

**The Temperatures
Attained By
Unprotected
Steelwork In
Building Fires**

Summary

This document has been prepared as a design tool for fire engineers to provide a relatively quick method for determining the temperatures attained by unprotected steel members in fire. It is based upon the relationships given in the European Design Codes which have been validated against a comprehensive data base of real fire tests covering a wide range of variables. The results can be applied to fires involving wood and plastics, characteristic and parametric fire curves. For parametric time temperature relationships described in Eurocode 1:Part 2.2, Nomograms are presented for determining the maximum steel temperatures covering a wide range of building types and fire severities. However, this guide should not be used in place of a full structural analysis for a fire safety engineering solution.

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The Temperatures Attained By Unprotected Steelwork In Building Fires

B R Kirby and L N Tomlinson

Validation of Heat Transfer Relationships

The European Standard EC1: Part 2.2 Actions on Structures Exposed to Fire⁽¹⁾ provides a detailed calculation method for determining the temperatures attained by unprotected steel members. The methodology is based upon calculating the net heat flux (h_{net}) incident upon the surface of the member by considering the convective and radiative heat transfer exponents from the environment using the general equation:

$$h_{net} = \gamma_r \cdot h_r + \gamma_c \cdot h_c \quad (\text{W/m}^2)$$

Where h_r = radiative heat flux (W/m²)
 h_c = convective heat flux (W/m²)

and γ_r, γ_c are factors which are used to align with National experience.

The radiative heat flux is given by the relationship:

$$h_r = \phi \cdot \epsilon_{res} \cdot 5.67 \times 10^{-8} (\theta_r + 273)^4 - (\theta_m - 273)^4 \quad (\text{W/m}^2)$$

Where: ϕ = configuration factor (-)
 ϵ_{res} = resultant emissivity = $\epsilon_f \cdot \epsilon_m$ (-)
 θ_r = radiation temperature of the environment (°C)
 θ_m = surface temperature of the material (steel) (°C)
 5.67×10^{-8} = Stefan Boltzmann constant (W/m² K⁴)

and ϵ_f = emmissivity of fire (-)
 ϵ_m = emmissivity of steel (-)

The convective heat flux is given by the equation:

$$h_c = a_c \cdot (\theta_g - \theta_m) \quad (\text{W/m}^2)$$

Where: α_c = coefficient of heat transfer by convection (W/m² K)
 θ_g = gas temperature of the environment (°C)

From the net flux incident upon the surface of the steel member its change in mean temperature, $\Delta\theta_m$, over a time step, Δt , is given from EC3: Part 1.2⁽²⁾ by:

$$\Delta\theta_m = h_{net} / c_p \cdot \rho \cdot A/V \cdot \Delta t \quad (^\circ\text{C})$$

Where c_p = specific heat of steel (J/kg K)
 ρ = density of steel = 7850 kg/m³
 A/V = section factor for the member (m⁻¹)

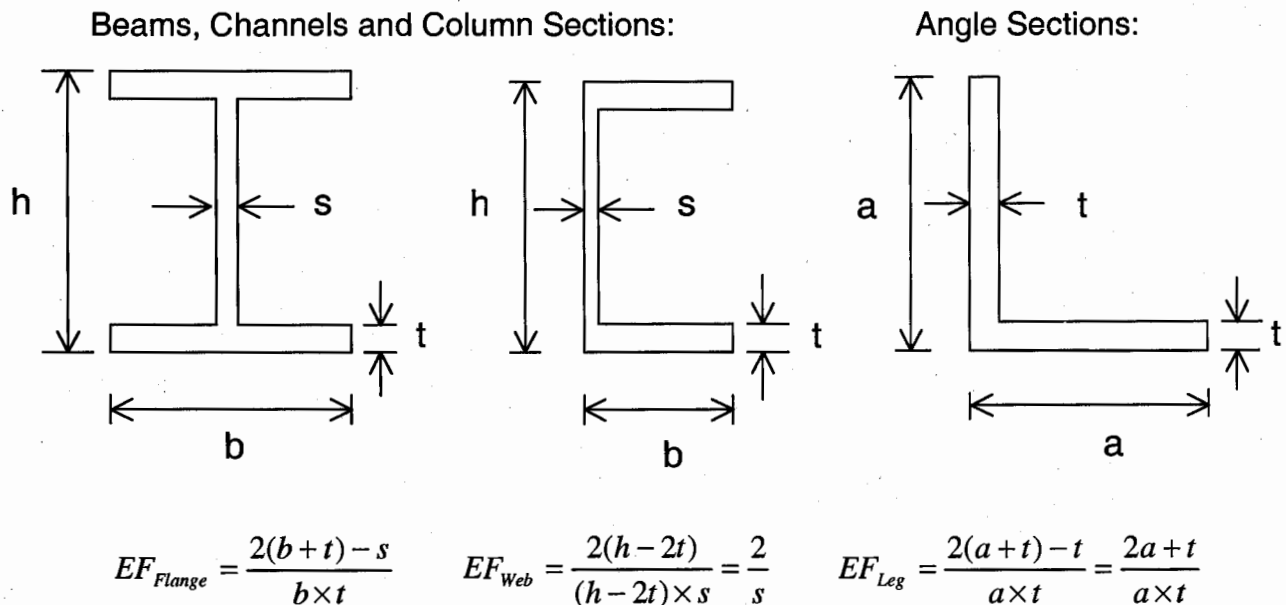
Validation of Heat Transfer Relationships

