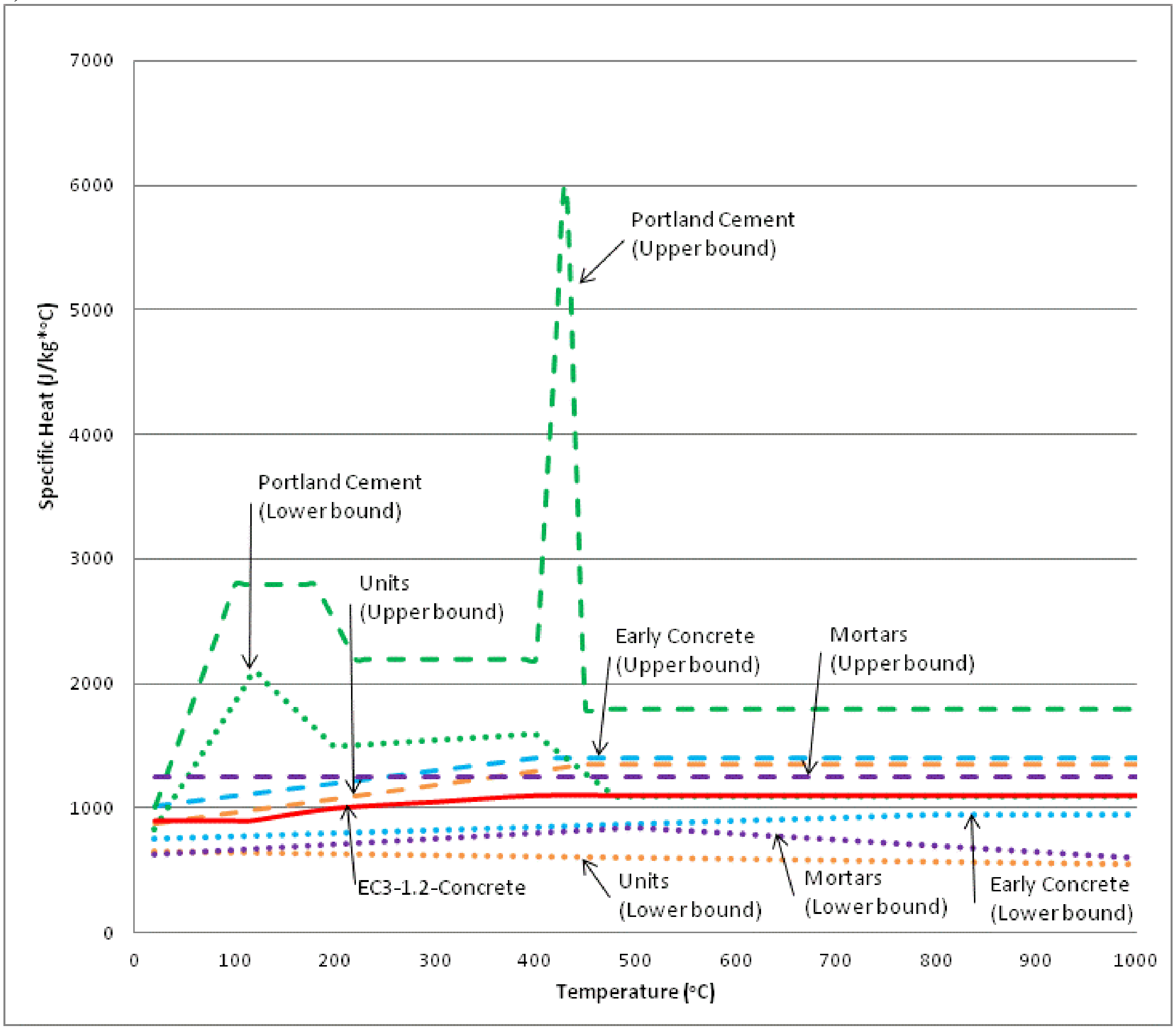


Figure 4: Lower and upper bound variations of: a) thermal conductivity and b) specific heat with temperature for the insulating materials of 19th century fireproof floors

2.3 Masonry

The data presented in the previous section include those for masonry units and for mortar. However, masonry construction is made of both masonry units and mortar. Therefore, it is necessary to combine the results for masonry units and for mortar to obtain those for masonry construction.

2.3.1 Thermal Conductivity

The experimental data collated by the authors [2] suggest that the thermal conductivities of mortar and bricks vary in a similar pattern, with the exception of temperatures ranging from 400^{o}C to 800^{o}C, in which mortars display a drop in thermal conductivity [2]. For heavyweight bricks, the measured values show minor differences. Furthermore, according to Brown and Wilson [4], the thermal conductivities of masonry walls and bricks tend to be almost identical for brick units with densities of 1600-2200 kg/m^3. Therefore, the thermal conductivity of masonry walls at elevated can be sufficiently described by that of the brick unit.

2.3.2 Specific Heat

The specific heat of a solid multi-component system can be calculated according to the additivity theorem, expressed in equation Eq.1:

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

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 with temperature can be calculated. Figure 5 includes a relevant plot, which is obtained by combining the lower and upper bound values of specific heat for different weight fractions (10%, 15% and 20% of the total weight) of mortar with the average value for the brick unit. The results show that the specific heat of masonry walls at elevated temperatures is almost identical with that of the brick units, with a difference of less than 5%. This is not surprising because the brick units are the predominant component of masonry construction.

In summary, in the following sensitivity study, the thermal properties of a masonry system will be represented by those of the brick units.

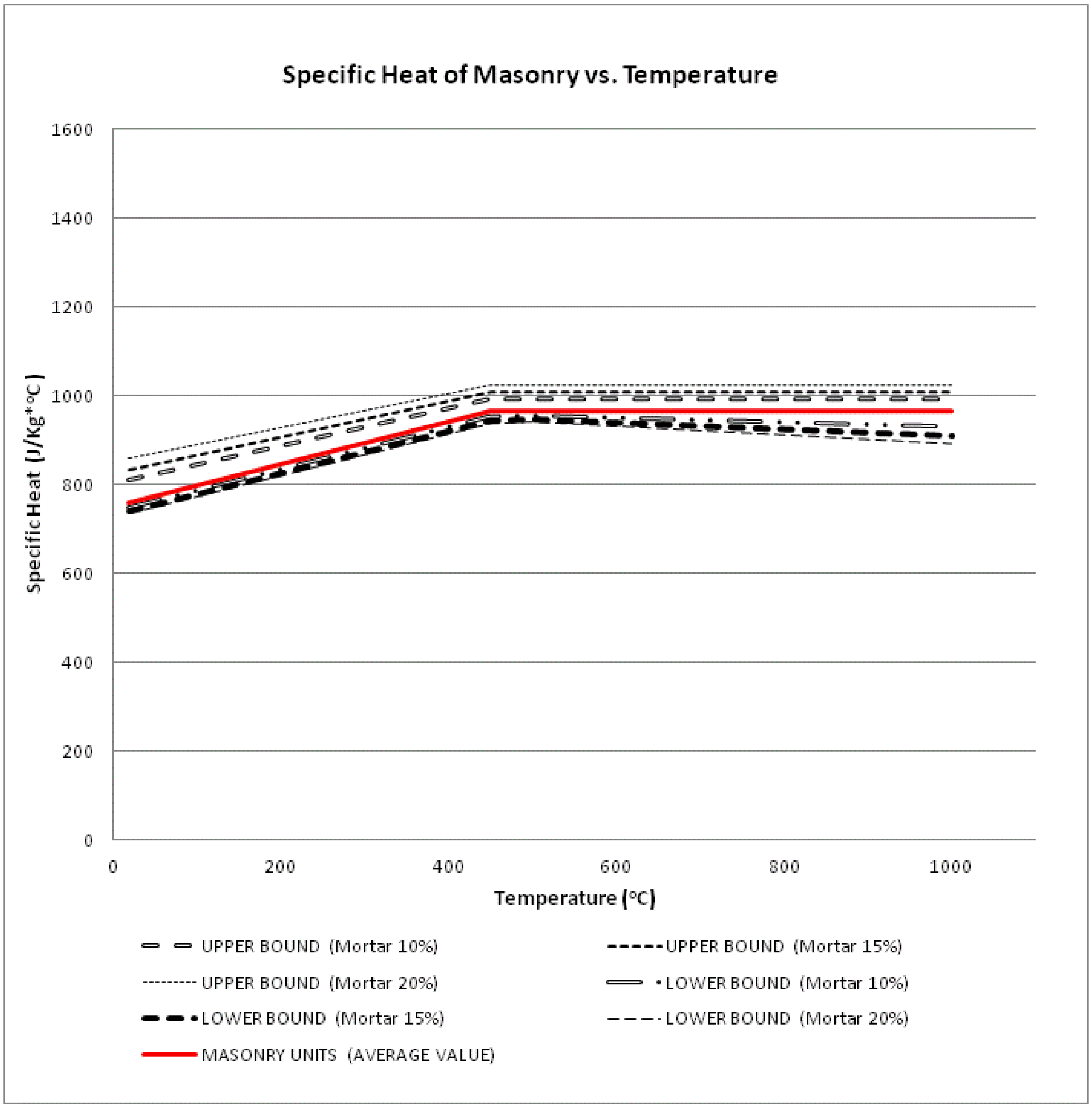


Figure 5: Variation of specific heat of masonry with temperature.

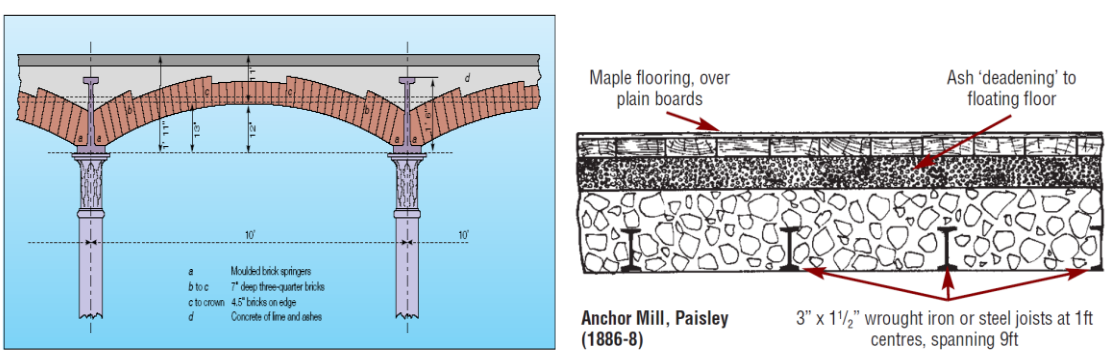
3. Sensitivity of structural temperature and mechanical behaviour to properties of the metals

Detailed dimensions of the two types of floor, namely the “jack arch” and “joist filler”, were according to Swailes [6]. These are presented in Figure 6. The cross-section of the cast iron beam in the “jack arch” floor (Figure 6a) is asymmetric with an overall height of 457.2mm, web thickness of 30mm and lower flange thickness of 40mm. The girder is simply supported with a span of 7.3m. The cross-section of the wrought iron or mild steel beam in the “joist filler” floor

(Figure 6b) is symmetric with an overall height of 76.2mm, web thickness of 10.2mm and flange thickness of 10.2mm. The girder is simply supported with a span of 2.74m. Despite the fact that the two systems under consideration have similar structural characteristics and materials, a comparison for their behavior under fire conditions is deemed necessary because the systems have different section factors.

