ArcelorMittal

Secure With Steel Training
19th and 20th March 2009

Natural Simplified Fire Model

***) Nominal temperature-time curve**

Standard temperature-, External fire - & Hydrocarbon fire curve

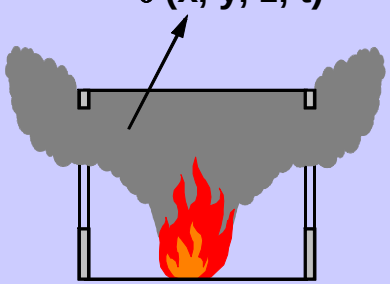
No data needed

***) Simplified Fire Models**

Localised Fire

- HESKESTADT
- HASEMI

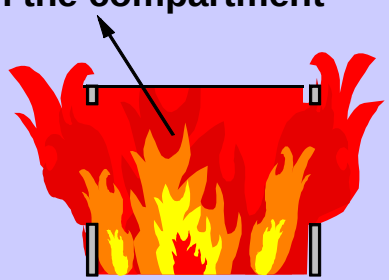
θ (x, y, z, t)



Fully Engulfed Compartment

- Parametric Fire

θ (t) uniform in the compartment



Rate of heat release
Fire surface
Boundary properties
Opening area
Ceiling height

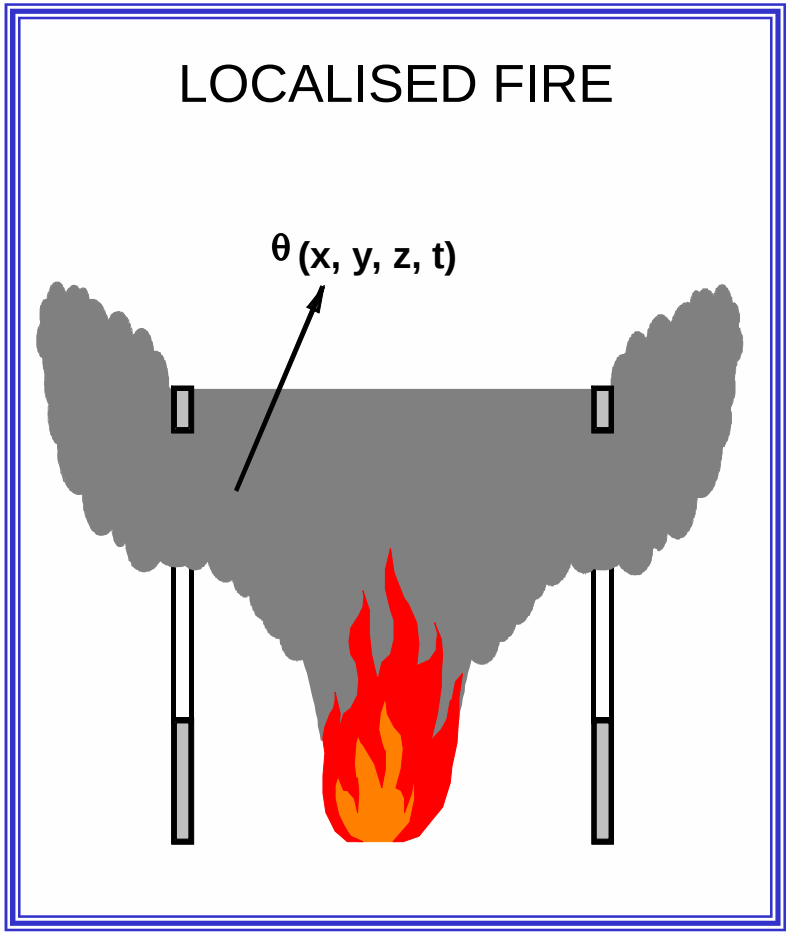
***) Advanced Fire Models**

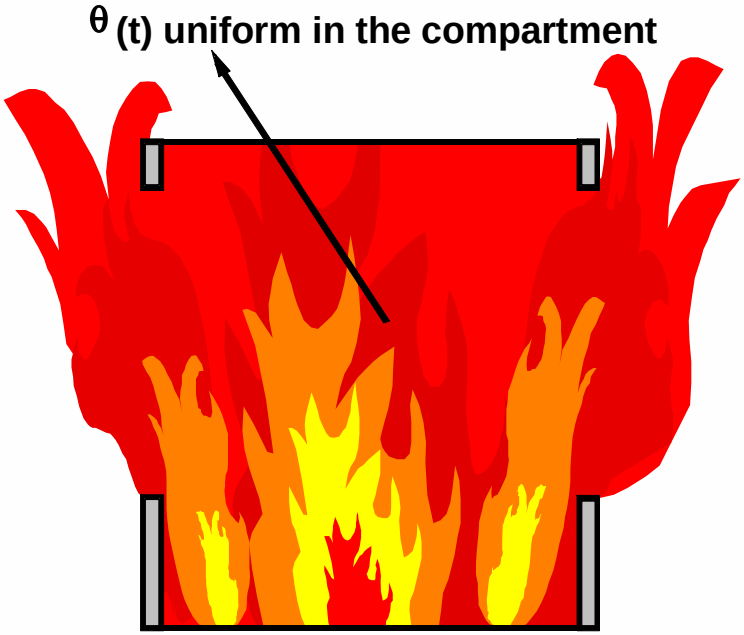
- Two-Zone Model
- One-Zone Model
- Combined Two-Zones and One-Zone fire
- CFD

+

Exact geometry

Simplified Fire Models
Localised Fire





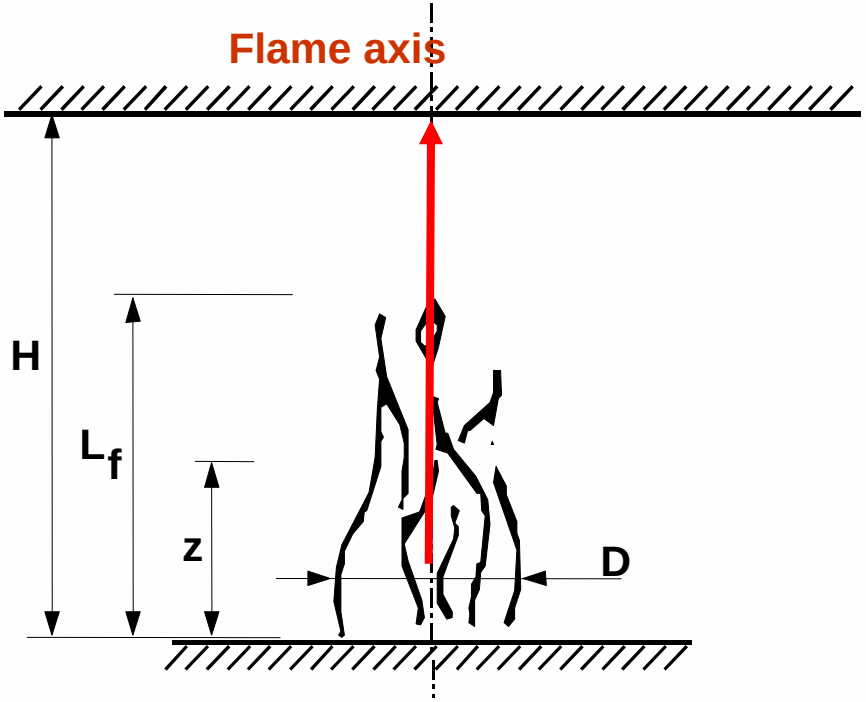
Real Localised Fire Test

Localised Fire: HESKESTAD Method

Annex C of EN 1991-1-2:

