

CONCRETE INSULATION FOR FIRE RESISTANCE: AN ANALYTICAL INVESTIGATION

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ABSTRACT

In any design of steel structures to resist fire, it is essential to know the temperature of the steel. A simple step-by-step calculation technique is illustrated to determine the temperature of non-insulated and insulated AISC rolled steel sections exposed to a standard fire. The time-temperature responses of the insulated rolled steel sections has been determined for varying thicknesses of two insulating materials viz. concrete and cement plaster. The rolled steel section has been idealized as a lumped mass of steel having a uniform temperature. The ISO 834 specified time-temperature curve has been used as an input in the analysis. The proposed procedure is a useful tool for predicting temperatures of non-insulated and insulated simple rolled steel sections in standard fire-resistance tests and also helps to illustrate the efficacy of the type and the thickness of the insulating material on the elevation of temperature in the steel sections. The results of this investigation can be used to determine the fire-resistance ratings in the temperature domain for simple steel members.

Keywords: Standard fire, time-temperature curve, standard fire resistance test, fire-resistance ratings

1. INTRODUCTION

When a steel structure is exposed to a fire, the steel temperatures increases and the strength and stiffness of the steel are reduced, leading to possible deformation and failure, depending on the applied loads and the support conditions. The increase in steel temperature depends on the severity of the fire, the area of steel exposed to the fire and the amount of applied fire protection. The design process for fire resistance requires verification that the fire resistance provided in a structural member exceeds the design fire severity. This verification may be in the time domain, the temperature domain or the strength domain.

In the time domain, the required codal fire resistance is compared with the fire-resistance rating of the selected assembly of the structural elements. The fire resistance ratings are obtained on the basis of a standard fire test or from calculations of the time required to reach

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the limiting temperature during exposure of the selected assembly to the standard fire.

In the temperature domain, the maximum temperature reached during a standard fire test is compared with the limiting steel temperature. The limiting temperature is the steel temperature at which the load carrying capacity of the member would be equal to the design loads. The BSI 1990 (a) [1] for example, gives a limiting temperature option for the fire design of single members. However, this methodology for assessing the fire resistance of steel structures is suitable when the steel cross section is assumed to be at a uniform temperature.

In the strength domain, the load carrying capacity of the structural element is compared with the expected loads on the element at the time of the fire. Evaluation of fire resistance ratings in the strength domain is preferred for a realistic assessment of structural behaviour especially if temperature gradients are expected across the steel cross section and also for investigating the fire behaviour of whole structures.

Irrespective of the domain in which the verification of the fire resistance of a structural element is carried out, it will be appreciated that a critical input for the above exercise is the determination of the temperatures developed in the member cross section when it is exposed to a standard fire or a more realistic fire curve, depending on the design philosophy. The most reliable estimates of these temperatures are available from full-size fire-resistance tests carried out in standard furnaces. However, as a prelude to comprehensive fire-resistance tests in furnaces, analytical procedures can be developed to simulate the time-temperature response of single members in relatively uncomplicated structures or even of complex structures with the help of rigorous algorithms [2].

In the present analytical investigation, a simple step-by-step calculation method has been illustrated for determining the time-temperature response of single non-insulated and insulated rolled steel sections exposed to ISO 834-1975 [3] specified standard time-temperature curve. The efficacy of varying thicknesses of two insulating media viz. concrete and cement plaster has been studied. From a perusal of the results of this investigation it is evident that the thermal properties as well as the thickness of the insulating material have a decisive influence on the time-temperature response of steel sections. These observations have to be tempered by the fact that there is a practical upper limit to the thickness of the insulating material which can be effectively used for thermal shielding of structural steel elements.

2. ALGORITHM FOR NONINSULATED SECTIONS

The proposed iterative algorithm [2] for determining the time-temperature response of single non-insulated sections is based on the principle that the heat entering the steel member over the exposed surface area in a small time step Δt (s) is equal to the heat required to raise the temperature of the steel by ΔT_s ($^{\circ}\text{C}$) assuming that the steel section is a lumped mass at uniform temperature. Hence, heat entering the member = heat required to raise the temperature of the member

$$q'' F \Delta t = \rho_s c_s V \Delta T_s \quad (1)$$

Where ρ_s is the density of steel (kg/m^3), c_s is the specific heat of steel (J/kg K), ΔT_s is the change in steel temperature ($^\circ\text{C}$ or K) in the time step Δt , F is the heated surface area (m^2) of unit length of the member, V is the heated volume (m^3) in unit length of the member and q'' is the heat transfer at the surface (W/m^2), given by

$$q'' = h_c (T_f - T_s) + \sigma \varepsilon (T_f^4 - T_s^4) \tag{2}$$

Where h_c is the convective heat transfer coefficient ($\text{W/m}^2 \text{K}$), σ is the Stefan-Boltzmann constant ($56.7 \times 10^{-12} \text{ kW/m}^2 \text{K}^4$), ε is the resultant emissivity, T_f is the temperature in the fire environment (K) and T_s is the temperature of the steel (K).

Eqs. (1) and (2) can be rearranged to give:

$$\Delta T_s = F/V (1/\rho_s c_s) [h_c (T_f - T_s) + \sigma \varepsilon (T_f^4 - T_s^4)] \Delta t \tag{3}$$

The convective heat transfer coefficient h_c , is recommended to have a value of $25 \text{ W/m}^2 \text{K}$. The Eurocode, EC1 [4], recommends an h_c value of $25 \text{ W/m}^2 \text{K}$ for the standard fire and $50 \text{ W/m}^2 \text{K}$ for the hydrocarbon fire. EC1 recommends a value of 0.50 for the resultant emissivity, ε .