a. Cast Iron beam in jack arch floor

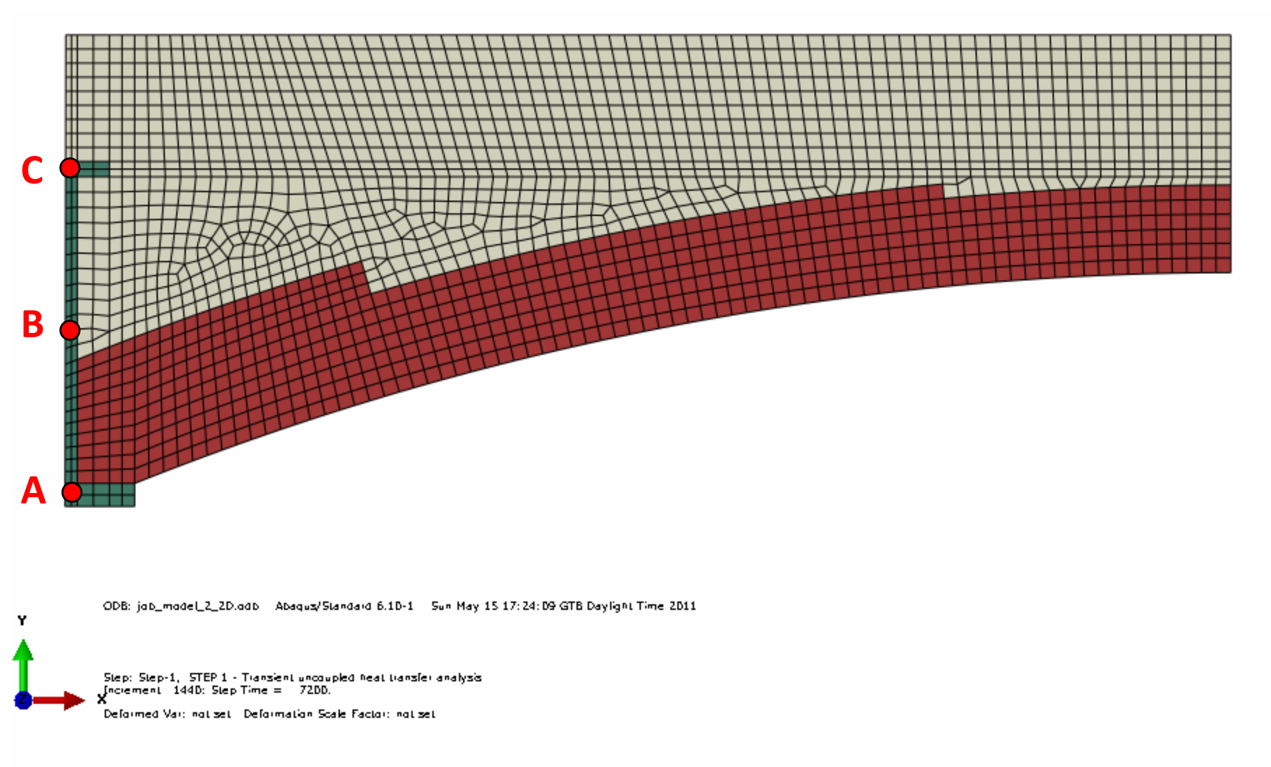
Two groups of simulations were carried out. In the first group investigating the sensitivity to thermal conductivity, the cast iron temperatures are compared between using three sets of thermal conductivity (EN 1993-1-2 [3] for steel, upper and lower bound curves for cast iron) while using the specific heat model of EN 1993-1-2 [3] for steel. The second group used three sets of specific heat (EN 1993-1-2 [3] for steel, upper and lower bound curves for cast iron) while maintaining the same thermal conductivity model of EN 1993-1-2 [3] for steel. Table 3 summarizes the heat transfer analysis cases. The temperature sensitivity study was carried out via 2D heat transfer analysis using the commercial software ABAQUS (Figure 7).



(a) (b)

Figure 6: Input geometry of modeled "jack-arch" flooring system (a) and joist filler (b) according to Swailes [6]

a)



b)

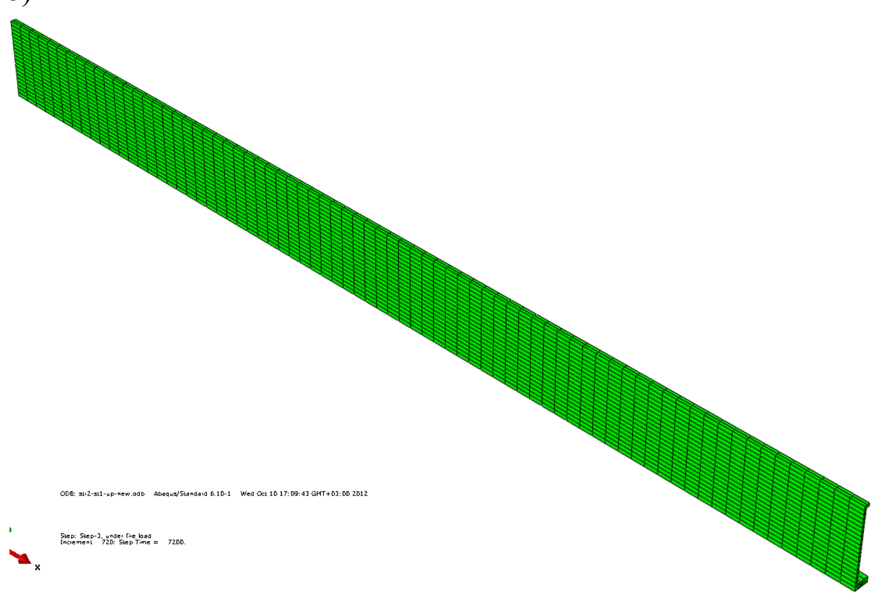


Figure 7: (a) Cross-section of 2D Finite element mesh for a typical cast iron "arch jack" floor. Node A: Upper Flange, Node B: Web, Node C: Upper Flange and (b) Structural analysis finite element model for a quarter of the symmetric beam.

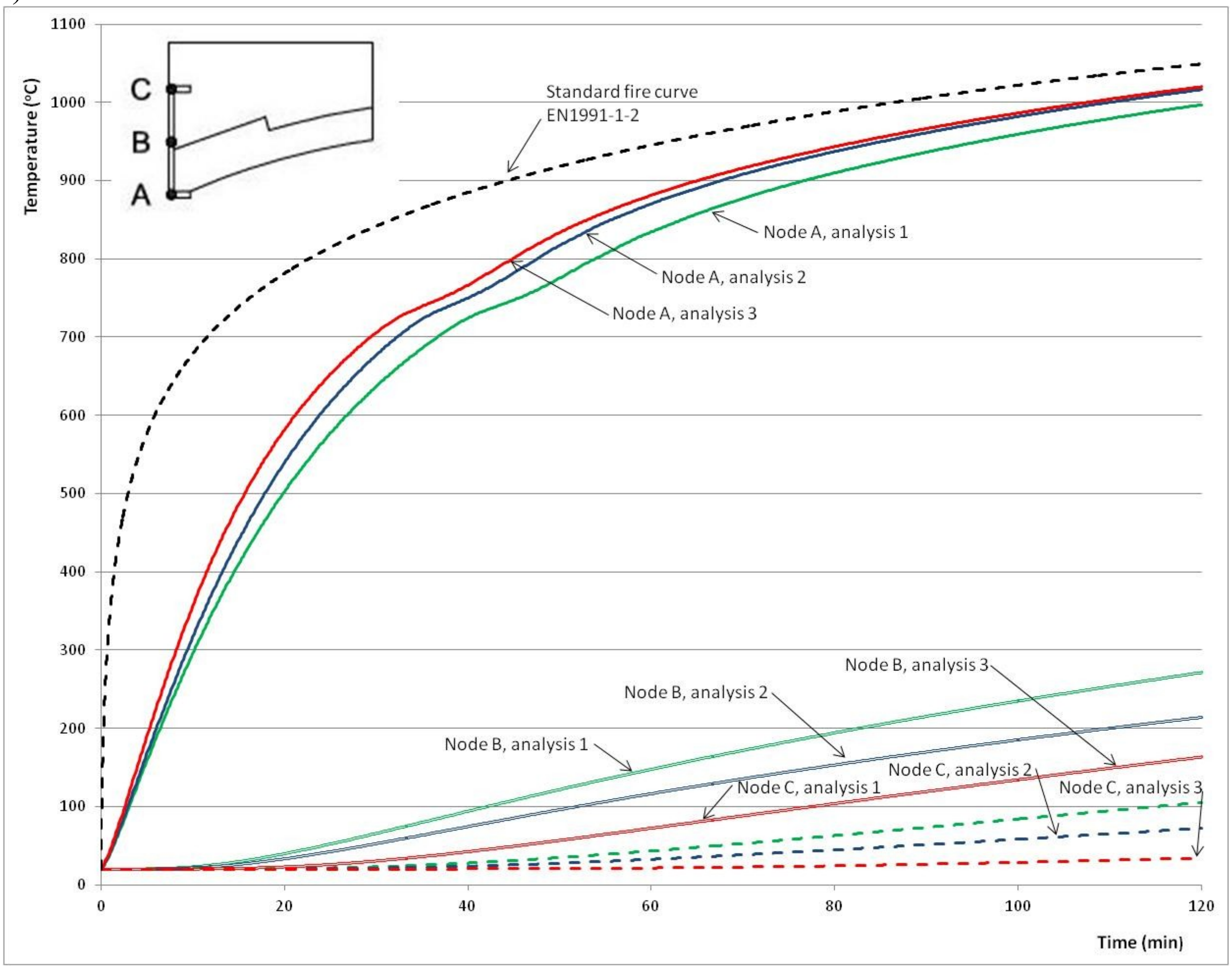
The thermal properties of the insulating materials were assumed to be invariable in these simulations: the thermal properties of the early concrete were those of normal weight concrete in EN1992-1-2 [7] with zero moisture content (u=0). The thermal properties of masonry were assumed to be the same as those in [8] for heavyweight brick with a density of 1935 kg/m^3. The floor system was assumed to be exposed to fire from below. The temperature of the fire was assumed to vary according to the EN1991-1-2 standard fire curve [9]. The heat transfer boundary conditions were according to EN1993-1-2 [3]: at the exposed surface, the convective heat transfer coefficient was 25 W/m^{2}K and the resultant emissivity value was 0.7; the total heat transfer coefficient for the unexposed surface was assumed to have a value of 9W/m^{2}K. The heat transfer analysis was carried out for 120 min.

