Fire design of a steel tube in tension

This example will show the fire design using the simple model on a steel tube in tension subjected to ISO fire.

1. Check if the section is R30.
2. Find out the necessary thermal protection thickness for R120 using a protective coating with the thermal conductivity of λ_p: 0.12 W/mK.

Cross Section

Steel tube with the diameter D = 250 mm and thickness of the wall 5 mm.

Material Properties

Steel grade: S 355
Yield strength: f_y = 355 N/mm^2
Unit mass: ρ_a = 7850 kg/m^3

Loads

Tension force: $N_{fi,Ed}$ = 100 kN

1. Check if section is R30

To check if the section is R30 we need to find out the temperature on the cross section after a 30 minutes fire exposure. With this temperature we will calculate the reduction factor for the yield strength and in the end the resistance of the element at 30 minutes $N_{fi,\theta,Rd}$.

Find out the temperature in the cross section after 30 minutes of ISO fire

The section factor is:

$$\frac{A_m}{V} = \frac{\pi \cdot D}{\pi\left(D^2 - d^2\right)/4} = \frac{\pi \cdot 0.25}{\pi\left(0.25^2 - 0.24^2\right)/4} = \frac{0.785\ \text{m}}{0.003848\ \text{m}^2} = 204\ \text{m}^{-1}$$

Interpolating in table 1 (increase of temperature in unprotected cross sections) for a section factor of 204 m^{-1}, at 30 minutes of ISO fire, the temperature of the cross section is 828°C.

Interpolating between 800°C and 900°C in table 3.1 (EN 1993-1-2), the reduction factor for the yield strength at 828°C is:

$k_{y,\theta}$ = 0.096.

With this reduction factor, the design resistance of the element (4.3) is:

$$N_{fi,\theta,Rd} = k_{y,\theta} \cdot N_{Rd} \frac{\gamma_{M,0}}{\gamma_{M,fi}} = 0.096 \cdot 0.003848 \cdot 355 \cdot 10^3 \frac{1.0}{1.0} = 131.1\,\text{kN}$$

Check the resistance

Using equation (4.1) (EN 1993-1-2):

$$N_{fi,\theta,Rd} = 131.1\,\text{kN} > 100\,\text{kN} = N_{fi,Ed}$$

Since the resistance at 30 minutes is greater than the design load the section is R30.

2. Find out the necessary protection thickness

To find out the necessary protection thickness for R120 we need to calculate first the critical temperature

Using the balancing equation (4.1):

$$N_{fi,Ed} = 100 = N_{fi,\theta,Rd} = k_{y,\theta} \cdot N_{Rd} \frac{\gamma_{M,0}}{\gamma_{M,fi}} = k_{y,\theta} \cdot 0.003848 \cdot 355 \cdot 10^3 \frac{1.0}{1.0}$$, we get

$$k_{y,\theta} \cdot = \frac{100}{0.003848 \cdot 355 \cdot 10^3} = 0.0732$$

Interpolating in table 3.1 we get the critical temperature of 876 °C

Interpolating in table 2 (increase of temperature in protected cross sections) we get the k_p = 2092. Using the expression of k_p we can find out the thickness of the protection.

$$k_p = \frac{\lambda_p}{d_p} \frac{A_p}{V} = \frac{0.12}{d_p} 204 = 2092$$, we get

$$d_p = \frac{0.12 \cdot 204}{2092} = 0.0117\text{m} = 11.7\text{mm}$$

Fire design of a column

This example will show the fire design of a column under ISO fire, using the simple model. The column is pinned at both ends having the height of *l* = 2.90 m.

1. Find out the fire resistance of the column, considering buckling about the major axis.
2. What's the minimum protection thickness for reaching R60? We use contour protection using a protective material with the thermal conductivity of λ_p = 0.12 W/mK.

Cross section

Profile:	HE 160 B
Depth *h*:	160 mm
Web height *d*:	104 mm
Breadth *b*:	160 mm
Thickness web t_w:	8 mm
Thickness flange t_f:	13 mm
Fillet radius:	15 mm
i_y:	6.78 cm
A:	54.25 cm^2

Material properties

Steel grade:	S 235
Yield strength:	f_y = 235 N/mm^2
Unit mass:	ρ_a = 7850 kg/m^3

Protection

Thermal conductivity λ_p: 0.12 W/mK

Loads

Design compressive force: $N_{fi,Ed}$ = 410 kN

1. Fire resistance of the unprotected cross section

Critical temperature

The first thing is to check for the class of the cross section. The reduced value for ε (4.2) is:

$$\varepsilon = 0.85\sqrt{\frac{235}{f_y}} = 0.85$$

Flanges:

$$\frac{c}{t_f} = \frac{b/2 - t_w/2 - r}{t_f} = \frac{80-4-15}{13} = 4.69 < 9 \cdot \varepsilon = 7.65$$, so the flange is Class 1.

The web:

$$\frac{c}{t_w} = \frac{d}{t_w} = \frac{104}{8} = 13 < 33 \cdot \varepsilon = 28.05$$, so the web is Class 1.

In the end, the cross section is Class 1 in fire design.

As for the tension member we will use the balancing equation (4.1) to find out the critical temperature. Since the reduction factor for flexural buckling χ_{fi} depends on the temperature of the cross section, this means that the process must be iterative.