In Eq. (3), the parameter F/V is the ‘section factor’ or the ‘massivity factor’ and is a measure of the ratio of the heated perimeter to the cross section area of the member. The section factor is an important parameter in thermal analysis because the rate of heat input is directly proportional to the area exposed to the fire environment and the subsequent rate of temperature increase is inversely proportional to the heat capacity of the member measured as the product of the specific heat, the density and the volume of the steel segment under consideration. Tables of section factors for common structural steel shapes are available from distributors of steel products. For instance, section factors for American, British and New Zealand steel sections are listed by UBC (1997) [5]. In a standard fire test of beam elements, only the sides and the soffit of the member are assumed to be exposed to fire [6]. Therefore, in the present investigation, only the sides and the soffit of the member are assumed to be exposed to fire and the heated perimeter for evaluation of the section factor has been calculated accordingly.

Table 1. Spreadsheet calculation for temperatures of unprotected steel sections [2]

Time	Steel Temperature, T_s	Fire Temperature, T_f	Difference in Temperature	Change in Steel Temperature, ΔT_s
$t_1 = \Delta t$	Initial steel temperature, T_{so}	Fire temperature halfway through time step (at $\Delta t/2$)	$T_f - T_{so}$	Calculate from Eq. (3) with values of T_f and T_{so} from this row
$t_2 = t_1 + \Delta t$	T_s from previous time step + ΔT_s from	Fire temperature halfway through time	$T_f - T_s$	Calculate from Eq. (3) with values of T_f and T_s

previous row	step (at $t_1 + \Delta t/2$)	from this row
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Milke and Hill [7] have proposed the spread sheet shown in Table 1 for calculating the steel temperatures using the above algorithm. For a reasonable convergence of the solution iteration without sacrificing accuracy, EC3 [8] suggests the time step Δt to be no more than 30 s. In addition, EC3 suggests a minimum value of the section factor of 10 m^{-1} . Kay et al [9] have shown that the above algorithm can result in a very good prediction of non-insulated steel beam temperatures in standard fire-resistance tests.

3. ALGORITHM FOR INSULATED SECTIONS

Insulated steel members heat up much more slowly than noninsulated members because of the applied thermal insulation which protects the steel from rapid absorption of heat. The iterative method [2] for determining the time-temperature response of insulated sections is similar to that for non-insulated sections except for the fact that unlike non-insulated sections, heat transfer coefficients are not required for analyzing the behaviour of insulated sections. This is because it is assumed that the external surface of the insulation is at the same temperature as the fire gases and the internal surface of the insulation is at the same temperature as the steel member. Care has to be taken during analysis that the section factor F/V , should strictly be calculated using the fire exposed perimeter rather than the inside perimeter of the steel section. The simplified procedure for insulated sections presented herein is not applicable for steel members protected with heavy insulating materials or those with temperature-dependent thermal properties. For such cases more rigorous procedures based on finite element applications should be employed.

The governing thermal equation for insulated members can be expressed as:

$$\Delta T_s = (F/V) (k_i / d_i \rho_s c_s) [\rho_s c_s / (\rho_s c_s + (F/V) d_i \rho_i c_i / 2)] (T_f - T_s) \Delta t \quad (4)$$

Where k_i is the thermal conductivity of the insulation (W/m K), d_i is the thickness of the insulation (m) which is assumed to be uniform over the perimeter of the rolled steel section, ρ_i is the density of the insulation (kg/m^3) and c_i is the specific heat of the insulating material (J/kg K). All other terms in Eq. (4) have the meaning described earlier. It is implied in Eq. (4) that no allowance is made for the temperature gradient across the insulating material and the fire gas temperature is assumed to be constant during the time interval Δt .

The spreadsheet for temperature calculations for insulated sections is similar to that shown in Table 1 except that Eq. (4) is used instead of Eq. (3) for the calculation of the temperature change in the steel section.

4. STANDARD FIRE

The time-temperature curve used in fire-resistance tests is called the standard fire. In the present investigation, the fire exposure condition has been specified in terms of a standard

fire which defines the ambient temperature due to the fire at various instants of time. The most widely used standard time-temperature curves are those specified in ASTM E 119 [10] and ISO 834. The ISO 834 time-temperature curve has been used in the present investigation and is defined by the following equation:

$$T = 345 \log_{10} (8t + 1) + T_0 \quad (5)$$

Where t is the time (minutes) and T_0 is the ambient temperature ($^{\circ}\text{C}$).

The ISO 834 specified time-temperature curve defined by Eq. (5) is illustrated in Figure 1.