- Flame is not impacting the ceiling of a compartment ($L_f < H$)
- Fires in open air

$$\Theta_{(z)} = 20 + 0{,}25\,(0{,}8\,Q_c)^{2/3}\,(z-z_0)^{-5/3} \leq 900℃$$



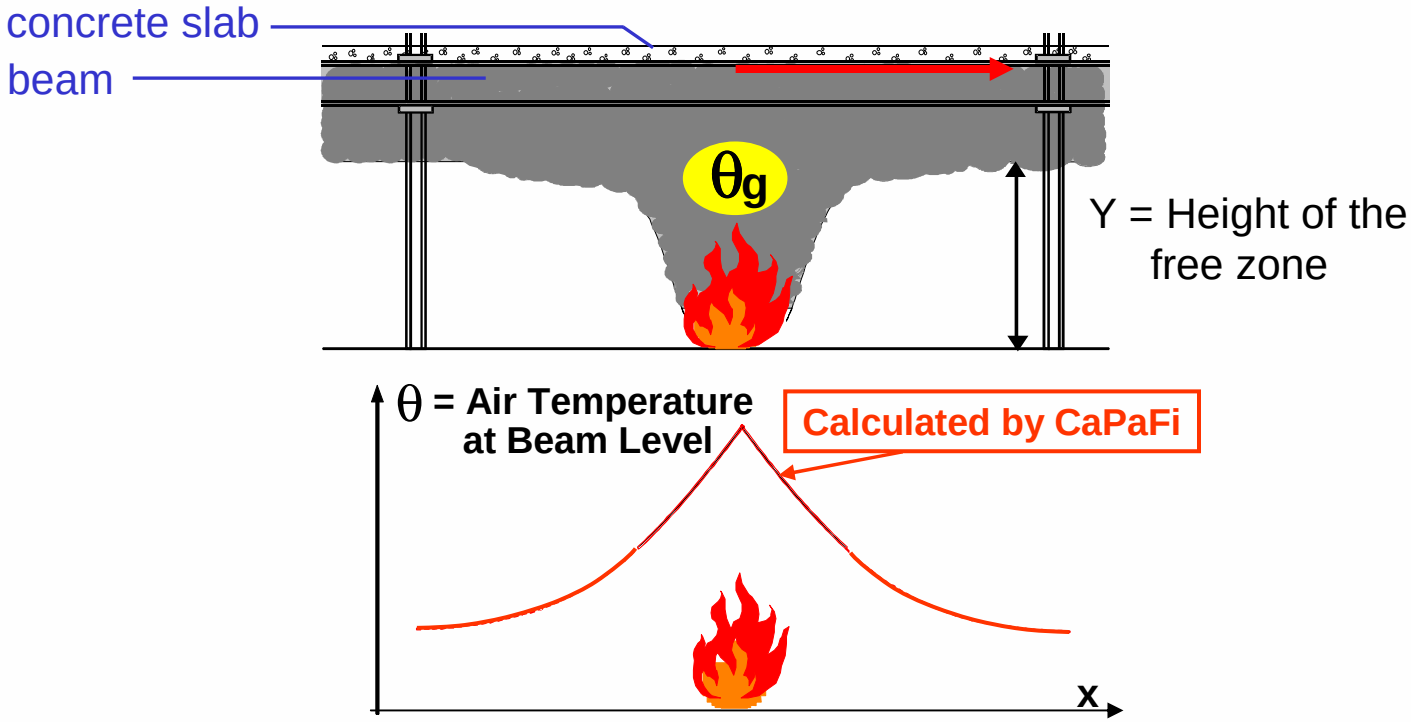
The flame length L_f of a localised fire is given by :

$$L_f = -1{,}02\,D + 0{,}0148\,Q^{2/5}$$

Localised Fire: HASEMI Method

Annex C of EN 1991-1-2:

- Flame is impacting the ceiling ($L_f > H$)



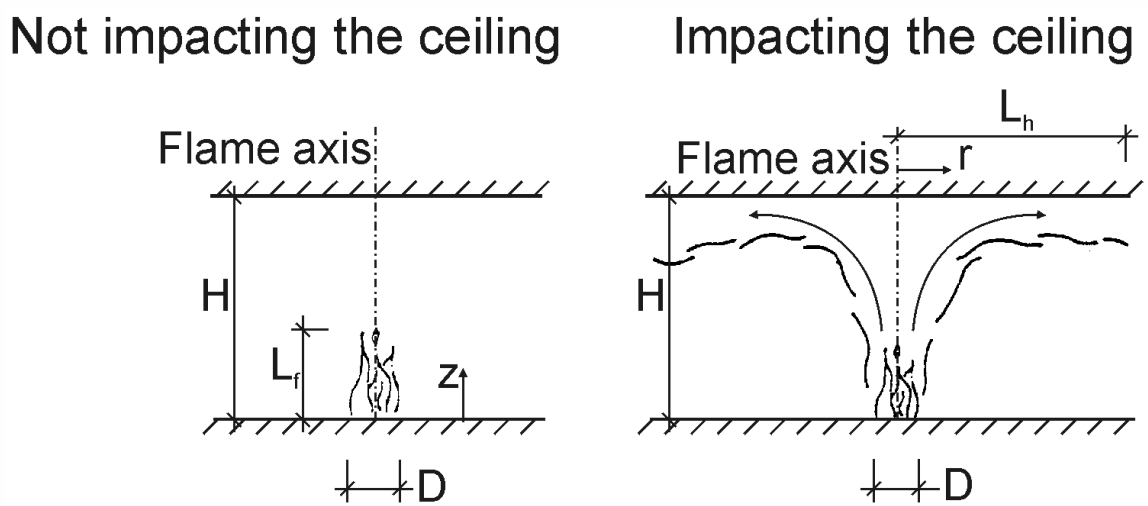
Worked examples - Overview

- Actions
  - Compartment fire
  - **Localised fire**
- Steel
  - Steel column
  - Steel beam (N + M)
  - Steel beam (hollow section)
- Composite
  - Composite slab
  - Composite beam (steel beam)
  - Composite beam (partially encased beam)
  - Composite column

Localised fire
Task

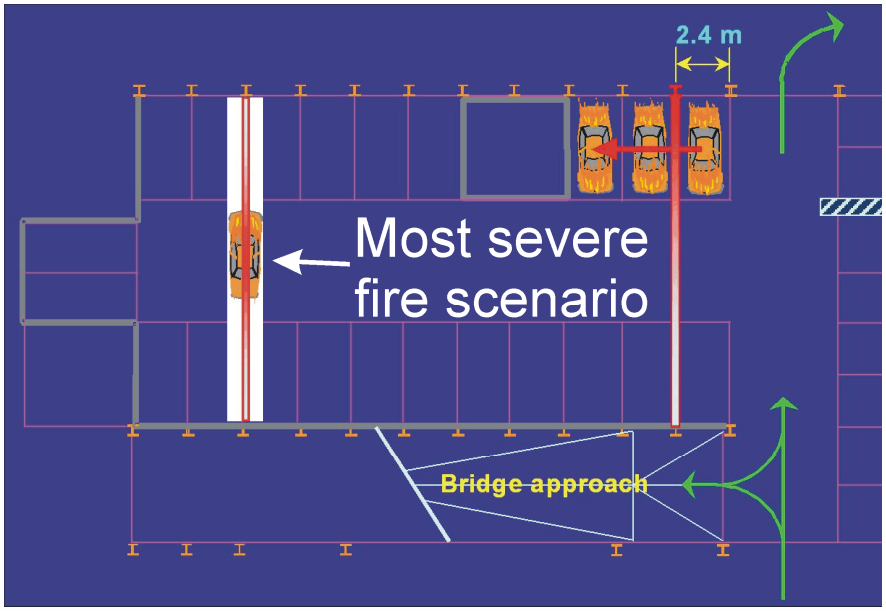
Determination of the steel temperatures of a steel beam exposed to fire by a burning car.