Iteration 1

We start from an arbitrary temperature of θ_a = 400°C

The reduction factors $k_{y,\theta}$ and $k_{E,\theta}$ (table 3.1) are:

$$k_{y,\theta} = 1.00$$

$$k_{E,\theta} = 0.7$$

The slenderness coefficient about the major axis is:

$$\lambda = \frac{l_f}{i_y} = \frac{290\text{ cm}}{6.78\text{ cm}} = 42.77$$

The Euler slenderness:

$$\lambda_E = \pi\sqrt{\frac{E}{f_y}} = \pi\sqrt{\frac{2.1 \cdot 10^5}{235}} = 93.91$$

The non-dimensional slenderness at θ_a = 400°C:

$$\bar{\lambda}_\theta = \bar{\lambda}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} = \frac{\lambda}{\lambda_E}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} = \frac{42.77}{93.91}\sqrt{\frac{1}{0.7}} = 0.544$$

The imperfection factor:

$$\alpha = 0,65\sqrt{\frac{235}{f_y}} = 0.65$$

$$\varphi_\theta = 0.5\left(1 + \alpha \cdot \bar{\lambda}_\theta + \bar{\lambda}_\theta^2\right) = 0.5\left(1 + 0.65 \cdot 0.544 + 0.544^2\right) = 0.824$$

So, the reduction factor for flexural buckling is:

$$\chi_{fi} = \frac{1}{\varphi_\theta + \sqrt{\varphi_\theta^2 - \bar{\lambda}_\theta^2}} = \frac{1}{0.824 + \sqrt{0.824^2 - 0.544^2}} = 0.693$$

We write down the balancing equation (4.1) to find out the reduction factor for the yield strength $k_{y,\theta}$:

$$N_{b,fi,t,Rd} = \chi_{fi} \cdot A \frac{k_{y,\theta} \cdot f_y}{\gamma_{M,fi}} = 0.693 \cdot 54.25 \cdot 10^2 \frac{k_{y,\theta} \cdot 235}{1.0} = N_{fi,Ed} = 410 \cdot 10^3$$

we get:

$$k_{y,\theta} = \frac{410 \cdot 10^3}{0.693 \cdot 54.25 \cdot 10^2 \cdot 235} = 0.464$$

Interpolating in table 3.1 (EN 1993-1-2) we get the critical temperature of θ_a = 607°C.

Iteration 2

We start from the previously obtained temperature θ_a = 607°C.

The reduction coefficients $k_{y,\theta}$ and $k_{E,\theta}$ form table 3.1 are:

$$k_{y,\theta} = 0.464$$

$$k_{E,\theta} = 0.29$$

The non-dimensional slenderness at θ_a = 615°C:

$$\bar{\lambda}_\theta = \bar{\lambda}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} = 0.455\sqrt{\frac{0.464}{0.29}} = 0.575$$

$$\varphi_\theta = 0.5\left(1 + 0.65 \cdot 0.575 + 0.575^2\right) = 0.852$$

$$\chi_{fi} = \frac{1}{0.852 + \sqrt{0.852^2 - 0.575^2}} = 0.675$$

$$k_{y,\theta} = \frac{410 \cdot 10^3}{0.675 \cdot 54.25 \cdot 10^2 \cdot 235} = 0.476$$

Interpolating in table 3.1 (EN 1993-1-2) we get a temperature of θ_a = 600°C.

Iteration 3

We start from the previously obtained temperature θ_a = 600°C.

The reduction coefficients $k_{y,\theta}$ and $k_{E,\theta}$ are:

$k_{y,\theta} = 0.470$

$k_{E,\theta} = 0.310$

The non-dimensional slenderness at θ_a = 600°C:

$$\bar{\lambda}_{\theta} = \bar{\lambda}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} = 0.455\sqrt{\frac{0.470}{0.310}} = 0.560$$

$$\varphi_{\theta} = 0.5\left(1 + 0.65 \cdot 0.560 + 0.560^2\right) = 0.839$$

$$\chi_{fi} = \frac{1}{0.839 + \sqrt{0.839^2 - 0.560^2}} = 0.683$$

$$k_{y,\theta} = \frac{410 \cdot 10^3}{0.683 \cdot 54.25 \cdot 10^2 \cdot 235} = 0.471$$

The iteration has converged in two steps. The critical temperature is θ_a = 600°C.

The fire resistance of the unprotected section

For I sections, taking into account the shadow factor, the section factor is:

$$\left[\frac{A_m}{V}\right]_{sh} = k_{sh}\frac{A_m}{V} = 0,9\frac{\left[A_m/V\right]_b}{\left[A_m/V\right]}\frac{A_m}{V} = 0.9\left[\frac{A_m}{V}\right]_b = 0.9\frac{2\left(h+b\right)}{A} = 0.9\frac{2\left(16+16\right)}{54.25}10^2 = 106\,\text{m}^{-1}$$

We need to interpolate in table 1 using the section factor $\left[\frac{A_m}{V}\right]_{sh} = 106\,\text{m}^{-1}$ and the critical temperature θ_a = 600°C.

For $\left[\frac{A_m}{V}\right]_{sh} = 100\,\text{m}^{-1}$, the critical temperature θ_a = 600°C is reached in 16.4 minute.

For $\left[\frac{A_m}{V}\right]_{sh} = 200\,\text{m}^{-1}$, the critical temperature θ_a = 600°C is reached in 11.5 minute.

For $\left[\frac{A_m}{V}\right]_{sh} = 106\,\text{m}^{-1}$, the critical temperature θ_a = 600°C is reached in 16 minute.

So, the fire resistance of the unprotected HE 160 B steel profile under ISO fire is 16 minute.