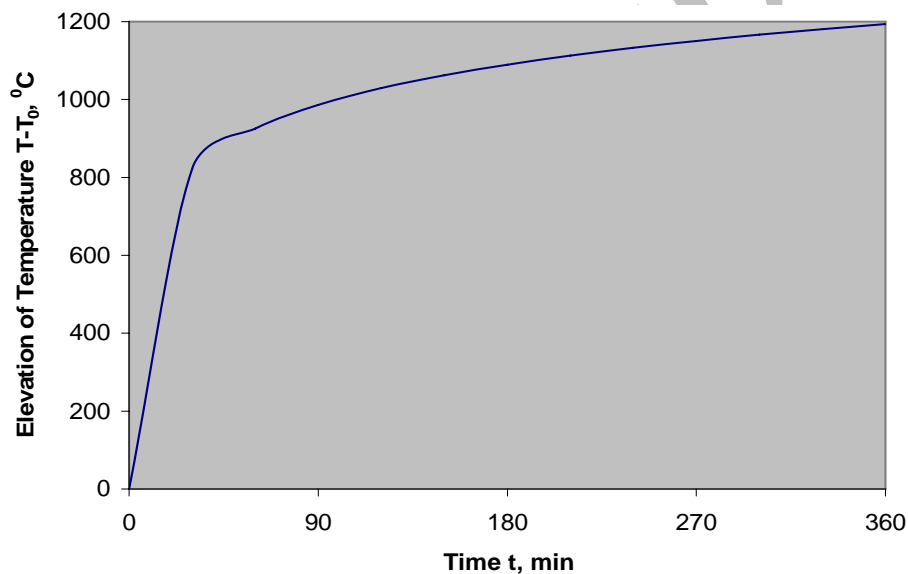


Figure 1. ISO 834-1975 Standard time-temperature curve

5. SCOPE OF THE INVESTIGATION

The temperature calculations have been carried out for three AISC wide flange beams: W610 x 125 (mm x kg/m), W610 x 101 and W610 x 82. Two types of insulation materials were investigated: cement concrete and cement plaster. The properties of these insulation materials are presented in Table 2. Three thicknesses of the concrete insulation were considered for each of the wide flange beams under investigation, viz. 25 mm, 37.5 mm and 50 mm. Similarly, three thicknesses of cement plaster insulation were evaluated: 12.5 mm, 25 mm and 37.5 mm. Although lighter insulation materials with vastly superior thermal properties like sprays, boards and compressed fibre boards are commonly available in the developed markets of the West, they are yet to be widely used in India. Hence, the scope of this investigation has been restricted to cement based insulation materials which are assumed

to be applied on the steel sections using guniting techniques.

Table 2. Properties of the Insulation Materials

Material Type	Density (kg/m^3)	Specific Heat, C_i (J/kgK)	Thermal Conductivity, k_i (W/mK)
Cement Concrete	2400	1130	1.279
Cement Plaster	1680	840	0.779

6. RESULTS AND DISCUSSION

The time-temperature response, which for convenience has been called as the fire behaviour in this investigation, of the three non-insulated rolled steel sections is presented in Figure 2. It may be observed that all the sections reach equilibrium with the ambient fire temperature after some time of exposure. The influence of varying the thickness of the concrete insulation on the fire behaviour of W610×125, W610×101 and W610×82 is illustrated by the time-temperature curves in Figures 3, 4 and 5. As expected, better thermal shielding is achieved with greater thickness of the insulation material.

