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DETERMINING THE RESPONSE OF PROTECTED STEEL TO FIRE LOADING

Introduction

This article discusses the methods used by SLP to predict the temperature time histories of steelwork with PFP (passive fire protection) under thermal loading.

The method described uses a simple theoretical model to predict steel temperatures. This theoretical model is also used to recover fundamental properties of the PFP material from vendor supplied furnace test results, in particular the conductivity of the PFP material.

The emissivity of the PFP is not relevant as there are no exposed, unheated PFP surfaces. For brevity most of the parameters used are defined in Table 73.1.

Theoretical Model

Consider a steel section protected by a layer of insulating material of thickness d (in metres).

It is appropriate to assume that the temperature of the steel 'T_s' is sensibly constant throughout the section and equal to the temperature of the inner surface of the insulating layer.

The basic heat accumulation equation for members exposed to heat may be written:

$$\delta T_s = Q_a\, \delta t / (\rho_s\, C_s\, A_s + \rho_M\, C_M\, A_M) \qquad (73.1)$$

where:

- δT_s is the increase of steel member temperature in the time interval δt,
- A_s is the cross-sectional area of the steel member (m^2),
- A_M is the cross-sectional area of the protective coating, Mandolite 550 (m^2),
- Q_a is the net heat flux into the member per metre length (W/m).

Other symbols are defined in Table 73.1.

This net heat flux 'Q_a' may depend on whether the member is engulfed and what convection conditions are present **but it will often be limited by the rate at which heat can be conducted through the insulating layer.** In these circumstances the net heat flux will be independent of external flux from the fire 'Q_{in}', the emissivity and the other factors which usually define heat loading. The heat flux will then depend only on the insulation outer surface temperature 'T_{ms}' and is given by:

$$Q_a = \frac{K_M}{d} (T_{ms} - T_s)\, H_p \qquad (73.2)$$

$$\text{If } Q_a < \epsilon_m Q_{in}$$

Here 'H_p' is the heated perimeter and 'd' is the insulation thickness in metres.

In the engulfed case it is also safe to assume that the temperature of the outer surface of the insulation is at or near the flame or furnace temperature and that the temperature distribution through the Mandolite thickness becomes linear a few minutes after the heat is applied. This time will depend on the insulation thickness and may be calculated using the full time dependent heat conduction equation (see Reference [1] Section 4.4.1).

Table 73.1
Thermal properties

Material	Density (Kg/m^3)	Specific Heat (J/Kg °C)	Conductivity (W/m °C)	Convection (W/m °C)	Emissivity
Steel	$\rho_s = 7850$	$C_s = 520$	$K_s = 45$	$h_s = 25$	$\epsilon_s = 0.80$
Mandolite 550	$\rho_M = 550$	$C_M = 800$	$K_M = 0.162$		$\epsilon_M = 0.85$
Rockwool	$\rho_R = 150$	$C_R = 800$	$K_R = 0.045$		
Durasteel 3DF1	$\rho_D = 1926$	$C_D = 800$	$K_D = 0.0397$		
Air gap	$\rho_g = 1.25$	$C_g = 1000$		$h_g = 1.31\ \sqrt[3]{\delta T}$	

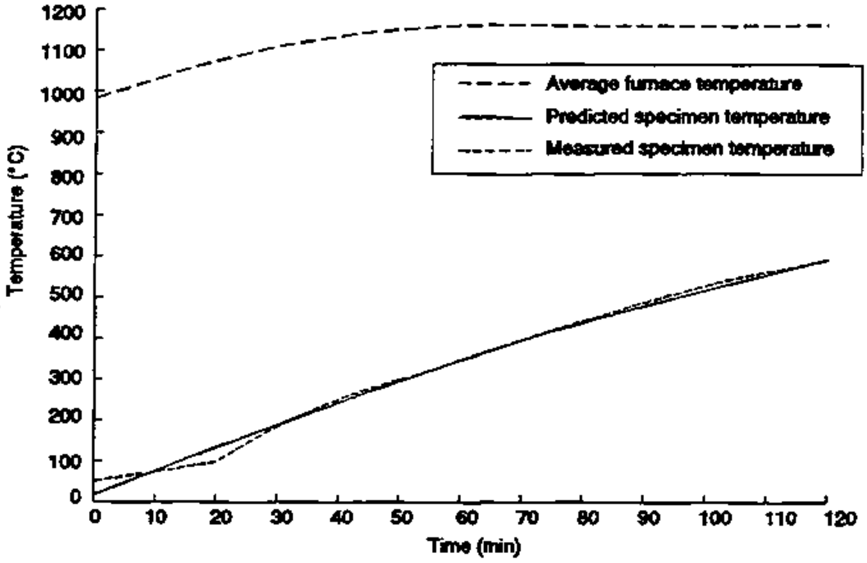

Figure 73.1
Mandoval test specimen UC305x305x283 - Temperature v Time History

Combining equations (73.1) and (73.2) gives:

$$\frac{K_m}{C_s \rho_s} = \frac{\delta T_s \; A \; d}{\delta t \; (T_{ms} - T_s) \; H_p} \qquad (73.3)$$

In other words the thermal diffusivity ($K_m/C_s\rho_s$) is proportional to the rate of change of steel temperature. This equation may be simply solved to derive the variation of steel temperature with time.

Derivation of PFP properties

A steel column (UC305×305×283), is protected by 20.5mm of Mandolite and subjected to a furnace test in which it is engulfed in flame with the furnace temperature controlled to follow the standard hydrocarbon furnace curve shown by the upper curve in Figure 73.1. The Mandolite surface temperature may be taken to be equal to the furnace temperature. The steel temperature was also measured and the temperature time history is given by the lower, dotted curve in Figure 73.1.

Equation 73.3 shows that if the density of Mandolite is known, the ratio of conductivity and specific heat determines the response for a given rate of heating of the steel '$\delta T_s / \delta t$' which in turn is available from the test results.

Mandolite 550 has a known density of 550 kg/m^3 and the specific heat is similar to that of concrete being 800 J/kg/°C. Hence the conductivity of the material may be estimated. In theory, as equation 73.3 holds at all rates of heating and steel temperatures the variation of the thermal properties with temperature may also be calculated. An average conductivity of 0.162 W/m/°C is indicated by the test results.

The lower, solid curve in Figure 73.1 shows the temperature versus time history of the test specimen as simulated by SLP software using the derived thermal properties of Mandolite 550. The curve provides a good correlation for the member temperatures except at its lower end, i.e. from 0 to 30 minutes. This is due to latent heat absorption as pore water evaporates.

The derived PFP properties may then be used to predict the thermal response of partially covered members and members protected by several layers of different materials.

Further details

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References

[1] 'Interim Guidance Notes for Design and Protection of Topside Structures Against Explosion and Fire', SCI, November 1991.