Table 3: Thermal analysis cases for the cast iron beam

Analysis number	Thermal Conductivity	Specific Heat
1	Upper bound	EC3-1-2
2	EC3-1-2	EC3-1-2
3	Lower bound	EC3-1-2
4	EC3-1-2	Upper bound
5	EC3-1-2	Lower bound

Figure 8 presents temperature evolution curves at the three representative locations (lower flange, web, upper flange) in the cast iron beam.

a)



Temperature (°C)
Time (min)
C
B
A
Standard fire curve
EN1991-1-2
Node A, analysis 1
Node A, analysis 2
Node A, analysis 3
Node B, analysis 1
Node B, analysis 2
Node B, analysis 3
Node C, analysis 1
Node C, analysis 2
Node C, analysis 3

.

b)

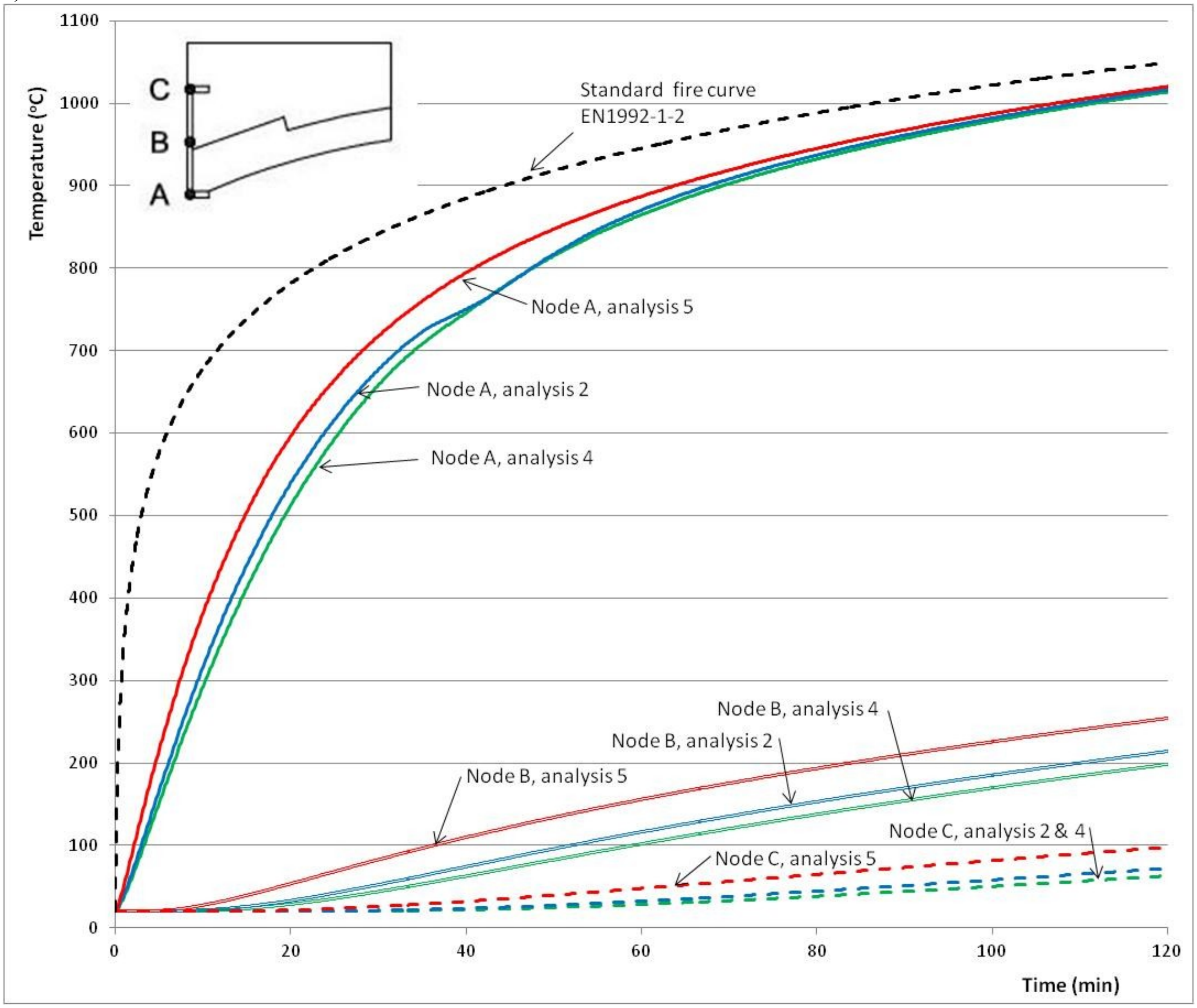
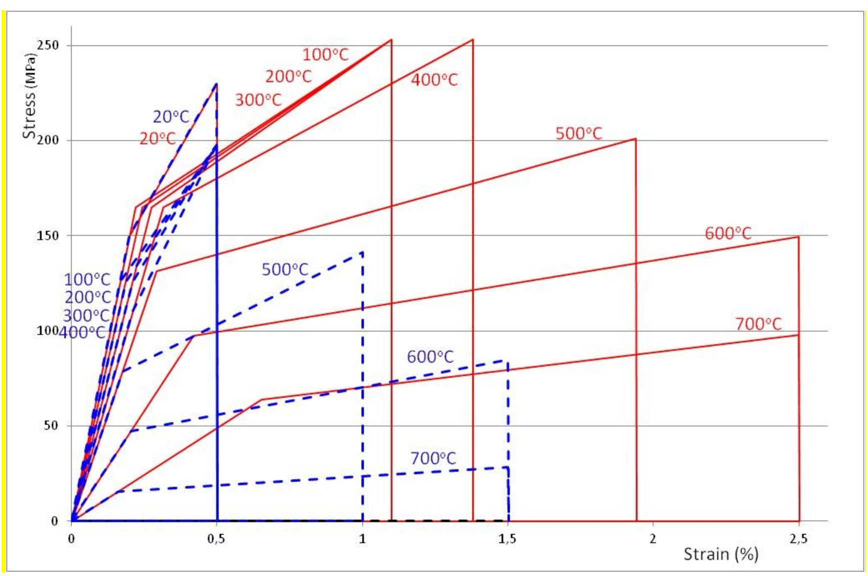


Figure 8: Temperature evolution curves for cast iron "arch jack" floor. a) Analysis cases 1 to 3 in Table 1 (constant specific heat, variable thermal conductivity), and b) Analysis cases 2,4,5 in Table 1 (constant thermal conductivity, variable specific heat).

The results in Figure 7 show that at point A on the fire exposed side, the metal temperature results are very close, with the variations being much lower than 10%. At points B and C which are protected by the insulation materials, the temperature results have higher percentage variations. However, since the absolute temperature results are low (no more than 300^{o}C even at 120 minutes), the metal stiffness and strength retention factors are high and change within a narrow range, as shown in Figure 1. Therefore, the structural performance of the different systems will not change much. This is to be compared below.

For this comparison, the thermal model was coupled with a structural analysis model, which is shown in Figure 7(b). During the structural analysis, the insulation materials were not taken into account and the applied load was 60% of that corresponding to the bending resistance of the beam at ambient temperature. Figure 9 shows the simplified bilinear diagrams that have been derived after taking into account the upper and lower bounds of the mechanical properties (Figure 3). The stress-strain-temperature relationships used in the first set of structural behaviour sensitivity analyses were according to the upper bound curves (red ones in Figure 9). The coefficient of thermal expansion was chosen to vary according to the EN1993-1-2 [3] expression for steel and the proposed upper and lower bound curves (Table 2). The results of the static analysis are presented in Figure 10.



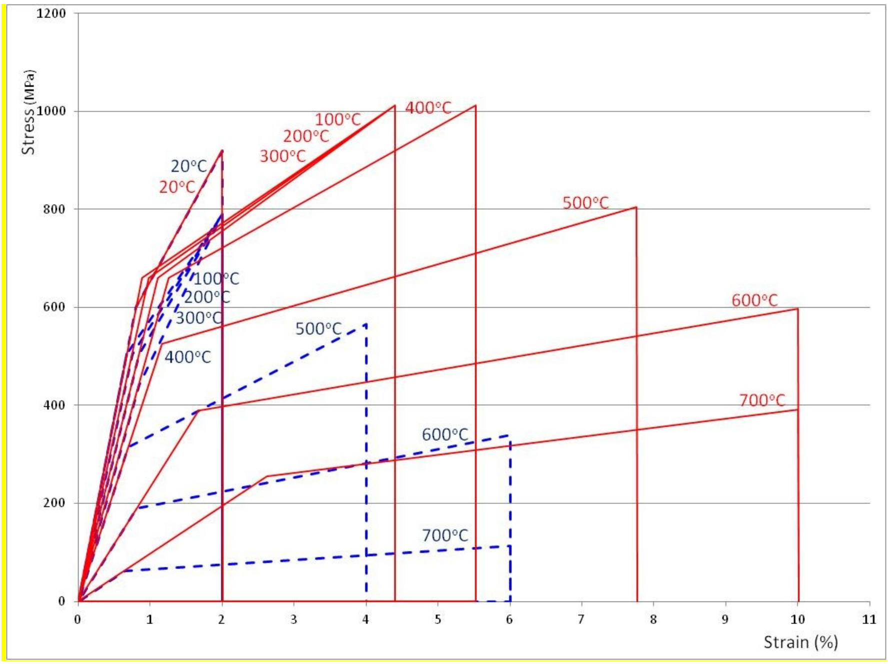


Figure 9: Assumed upper (red colour) and lower (blue colour) bound stress-strain-temperature relationships for tension (above) and compression (below) for cast iron.

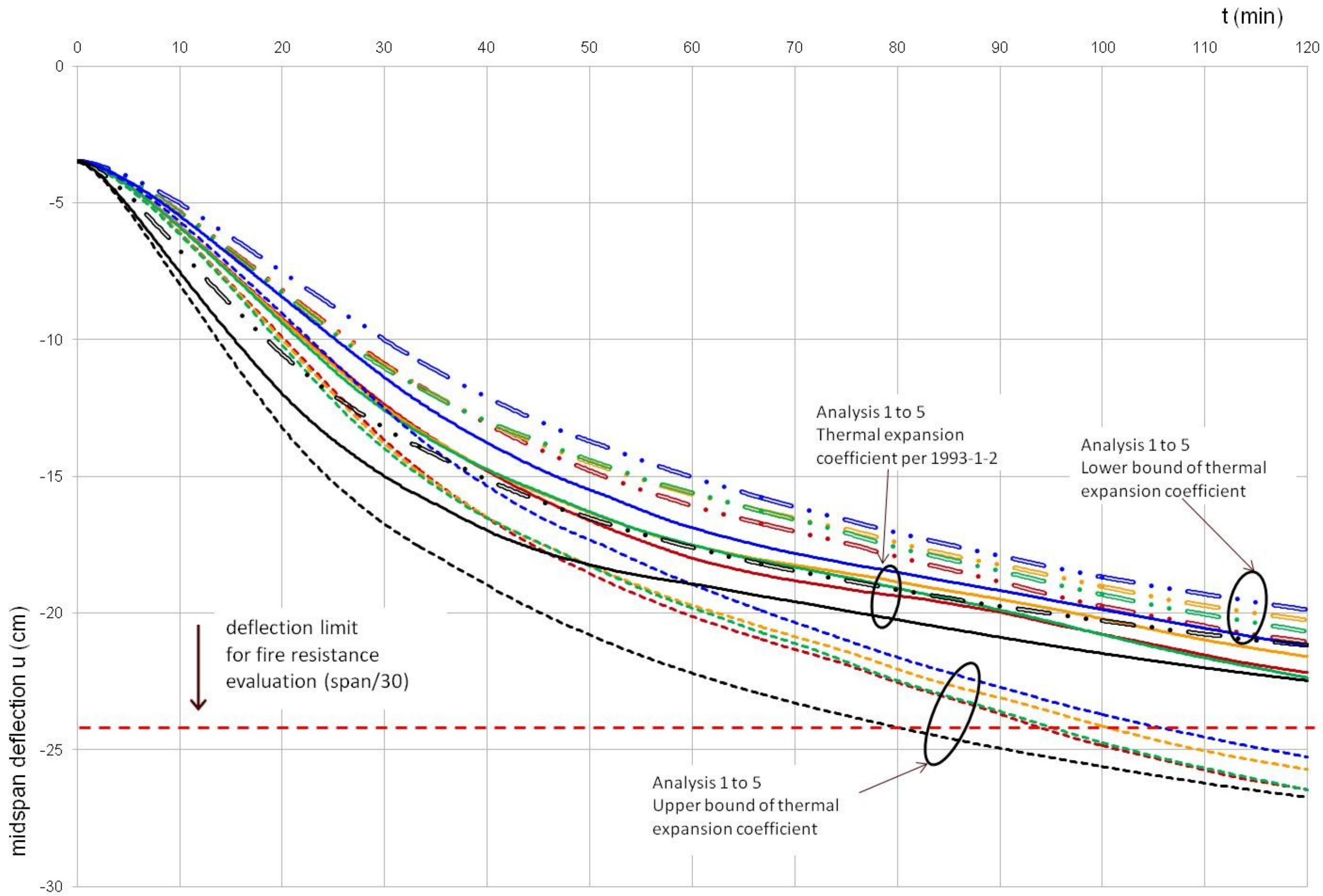


Figure 10: Comparison of midspan deflections of a cast iron beam as a function of the fire exposure time

From these results, it is obvious that the beam behaviour is only moderately sensitive to using different thermal properties of cast-iron as Figure 10 shows that the time-deflection curves for the five different thermal property cases in Table 1 are grouped closely. Therefore, it is recommended to use the EN 1993-1-2 [3] thermal properties of steel for cast iron.