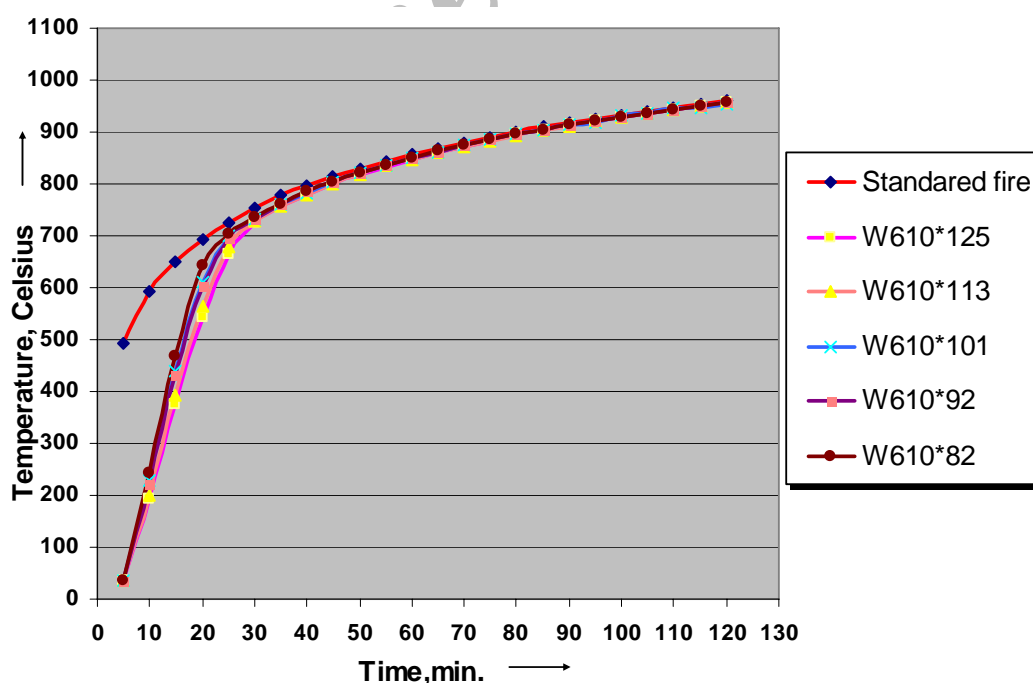


Figure 2. Fire behaviour of non-insulated AISC rolled steel sections

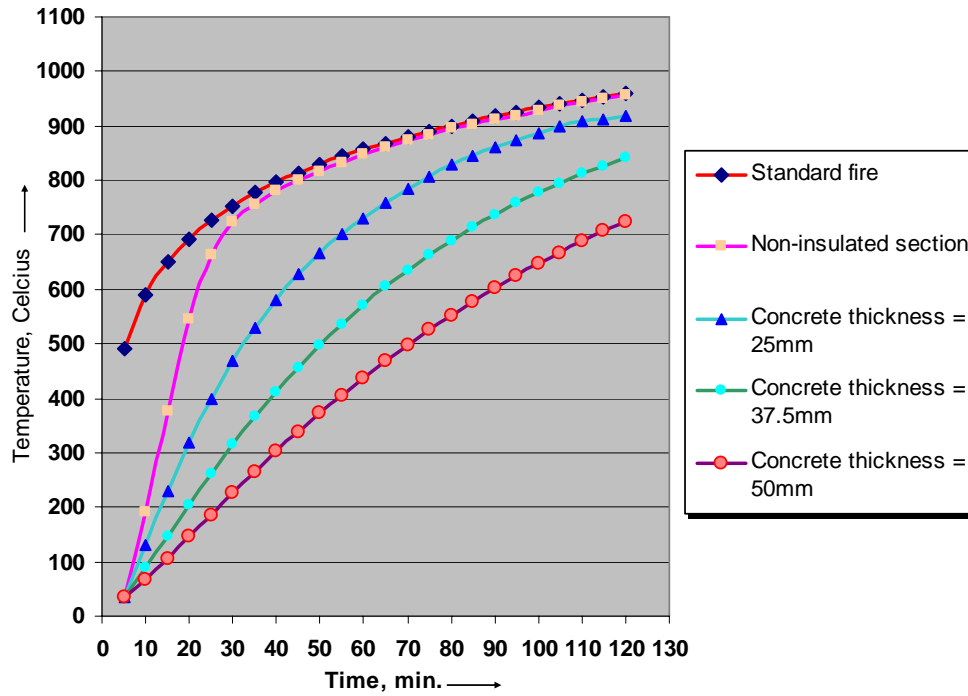


Figure 3. Fire behaviour of Concrete insulated AISC rolled steel section [W610×125]

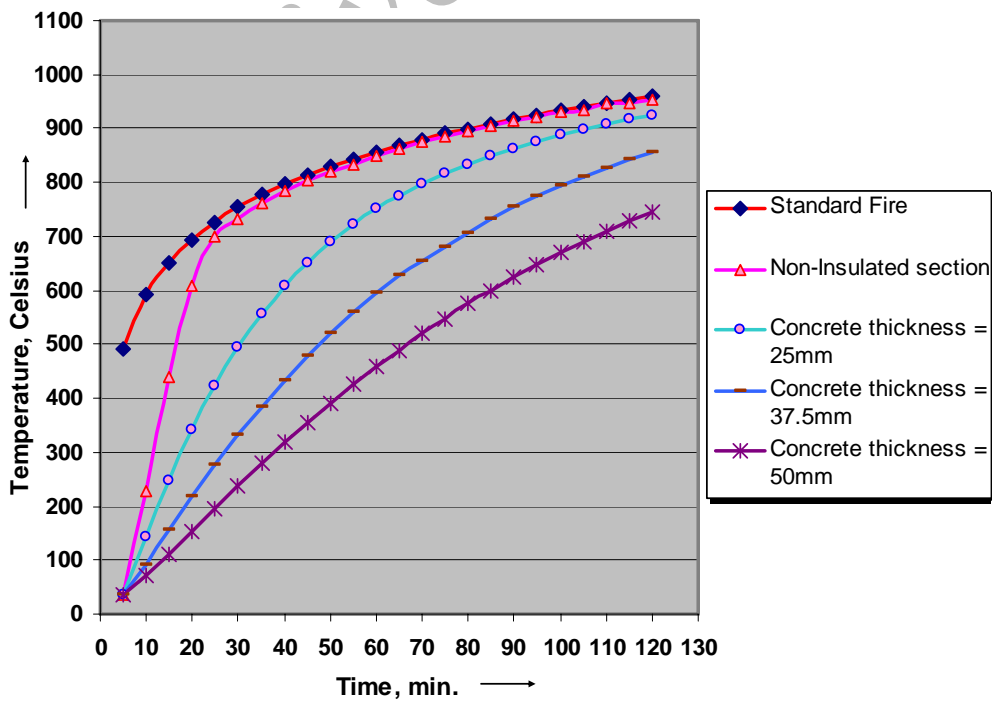


Figure 4. Fire behaviour of Concrete Insulated AISC rolled steel section [W610×101]