Assuming members are fully engulfed in fire, i.e. $\phi = 1.0$, fixing $\gamma_r, \gamma_c = 1.0, \alpha_c = 25 \text{ W/m}^2$ and making ϵ_f and $\epsilon_m = 0.8^{(3)}$, the temperature rise of unprotected steel can be conservatively predicted for all types of fire using as an input into the calculations, the heating cycle for the hot gases (atmosphere).

Using these values the above relationships have been validated against a large body of experimental data obtained from fires carried out in both large and small scale compartments in which variations in the following parameters have been studied:

- Quantity of fire loading or fire load density.
- Type of fire loading (wood and plastic).
- Compartment height (max. 4.2 m), shape and floor area.
- Compartment construction and lining materials.
- Ventilation characteristics.

In the analysis, the section factor A/V (H_p/A) which is based upon the entire section profile, is replaced by a more exact relationship 'Element Factor' whereby the temperature can be determined for the critical portion of the steel profile (m^{-1}). The element factor is defined as the ratio of the surface area of a flange or web of a section exposed to fire to the cross section area of that part of the section. This approach aligns with the calculations given in BS 5950: Part 8⁽⁴⁾ for the fire limit state and assumes the portion of the member in question is engulfed in fire. In cases where the element is in direct contact with a poor conductor of heat e.g. concrete, brick and wood, the calculations will yield over conservative results. The following examples illustrate how the Element Factor is determined:



units in m

For hollow sections the Element Factor = $1/t$, where t is the wall thickness in m.

Development of Design Tools – Nomograms

In EC1: Part 2.2 parametric equations are presented which describe the heating and cooling phases of the atmosphere for a range of fire severity and compartment conditions.

The heating phase within an enclosure is described by the relationship:

$$\theta_g = 1324(1 - 0.324 e^{-0.2t^*} - 0.204 e^{-1.7t^*} - 0.472 e^{-19t^*})$$

Where	θ_g	=	temperature of the fire in the compartment	(°C)
	t^*	=	$t\Gamma$	(h)
	t	=	time	(h)
	Γ	=	$(O/b)^2 / (0.04/1160)^2$	(-)

in which	O	=	the ventilation opening factor described as $A_v \sqrt{h/A_t}$	(m ^{1/2})
	b	=	the thermal properties of the enclosure	(J/m ² s ^{1/2} K)

In the relationship $A_v \sqrt{h/A_t}$,

	A_v	=	area of vertical openings	(m ²)
	h	=	weighted mean height of the openings	(m)
	A_t	=	total surface area of the enclosure (walls, floor and ceiling including the openings)	(m ²)

To account for the thermal characteristics of the different materials used in the construction of walls, floor and ceiling, $b = (\rho c \lambda)^{1/2}$ and should be introduced as:

$$b = \frac{\sum b_j A_{ij}}{\sum A_{ij}} \quad (\text{J/m}^2 \text{s}^{1/2} \text{K})$$

Where:	ρ	=	density of the boundary material	(kg/m ³)
	c	=	specific heat of the boundary material	(J/kg K)
	λ	=	thermal conductivity of the boundary material	(W/mK)
	A_{ij}	=	area of enclosure, including the openings of thermal property, b_j	(m ²)

The cooling phase is described by the relationships:

$$\begin{aligned} \theta_g &= \theta_{\max} - 625 (t^* - t_d^*) && \text{for } t_d^* \leq 0.5 \\ \theta_g &= \theta_{\max} - 250 (3 - t_d^*) (t^* - t_d^*) && \text{for } 0.5 < t_d^* < 2 \\ \theta_g &= \theta_{\max} - 250 (t^* - t_d^*) && \text{for } t_d^* \geq 2 \end{aligned}$$