However, the time – deflection behaviour of cast iron beams is sensitive to the coefficient of thermal expansion, as was expected according to [5]. Because of the very large thermal gradients in such beams, which lead to very large deflections, their fire resistance will be governed by their deflections, rather than their bending moment capacities.

To test the sensitivity of the results with respect to the mechanical properties of cast iron at elevated temperatures, the temperature results from Analysis case 2 (Table 3) were used and comparison was made between selecting the upper bound or lower bound stress-strain curves in Figure 9. In this analysis set, the thermal expansion coefficient was also according to EN1993-1-2 [3] for steel. For comparison purposes, similar analyses in which the thermal expansion was neglected (α=0) were conducted. The results of the second sensitivity static analysis set are presented in Figure 11.

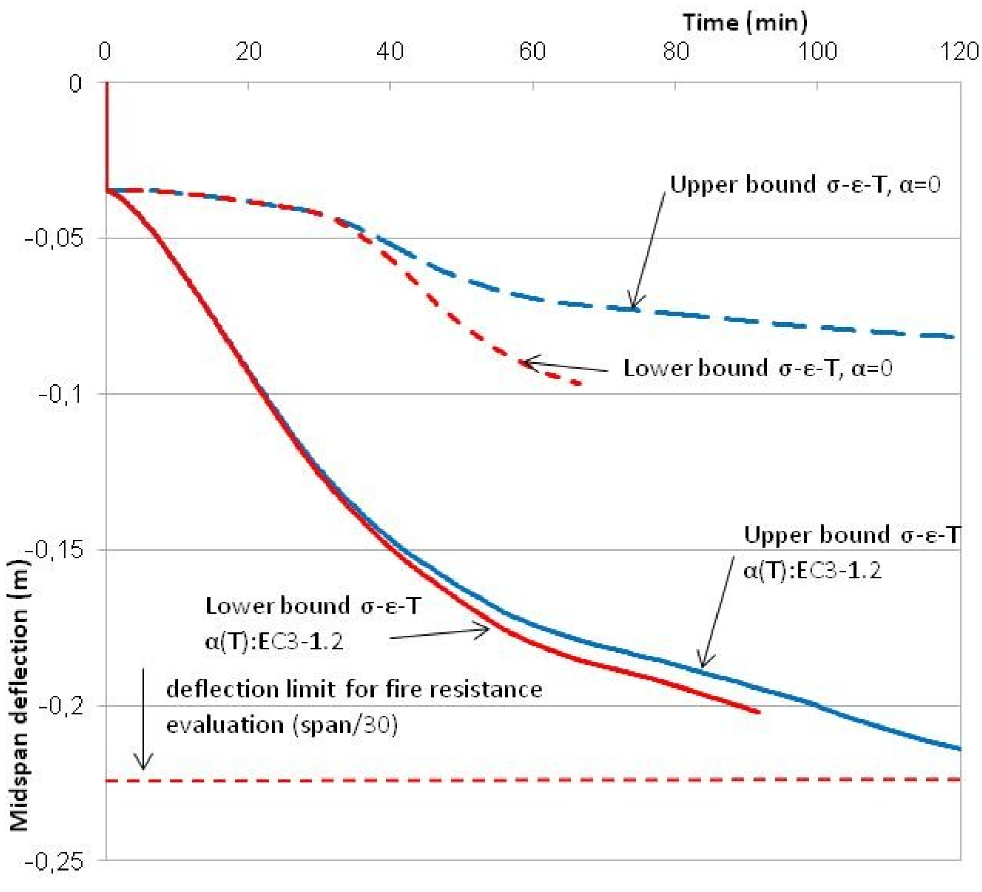


Figure 11: Comparison of midspan deflections of cast iron beam as a function of the fire exposure time for upper and lower bound σ-ε-T relationships

The following observations can be made from the results presented in Figure 11:

- Large temperature gradients in the cross-sections of the beams dominate the deflections of the beams. The thermal expansion coefficient is an important property for this type of beams.
- The ultimate bending moment resistance of the beam clearly depends on the mechanical properties and the analysis results show significant discrepancies arising from the use of different stress-strain curves. Because of the difficulty in identifying only one set of stress-strain-temperature relationships for cast-iron, a reliability based approach, in which the stress-strain-temperature relationship is considered a random variable, should be considered. The results in Figure 11 show that the stiffness of the beams are similar but the failure times differ, suggesting that the actual shapes (including initial modulus of elasticity) of the elevated temperature stress-strain curves are less important than the ultimate stresses of cast iron at elevated temperature. This will be pursued further in future research.

b. Wrought Iron and Old Mild steel beam in a joist filler

A similar set of thermal analyses as described in (a) were conducted. The thermal conductivity was selected as that of wrought iron, old mild steel or steel in EN1993-1-2 [3]. The specific heat was chosen to vary according to EN-1993-1-2 [3] for all analysis cases in the absence of raw data. The concrete properties were identical with those in (a). The results are presented in Figure 12. There is little difference in the results when using either the thermal conductivity of wrought iron or mild steel. However, there is noticeable difference when using the thermal conductivity of EN1993-1-2 [3]. In addition, the metal temperatures are quite high, indicating that due to the small section size, the fireproof floors are not particularly efficient in reducing the heat conduction.

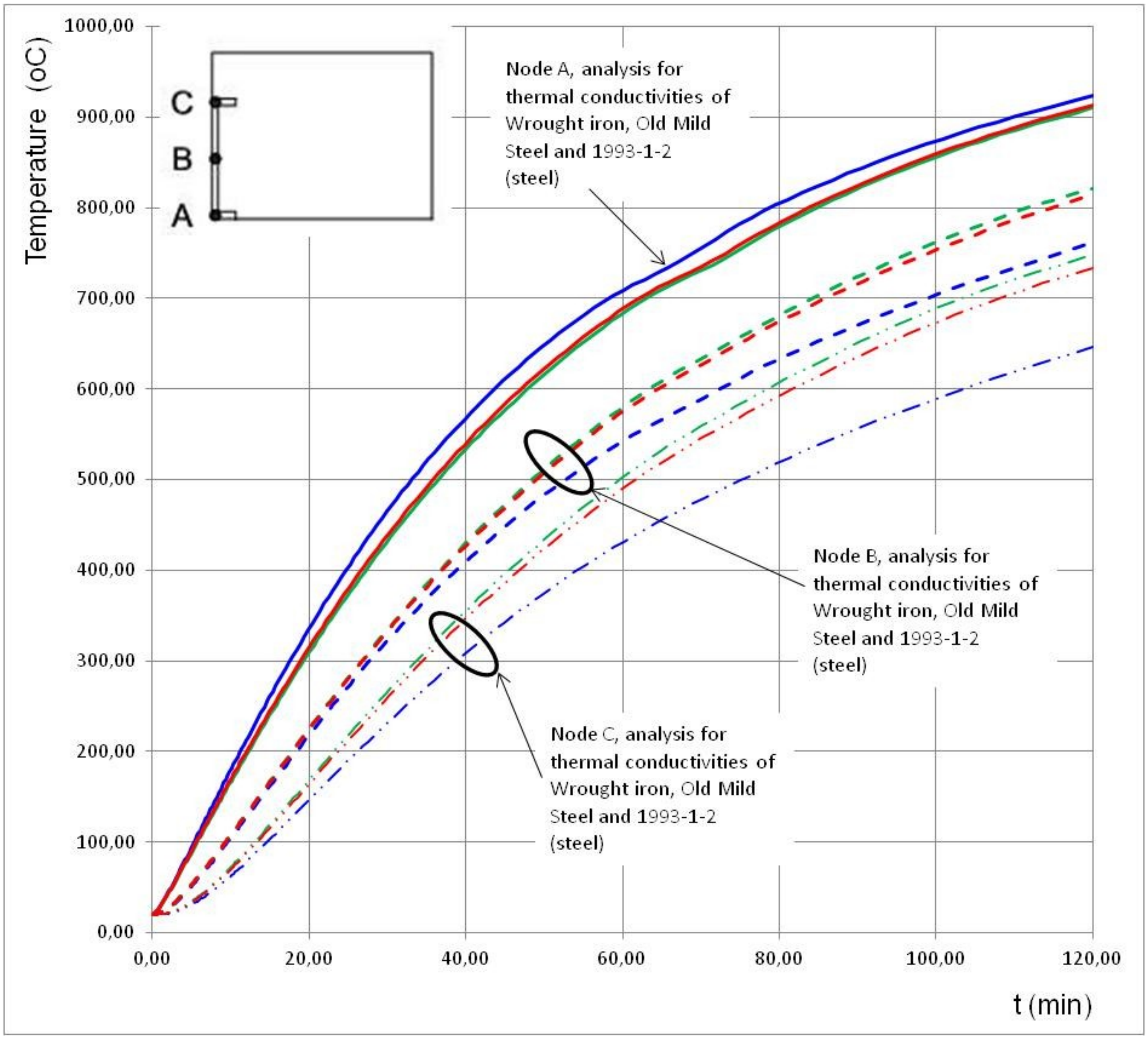
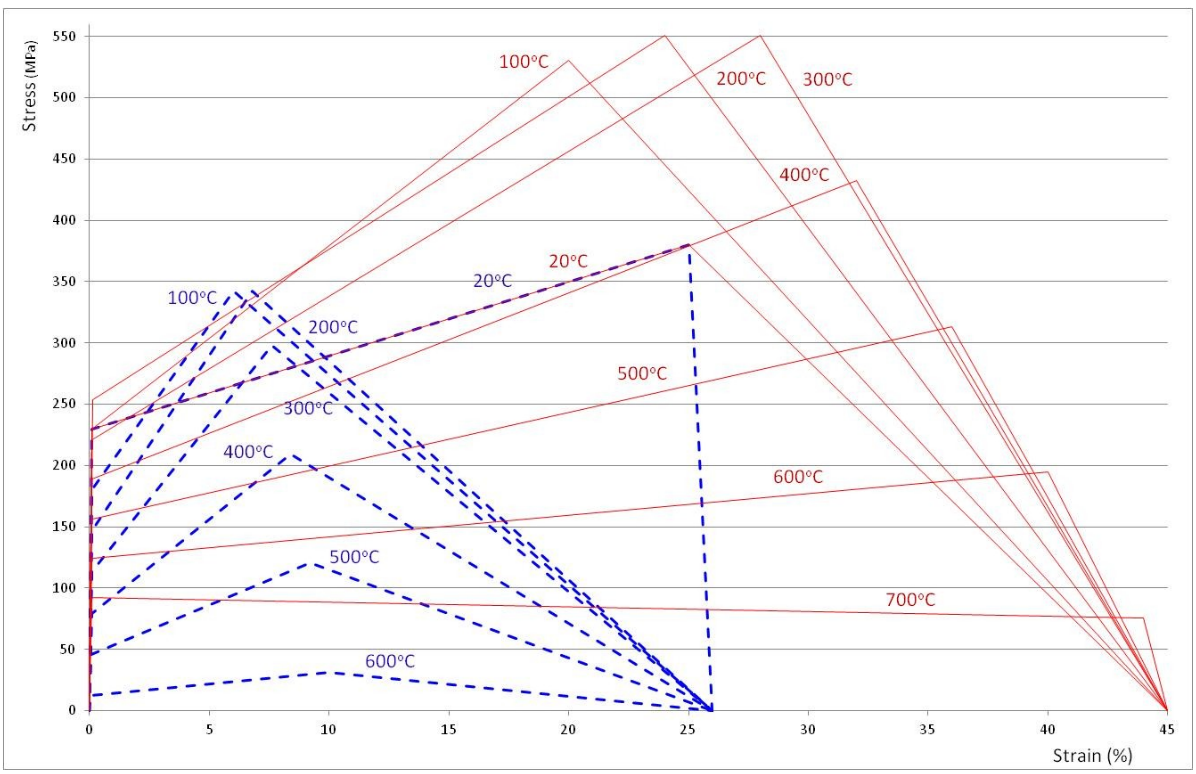