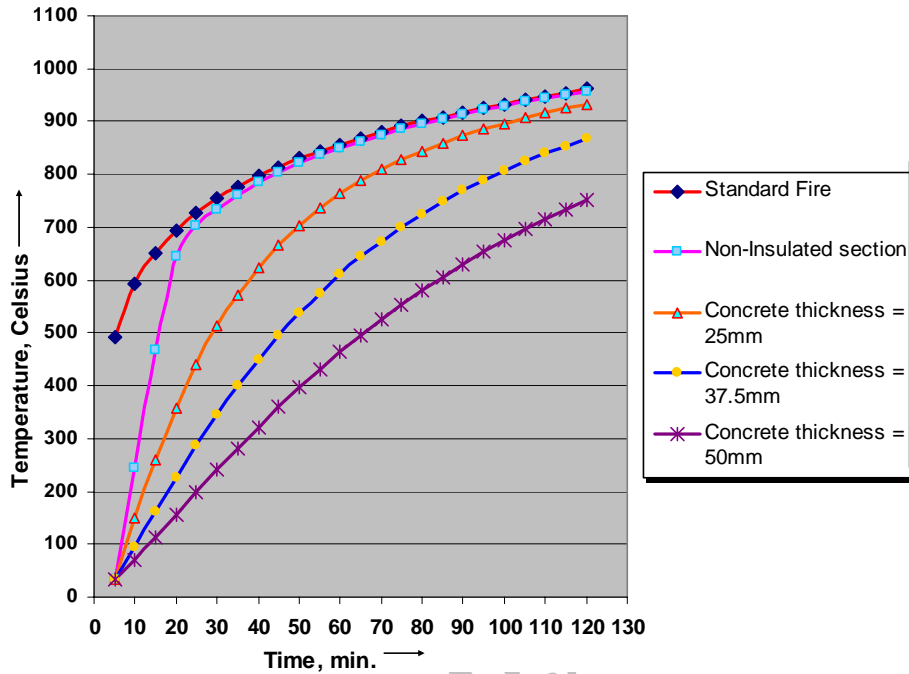


Figure 5. Fire behaviour of Concrete Insulated AISC rolled steel section [W610×82]

An interesting observation which can be made from the graphical results presented in Figures 6, 7 and 8 is that the time-temperature response of the three insulated rolled sections under investigation for a given thickness of the insulation is independent of the geometric properties of the section.