Where:	θ_{\max}	=	maximum temperature in the heating phase for $t^* = t_d^*$	(°C)
	t_d^*	=	$(0.13 \cdot 10^{-3} q_{ld} \cdot \Gamma) / O$	(h)
	q_{ld}	=	design value of the fire load density related to the internal surface area A_t of the enclosure	(MJ/m ²)

Using the appropriate equations and heat transfer factors, maximum temperatures of the critical element of steel members have been determined using the parametric relationships described above. These are presented as a series of nomograms and are based upon an incremental increase in the ventilation opening factor ($A_v \sqrt{h}/A_e$) from $0.02 \text{ m}^{1/2}$ to $0.2 \text{ m}^{1/2}$ and cover the limits of $1000 \leq b \leq 2000 \text{ J/m}^2 \text{ s}^{1/2} \text{ K}$

In the nomograms, the Design Fire Load Density (q_{fd}), is related to the surface area of the enclosure (MJ/m^2) and maximum steel temperatures are provided for element factors (EF) over the useful range from 30 m^{-1} to 300 m^{-1} .

References

- 1 Eurocode 1: 'Basis of design and actions on structures Part 2.2: Actions on structures exposed to fire', ENV 1991-2-2, British Standards Institution, 1996.
- 2 Eurocode 3: 'Design of steel structures Part 1.2: General Rules - Structural fire design', ENV 1993-1-2, British Standards Institution, 1995.
- 3 T.R. Kay, B.R. Kirby and R.R. Preston: 'Calculation of the heating rate of an unprotected steel ember in a standard fire resistance test', Fire Safety Journal, Vol. 26, (1996), pp327-350.
- 4 BS 5950: 'The structural use of steelwork in buildings Part 8: Code of practice for Fire Resistant Design', British Standards Institution, 1990.

Table 1: Thermal Properties of Typical Materials

Material	Thermal Inertia ($b = \text{J/m}^2 \text{ s}^{1/2} \text{ K}$)
Dense concrete (density = 2400 kg/m^3)	2,000
Medium dense concrete (density = 1800 kg/m^3)	1,225
Cellular blocks (density = 1000 kg/m^3)	700
Brickwork	1,500
Ordinary plasterboard	750
Vermiculite plaster	650
Wood	450
Steel	14,500

Design Example

Consider a compartment in a building measuring 20m long x 10m wide and 4m high. Ventilation (windows) is provided along two walls measuring 8m long x 2.5m high and 18m wide x 2.5m high. The compartment is constructed using dense concrete for the floor and lightweight block-work for the walls. The primary members in the structural steel frame include the following sections sizes:

Columns: 305 x 305mm x 158kg/m
Beams: 610 x 305mm x 149kg/m

The fire load density = 100MJ/m² of bounding surfaces (walls, floor and ceiling)

Check to see whether the members can be left unprotected.

Compartment and ventilation geometry:

Total area of walls, floor and ceiling, including the openings, A_t ,

$$= (20 \times 10) \times 2 + (20 + 10) \times 2 \times 4 = 640\text{m}^2$$

$$\text{Total ventilation area, } A_v, = (18 + 8) \times 2.5 = 65\text{m}^2$$

$$\text{Ventilation opening factor, } \frac{A_v}{A_t} \sqrt{h}, = \frac{65}{640} \sqrt{2.5} = 0.16\text{m}^{1/2}$$

Thermal inertia of the compartment:

$$\begin{aligned} \text{Total area of dense concrete} &= 200 \times 2 = 400\text{m}^2 \\ \text{Thermal inertia of dense concrete} &= 2,000\text{J/m}^2\text{s}^{1/2}\text{K} \end{aligned}$$

$$\begin{aligned} \text{Total area of block-work walls} &= 240\text{m}^2 - 65\text{m}^2 = 175\text{m}^2 \\ \text{Thermal inertia of block-work} &= 700\text{J/m}^2\text{s}^{1/2}\text{K} \end{aligned}$$

$$\text{Weighted mean thermal inertia} = \frac{(175 \times 700) + (400 \times 2000)}{575} = 1604\text{J/m}^2\text{s}^{1/2}\text{K}$$

Determination of the maximum temperature:

1. In BS 5950: Part 8, the fire limit state of a column is based upon the average flange temperature.

For a 305 x 305mm x 158kg/m universal column:

$$\begin{aligned} \text{Flange width (b)} &= 327.1\text{mm} \\ \text{Flange thickness (t)} &= 25.0\text{mm} \\ \text{Web thickness (s)} &= 15.8\text{mm} \end{aligned}$$

$$EF_{\text{Flange}} = \frac{2(b+t) - s}{b \times t} = 84\text{m}^{-1}$$

By interpolation the maximum steel temperature = 553°C

2. In BS 5950: Part 8, the fire limit state of a floor beam is based upon the lower flange temperature.

For a 610 x 305mm x 149kg/m universal beam:

Flange width (b) = 304.8mm

Flange thickness (t) = 19.7mm

Web thickness(s) = 11.8mm

$$EF_{\text{Flange}} = \frac{2(b+t)-s}{b \times t} = 106\text{m}^{-1}$$

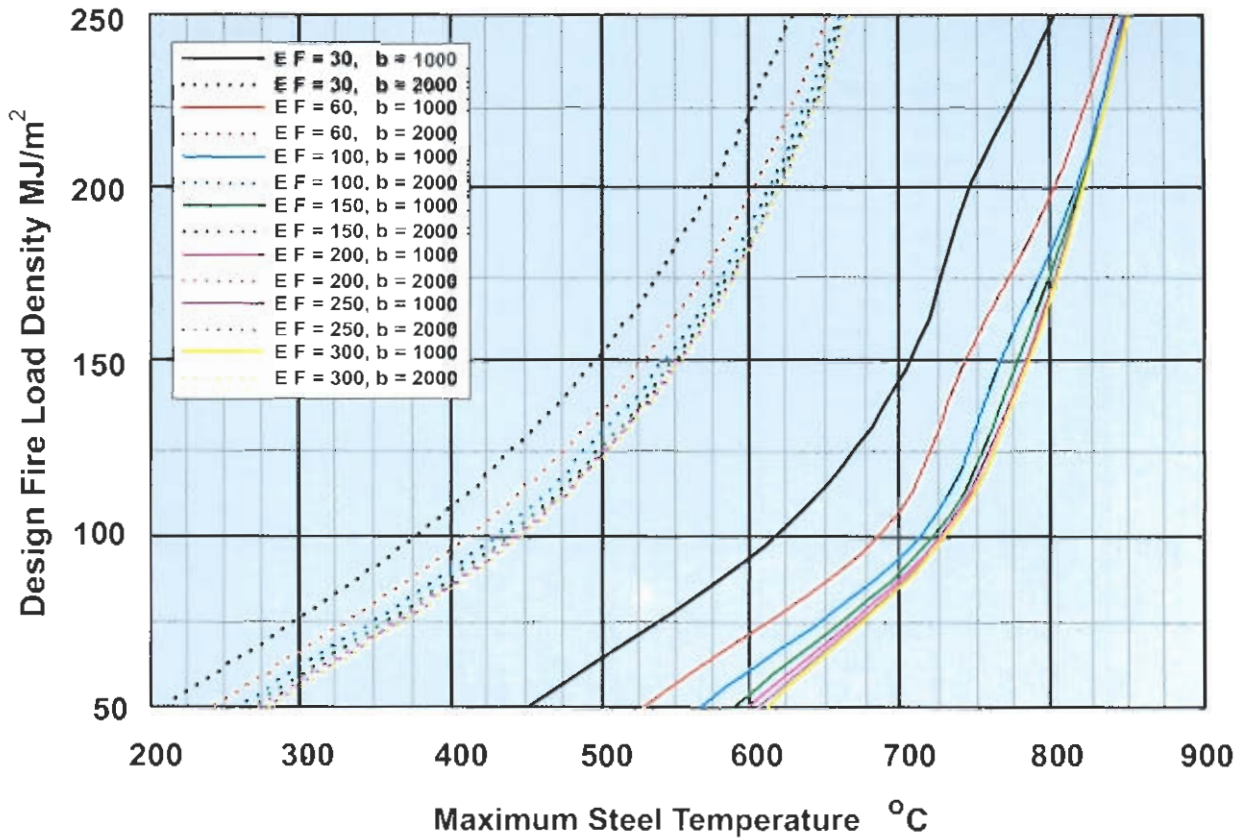
By interpolation the maximum steel temperature = 598°C