2. Protection thickness for R60

We need first to calculate the section factor for the contour protected cross section:

$$\frac{A_p}{V} = \frac{2b + 2(b - t_w) + 2(h - 2t_f)}{A} = \frac{2 \cdot 16 + 2(16 - 0.8) + 2(16 - 2 \cdot 1.3)}{54.25} 10^2 = 164 \text{ m}^{-1}$$

For a critical temperature of 600°C and a fire resistance of 60 minutes, interpolating in table 2 we find the k_p coefficient as being k_p = 1692 W/m^{3}K.

The minimum protection thickness will be:

$$d_p \geq \frac{\lambda_p}{k_p} \frac{A_p}{V} = \frac{0,12}{1692} \cdot 164 = 0.0116 \text{ m} = 11.6 \text{ mm}$$

We select a protection thickness of at least d_p = 12 mm.

Fire design of a beam with a concrete slab on top

This example will show the fire design of a beam under ISO fire, using the simple model. The beam with a span of 4 m is clamped at both ends. The cross section of the beam is HE160A with a steel grade of S355. On top of the beam there's a concrete slab. The beam is loaded with a uniformly distributed load of 9500 N/m.

1. Check if the beam is R30 if unprotected;
2. Find out the fire resistance if the section is box protected, using 12mm boards with a thermal conductivity of 0.15 W/mK.

Cross section

Profile:	HE 160 A.
Depth h:	152 mm
Breadth b:	160 mm
Thickness web t_w:	6 mm
Thickness flange t_f:	9 mm
Fillet radius:	15 mm
A:	38.77 cm^2
W_{pl}	245.1 cm^3

Material properties

Steel grade:	S 355
Yield strength:	f_y = 355 N/mm^2
Unit mass:	ρ_a = 7850 kg/m^3

Protection

Thermal conductivity λ_p:	0.15 W/mK

1. Unprotected cross section

The first thing is to check for the class of the cross section. The reduced value for ε (4.2) is:

$$\varepsilon = 0.85\sqrt{\frac{235}{f_y}} = 0.692$$

Flanges:

$$\frac{c}{t_f} = \frac{b/2 - t_w/2 - r}{t_f} = \frac{80-3-15}{9} = 6.89 < 10 \cdot \varepsilon = 6.92$$, so the flange is Class 2.

The web:

$$\frac{c}{t_w} = \frac{\left(h - 2t_f - 2r\right)}{t_w} = \frac{152-18-30}{6} = 17.33 < 72 \cdot \varepsilon = 49.8$$, so the web is Class 1.

In the end, the cross section is Class 2 in fire design.

For I sections, exposed on 3 sides taking into account the shadow factor, the section factor is:

$$\left[\frac{A_m}{V}\right]_{sh} = k_{sh}\frac{A_m}{V} = 0.9\frac{[A_m/V]_b}{[A_m/V]}\frac{A_m}{V} = 0.9\left[\frac{A_m}{V}\right]_b = 0.9\frac{2h+b}{A} = 0.9\frac{2\cdot 0.152+0.16}{38.77\cdot 10^{-4}} = 108\,\mathrm{m}^{-1}$$

Interpolating in table 1 using the section factor $\left[\frac{A_m}{V}\right]_{sh} = 108\,\mathrm{m}^{-1}$ and the time t_f = 30 min, the temperature on the cross section is θ_a = 772°C.

Interpolating in table 3.1 (EN 1993-1-2), the reduction factor for the yield strength at 772°C is:

$k_{y,\theta}$ = 0.144.

Check at the support

The first thing to check is the shear force. The design shear force at support is:

$$V_{fi,Ed} = \frac{9500\cdot 4}{2} = 19\,000\ \mathrm{N}$$

The section factor of the web is $\left(\frac{A_m}{V}\right)_{web} = \frac{2}{t_w} = \frac{2}{0.006} = 333m^{-1}$

For this section factor and the time of 30 minutes from table 1 the temperature of the web is θ_{web} = 834°C. Interpolating in table 3.1 for this temperature the reduction factor will be $k_{y,\theta,web}$ = 0,093.

The design shear resistance will be:

$V_{fi,t,Rd} = k_{y,\theta,web}\cdot V_{Rd}\frac{\gamma_{M,1}}{\gamma_{M,fi}}$, where $V_{Rd} = \frac{A_V\cdot f_y}{\sqrt{3}\cdot\gamma_{M0}}$ and

$$A_V = A - 2\cdot b\cdot t_f + (t_w + 2r)t_f = 3877 - 2\cdot 160\cdot 9 + (6+2\cdot 15)9 = 1321\,\mathrm{mm}^2$$

$$V_{Rd} = \frac{1321\cdot 355}{\sqrt{3}\cdot 1} = 270\,750\ \mathrm{N}$$

$$V_{fi,t,Rd} = 0.093\cdot 270\,750\frac{1}{1} = 25\,180\ \mathrm{N}$$

Since $V_{fi,t,Rd} = 25\,180\ \mathrm{N} > V_{fi,Ed} = 19\,000\ \mathrm{N}$ the shear force is checked.

The second check is against the bending moment.

If the design shear is larger than half the shear resistance, the bending moment resistance needs to be reduced.