Figure 12: Temperature evolution curves for wrought Iron / old mild steel beam in a joist filler floor. The thermal conductivities investigated are the following: EN1993-1-2 [3] steel (blue colour), wrought iron (green colour) and old mild steel (red colour).

The above temperature data were used as input in the subsequent structural analysis to evaluate the sensitivity of the structural response to different thermal and mechanical models. The time - deflection curves for the same stress-strain-temperature relationships (upper bound curves in Figure 13(a) for wrought iron and in Figure 13(b) for old mild steel), the same coefficient of thermal expansion (as specified in EN1993-1-2 [3] for steel) but different thermal conductivities, are compared in Figure 14. Despite the differences in temperature results (Figure 12) arising from using the EN1993-1-2 [3] thermal properties or the proposed wrought iron/old mild steel thermal properties, the observed deviations in the structural responses are small.



a)

b)

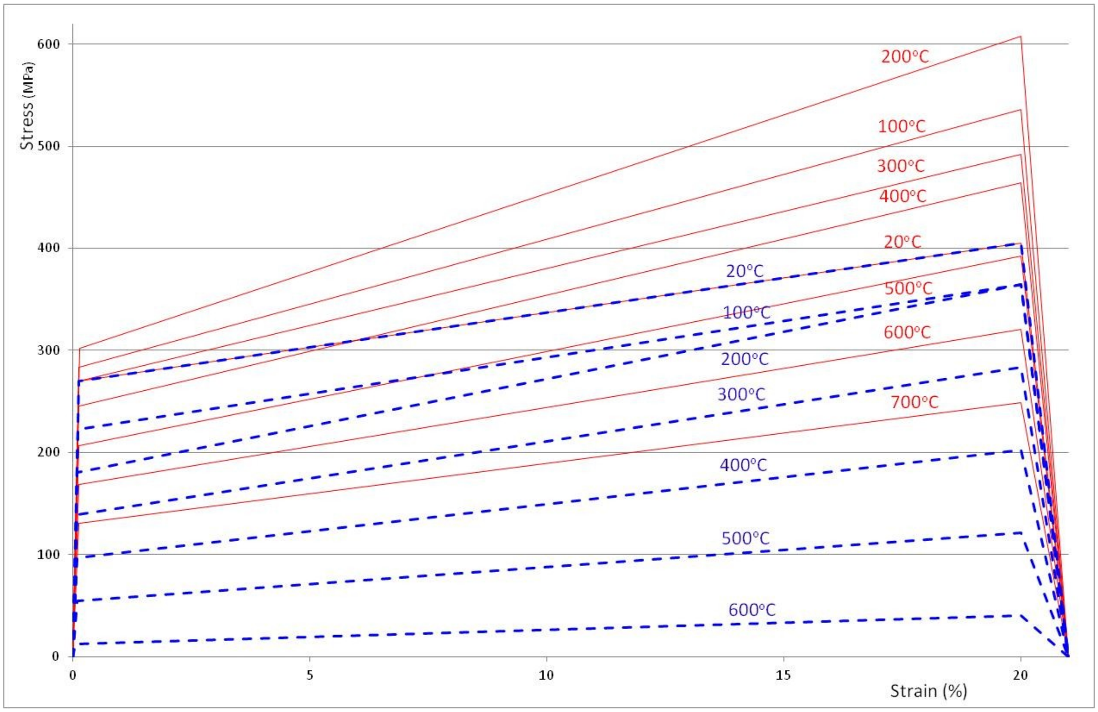


Figure 13: Upper (red) and lower (blue) bound stress-strain-temperature relationships for: a) wrought iron (above) and b) old mild steel (below).

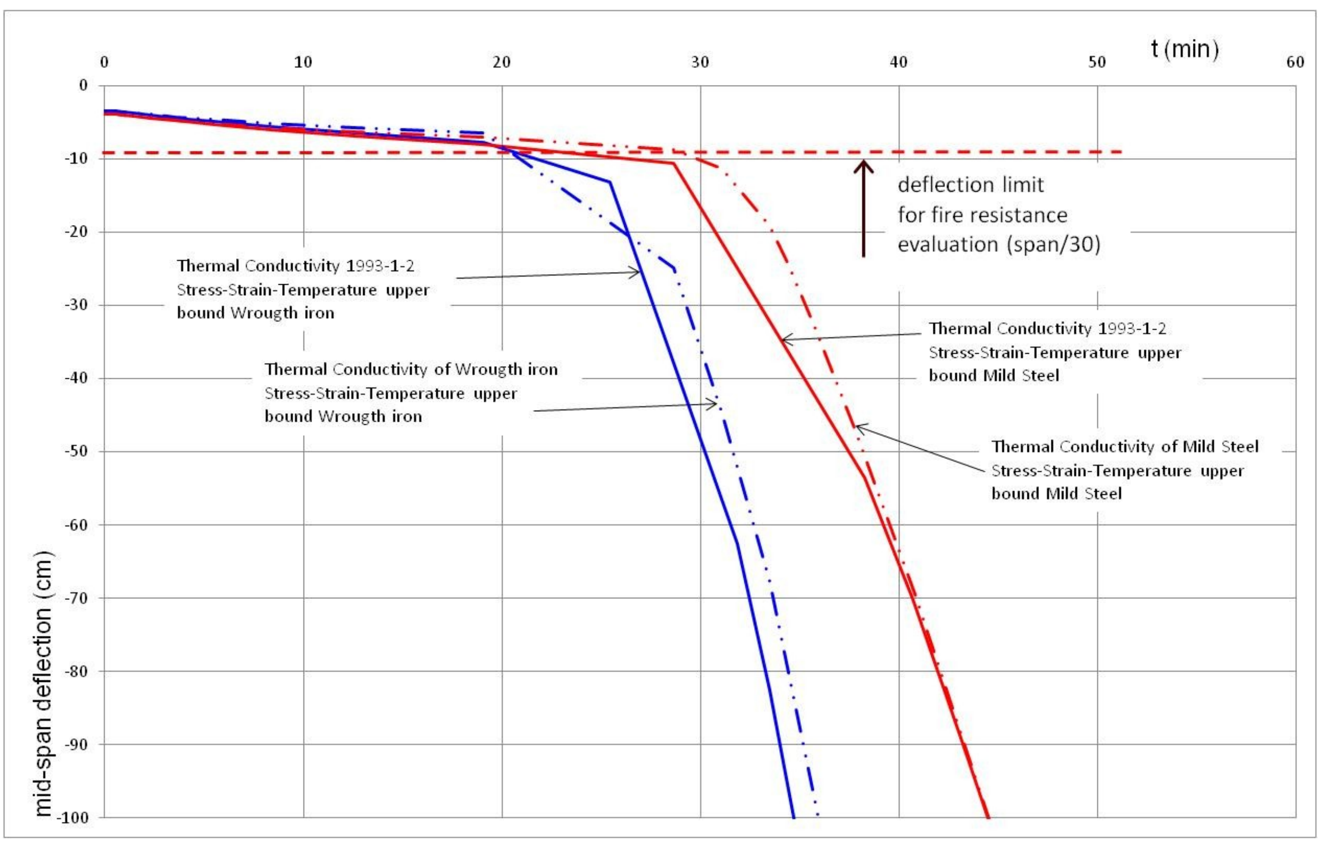


Figure 14: Comparison of midspan deflections of wrought iron/old mild steel beam as a function of the duration of fire exposure for various “selected” thermal properties.

As with the cast iron structure results, for the same temperature data but varying stress-strain-temperature relationships (upper and lower bound curves in Figure 13), the obtained structural responses are different, as shown in Figure 15. Again, due to the difficulty of using one set of stress-strain-temperature relationships for wrought iron or old mild steel, a reliability based analysis will be necessary.

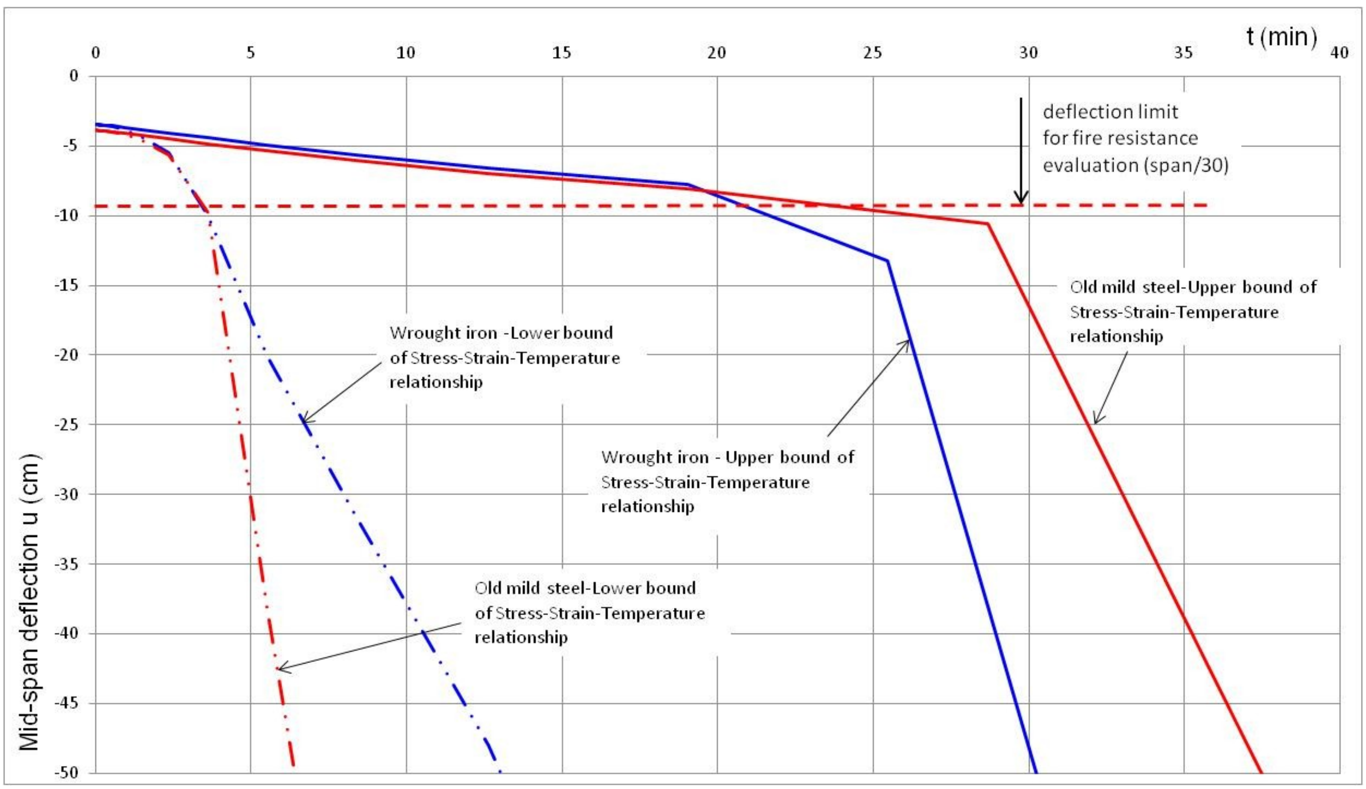


Figure 15: Comparison of midspan deflections of wrought iron / old mild steel beams as a function of fire exposure time for using upper and lower bound σ-ε-T relationships