Conclusion

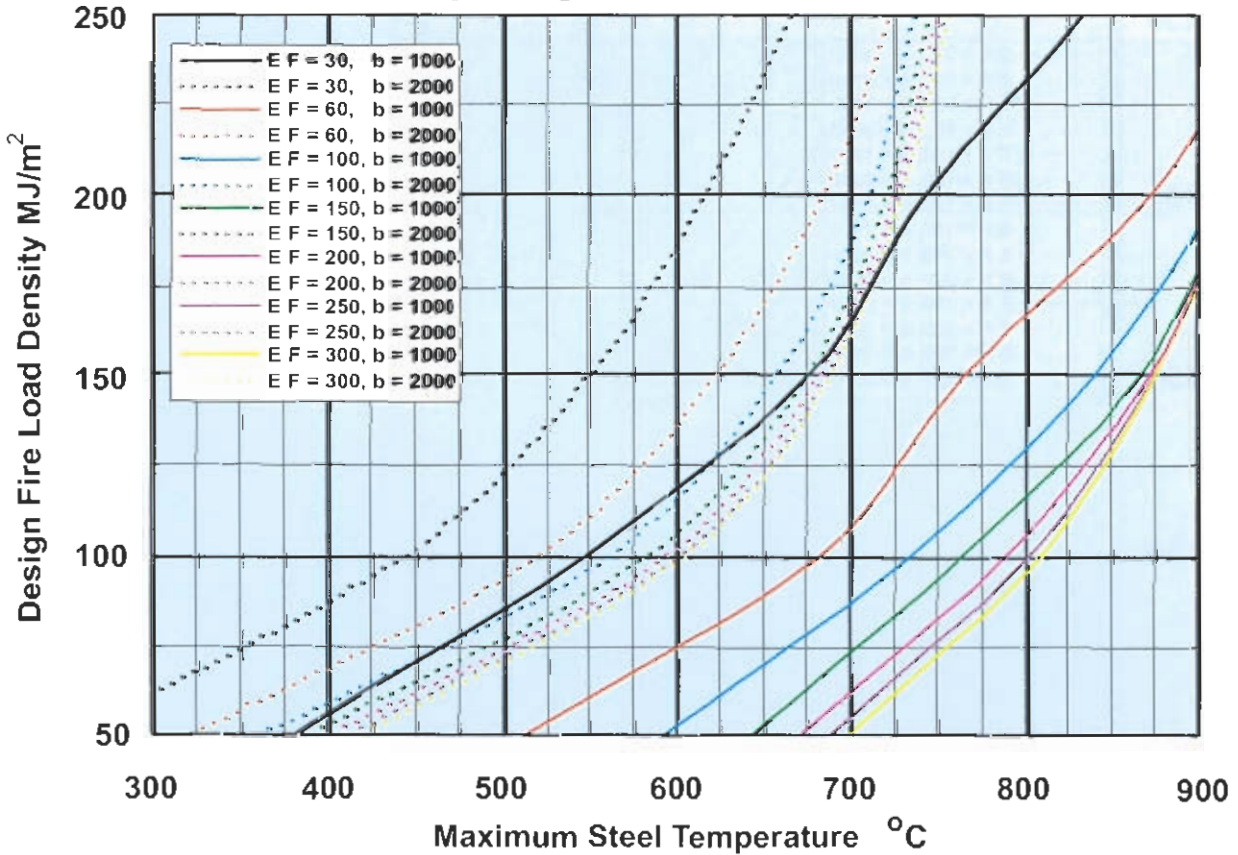
Reference: BS5950: Part 8 table 5;

1. For a slenderness ratio ≤ 70 , the column may be used unprotected providing the load ratio is not greater than 0.55.
2. For a beam supporting a concrete floor, protection is not required for all load ratios up to 0.67.