Since $V_{fi,Ed} = 19\,000\ \text{N} > \frac{V_{fi,t,Rd}}{2} = \frac{25\,180\ \text{N}}{2} = 12\,590\ \text{N}$, we need to reduce the design moment resistance with a factor:

$$\rho = \left(\frac{2V_{fi,Ed}}{V_{fi,t,Rd}} - 1\right)^2 = \left(\frac{2 \cdot 19}{25.18} - 1\right)^2 = 0.259$$

The design moment resistance is

$$M_{fi,t,Rd} = \frac{k_{y,\theta} f_y \left[W_{pl} - \frac{\rho (h_w t_w)^2}{4t_w}\right]}{\kappa_1 \kappa_2} = \frac{0.144 \cdot 355 \left[245100 - \frac{0.259(104 \cdot 6)^2}{4 \cdot 6}\right]}{0.7 \cdot 0.85} = 20.7\ \text{kNm}$$

The design bending moment in fire situation at the support is:

$$M_{fi,Ed} = \frac{p \cdot l^2}{12} = \frac{9.5 \cdot 4^2}{12} = 12.67\ \text{kNm}$$

Since $M_{fi,t,Rd} = 20.7\ \text{kNm} > M_{fi,Ed} = 12.67\ \text{kNm}$ the bending moment is checked at the support.

Check at mid-span

The design bending moment in fire situation in the middle of the beam is:

$$M_{fi,Ed} = \frac{p \cdot l^2}{24} = \frac{9.5 \cdot 4^2}{24} = 6.33\ \text{kNm}$$

The design moment resistance in the middle of the beam is:

$$M_{fi,t,Rd} = \frac{k_{y,\theta} f_y W_{pl}}{\kappa_1 \kappa_2} = \frac{0.144 \cdot 355 \cdot 245100}{0.7 \cdot 1.0} = 17.9\ \text{kNm}$$

Since $M_{fi,t,Rd} = 17.9\ \text{kNm} > M_{fi,Ed} = 6.33\ \text{kNm}$ the bending moment is checked in the middle.

2. Protected cross section

The check at the support will give the critical temperature. The problem is the interaction between bending and shear (since the bending resistance needs to be reduced based on the shear value). We cannot write the balancing equation to directly find out the reduction factor $k_{y,\theta}$. Instead we need to find out through trial and error the value of the reduction factor. An Excel sheet with goal seek would help to find out the value of the reduction factor. (An important hypothesis is that we consider $k_{y,\theta,web}$ the same as $k_{y,\theta}$.)

Trial #1

We take $k_{y,\theta}$= 0.088

$$V_{fi,t,Rd} = 0.088 \cdot 270\,750 \frac{1}{1} = 23.83 \text{ kN} > V_{fi,t,Rd} = 19 \text{ kN}$$

$$\rho = \left(\frac{2 \cdot 19}{23.83} - 1 \right)^2 = 0.354$$

$$M_{fi,t,Rd} = \frac{0.088 \cdot 355 \left[245100 - \frac{0.354 (104 \cdot 6)^2}{4 \cdot 6} \right]}{0.7 \cdot 0.85} = 12.57 \text{ kNm}$$

$M_{fi,t,Rd} = 12.57 \text{ kNm} < M_{fi,Ed} = 12.67 \text{ kNm}$ so the check is not satisfied, but the bending resistance is very close to the design bending.

Trial #2

We take $k_{y,\theta}$= 0.089

$$V_{fi,t,Rd} = 0.089 \cdot 270\,750 \frac{1}{1} = 24.10 \text{ kN} > V_{fi,t,Rd} = 19 \text{ kN}$$

$$\rho = \left(\frac{2 \cdot 19}{24.10} - 1 \right)^2 = 0.333$$

$$M_{fi,t,Rd} = \frac{0.089 \cdot 355 \left[245100 - \frac{0.333 (104 \cdot 6)^2}{4 \cdot 6} \right]}{0.7 \cdot 0.85} = 12.73 \text{ kNm}$$

$M_{fi,t,Rd} = 12.73 \text{ kNm} > M_{fi,Ed} = 12.67 \text{ kNm}$ so the check is satisfied.

For the $k_{y,\theta}$= 0.089 reduction factor from table 3.1 we find a temperature θ_a = 842°C

To find out the fire resistance of the protected cross section we need to calculate the k_p coefficient.

$$k_p = \frac{A_p}{V} \frac{\lambda_p}{d_p}$$

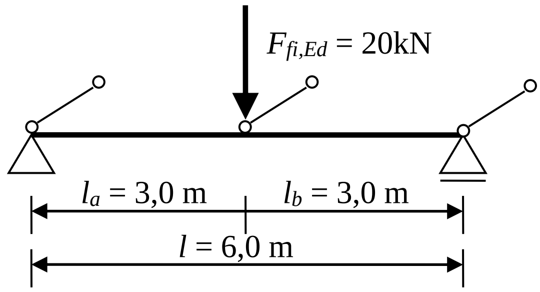
For a section protected with boards on 3 sides: $\frac{A_p}{V} = \frac{(2h + b)}{A} = \frac{2 \cdot 0.152 + 0.160}{38.77 \cdot 10^{-4}} = 120 \text{ m}^{-1}$

$$k_p = 120 \frac{0.15}{0.012} = 1500 \frac{\text{W}}{\text{m}^2\text{K}}$$

Interpolating from table 2 for the temperature θ_a = 842°C and the k_p =1500 we find the time (fire resistance) 146 min

Fire design of a beam with class 3 cross section with lateral torsional bending

This example will show the fire design of a simply supported beam with class 3 cross section under ISO fire, using the simple model. The beam with a span of 6 m is loaded at mid-span with a concentrated load of 20kN. A secondary beam at mid span ensures a lateral support. The cross section of the beam is HE180A with a steel grade of S355.