The results presented in Figure 14 and Figure 15 suggest that:

- Selecting the expressions of EN1993-1-2 [3] to describe the thermal properties of the metals at elevated temperatures produces accurate results in terms of the mechanical response of the “filler joist” system under fire exposure.
- As in the “jack arch” floor, selection of the stress-strain-temperature relationship for the metal beam is crucial in determining the structural response of the system subjected to fire. The major differences in the results suggest that this can be achieved via a reliability based method. This should also be the approach for selecting the ultimate strength variation, as the calculated failure times (which heavily depend on it) differ greatly too. The deflection evolution shows that the mechanical behavior is not sensitive to the elastic modulus (deflection curves have similar slopes) of the metal beams, which can be sufficiently described by that of EN1993-1-2 [3] for steel.

4. Sensitivity of metal temperatures to properties of insulating materials

Four sets of sensitivity analyses have been conducted for a typical geometry of the "jack-arch" flooring system (Figure 7a). In all analysis cases the thermal properties of the metals (cast iron, wrought iron and mild steel) were those of steel according to EN 1993-1-2 [3]. In each analysis set, the thermal properties of one insulating material were kept constant and those of the other material were selected from the various upper and lower bound curves. Tables 4 to 7 describe specific details for the material curves selected in each analysis set.

Table 4: Analysis set 1- Sensitivity to variation in thermal properties of early concrete with fixed masonry thermal conductivity (heavyweight upper bound) and specific heat (upper bound).

Analysis Number	Early Concrete						
	Thermal Conductivity				Spesific Heat		
	Upper bound	Lower Bound	EC2-1-2 Upper curve	EC2-1-2 Lower curve	Upper bound	Lower bound	EC2-1-2
1	*				*		
2	*					*	
3	*						*
4		*			*		
5		*				*	
6		*					*
7			*		*		
8			*			*	
9			*				*
10				*	*		
11				*		*	
12				*			*

Table 5: Analysis set 2: Sensitivity to variations in thermal properties of early concrete for fixed masonry thermal conductivity (lightweight lower bound) and specific heat (lower bound).

Analysis Number	Early Concrete						
	Thermal Conductivity				Spesific Heat		
	Upper bound	Lower Bound	EC2-1-2 Upper curve	EC2-1-2 Lower curve	Upper bound	Lower bound	EC2-1-2
13	*				*		
14	*					*	
15	*						*
16		*			*		
17		*				*	
18		*					*
19			*		*		
20			*			*	
21			*				*
22				*	*		
23				*		*	
24				*			*

Table 6: Analysis set 3: Sensitivity to variations in thermal properties of masonry for fixed early concrete thermal conductivity (EC-1-2 upper bound) and specific heat (EC-1-2).

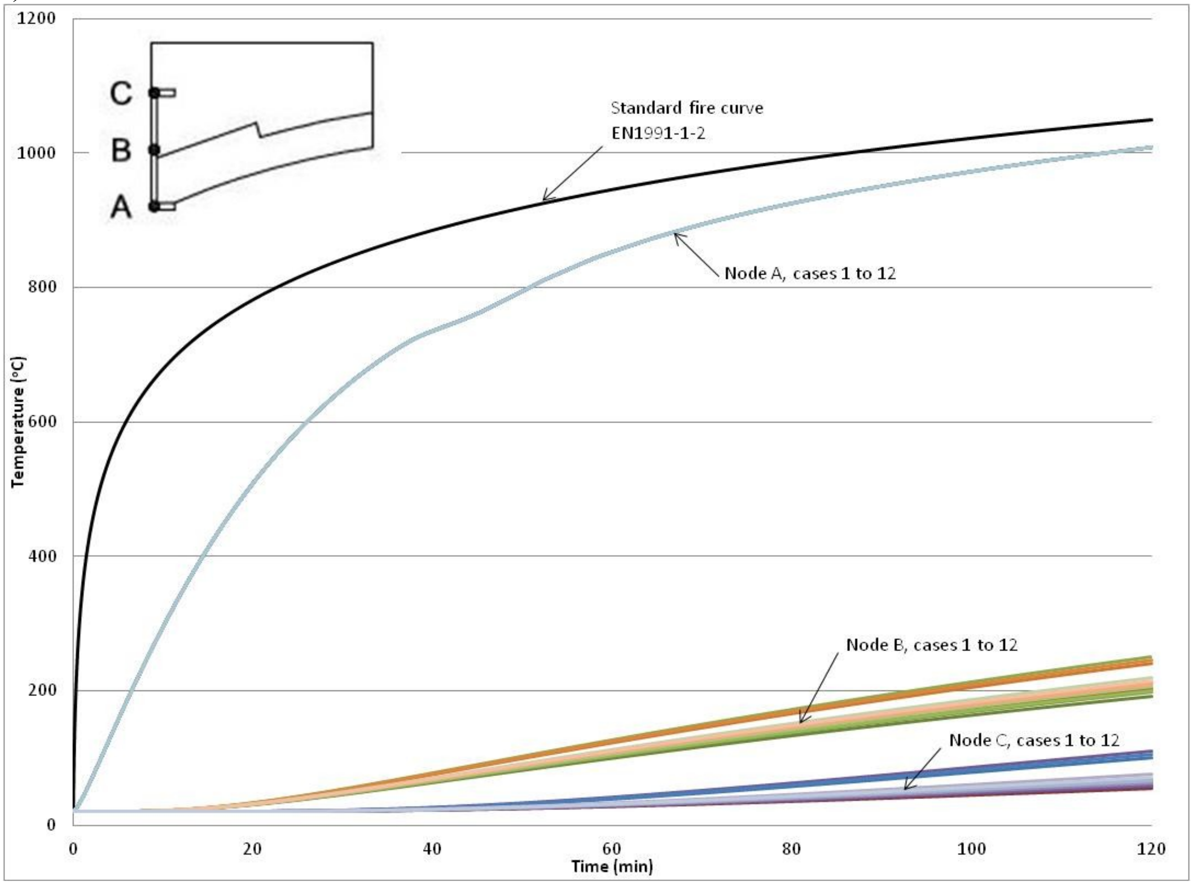
Analysis Number	Masonry					
	Thermal Conductivity				Specific Heat	
	Upper bound heavy	Lower bound heavy	Upper bound light	Lower bound light	Upper bound	Lower bound
25	*				*	
26		*			*	
27			*		*	
28				*	*	
29	*					*
30		*				*
31			*			*
32				*		*

Table 7: Analysis set 4: Sensitivity to variations in thermal properties of masonry for fixed early concrete thermal conductivity (EC-1-2 lower bound) and specific heat (EC-1-2).

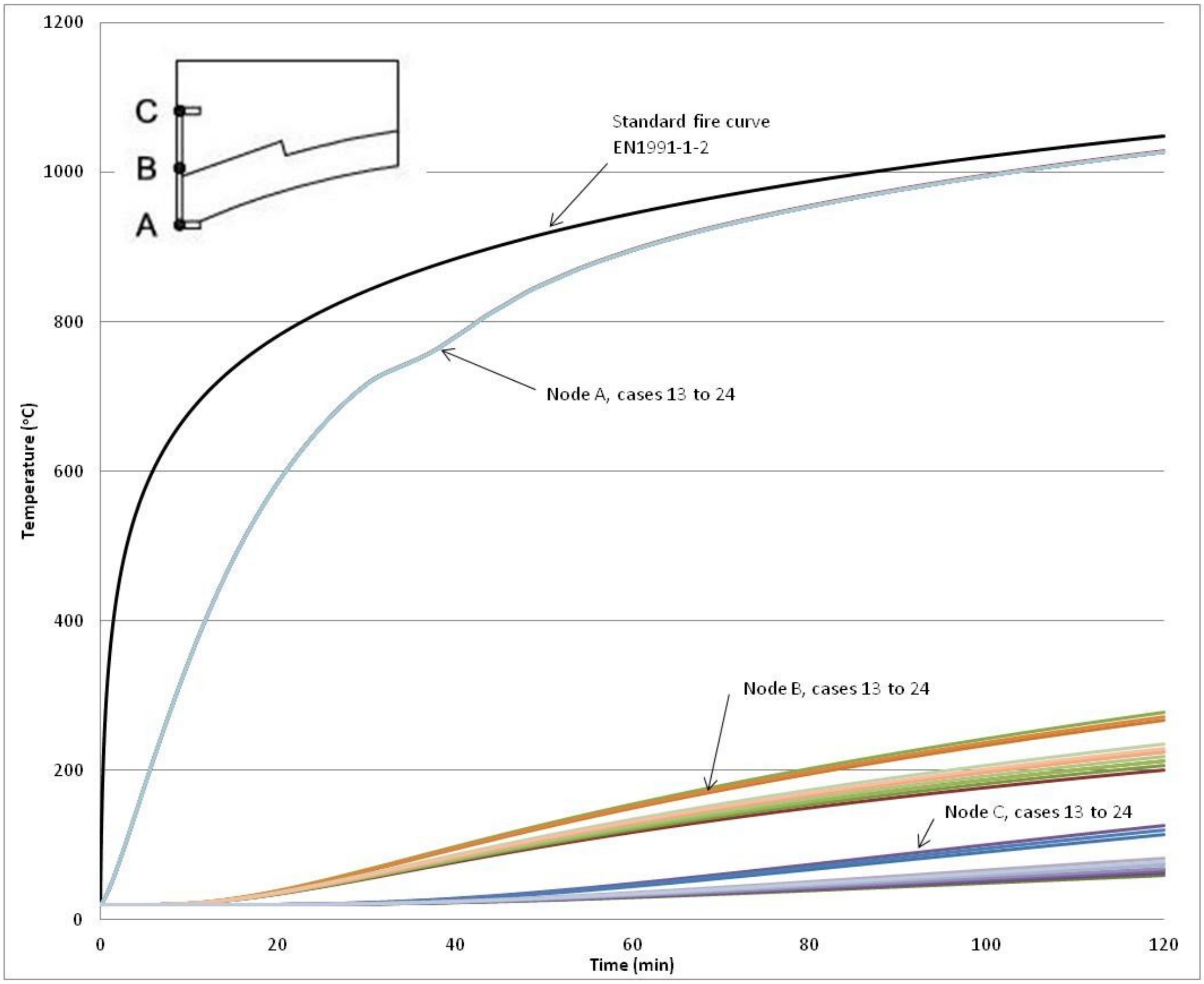
Analysis Number	Masonry					
	Thermal Conductivity				Specific Heat	
	Upper bound heavy	Lower bound heavy	Upper bound light	Lower bound light	Upper bound	Lower bound
33	*				*	
34		*			*	
35			*		*	
36				*	*	
37	*					*
38		*				*
39			*			*
40				*		*