⇒ Natural fire model for localised fires



EN 1991-1-2: Annex C

Localised fire
Parameters



Building: Car park Auchan, Luxembourg

Type: Underground car park

Height: H = 2.7 m

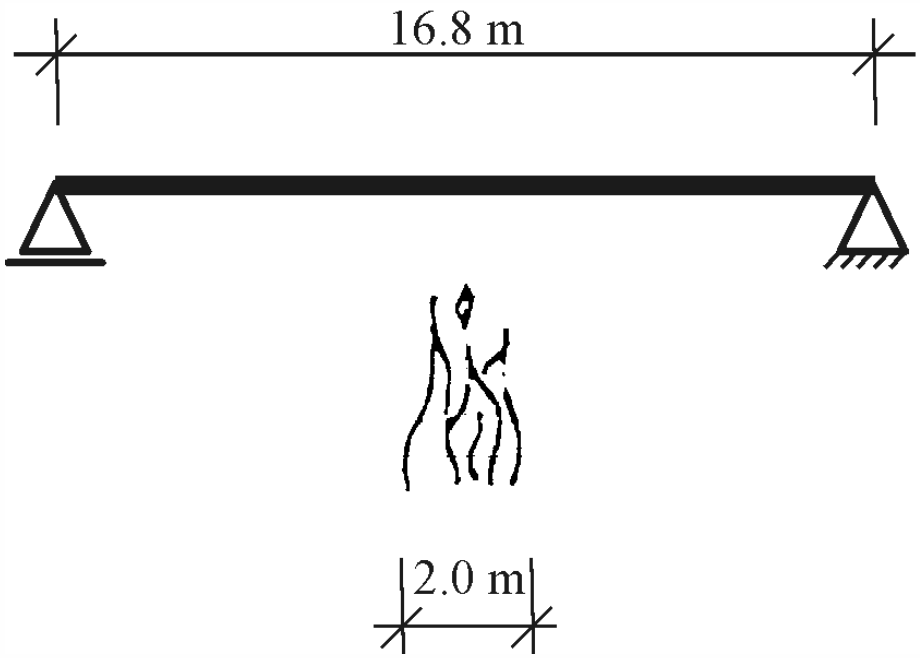
Horizontal distance from flame axis to beam: r = 0.0 m

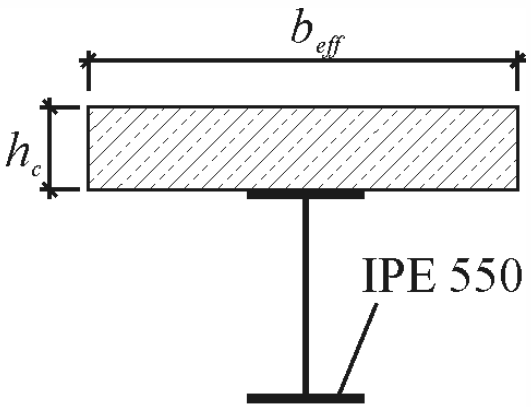
Diameter of flame: D = 2.0 m

Steel Beam: IPE 550

Localised fire

Static system and cross-section of the beam





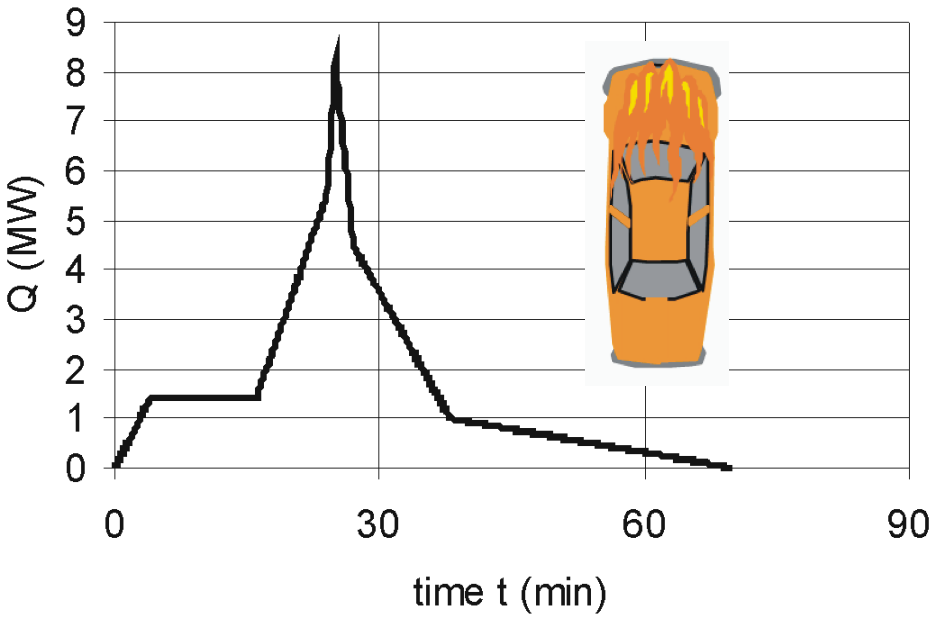
Localised fire

Hypothesis

- Diameter of the fire: D = 2.0 m
  It must be 3.91 m
- Vertical distance between fire source and ceiling:
  H = 2.7 m
- Horizontal distance between beam and flame axis:
  r = 0.0 m
- Emissivity of the fire: εf = 1.0
- Configuration factor: Φ = 1.0
- Stephan Boltzmann constant: σ = 5.67 · 10-8 W/m2K4
- Coefficient of the heat transfer: αc = 25.0 W/m²
  It must be 35.0 W/m²
- Steel profile: IPE 550
  - Section factor: Am/V = 140 1/m
  - Unit mass: ρa = 7850 kg/m³
  - Surface emissivity: εm = 0.7
  - Correction factor: ksh = 1.0

Localised fire
Rate of Heat Release

Curve of the rate of heat release of one car



From ECSC project: Development of design rules for steel structures subjected to natural fires in closed car parks.