1. Find out the fire resistance if the section is unprotected.
2. Find out the necessary thermal protection thickness for R60 using thermal protective boards with the thermal conductivity of λ_p: 0.2 W/mK.

Cross section

Profile:	HE 180 A.
Depth h:	171 mm
Breadth b:	180 mm
Thickness web t_w:	6 mm
Thickness flange t_f:	9.5 mm
Fillet radius:	15 mm
$W_{el,y}$	293.6 cm^3
A	*4530* mm^2
I_z	*924*.6 cm^4
I_w	60 210 cm^6
I_t	14.8 cm^4

Material properties

Steel grade:	S 355
Yield strength:	f_y = 355 N/mm^2
Unit mass:	ρ_a = 7850 kg/m^3

1. Critical temperature. Fire resistance unprotected cross section

The first thing is to check for the class of the cross section. The reduced value for ε (4.2) is:

$$\varepsilon = 0.85\sqrt{\frac{235}{f_y}} = 0.692$$

Flanges:

$$\frac{c}{t_f} = \frac{b/2 - t_w/2 - r}{t_f} = \frac{90 - 3 - 15}{9.5} = 7.57 < 14 \cdot \varepsilon = 9.69$$, so the flange is Class 3.

The web:

$$\frac{c}{t_w} = \frac{\left(h - 2t_f - 2r\right)}{t_w} = \frac{171 - 19 - 30}{6} = 20.33 < 72 \cdot \varepsilon = 49.8$$, so the web is Class 1.

In the end, the cross section is Class 3 in fire design.

Since the beam is not supported laterally on the whole length, the check will be against the design lateral torsional buckling resistance moment $M_{b,fi,t,Rd}$. As in the case of columns where there's a reduction factor for buckling χ which is computed at critical temperature which leads to an iterative procedure to finding the critical temperature.

The design effect of actions in fire situation

The maximum design bending moment: $M_{fi,Ed} = \frac{F_{fi,d} \cdot l_a \cdot l_b}{l} = \frac{20 \cdot 3 \cdot 3}{6} = 30 \text{ kNm}$

The design shear (support): $V_{fi,Ed} = \frac{F_{fi,d} \cdot l_a}{l} = \frac{20 \cdot 3}{6} = 10 \text{ kN}$

The elastic critical moment may be calculated from the following formula derived from the buckling theory (for uniform straight members for which the cross-section is symmetric about the bending plane):

$$M_{cr} = C_1 \frac{\pi^2 E \cdot I_z}{(kL)^2} \left[\sqrt{\frac{I_w}{I_z}\left(\frac{k}{k_w}\right)^2 + \frac{(kL)^2}{\pi^2}\frac{G \cdot I_t}{E \cdot I_z} + \left(C_2 z_g\right)^2} - C_2 z_g \right]$$

In the common case of normal support conditions at the ends (fork supports), k and k_w are taken equal to 1.

When the bending moment diagram is linear along a segment of a member delimited by lateral restraints, or when the transverse load is applied in the shear centre, C2 z_g = 0.

In our case (the beam length between points which have lateral restraint):

$L = l_a$ = 3.0 m and C_1 = 1.77 (from Table 3.1 NCCI: Elastic critical moment for lateral torsional buckling).

$$M_{cr} = 1{,}77 \frac{\pi^2 210\,000 \cdot 9.246 \cdot 10^6}{(1 \cdot 3000)^2} \sqrt{\frac{6.021 \cdot 10^{10}}{9.246 \cdot 10^6} + \frac{(1 \cdot 3000)^2}{\pi^2} \frac{80\,770 \cdot 1.48 \cdot 10^5}{210000 \cdot 9.246 \cdot 10^6}} \cdot 10^{-6}$$ = 415.016 kNm.

The non-dimensional slenderness is:

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_{el,y} \cdot f_y}{M_{cr}}} = \sqrt{\frac{293.6 \cdot 10^3 \cdot 355}{4.15 \cdot 10^8}} = 0.501$$

The α factor:

$$\alpha = 0.65\sqrt{\frac{235}{f_y}} = 0.65\sqrt{\frac{235}{355}} = 0.5289$$

Iteration 1

We start from an arbitrary temperature of θ_a = 400°C. The reduction factors $k_{y,\theta}$ and $k_{E,\theta}$ (table 3.1) are:

$$k_{y,\theta} = 1.00\,;\; k_{E,\theta} = 0.7$$

The non-dimensional slenderness in fire situation at θ_a = 400°C:

$$\bar{\lambda}_{LT,\theta} = \bar{\lambda}_{LT}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} = 0.501\sqrt{\frac{1.000}{0.700}} = 0.599\,.$$

$$\phi_{LT,\theta} = 0.5\left(1 + \alpha \cdot \bar{\lambda}_{LT,\theta} + \bar{\lambda}^2_{LT,\theta}\right) = 0.5\left(1 + 0.5289 \cdot 0.599 + 0.599^2\right) = 0.838\,.$$

The reduction factor for lateral-torsional buckling in the fire design situation:

$$\chi_{LT,fi} = \frac{1}{\phi_{LT,\theta} + \sqrt{\phi^2_{LT,\theta} - \bar{\lambda}^2_{LT,\theta}}} = \frac{1}{0.838 + \sqrt{0.838^2 - 0.599^2}} = 0.702\,,$$

Writing the balancing equation:

$$M_{fi,Ed} = M_{b,fi,t,Rd} = \chi_{LT,fi}\frac{W_{el,y} k_{y,\theta} f_y}{\gamma_{M,fi}}\,,$$

we can find out the reduction factor for the yield strength:

$$k_{y,\theta} = \frac{M_{fi,Ed} \cdot \gamma_{M,fi}}{W_{el,y} \cdot f_y \cdot \chi_{LT,fi}} = \frac{30 \cdot 10^6 \cdot 1}{2.936 \cdot 10^5 \cdot 355 \cdot 0.702} = 0.401$$

Interpolating in table 3.1 (EN 1993-1-2) we get a temperature of θ_a = 625°C.