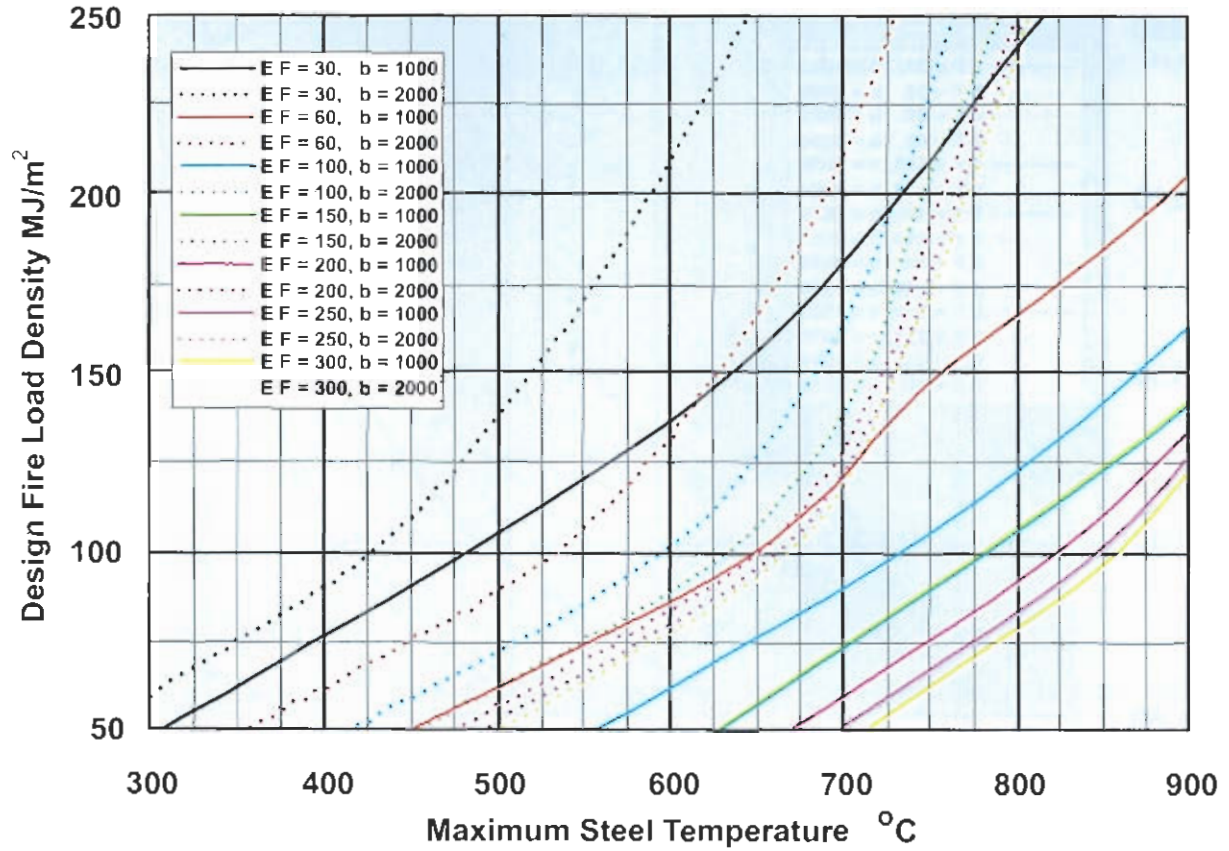
Opening Factor = $0.02 \text{ m}^{1/2}$



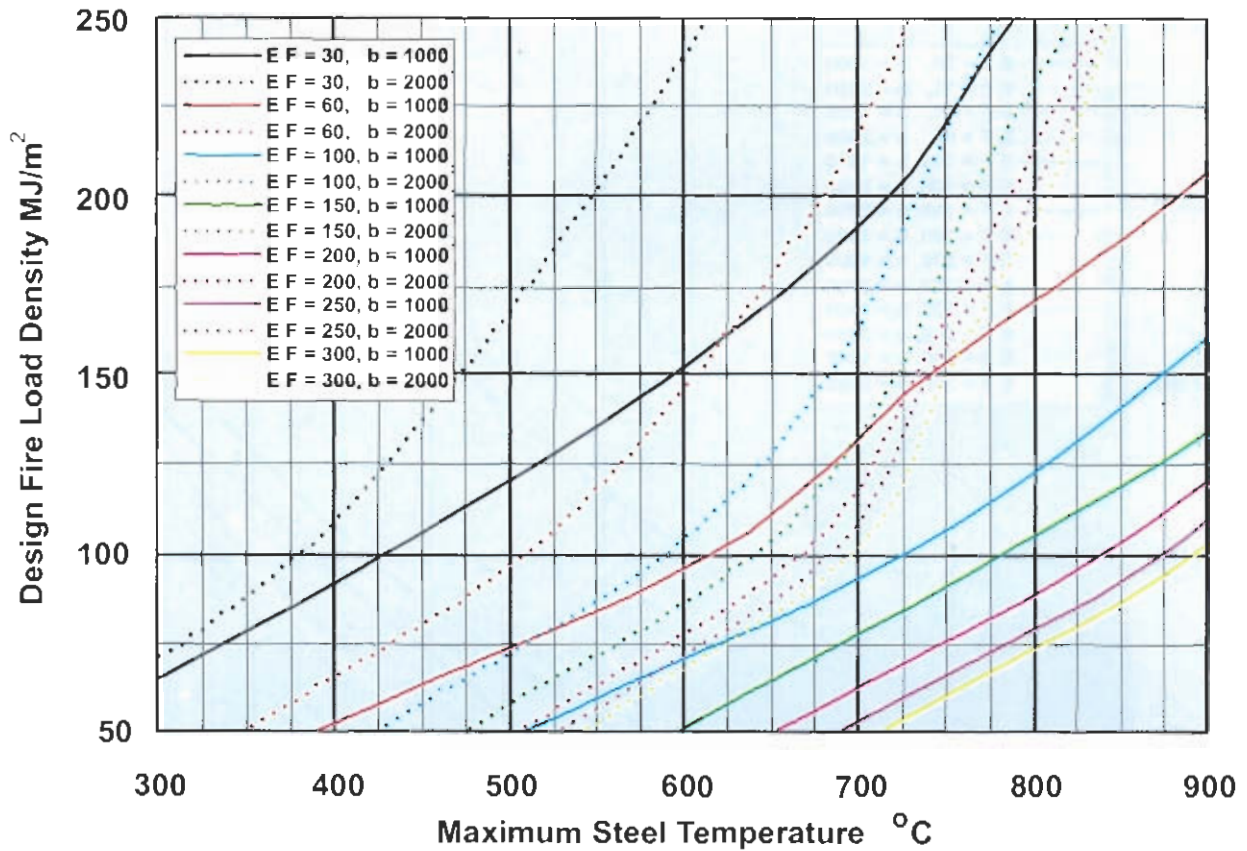
Opening Factor = $0.04 \text{ m}^{1/2}$