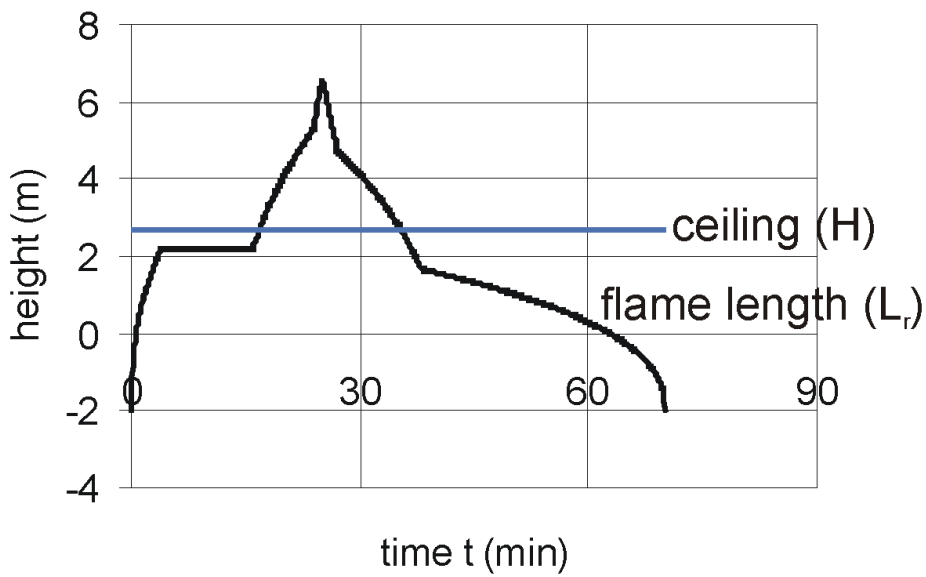
Localised fire

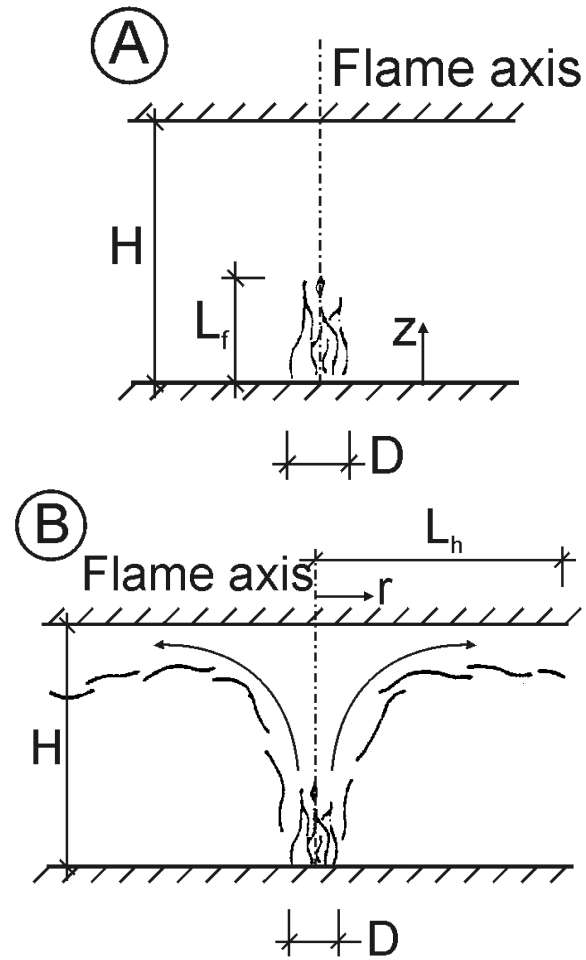
Flame Length

$$L_f = -1.02 \cdot D + 0.0148 \cdot Q^{2/5} = -2.04 + 0.0148 \cdot Q^{2/5}$$

if $L_r \geq H$ $\Rightarrow$ Model A has to be used

if $L_r < H$ $\Rightarrow$ Model B has to be used





1st case: The flame is not impacting the ceiling

- The net heat flux is calculated according to Section 3.1 of EN 1991-1-2.

$$\dot{h}_{net} = \alpha_c \cdot \left(\theta_{(z)} - \theta_m\right) + \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot \left(\left(\theta_{(z)} + 273\right)^4 - \left(\theta_m + 273\right)^4\right)$$

$$= 25.0 \cdot \left(\theta_{(z)} - \theta_m\right) + 3.969 \cdot 10^{-8} \cdot \left(\left(\theta_{(z)} + 273\right)^4 - \left(\theta_m + 273\right)^4\right)$$

1st case: The flame is not impacting the ceiling

The gas temperature is calculated to:

$$\theta_{(z)} = 20 + 0.25 \cdot (0.8 \cdot Q)^{2/3} \cdot (z - z_0)^{-5/3} \leq 900\ °\mathrm{C}$$

$$= 20 + 0.25 \cdot (0.8 \cdot Q)^{2/3} \cdot \left(4.74 - 0.0052 \cdot Q^{2/5}\right)^{-5/3} \leq 900\ °\mathrm{C}$$

where:

z is the height along the flame axis (2.7 m)

*z*0 is the virtual origin of the axis [m]

$$z_0 = -1.02 \cdot D + 0.0052 \cdot Q^{2/5} = -2.04 + 0.0052 \cdot Q^{2/5}$$

2nd case: The flame is impacting the ceiling

Net heat flux, if the flame is impacting the ceiling, is given by:

$$\dot{h}_{net} = \dot{h} - \alpha_c \cdot (\theta_m - 20) - \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot \left((\theta_m + 273)^4 - (293)^4 \right)$$

$$= \dot{h} - 25.0 \cdot (\theta_m - 20) - 3.969 \cdot 10^{-8} \cdot \left((\theta_m + 273)^4 - (293)^4 \right)$$

2nd case: The flame is impacting the ceiling

The heat flux depends on the parameter *y*. For different dimensions of *y*, different equations for determination of the heat flux have to be used.

if $y \leq 0.30$:

$$\dot{h} = 100{,}000$$

if $0.30 < y < 1.0$:

$$\dot{h} = 136{,}300 - 121{,}000 \cdot y$$

if $y \geq 1.0$:

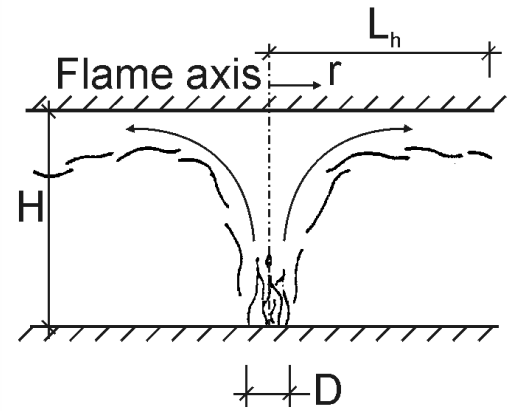
$$\dot{h} = 15{,}000 \cdot y^{-3.7}$$

where:

$$y = \frac{r + H + z'}{L_h + H + z'} = \frac{2.7 + z'}{L_h + 2.7 + z'}$$

2nd case: The flame is impacting the ceiling

$$y = \frac{r + H + z'}{L_h + H + z'} = \frac{2.7 + z'}{L_h + 2.7 + z'}$$



The horizontal flame length is calculated by:

$$L_h = \left(2.9 \cdot H \cdot \left(Q_H{}^*\right)^{0.33}\right) - H = \left(7.83 \cdot \left(Q_H{}^*\right)^{0.33}\right) - 2.7$$

where:

$$Q_H{}^* = Q \Big/ \left(1.11 \cdot 10^6 \cdot H^{2.5}\right) = Q \Big/ \left(1.11 \cdot 10^6 \cdot 2.7^{2.5}\right)$$

The vertical position of the virtual heat source is determined by:

if $QD^* < 1.0$: $$z' = 2.4 \cdot D \cdot \left(\left(Q_D{}^*\right)^{2/5} - \left(Q_D{}^*\right)^{2/3}\right) = 4.8 \cdot \left(\left(Q_D{}^*\right)^{2/5} - \left(Q_D{}^*\right)^{2/3}\right)$$

if $QD^* \geq 1.0$: $$z' = 2.4 \cdot D \cdot \left(1.0 - \left(Q_D{}^*\right)^{2/5}\right) = 4.8 \cdot \left(1.0 - \left(Q_D{}^*\right)^{2/5}\right)$$

where: $$Q_D{}^* = Q \Big/ \left(1.11 \cdot 10^6 \cdot D^{2.5}\right) = Q \Big/ \left(1.11 \cdot 10^6 \cdot 2.0^{2.5}\right)$$

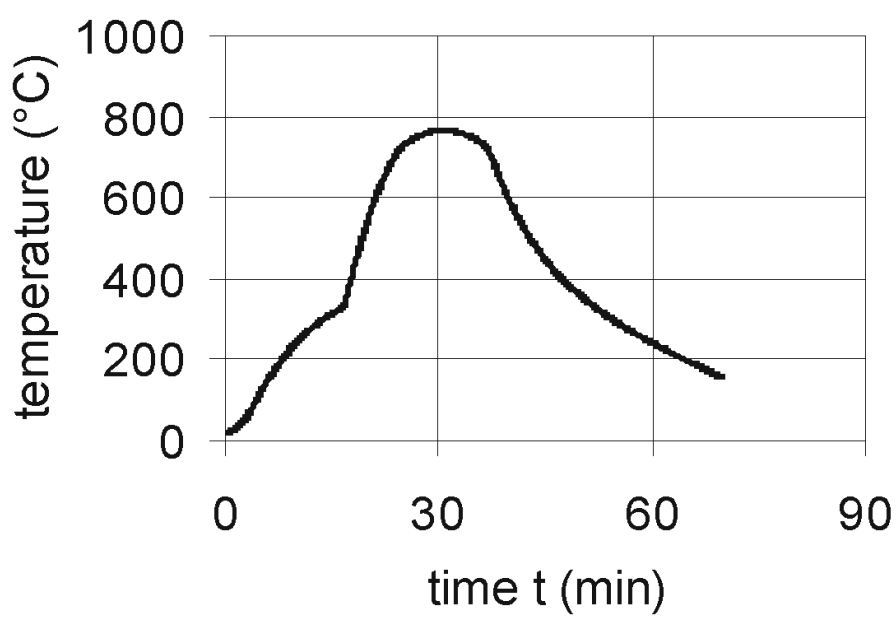
Localised fire
Steel temperatures

Temperature-time curve for the unprotected steel beam:

$$\theta_{a,t} = \theta_m + k_{sh} \cdot \frac{A_m/V}{c_a \cdot \rho_a} \cdot \dot{h}_{net} \cdot \Delta t = \theta_m + \frac{1.78 \cdot 10^{-2}}{c_a} \cdot \dot{h}_{net}$$

