DIFISEK

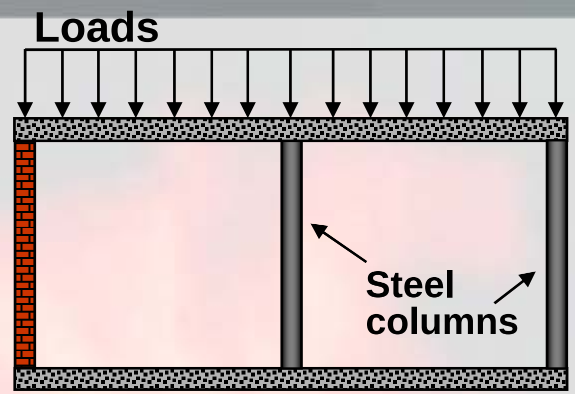
PART 5a

WORKED EXAMPLES

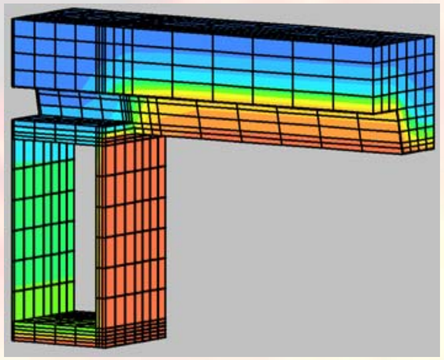
Resistance to fire - Chain of events

1: Ignition

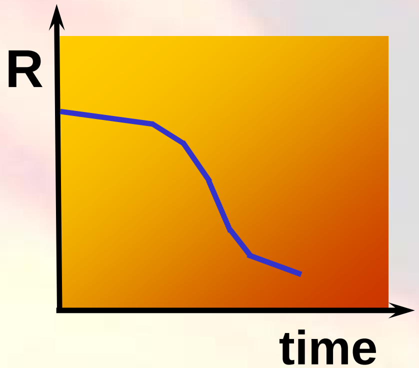
2: Thermal action



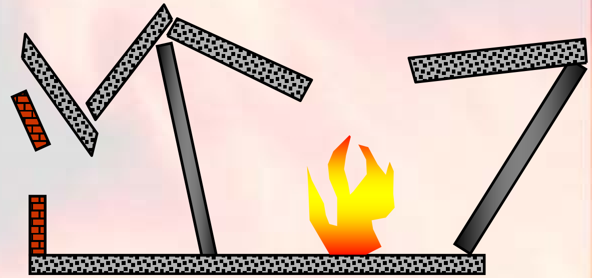
3: Mechanical actions



4: Thermal response



5: Mechanical response



6: Possible collapse

Used standards

Ambient temperature design

➢ EN 1990	Basis of structural design
➢ EN 1993-1-1	Design of steel structures
➢ EN 1994-1-1	Design of composite structures

Fire design

➢ EN 1990	Basis of structural design
➢ EN 1991-1-2	Thermal actions
➢ EN 1993-1-2	Fire design of steel structures
➢ EN 1994-1-2	Fire design of composite structures

Worked examples – Overview

		Number of examples
➢ EN 1991:	Actions on structures	2
Part 1-2:	General actions – Actions on structures exposed to fire	
➢ EN 1993:	Design of steel structures	3
Part 1-2:	General rules – Structural fire design	
➢ EN 1994:	Design of composite steel and concrete structures	4
Part 1-2:	General rules – Structural fire design	