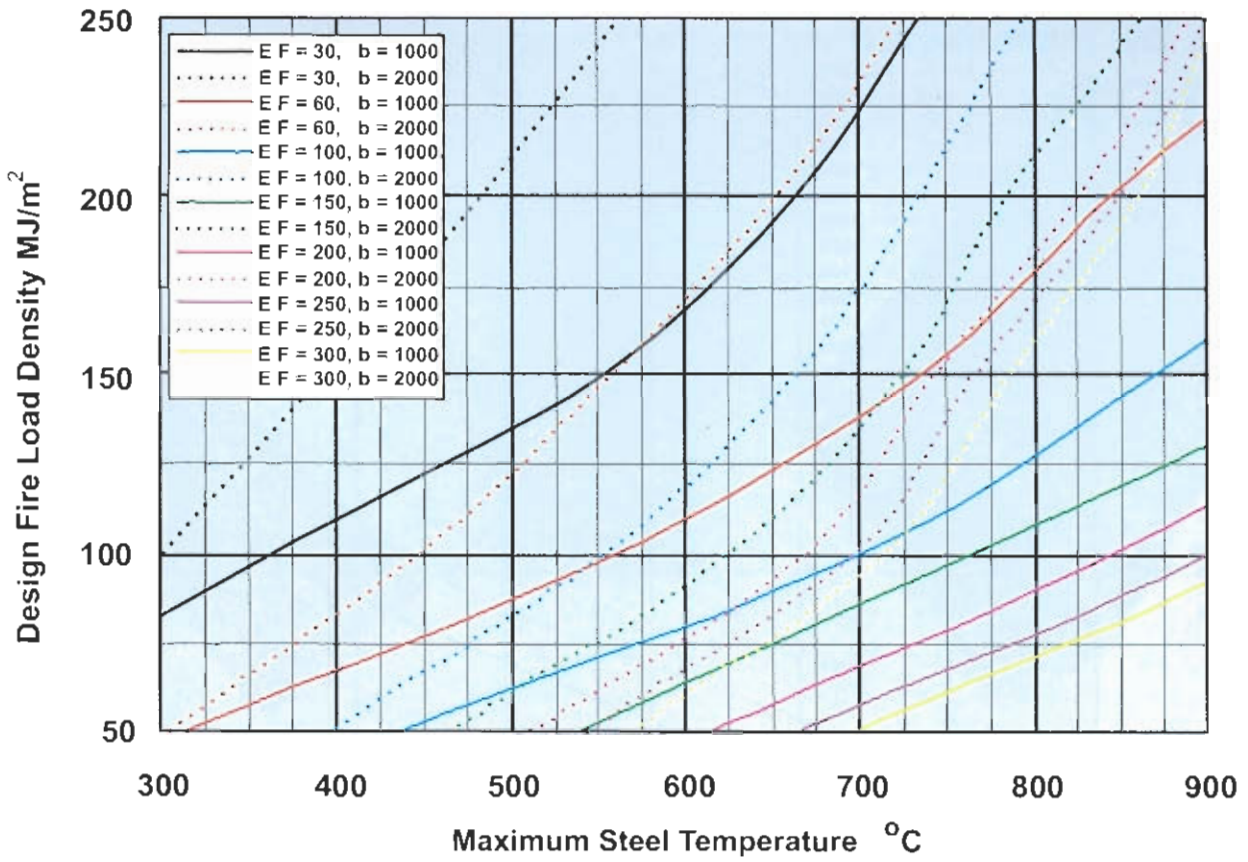
Opening Factor = $0.06 \text{ m}^{1/2}$



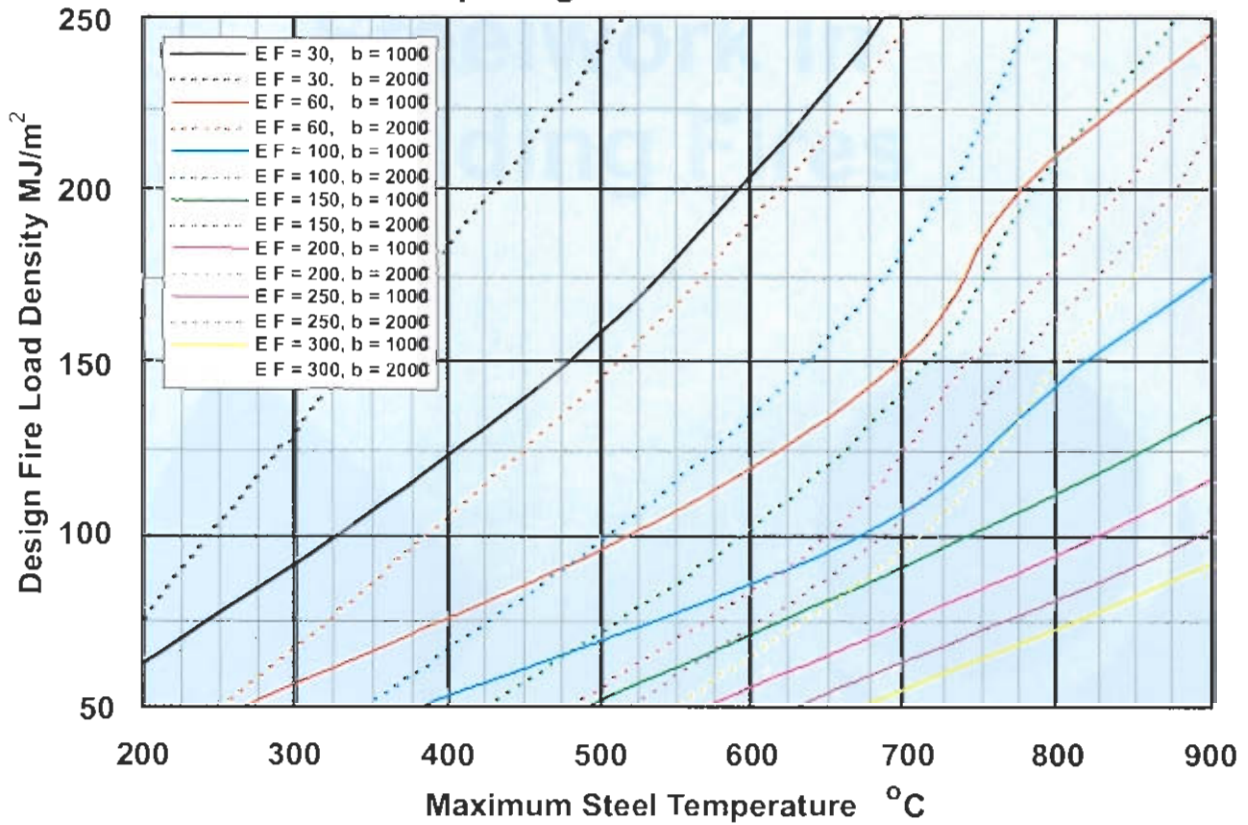
Opening Factor = $0.08 \text{ m}^{1/2}$



Opening Factor = $0.12 \text{ m}^{1/2}$



Opening Factor = $0.16 \text{ m}^{1/2}$



Opening Factor = $0.20 \text{ m}^{1/2}$