$\theta_{a,max} = 770$ °C

at $t_{\theta,max} = 31.07$ min



Thank you for your attention

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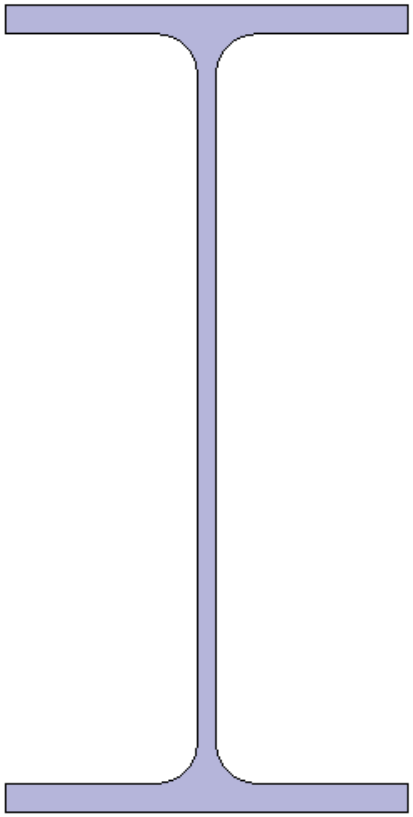
Steel profile
Task

Determination of the steel temperature after 30 minutes

ISO fire Exposure

IPE500

Am/V : 150 m-1



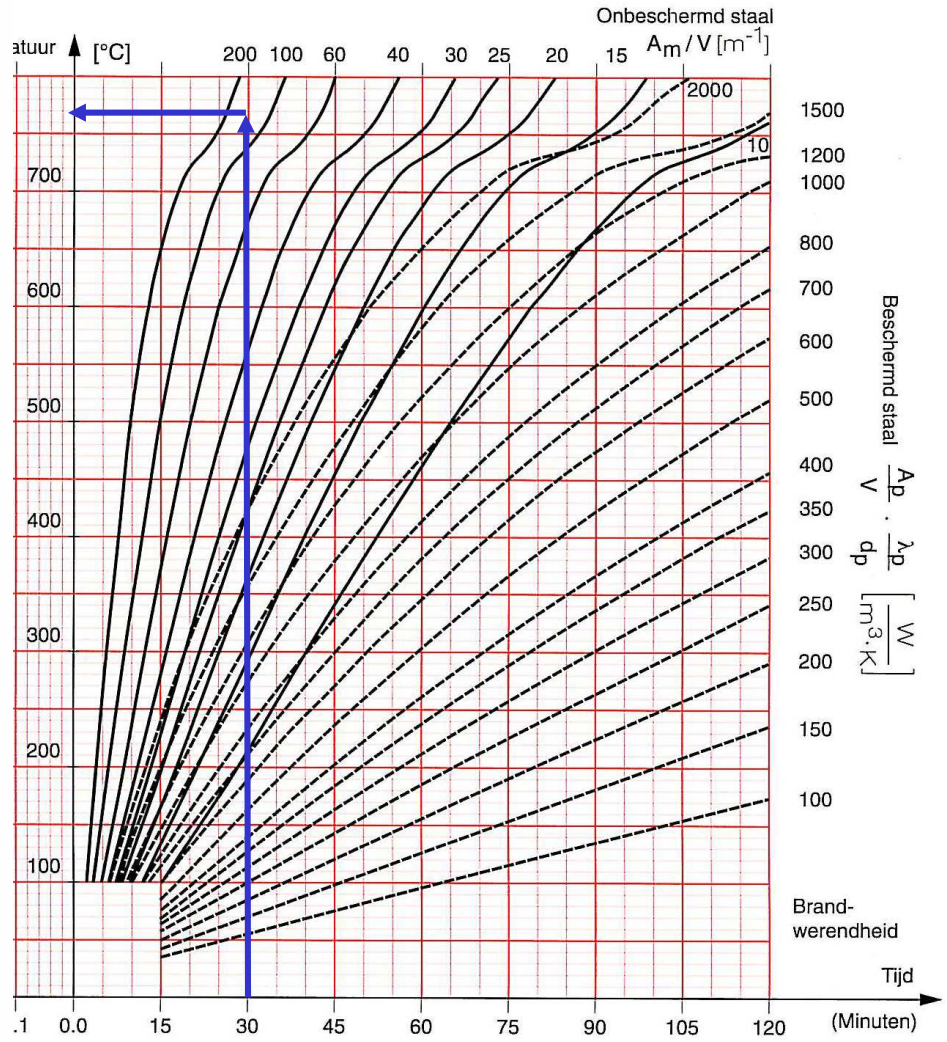
Steel profile
steel temperature

IPE300
Am/V : 215 m-1

$$\theta_{a,t} = \theta_m + k_{sh} \cdot \frac{A_m/V}{c_a \cdot \rho_a} \cdot \dot{h}_{net} \cdot \Delta t$$

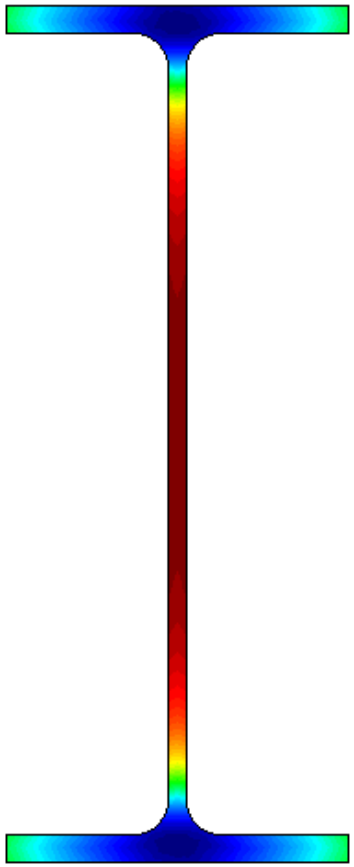
Euro-Nomogram:

$\Rightarrow$ $\theta_{a,max,30} \approx 770$ °C



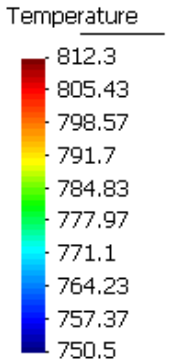
Steel profile

steel temperature



Euro-Nomogram:

$\Rightarrow \theta_{a,max,30} \approx 770$ °C



Worked examples - Overview

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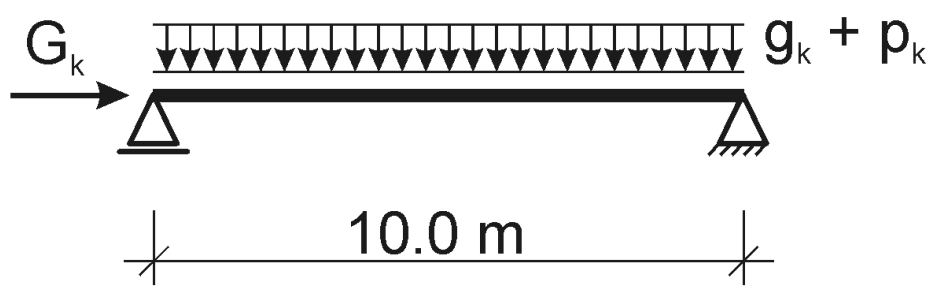
Steel beam (N + M)
Task

Verification of a steel beam subjected to bending and compression loads.