Iteration 2

We start from the previously obtained temperature of θ_a = 625°C. The reduction factors $k_{y,\theta}$ and $k_{E,\theta}$ (table 3.1) are:

$$k_{y,\theta} = 0.401\,;\; k_{E,\theta} = 0.265$$

$$\bar{\lambda}_{LT,\theta} = \bar{\lambda}_{LT}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} = 0.501\sqrt{\frac{0.401}{0.265}} = 0.616.$$

$$\phi_{LT,\theta} = 0.5\left(1+\alpha\cdot\bar{\lambda}_{LT,\theta}+\bar{\lambda}_{LT,\theta}^{2}\right) = 0.5\left(1+0.5289\cdot0.616+0.616^{2}\right) = 0.853.$$

The reduction factor for lateral-torsional buckling in the fire design situation:

$$\chi_{LT,fi} = \frac{1}{\phi_{LT,\theta}+\sqrt{\phi_{LT,\theta}^{2}-\bar{\lambda}_{LT,\theta}^{2}}} = \frac{1}{0.853+\sqrt{0.853^{2}-0.616^{2}}} = 0.693,$$

$$k_{y,\theta} = \frac{30\cdot10^{6}\cdot1}{2.936\cdot10^{5}\cdot355\cdot0.693} = 0.415$$

Interpolating in table 3.1 (EN 1993-1-2) we get a temperature of θ_a = 622°C. Since the difference between the current temperature and the previous one is less than 3°C, we can stop the iterative process.

For I sections, exposed on 4 sides taking into account the shadow factor, the section factor is:

$$\left[\frac{A_m}{V}\right]_{sh} = 0.9\left[\frac{A_m}{V}\right]_{b} = 0.9\frac{2(h+b)}{A} = 0.9\frac{2\cdot(171+180)}{4530}10^{3} = 140\,\mathrm{m}^{-1}$$

Interpolating in table 1 using the section factor $\left[\frac{A_m}{V}\right]_{sh} = 140\,\mathrm{m}^{-1}$ and the critical temperature θ_a = 622°C the fire resistance is 14 minutes.

2. Minimum thickness protection

In the case of protective boards the section factor is:

$$\frac{A_p}{V} = \frac{2(h+b)}{A} = \frac{2\cdot(171+180)}{4530}10^{3} = 155\,\mathrm{m}^{-1}$$

From table 2 for 60 minutes requirement and a temperature of θ_a = 622°C the k_p coefficient is: 1798

$$k_p = \frac{\lambda_p}{d_p}\frac{A_p}{V} = \frac{0.2}{d_p}155 = 1798$$, we get

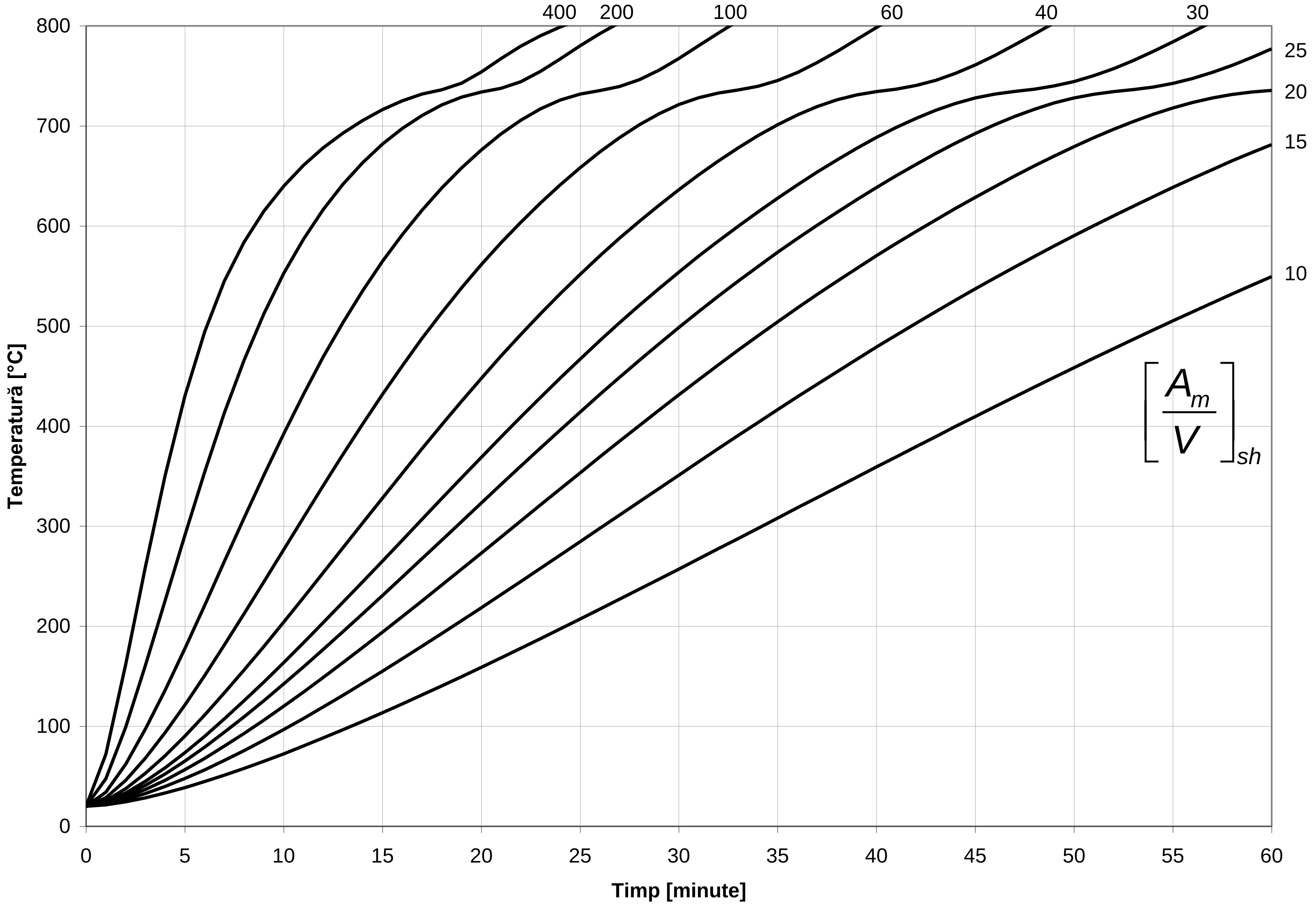
$$d_p = \frac{0.2\cdot155}{1798} = 0.0172\mathrm{m} = 17.2\mathrm{mm}$$