The analysis results are summarized in Figure 16(a) to 16(d), which compare the results for each analysis set. Figure 17 compares the average values of the four analysis sets.

a)

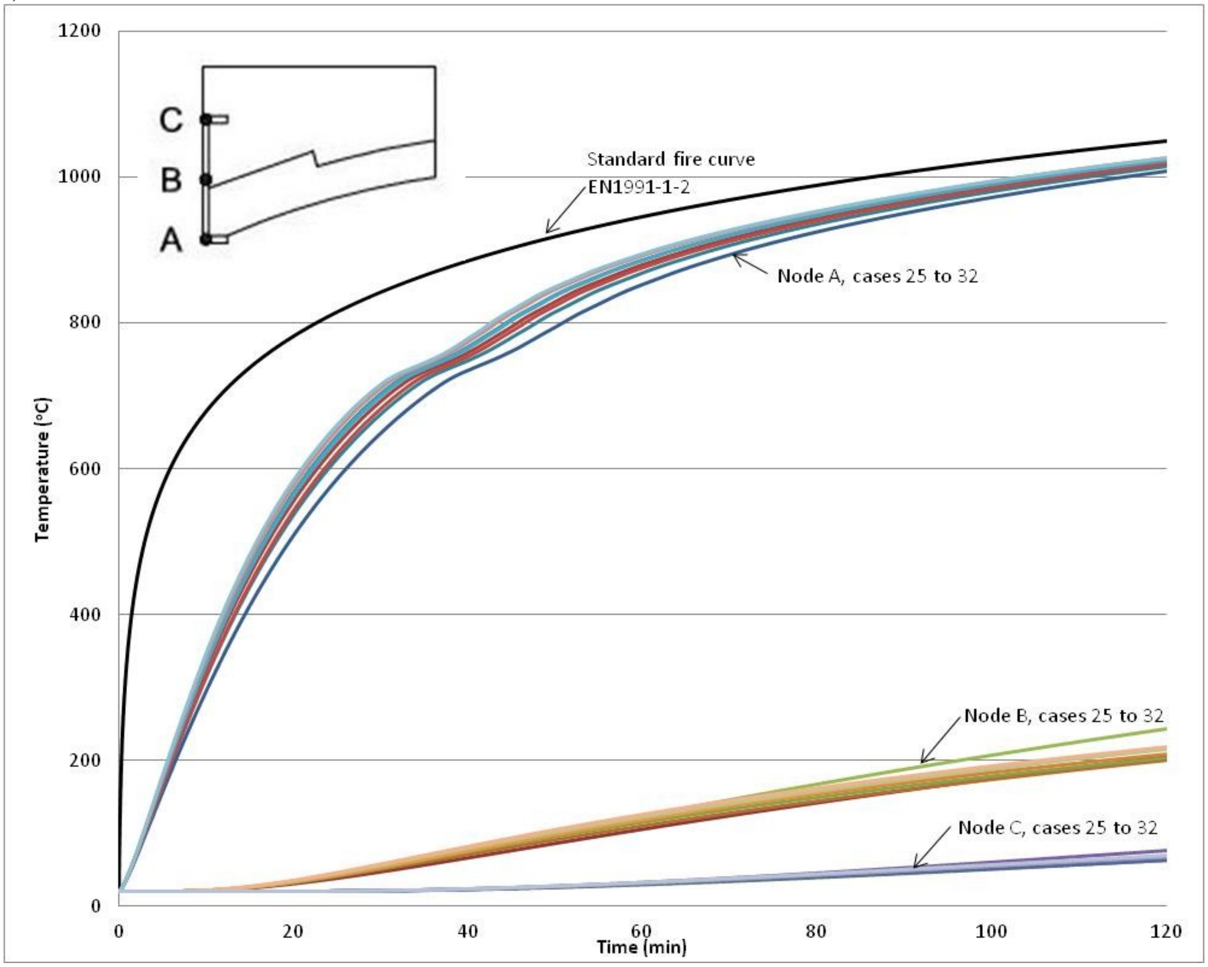

1200
1000
800
600
400
200
0
Temperature (°C)
0
20
40
60
80
100
120
Time (min)
C
B
A
Standard fire curve
EN1991-1-2
Node A, cases 1 to 12
Node B, cases 1 to 12
Node C, cases 1 to 12

b)



1200
1000
800
600
400
200
0
Temperature (°C)
0
20
40
60
80
100
120
Time (min)
C
B
A
Standard fire curve
EN1991-1-2
Node A, cases 13 to 24
Node B, cases 13 to 24
Node C, cases 13 to 24

c)



1200
1000
800
600
400
200
0
Temperature (°C)
0
20
40
60
80
100
120
Time (min)
C
B
A
Standard fire curve
EN1991-1-2
Node A, cases 25 to 32
Node B, cases 25 to 32
Node C, cases 25 to 32

d)

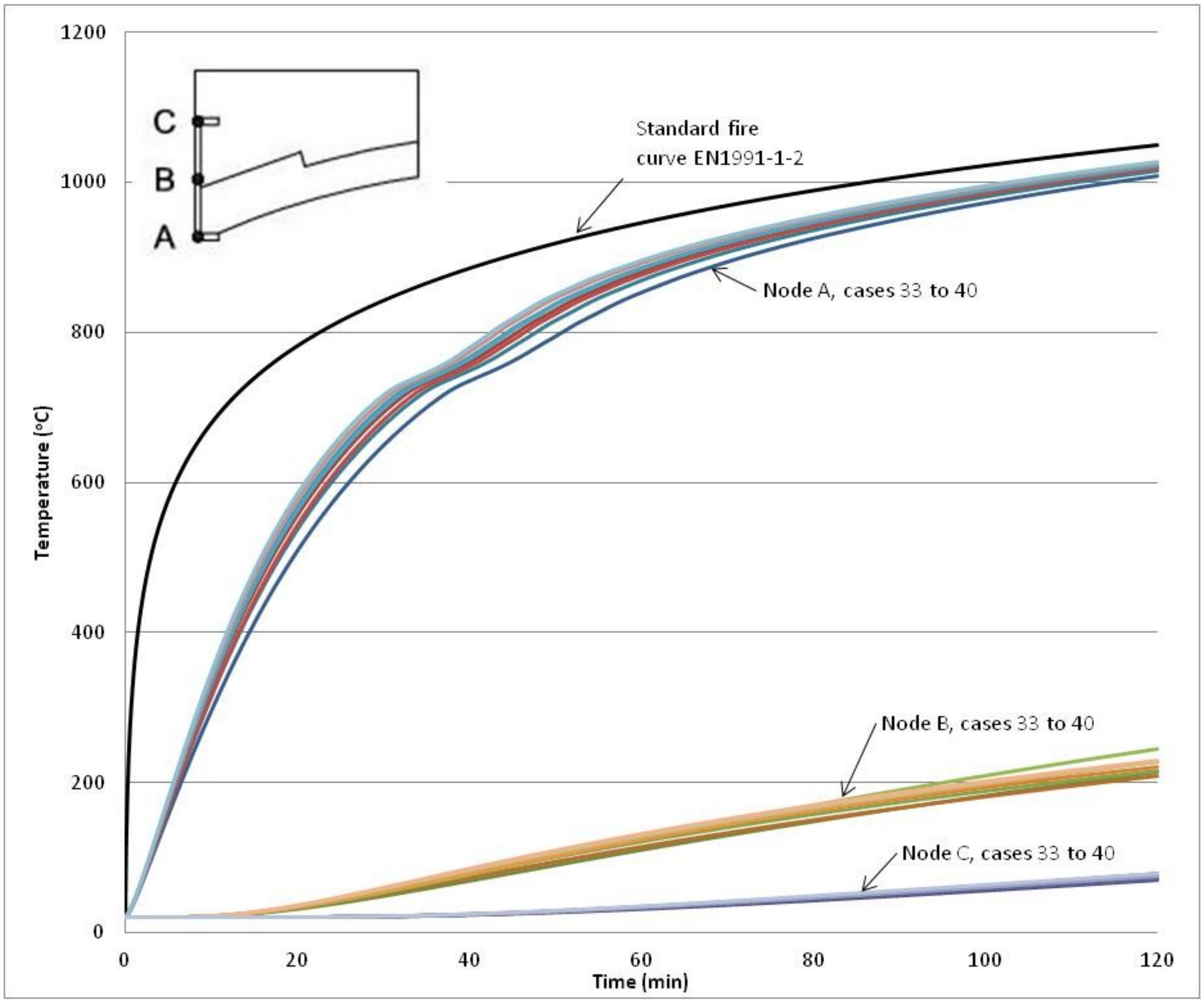


Figure 16: Temperature evolution curves for cast iron “arch jack” floor. a) Analysis set 1 (variation in thermal properties of early concrete with fixed masonry thermal conductivity (heavyweight upper bound) and specific heat (upper bound)) b) Analysis set 2 (variation in thermal properties of early concrete for fixed masonry thermal conductivity (lightweight lower bound) and specific heat (lower bound)). c) Analysis set 3(variation in thermal properties of masonry for fixed early concrete thermal conductivity (EC-1-2 upper bound) and specific heat (EC-1-2)). d) Analysis set 4 (variation in thermal properties of masonry for fixed early concrete thermal conductivity (EC-1-2 lower bound) and specific heat (EC-1-2)).