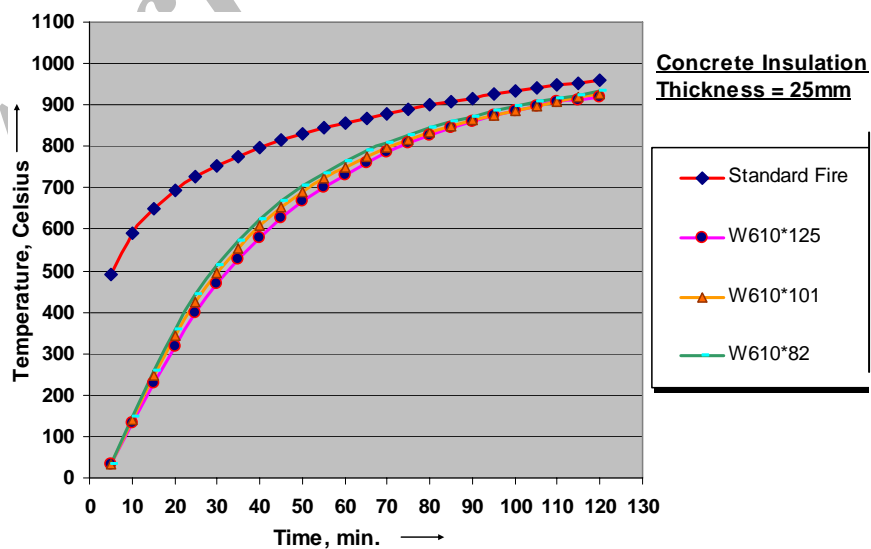


Figure 6. Influence of section characteristics on fire behaviour

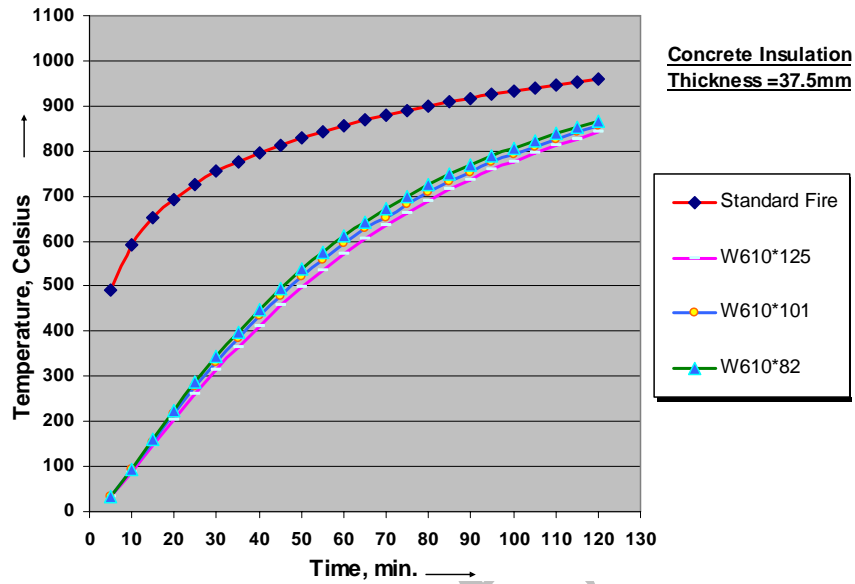


Figure 7. Influence of section characteristics on fire behaviour

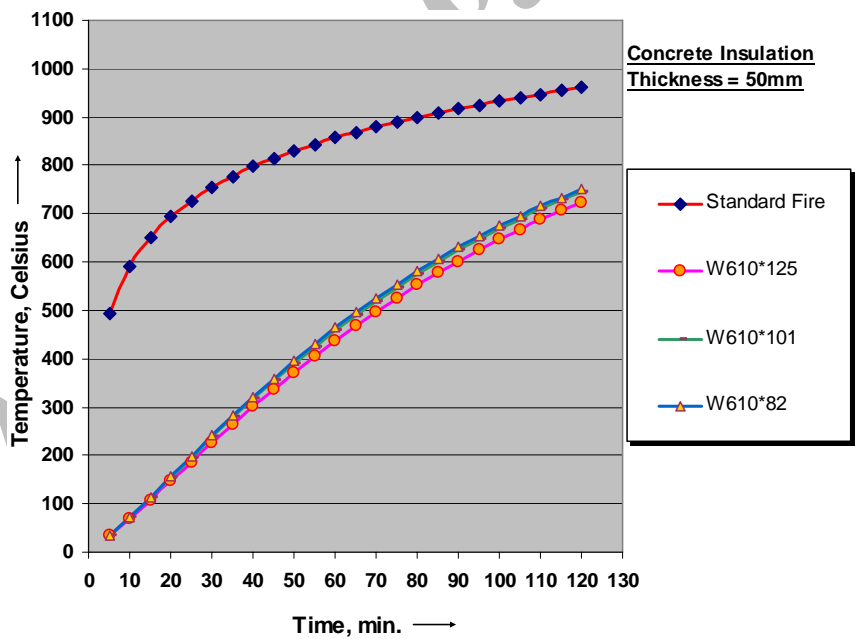


Figure 8. Influence of section characteristics on fire behaviour

The influence of varying the thickness of the cement plaster insulation on the time-temperature responses of W610×125, W610×101 and W610×82 is presented in Figures 9,

10 and 11. As observed with the case of concrete insulation, better thermal shielding is achieved with greater thickness of the cement plaster.

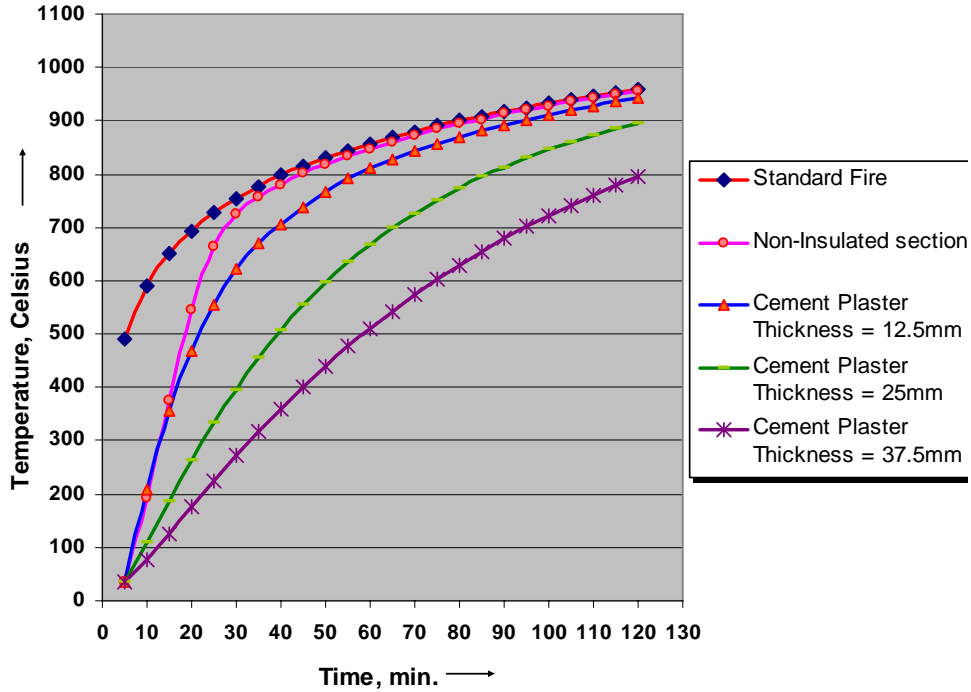


Figure 9. Fire behaviour of cement plaster insulated AISC rolled steel section [W610×125]