⇒ Simple calculation model for members subjected to bending and compression loads

EN 1993-1-2: Section 4.2.3.5

Steel beam (N + M)

Parameters

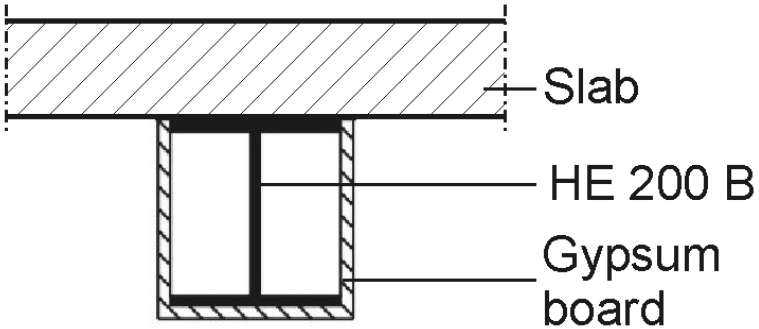
Building: Office building

Fire resistance class: R 90

Loads: G_k = 96.3 kN

g_k = 1.5 kN/m

p_k = 1.5 kN/m



Profile: Rolled section HE 200 B

Fire protection: Hollow encasement of gypsum board (d_p = 2 cm)

Steel grade: S 235

Steel beam (N + M)

Mechanical actions during fire exposure

Accidental situation:

$$E_{dA} = E \cdot \left(\sum G_k + A_d + \sum \psi_{2,i} \cdot Q_{k,i} \right)$$

Combination factor for office areas: $\Rightarrow \psi_{2,1} = 0.3$

$$\Rightarrow \quad N_{fi,d} = 96.3\,\text{kN}$$

$$M_{fi,d} = 24.38\,\text{kNm}$$

Steel beam (N + M)

Maximum steel temperature

$$\frac{2 \cdot h + b}{A_a} \cdot \frac{\lambda_p}{d_p} = 770 \frac{W}{m^3 \cdot K}$$

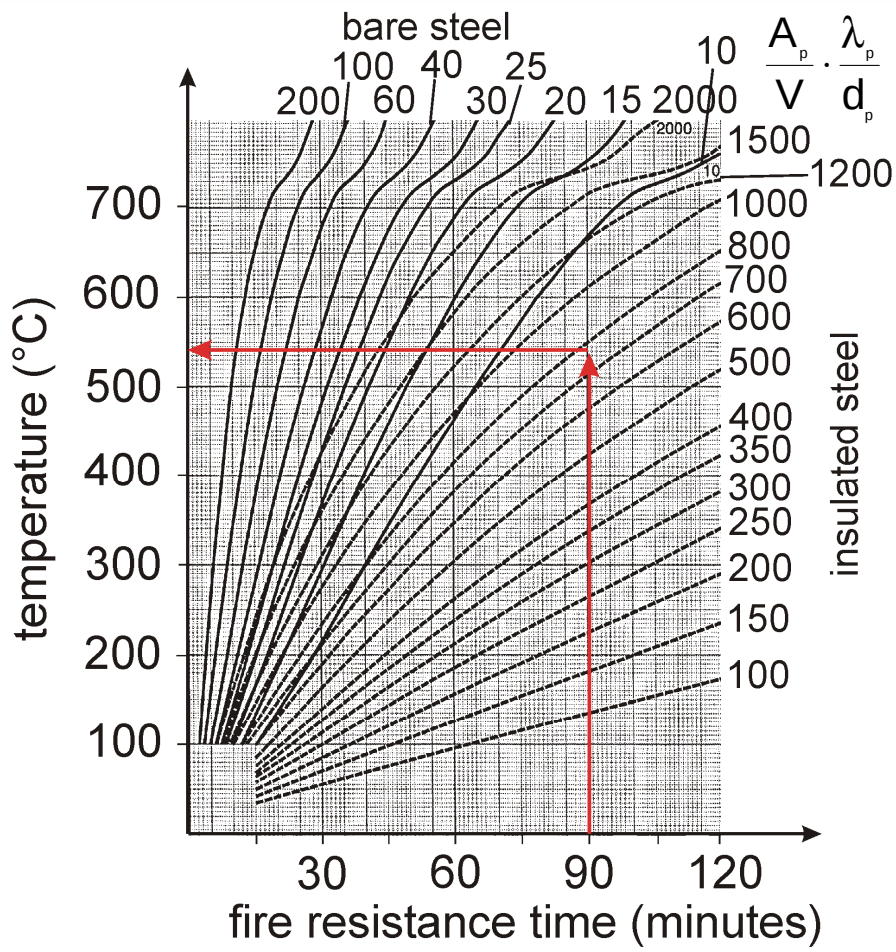
Euro-Nomogram:

$\Rightarrow \theta_{a,max,90} \approx 540\ ℃$

Reduction factors:

$\Rightarrow k_{y,\theta} = 0.656$

$k_{E,\theta} = 0.484$



Steel column
Reduction factor

- non-dimensional slenderness in the fire situation can be determined:

$$\bar{\lambda}_{y,\theta} = \bar{\lambda}_y \sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} = 1.25\sqrt{\frac{0.656}{0.484}} = 1.46$$

$$\bar{\lambda}_{z,\theta} = \bar{\lambda}_z \sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} = 2.1\sqrt{\frac{0.656}{0.484}} = 2.44$$

$$\varphi_{y,\theta} = \frac{1}{2}\cdot\left(1+\alpha\cdot\bar{\lambda}_{y,\theta}+\bar{\lambda}_{y,\theta}{}^2\right) = \frac{1}{2}\cdot\left(1+0.65\cdot 1.46+1.46^2\right) = 2.04$$

$$\varphi_{z,\theta} = \frac{1}{2}\cdot\left(1+\alpha\cdot\bar{\lambda}_{z,\theta}+\bar{\lambda}_{z,\theta}{}^2\right) = \frac{1}{2}\cdot\left(1+0.65\cdot 2.44+2.44^2\right) = 4.27$$

Steel beam (N + M)

Reduction factors and verification

- Reduction factors $\chi_{i,fi}$:

$$\chi_{y,fi} = \frac{1}{\varphi_{y,\theta} + \sqrt{\varphi_{y,\theta}^{\ 2} - \bar{\lambda}_{y,\theta}^{\ 2}}} = \frac{1}{2.04 + \sqrt{2.04^2 - 1.46^2}} = 0.29$$

$$\chi_{z,fi} = \frac{1}{\varphi_{z,\theta} + \sqrt{\varphi_{z,\theta}^{\ 2} - \bar{\lambda}_{z,\theta}^{\ 2}}} = \frac{1}{4.27 + \sqrt{4.27^2 - 2.44^2}} = 0.13$$

- Flexural buckling:

$$\frac{N_{fi,d}}{\chi_{min,fi} \cdot A \cdot k_{y,\theta} \cdot f_y / \gamma_{M,fi}} + \frac{k_y \cdot M_{y,fi,d}}{W_{pl,y} \cdot k_{y,\theta} \cdot f_y / \gamma_{M,fi}} = 0.98 \leq 1$$