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

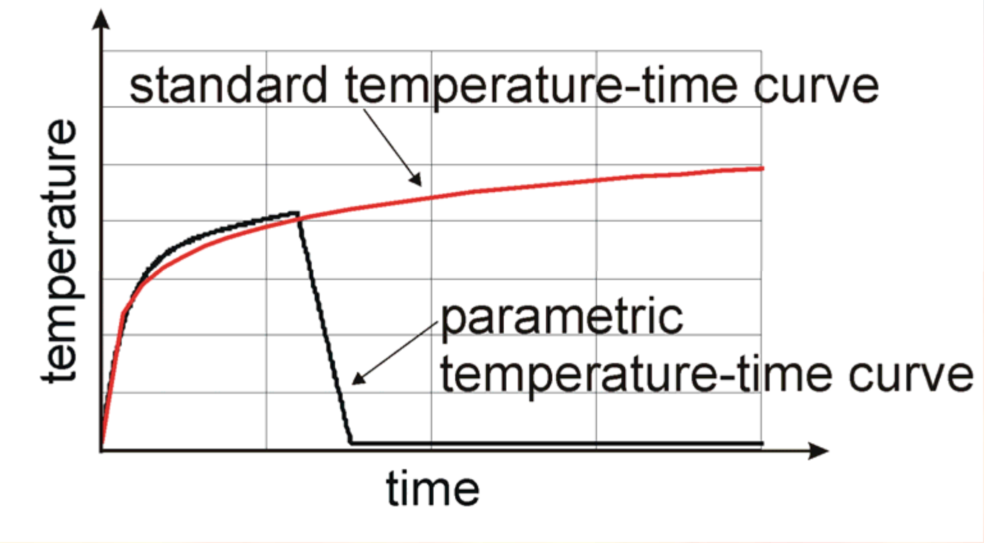
Compartment Fire
Task

Determination of the gas temperature
of a fully engulfed fire

⇒ Natural fire model for compartment fires

⇒ Parametric temperature – time curve

$\theta_g = f\,(q_{f,d}, O, b)$



EN 1991-1-2: Annex A

Compartment Fire
Parameters

Building: Cardington test facility
Type: Office

Fire load: $q_{f,d}$ = 483 MJ/m²

Floor area: A_f = 135 m²
Height: H = 4.0 m

Average window height: h_{eq} = 1.8 m
Area of vertical openings: A_v = 27 m²
Vertical opening factor: O = 0.076 m

Material of boundaries: Lightweight concrete
$b = 1263.3\ J/(m^2 s^{1/2} K)$

Compartment Fire
Fuel or ventilation controlled?

$$0.2 \cdot 10^{-3} \cdot q_{t,d} / O = 0.363 \text{ h}$$

$$0.363 \text{ h} < t_{lim} = 0.333 \text{ h} \quad \text{fuel controlled}$$

$$0.363 \text{ h} > t_{lim} = 0.333 \text{ h} \quad \text{ventilation controlled}$$

where

$$q_{t,d} = q_{f,d} \cdot A_f / A_t$$

Compartment Fire

Heating curve

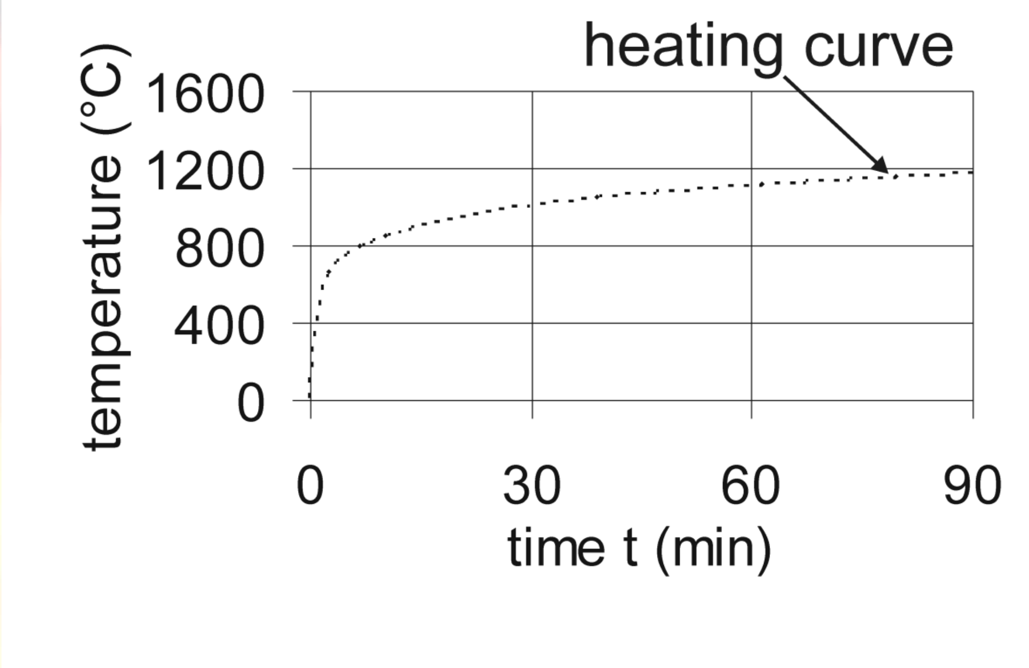
Calculation of the heating curve:

$$\theta_g = 20 + 1325 \cdot \left(1 - 0.324 \cdot e^{-0.2 \cdot t^*} - 0.204 \cdot e^{-1.7 \cdot t^*} - 0.472 \cdot e^{-19 \cdot t^*}\right)$$

where:

$$t^* = t \cdot \Gamma$$

$$\Gamma = \frac{(O/b)^2}{(0.04/1160)^2}$$



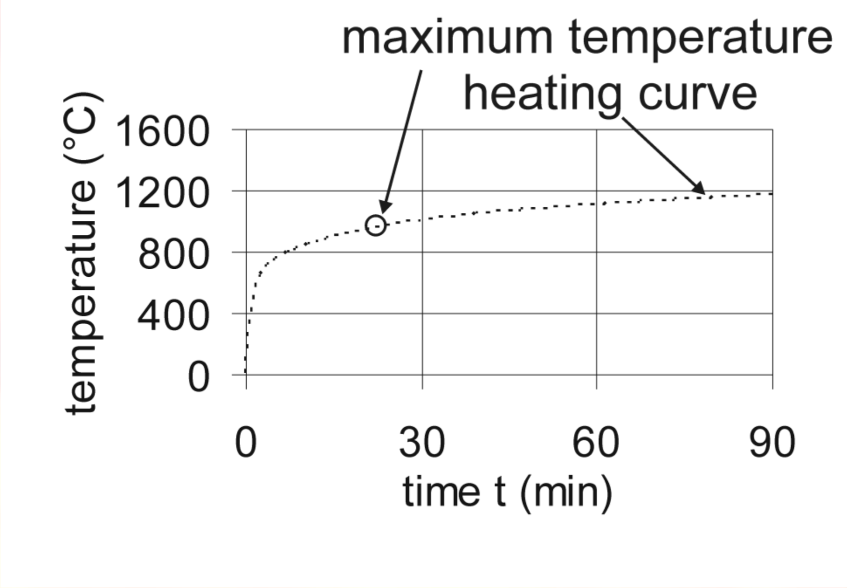
Compartment Fire

Maximum temperature

Equal to the calculation of the heating curve, except:

$$t = t_{max} = \max \begin{cases} 0.2 \cdot 10^{-3} \cdot q_{t,d} / O \\ t_{lim} \end{cases}$$

The maximum temperature is needed to determine the cooling curve.



Compartment Fire
Cooling curve

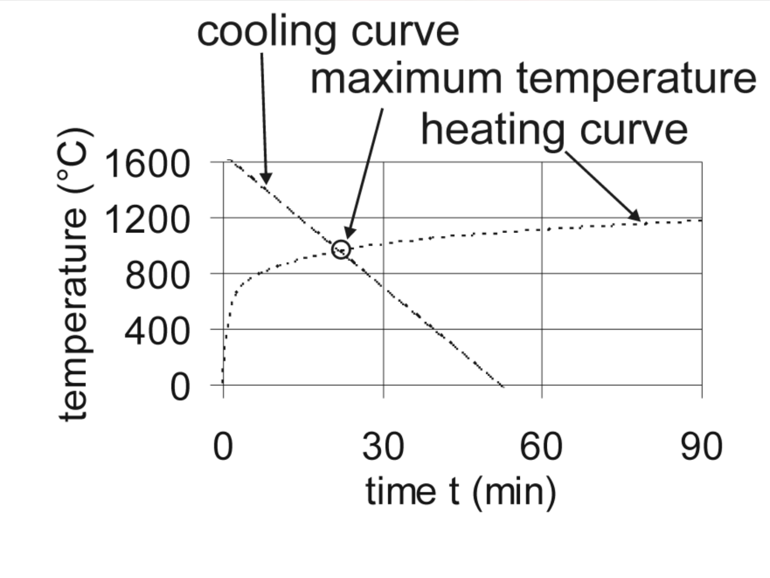
Calculation of the cooling curve:

$$\theta_g = \theta_{max} - 625 \cdot \left(t^* - t^*_{max} \cdot x\right)$$

where

$$t^*_{max} = \left(0.2 \cdot 10^{-3} \cdot q_{t,d} / O\right) \cdot \Gamma$$

$$t^* = t \cdot \Gamma$$

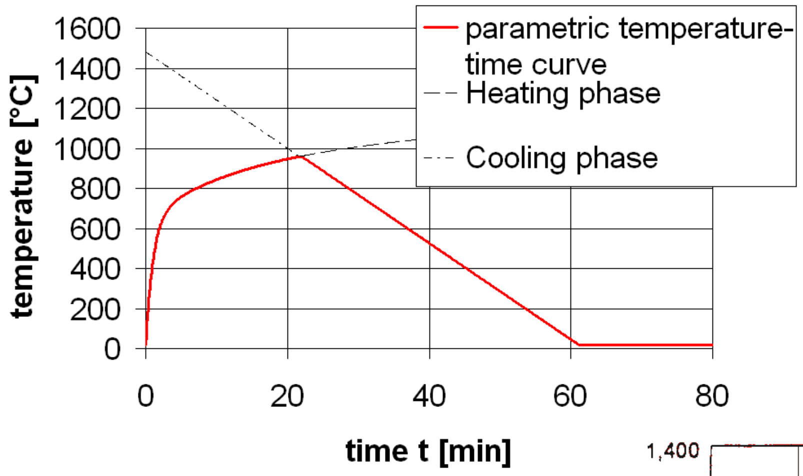


If fire is ventilation controlled: $x = 1.0$

If fire is fuel controlled: $x = t_{lim} \cdot \Gamma / t^*_{max}$

Compartment Fire

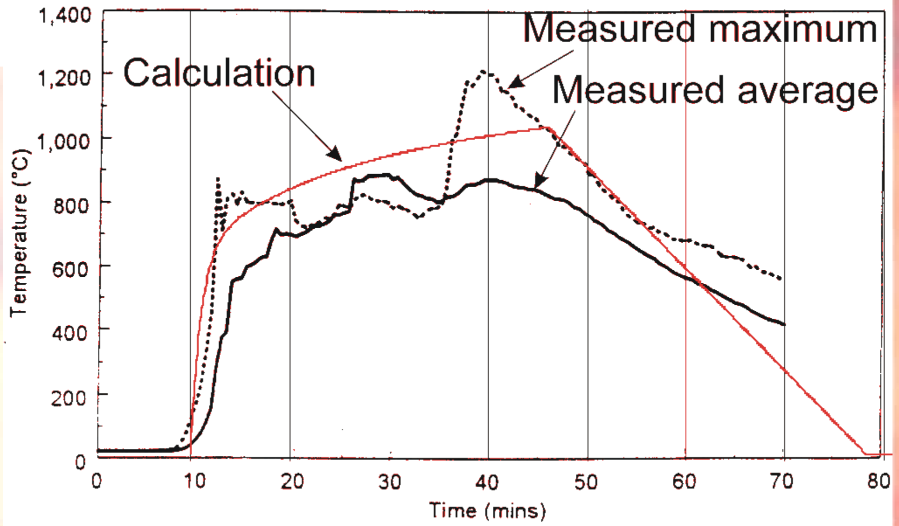
Final curve and comparison



Parametric temperature-time curve

Comparison calculation – measurement

(Factors of $q_{fi,d}$: δ_{q1} =1.0,
δ_{q2} = 1.0,
δ_n = 1.0



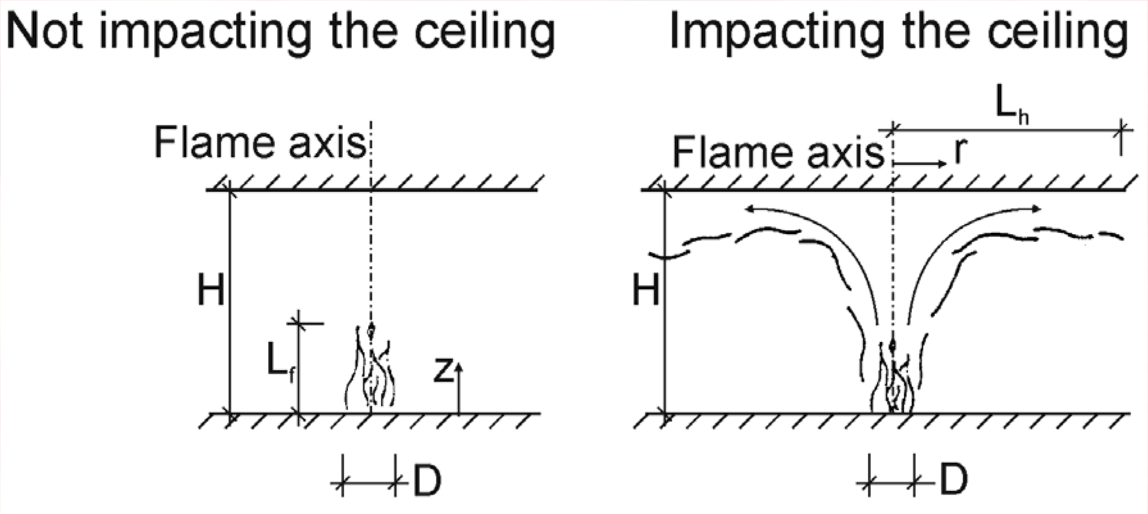
Worked examples - Overview

- 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

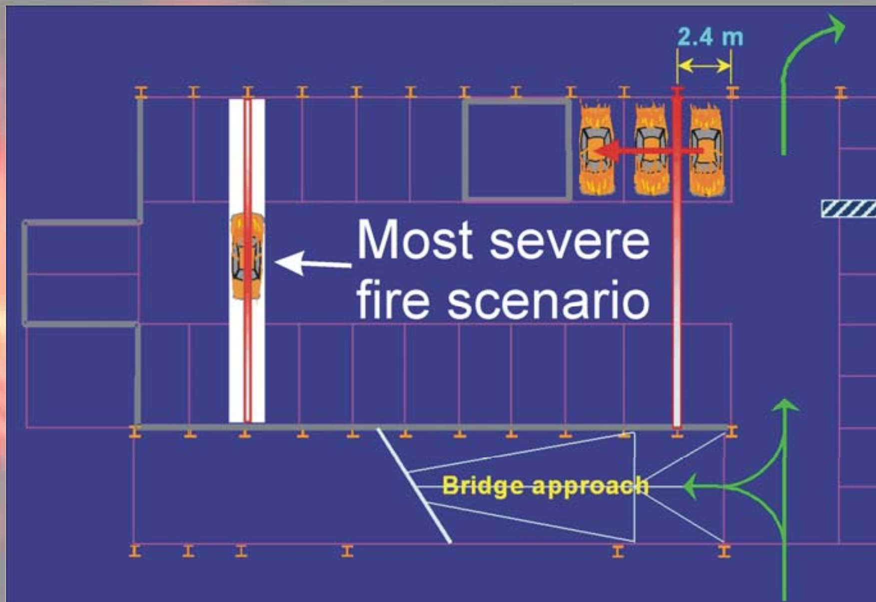
Determination of the steel temperatures of a steel beam exposed to fire by a burning car.