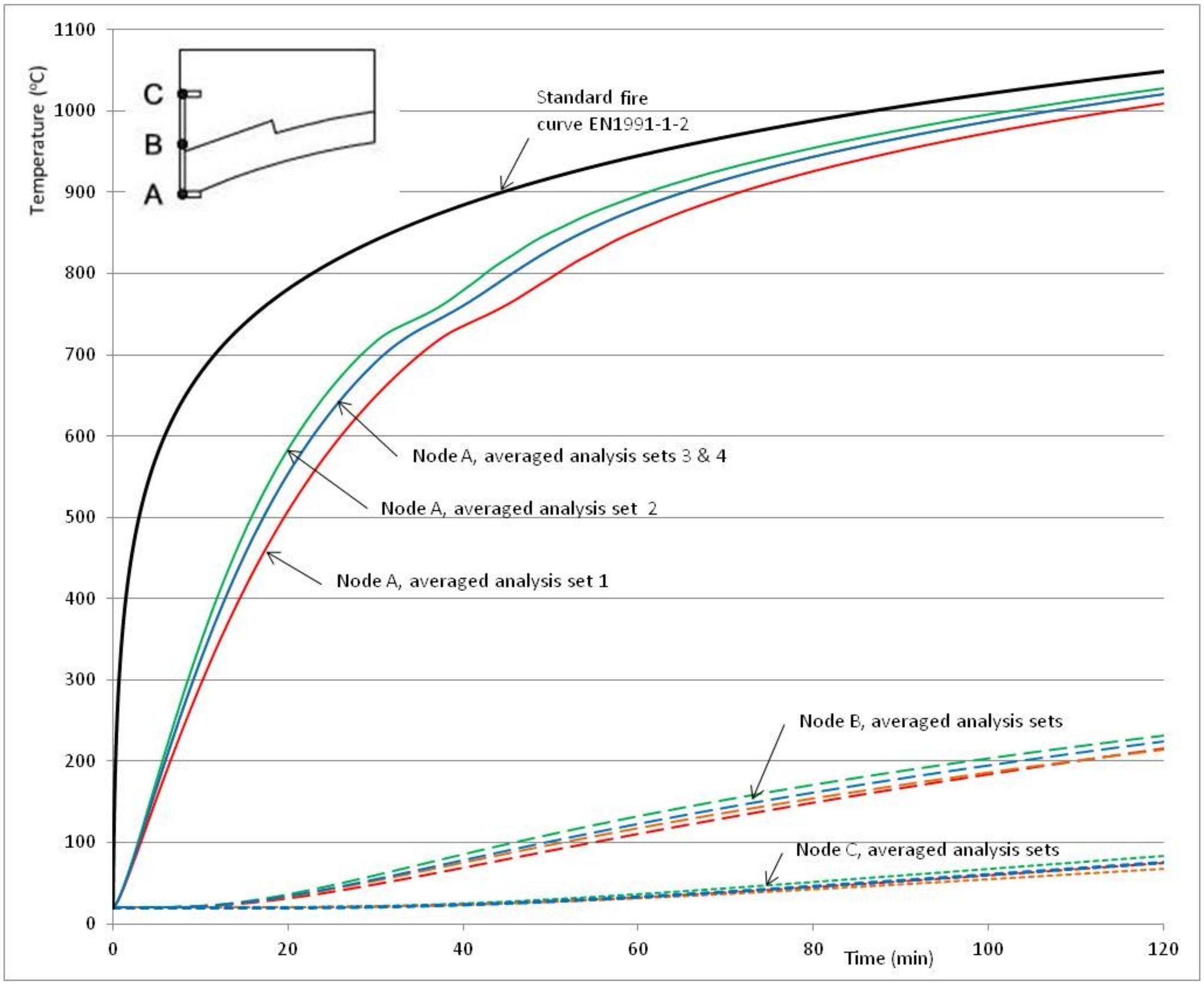


Figure 17: Averaged (per analysis set (Tables 2 to 5)) temperature evolution curves for cast iron "arch jack" floor

The above results show that there is little variation in the time-temperature evolution of the cast iron beam, despite the large variations in the selected thermal property curves of the insulating materials. Because of the heavy insulations afforded to the metal sections, in all analysis cases the temperature at the midheight of the beam only reaches 200^{o}C to 250 ^{o}C approximately after 120min of heating. There is almost no variation at the top flange, where temperatures of around 100^{o}C are reached at 120min. At this temperature region, since the metal will still retain high proportions of the ambient temperature mechanical properties, these variations in the temperatures will have minor effects on the load carrying capacities of the structure. The unprotected lower flange quickly develops high temperatures (higher than 500^{o}C at 20min and 850^{o}C at 60min).

Because the temperature profiles of the cast iron beam are not sensitive to the thermal properties of the various insulation materials, a simplified approach may be used. It is proposed to use the thermal properties of concrete given in EN1992-1-2 [7] for the insulation materials (masonry and "early" concrete) of fireproof floors.

The heat transfer analysis for the construction shown in Figure 7a has been repeated and the results are shown in Figure 18. A direct comparison with the averaged values of the four analysis sets presented in the previous section shows that it is acceptable to use the thermal properties of concrete in EN 1992-1-2 [7] to analyse 19th century fireproofing floors with "early concrete" and masonry as insulating materials.

A relevant analysis pertaining to the "filler joist" system was not carried out here. However, the above conclusion will hold true for a "filler joist" floor, because the insulation material ("early concrete") is also used in the "arch jack" system and the exposure surface of the metal beam (lower flange) is the same.

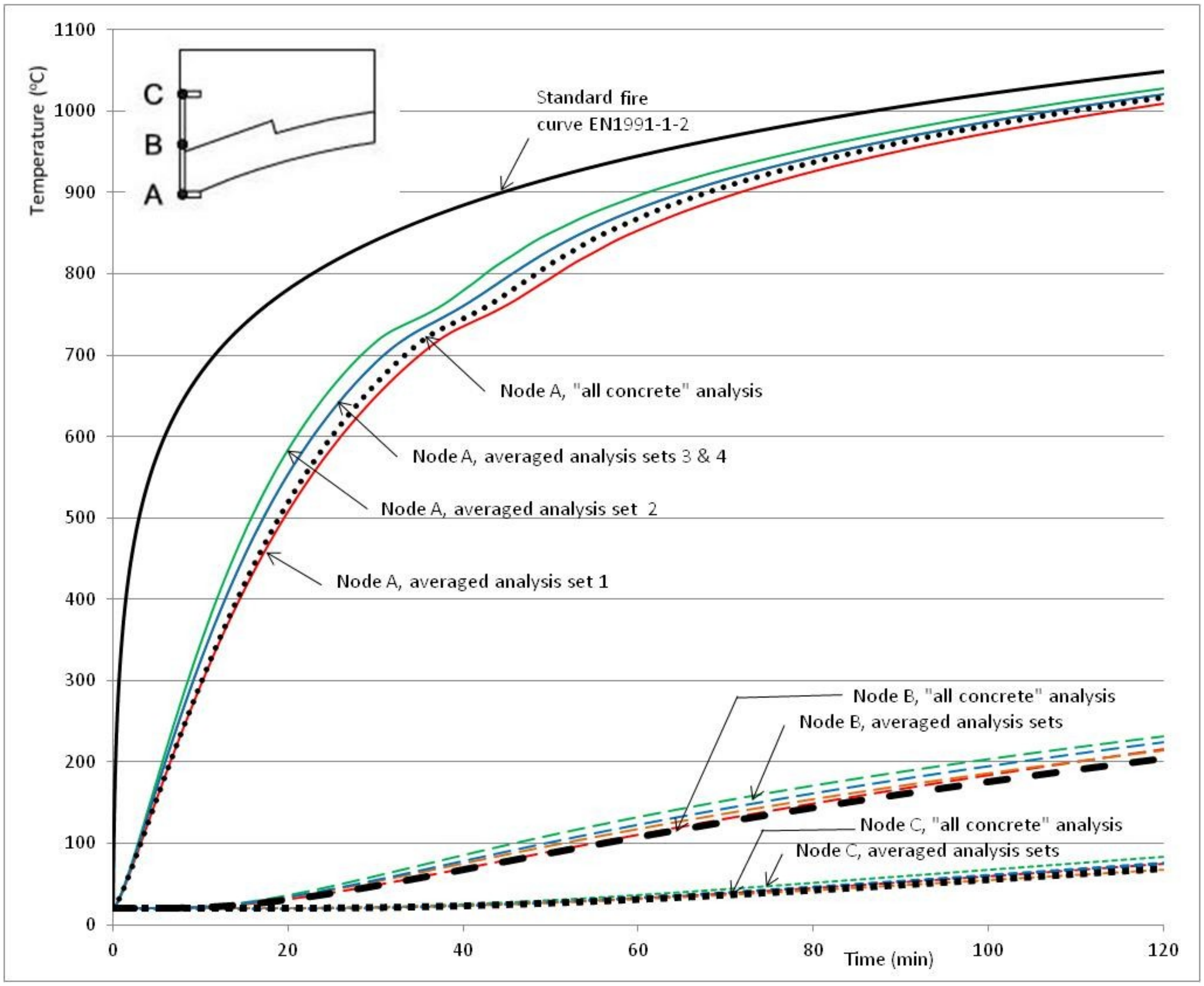


Figure 18: Temperature evolution curves for cast iron "jack arch" floor. Comparison between the average values of the four analysis sets and the results from using the thermal properties of concrete in EN1992-1-2 [7] for the insulating materials.

6. Conclusions

The thermal and mechanical properties of the metals used in 19th century fireproof flooring-systems have different degrees of uncertainty. However, uncertainties in some of these properties in most cases have only minor influence on the structural performance of the flooring systems. Based on the sensitivity study results, the following recommendations may be made:

- Due to heavy insulation, the structural behaviour of this type of construction is mainly influenced by thermal bowing. Therefore, the lower bound thermal conductivity values should be used to maximize the temperature gradients. These values for cast iron, wrought iron and old mild steel are given in Table 1. However, since the average curves for wrought iron and mild steel and the upper bound curve of cast iron (Figure 2a) are higher than that of steel, the steel values can be used. The specific heat of steel in EN 1993-1-2 can also be used for these metals.

- The structural behaviour of the fireproof floors was found to be sensitive to variations in the mechanical properties (coefficient of thermal expansion, stress-strain-temperature relationships). Because of the high temperature gradients in this type of construction, thermal expansion coefficient is a particularly important value influencing the beam deflections. The stiffness of the metals has a relatively minor influence. On the other hand, the ultimate tensile stress of the metals is highly influential. Due to the large scatter in historic data for these two properties, it is not possible to identify one unique value for each. One possibility is to select one set of values for the thermal expansion coefficient and the stress-strain-temperature curves (e.g. based on those in EN 1993-1-2 for steel), but carry out reliability based simulations to establish appropriate material partial safety factors to ensure that the probability of failure is within acceptable limits. This is now being pursued by the authors.
- Although there may be considerable variations in the thermal properties of the insulating materials from different sources, these variations have only minor effects on the load carrying capacities of the structure in 19th century fireproofing structural systems because of the heavy insulations to the metal sections. Consequently, the elevated temperature thermal properties of the insulating materials commonly encountered in

such 19th century fireproof flooring-systems can be sufficiently described by the relevant expressions given in the Eurocodes for similar contemporary materials.

- As further simplification, the thermal properties of concrete in EN1992-1-2 (specific heat and lower bound thermal conductivity) can be used for the insulating materials of both fireproof flooring systems studied here.

7. References

[1] Bailey CG. The behavior of asymmetric slim floor steel beams in fire. J Constr Steel Res 1999;50:235-57.

[2] C. Maraveas, Y.C. Wang, T. Swailes, Thermal and mechanical properties of 19th century fireproof flooring systems at elevated temperatures, Construction and Building Materials, Vol. 48, 2013, pp 248-264

[3] European Committee for Standardization. Eurocode 3 - Design of steel structures - Part 1-2: General rules - Structural fire design. Brussels: The Committee; 2005.

[4] Brown WP, Wilson AG. The Thermal Conductivity of Brick Walls - A summary of literature reviewed. National Research Council of Canada, Division of Building Research; 1962. Technical Note No.380.

[5] Maraveas, C., Swailes, T. and Wang Y.C. , A detailed methodology for the finite element analysis of asymmetric slim floor beams in fire, Steel Construction, 2012, Vol. 5, Issue 3, pp.191-198.

[6] Swailes, T. 19th century "fireproof" buildings, their strength and robustness. The Structural Engineer 2003; 81(19): 27-34.

[7] European Committee for Standardization. Eurocode 2 - Design of concrete structures - Part 1-2: General rules - Structural fire design. Brussels: The Committee; 2004.

[8] Harmathy TZ. Properties of building materials at elevated temperatures. National Research Council of Canada, Division of Building Research; 1983. DBR Paper No. 1080.

[9] European Committee for Standardization. Eurocode 1 – Actions on structures - Part 1-2: General actions – Actions on structures exposed to fire. Brussels: The Committee; 2002