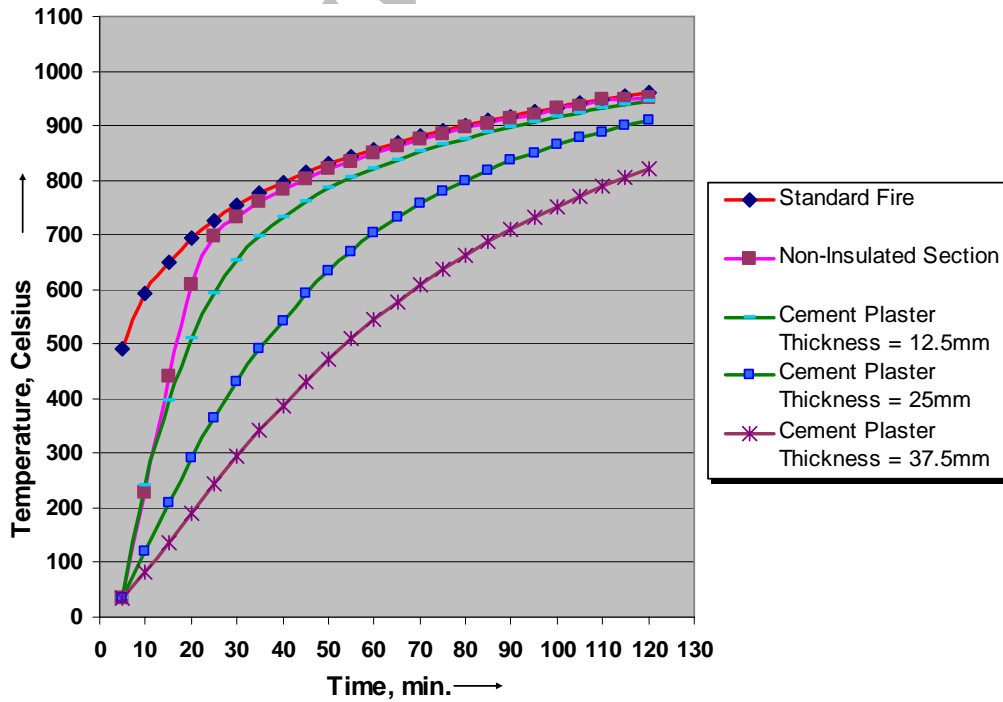


Figure 10. Fire behaviour of cement plaster insulated AISC rolled steel section [W610×101]

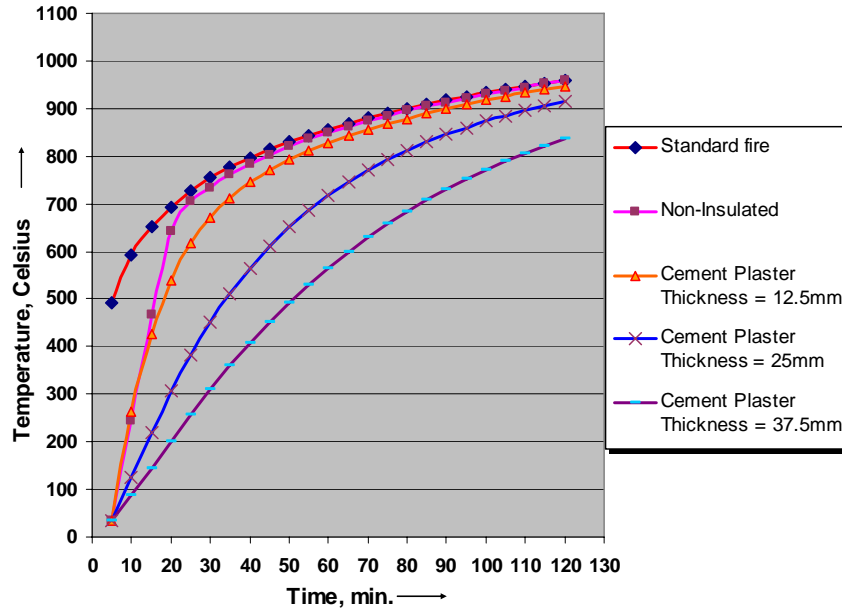


Figure 11. Fire behaviour of cement plaster insulated AISC rolled steel section [W610×82]

Of particular interest is the relative thermal shielding efficiency of the two insulating materials under investigation in this study. The performance of the two insulating materials is compared in the time-temperature curves of Figures 12, 13 and 14 for the three rolled sections for similar thicknesses of the two insulating materials. The influence of the lower coefficient of thermal conductivity of cement plaster is clearly reflected in the better time-temperature response of sections insulated with this material.

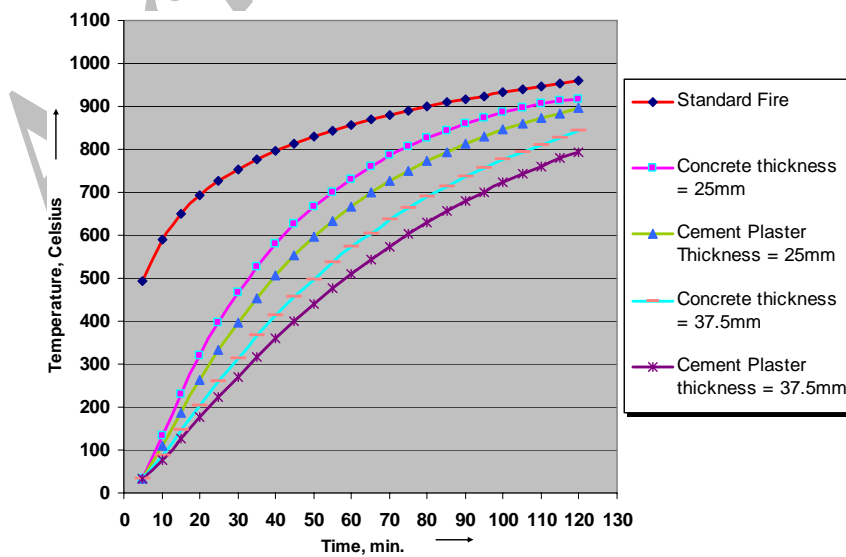


Figure 12. Relative performance of insulating material for AISC section [W610×125]