⇒ Natural fire model for localised fires



EN 1991-1-2: Annex C

Localised fire
Parameters



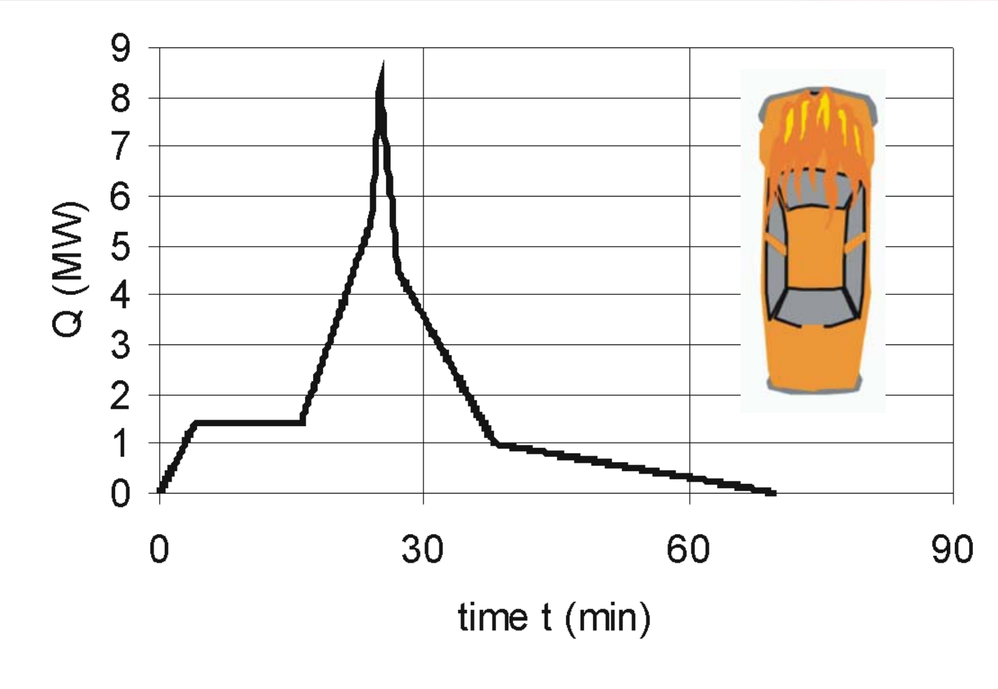
Building: Car park Auchan, Luxembourg
Type: Underground car park