- Lateral torsional buckling:

$$\frac{N_{fi,d}}{\chi_{z,fi} \cdot A \cdot k_{y,\theta} \cdot f_y / \gamma_{M,fi}} + \frac{k_{LT} \cdot M_{y,fi,d}}{\chi_{LT,fi} \cdot W_{pl,y} \cdot k_{y,\theta} \cdot f_y / \gamma_{M,fi}} = 1.14 \leq 1$$

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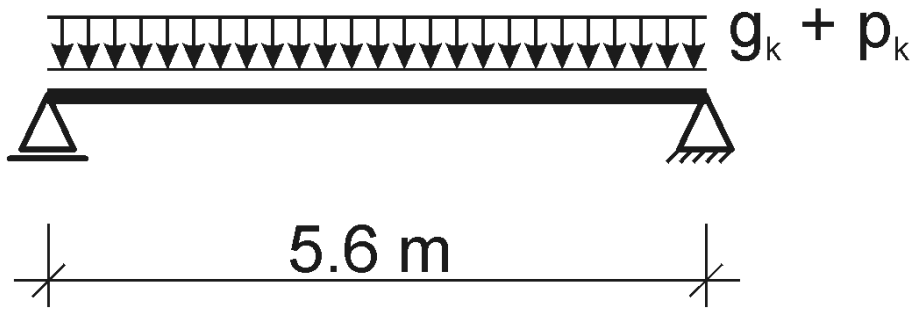
  - Composite slab
  - **Composite beam (steel beam)**
  - Composite beam (partially encased beam)
  - Composite column

Composite beam (steel beam)
Task

Determination of the design sagging moment resistance for the composite beam.



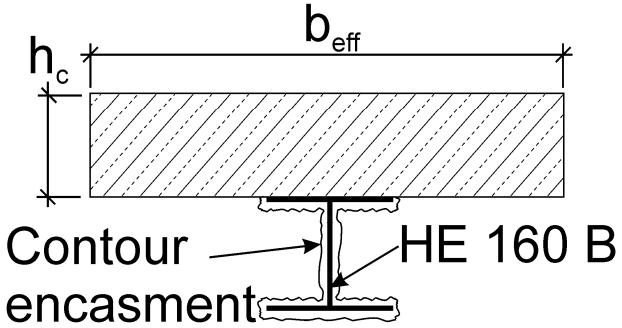
⇒ Simple calculation model for composite beams exposed to fire

EN 1994-1-2: Annex E

Composite beam (steel beam)

Parameters

Building:	Office building
Fire resistance class:	R 60
Loads:	g_k = 28.0 kN/m p_k = 15.0 kN/m
Heigth of slab:	h_c = 16.0 cm
Strength class:	C 25/30
Profile:	Rolled section HE 160 B
Fire protection:	Contour encasement of plaster (d_p = 1.5 cm)
Steel grade:	S 235



Composite beam (steel beam)

Mechanical actions during fire exposure

Accidental situation:

$$E_{dA} = E \cdot \left(\sum G_k + A_d + \sum \psi_{2,i} \cdot Q_{k,i} \right)$$

Combination factor for office areas: $\Rightarrow \psi_{2,1} = 0.3$

$$M_{fi,d} = (20.5 + 7.5) + 0.3 \cdot (15.0) \cdot \frac{5.6^2}{8} = 127.4 \text{ kNm}$$

Composite beam (steel beam)

Maximum steel temperature

Upper flange:

$\theta_{a,max,u} \approx 390$ °C

$\Rightarrow k_{y,\theta} = 1.0$

Web:

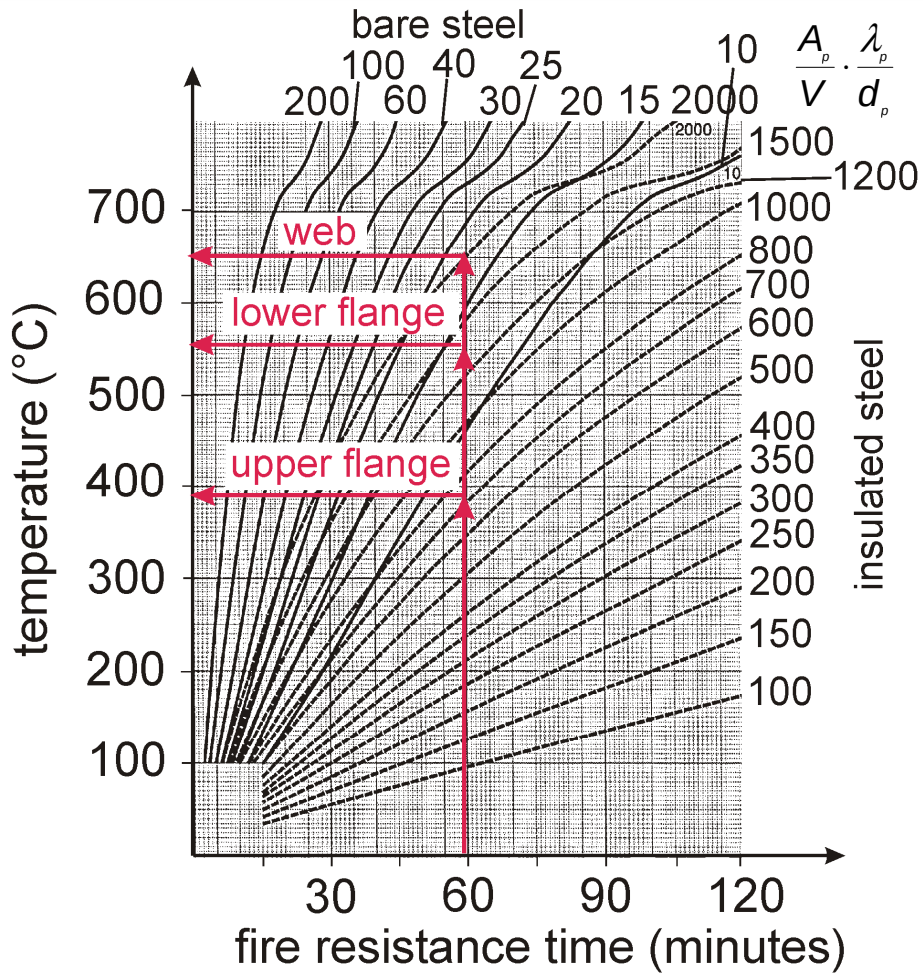
$\theta_{a,max,w} \approx 650$ °C

$\Rightarrow k_{y,\theta} = 0.350$

Lower flange:

$\theta_{a,max,l} \approx 550$ °C

$\Rightarrow k_{y,\theta} = 0.625$

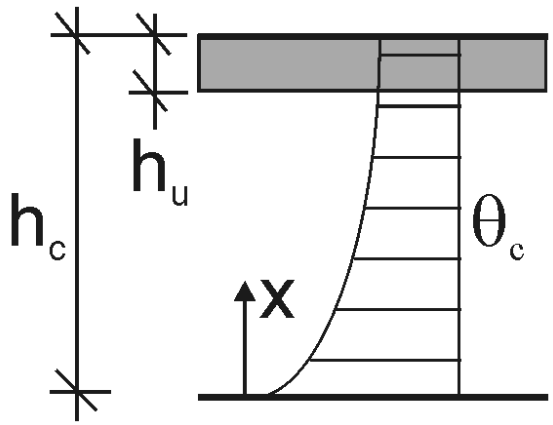


Composite beam (steel beam)

Temperatures of the concrete compression zone

Check, if the temperatures in the compression zone are lower than 250 ℃:

$$(h_c - h_u) = 12.2 \text{ cm} > x = 5 \text{ cm}$$



$\Rightarrow$ Concrete compression strength is not reduced.