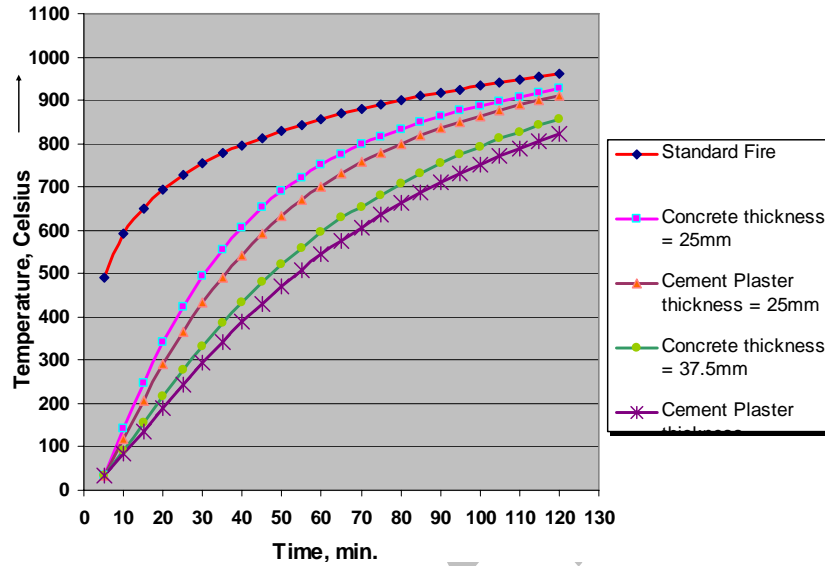


Figure 13. Relative performance of insulating material for AISC section [W610×101]

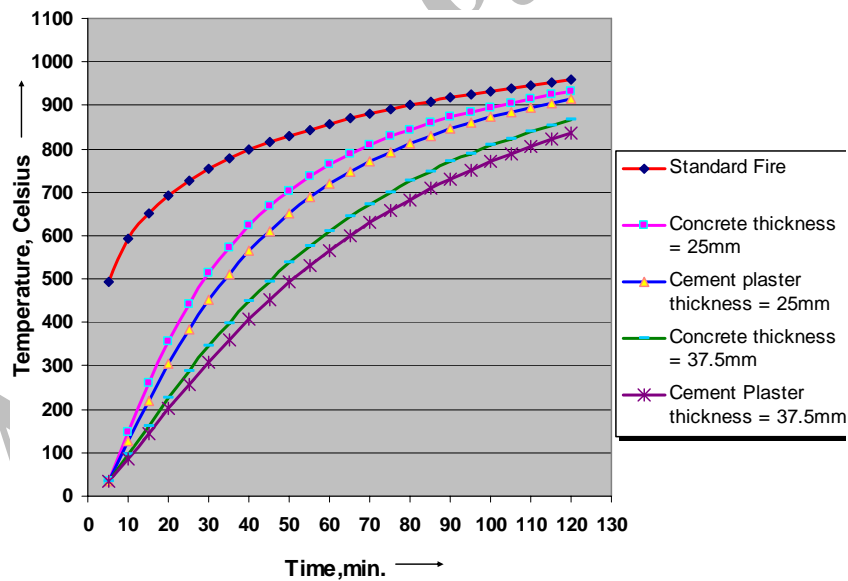


Figure 14. Relative performance of insulating material for AISC section [W610×82]

7. CONCLUSIONS

On the basis of a step-by-step iterative calculation procedure, it has been possible to

determine the elevation in temperature in noninsulated and insulated rolled steel sections exposed to a standard fire. The results of this investigation also illustrate qualitatively the efficiency of cement based insulating materials like plaster and concrete. The time-temperature curves obtained from this study can be used to develop fire-resistance ratings for simple steel members in the temperature domain if information is available about the limiting steel temperatures. Similarly, the more practically relevant fire-resistance ratings in the strength domain can be carried out on the basis of this investigation by incorporating thermal-stress coupling in the analysis procedures.

REFERENCES

1. BS 5950. Structural Use of Steelwork in Buildings, Part 8, Code of Practice for Fire Resistant Design, British Standards Institution, U.K., 1990.
2. Buchanan, A.H. *Structural Design for Fire Safety*, John Wiley, New York, 2001, p. 421.
3. ISO 834. Fire Resistance Tests-Elements of Building Construction, International Organisation for Standardisation.
4. EC1. Eurocode 1: Basis of Design and Design Actions on Structures. Part 2-2: Actions on Structures Exposed to Fire. ENV 1991-2-2, European Committee for Standardisation, Brussels, Belgium, 1994.
5. UBC. Uniform Building Code, International Conference of Building Officials, Whittier, California, USA, 1997.
6. BS 8110-2:1985. Structural Use of Concrete-Part 2: Code of Practice for Special Circumstances, British Standards Institution, London, Nov. 2005, 59 pp.
7. Milke, J.A. and Hill, S. Initial Development of Draft Performance-based Fire Protection Standard on Construction, *American Society of Civil Engineers*, 1996.
8. EC3. Eurocode 3: Design of Steel Structures. ENV 1993-1-2: General Rules-Structural Fire Design, European Committee for Standardisation, Brussels, Belgium, 1995.
9. Kay, T.R., Kirby, B.R. and Preston, R.R. Calculation of the Heating Rate of an Unprotected Steel Member in a Standard Fire-resistance Test, *Fire Safety Journal*, No. 4, **26**(1996) 327-350.
10. ASTM E119-88. Standard Test Methods for Fire Tests of Building Construction and Materials, American Society for Testing and Materials, USA.