Table 1. Temperatures on unprotected cross sections under ISO fire

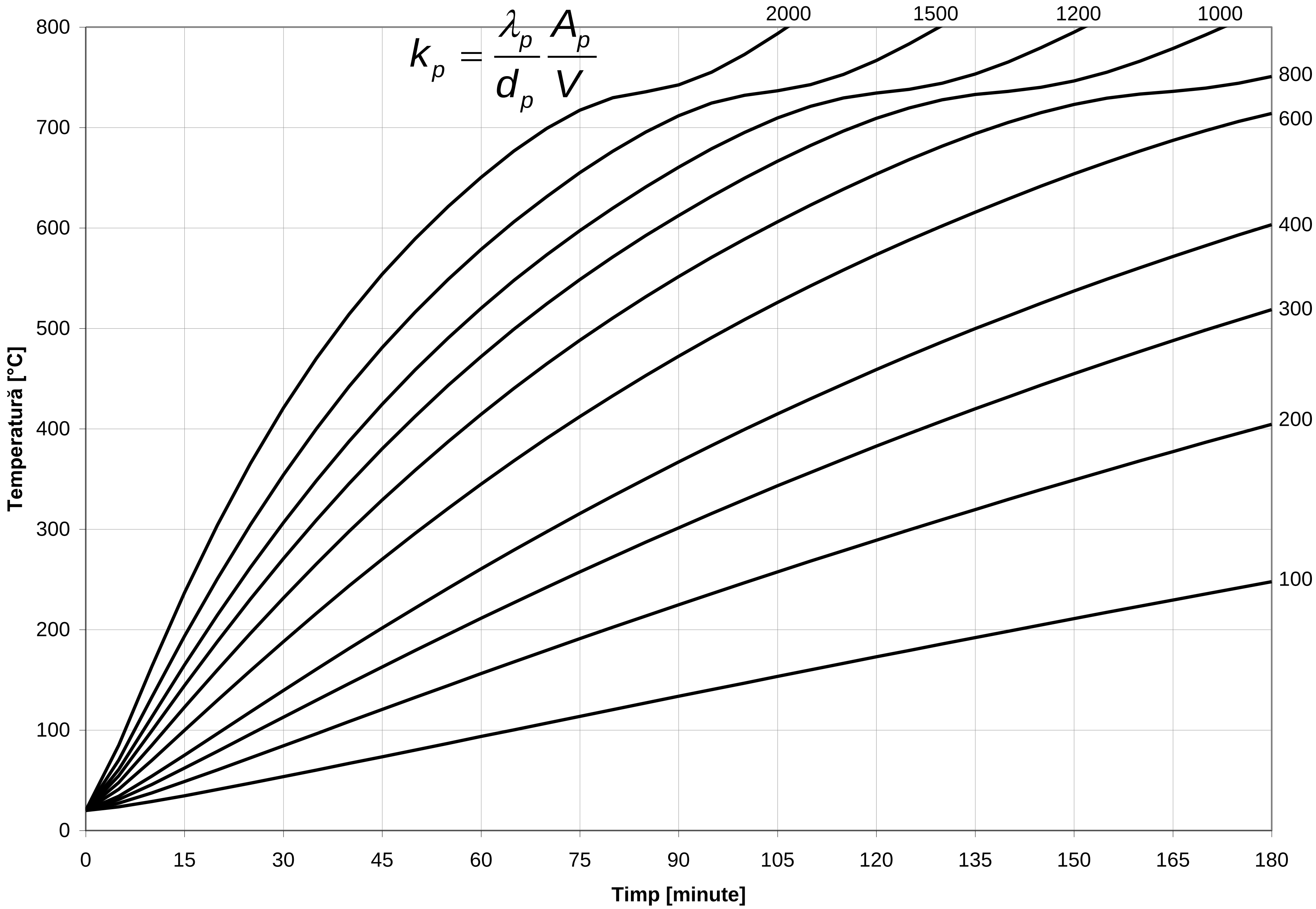
	Section factor [Am/V]$_{sh}$ [m^{-1}]									
Time [min]	10	15	20	25	30	40	60	100	200	400
0	20	20	20	20	20	20	20	20	20	20
5	39	48	57	65	74	90	121	178	291	430
10	73	97	120	142	164	204	277	392	553	640
11	80	108	134	159	183	229	309	432	587	661
12	88	119	149	177	204	253	340	469	616	678
13	97	131	164	195	224	278	372	504	642	693
14	105	143	179	213	245	303	402	535	663	706
15	114	155	194	231	265	328	432	565	682	716
16	122	168	210	249	286	353	460	591	698	725
17	131	180	225	268	307	377	488	616	711	732
18	140	193	241	286	328	401	514	638	721	736
19	150	206	257	305	348	425	538	658	729	743
20	159	219	273	323	369	448	561	676	734	754
21	168	232	289	342	389	470	583	692	738	767
22	178	245	305	360	409	492	604	706	744	780
23	188	258	321	378	429	512	623	717	755	790
24	197	271	337	396	448	532	641	726	767	799
25	207	285	353	414	467	552	658	732	780	807
26	217	298	369	432	485	570	674	735	792	813
27	227	311	385	449	503	588	688	740	803	820
28	237	325	401	466	521	605	701	746	813	826
29	247	338	416	482	538	621	712	756	821	831
30	257	351	431	499	554	636	721	767	828	837
31	267	364	446	514	570	651	728	780	835	842
32	278	378	461	530	585	665	733	793	841	847
33	288	391	476	545	600	678	736	805	846	852
34	298	404	490	560	614	690	740	816	851	856
35	308	417	504	574	628	701	745	827	856	861
36	318	429	518	587	641	711	753	836	861	865
37	329	442	532	601	654	720	763	845	866	870
38	339	454	545	614	666	726	775	852	870	874
39	349	467	558	626	678	731	786	859	874	878
40	359	479	570	639	689	734	798	865	878	882
41	369	491	583	650	699	737	810	871	882	886
42	380	503	595	662	708	740	822	876	886	889
43	390	515	606	673	716	746	832	881	890	893
44	400	526	618	683	723	753	842	885	894	896
45	410	537	629	693	728	761	852	890	897	900
46	420	548	640	701	732	771	860	894	901	903
47	429	559	650	710	735	781	868	897	904	906
48	439	570	660	717	737	792	875	901	907	910
49	449	580	670	723	740	803	882	905	910	913
50	458	590	679	728	744	814	888	908	914	916
51	468	600	688	732	750	825	894	912	917	919
52	477	610	697	734	757	835	899	915	920	922
53	487	620	705	736	765	845	904	918	923	925
54	496	629	712	739	775	855	909	921	926	928
55	505	639	718	743	784	864	913	924	928	930
56	514	648	723	748	794	872	917	927	931	933
57	523	657	728	754	804	880	921	930	934	936
58	532	665	731	761	815	887	924	933	937	939
59	541	673	734	769	825	894	927	935	939	941
60	549	681	736	777	835	901	931	938	942	944