where

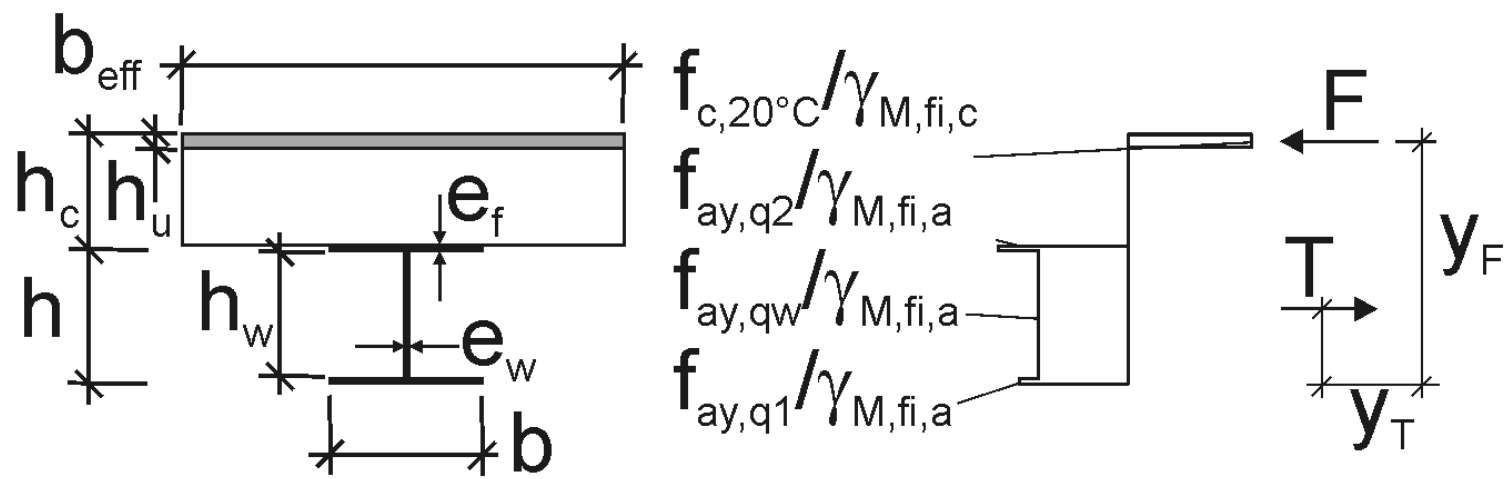
x: Concrete zone with temperatures θ_c > 250 ℃

h_u: Height of the compression zone

Composite beam (steel beam)

Design sagging moment resistance and verification

- Design sagging moment resistance:



Composite beam (steel beam)

Calculation of the reduced yield stresses

	$\theta_{a,max,60}$ [°C]	$k_{y,\theta}$ [-]	$f_{ay,\theta}$ [N/mm²]
Upper flange	390	1.00	355
Web	650	$(0.47+0.23)/2=0.35$	124
Lower flange	550	$(0.78+0.47)/2=0.625$	222

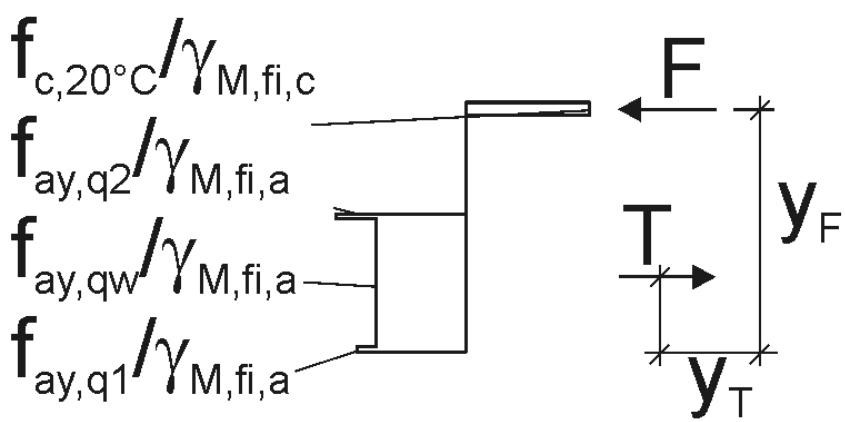
Composite beam (steel beam)

tensile force T of the steel beam

$$T = \frac{f_{ay,\theta 1} \cdot \left(b \cdot e_f\right) + f_{ay,\theta w} \cdot \left(h_w \cdot e_w\right) + f_{ay,\theta 2} \cdot \left(b \cdot e_f\right)}{\gamma_{M,fi,a}}$$

$$= \frac{22.2 \cdot (16 \cdot 1.3) + 12.4 \cdot (13.4 \cdot 0.8) + 35.5 \cdot (16 \cdot 1.3)}{1.0}$$

$$= 1333.1 \text{ kN}$$



Composite beam (steel beam)

location of the tensile an compression force

$$y_T = \frac{f_{ay,\theta 1} \cdot \left(b \cdot \frac{e_f^2}{2} \right) + f_{ay,\theta w} \cdot \left(h_w \cdot e_w \right) \cdot \left(e_f + \frac{h_w}{2} \right) + f_{ay,\theta 2} \cdot \left(b \cdot e_f \right) \left(h - \frac{e_f}{2} \right)}{T \cdot \gamma_{M,fi,a}}$$

$$= \frac{22.2 \cdot \left(16 \cdot \frac{1.3^2}{2} \right) + 12.4 \cdot \left(13.4 \cdot 0.8 \right) \cdot \left(1.3 + \frac{13.4}{2} \right) + 35.5 \cdot \left(16 \cdot 1.3 \right) \cdot \left(16 - \frac{1.3}{2} \right)}{1333.1 \cdot 1.0}$$

$$= 9.53 \text{ cm}$$

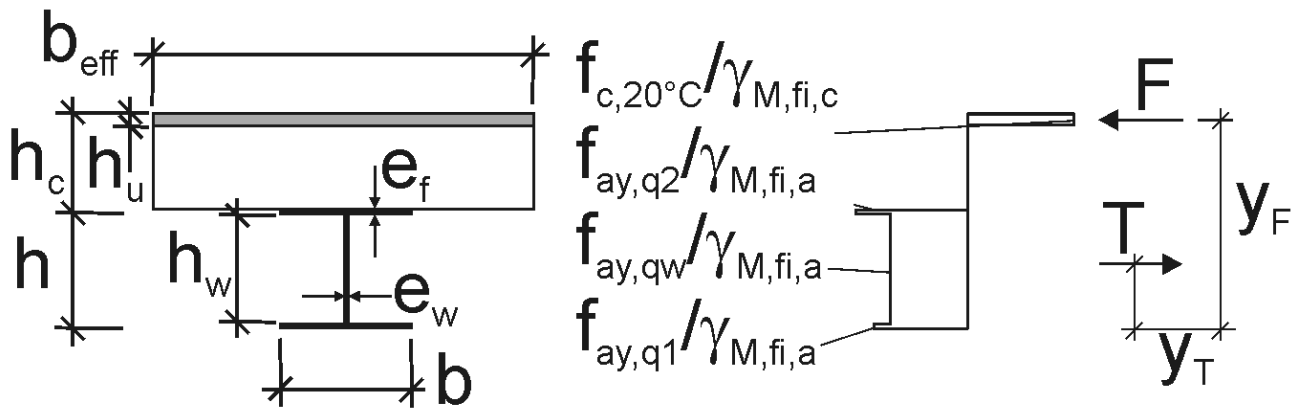
$$y_F = h + h_c - \left(h_u / 2 \right) = 16 + 16 - \left(3.8/2 \right) = 30.1 \text{ cm}$$

Composite beam (steel beam)

Design sagging moment resistance and verification

- Design sagging moment resistance:

$$M_{fi,Rd} = T \cdot (y_F - y_T) = 274.2 \text{ kNm}$$



- Verification:

$$\frac{M_{fi,d}}{M_{fi,Rd}} = 0.46 < 1$$