Table 2. Temperatures on protected cross sections under ISO fire

	Factor k_p [W/m³K]									
Time [min]	100	200	300	400	600	800	1000	1200	1500	2000
0	20	20	20	20	20	20	20	20	20	20
5	24	27	31	34	41	48	54	61	70	85
10	29	38	46	54	70	85	99	113	133	163
15	35	49	62	75	100	123	144	165	193	237
20	41	60	79	97	130	160	188	215	251	304
25	47	72	96	118	159	196	231	262	305	366
30	54	84	113	139	188	232	271	307	354	421
35	60	96	130	161	216	265	309	348	400	470
40	67	109	146	181	244	298	346	388	442	514
45	73	121	163	202	270	329	380	424	481	554
50	80	133	179	222	296	359	413	459	516	589
55	87	144	195	241	321	387	443	491	549	621
60	94	156	211	261	345	414	472	520	579	651
65	100	168	227	279	368	440	499	548	606	677
70	107	180	242	298	391	465	525	573	631	699
75	114	191	258	316	412	488	549	597	655	717
80	120	202	272	333	433	510	571	620	677	730
85	127	214	287	350	453	532	592	641	696	736
90	134	225	302	367	472	552	612	661	712	743
95	140	236	316	383	491	571	632	679	724	755
100	147	247	330	399	509	589	650	695	732	773
105	153	258	343	415	526	606	667	710	737	794
110	160	268	357	430	542	623	682	721	743	816
115	166	279	370	445	558	639	697	730	753	838
120	173	289	383	459	573	654	709	734	767	859
125	179	299	395	473	588	668	720	738	783	880
130	186	310	408	487	602	682	728	744	802	900
135	192	320	420	500	616	694	733	753	821	918
140	198	330	432	513	629	705	736	765	839	935
145	205	339	444	525	642	715	740	780	858	950
150	211	349	455	537	654	723	746	795	876	965
155	217	359	466	549	666	729	755	811	893	978
160	223	368	477	560	677	733	766	828	910	990
165	230	377	488	572	687	736	779	845	926	1002
170	236	387	498	582	697	739	792	861	940	1013
175	242	396	509	593	706	744	807	877	954	1023
180	248	405	519	603	714	751	822	892	967	1032



Nomogram 1. Temperatures on unprotected cross sections under ISO fire



Nomogram 2. Temperatures on protected cross sections under ISO fire