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
Rate of Heat Release

Curve of the rate of heat release of one car

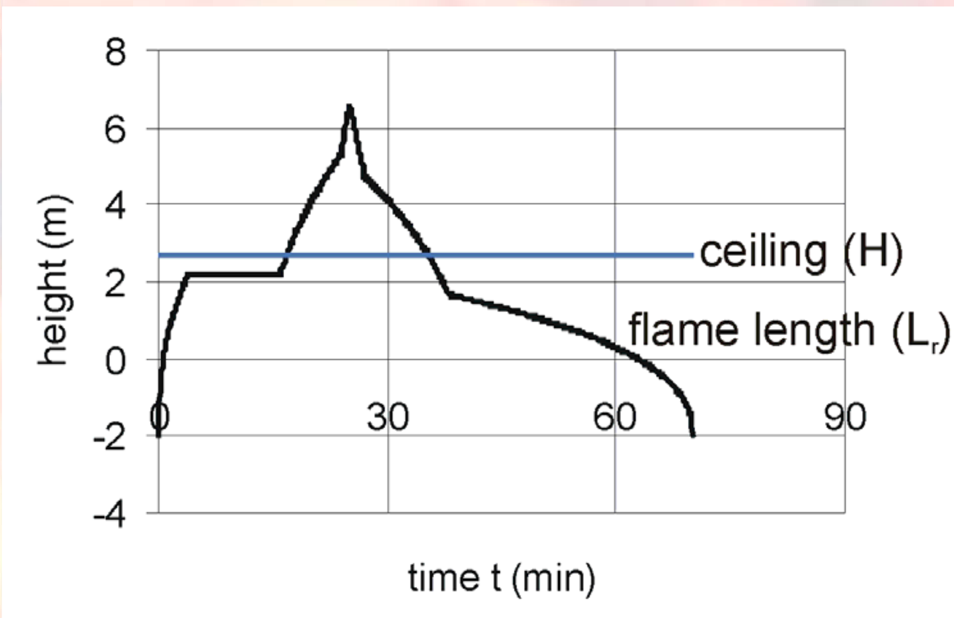


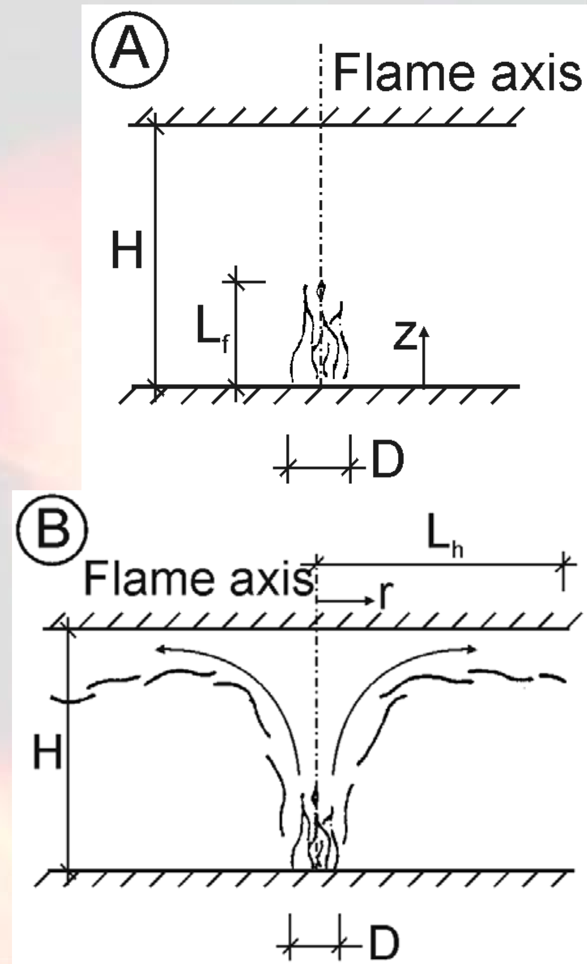
From ECSC project: Development of design rules for steel structures subjected to natural fires in closed car parks.

Localised fire
Flame Length

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

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





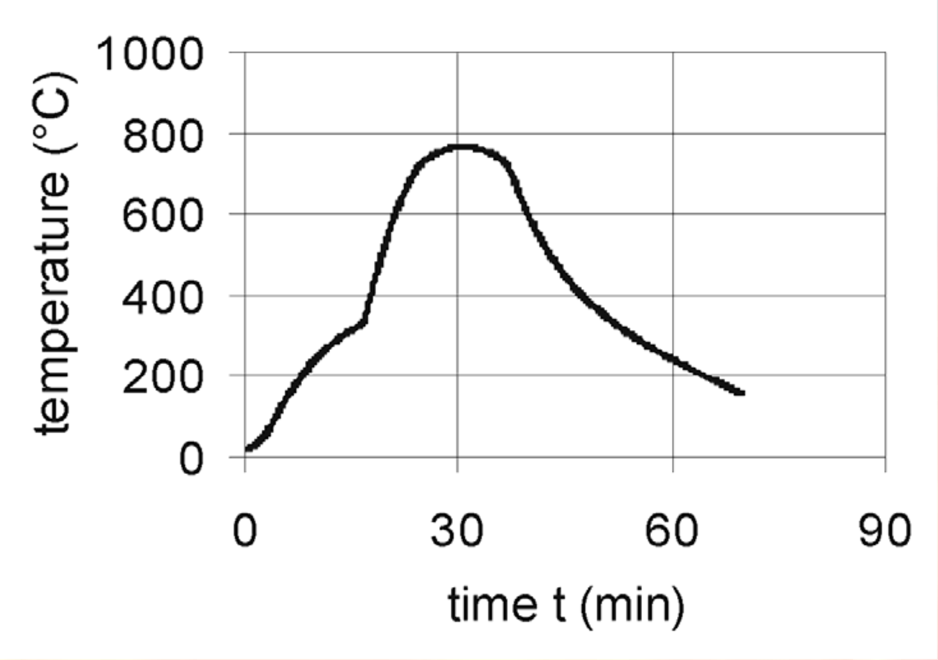
Localised fire
Steel temperatures

Temperature-time curve for the unprotected steel beam:

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

$$\theta_{a,max} = 770\ °C$$

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



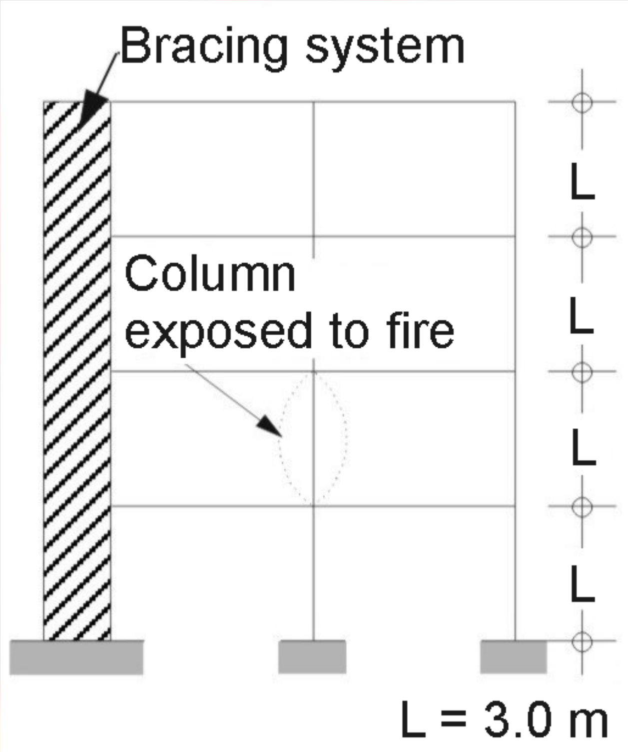
Worked examples - Overview

- 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

Steel column
Task

Determination of the design axial resistance for a steel column.

⇒ Simple calculation model for compression members

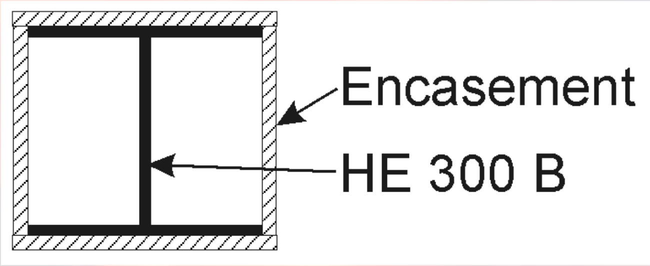


EN 1993-1-2: Section 4.2.3.2

Steel column
Parameters

Building: Department store
Fire resistance class: R 90

Loads: G_k = 1200 kN
P_k = 600 kN



Profile: Rolled section
HE 300 B
Fire protection: Hollow encasement
of gypsum board (d_p = 3 cm)
Steel grade: S 235

Steel column

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 shopping areas: $\Rightarrow \psi_{2,1} = 0.6$

$$\Rightarrow \quad N_{fi,d} = 1560 \text{ kN}$$

Steel column

Maximum steel temperature

$$\frac{2\cdot(b+h)}{A_a}\cdot\frac{\lambda_p}{d_p}=540\ \frac{W}{m^3\cdot K}$$

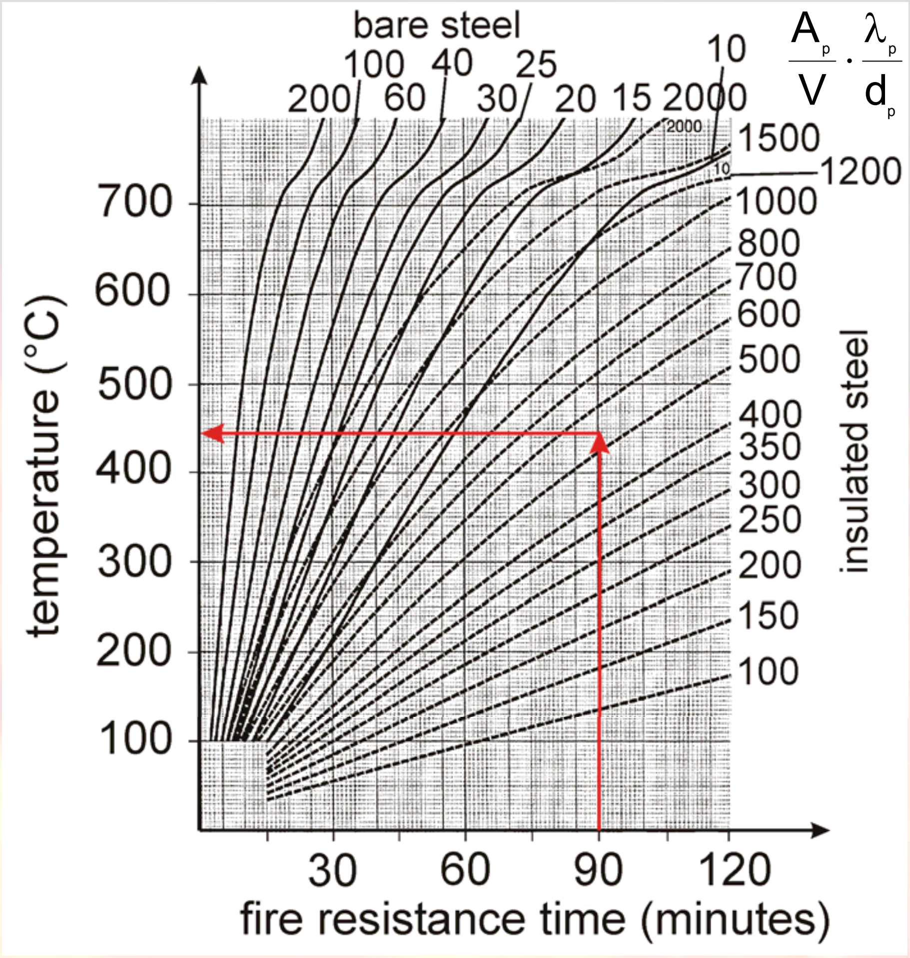
Euro-Nomogram:

$\Rightarrow\ \theta_{a,max,90}\approx 445$ °C

Reduction factors:

$\Rightarrow k_{y,\theta} = 0.901$

$k_{E,\theta} = 0.655$



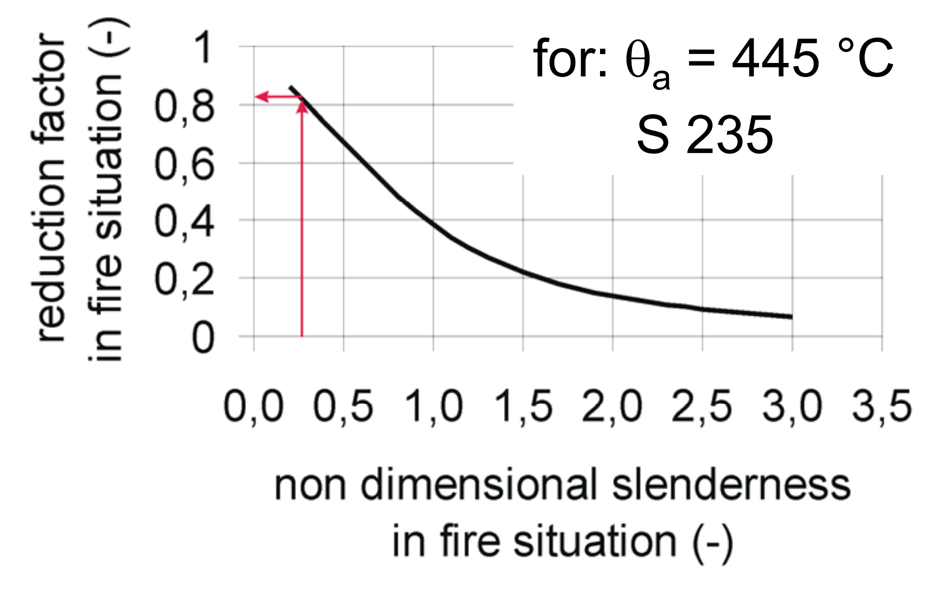
Steel column

Reduction factor and verification

- Reduction factor χ_{fi}:

$$\bar{\lambda}_{fi,\theta} = \bar{\lambda} \cdot \sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} = 0.25$$

$$\Rightarrow \quad \chi_{fi} = 0.86$$



- Flexural buckling:

$$N_{b,fi,t,Rd} = \chi_{fi} \cdot A \cdot k_{y,\theta,max} \cdot \frac{f_y}{\gamma_{M,fi}}$$

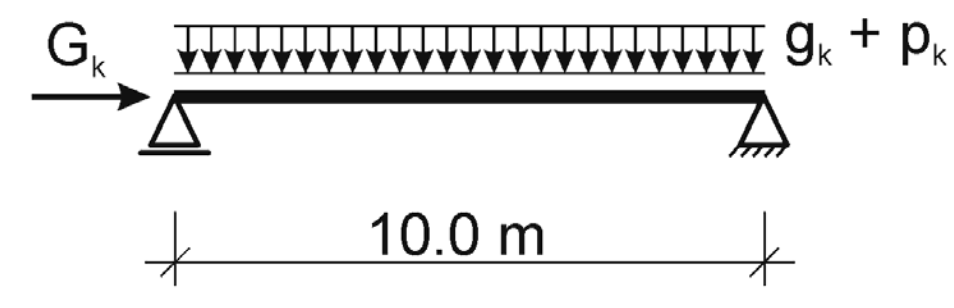
$$N_{fi,d} / N_{b,fi,t,Rd} = 0.58 < 1$$

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

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

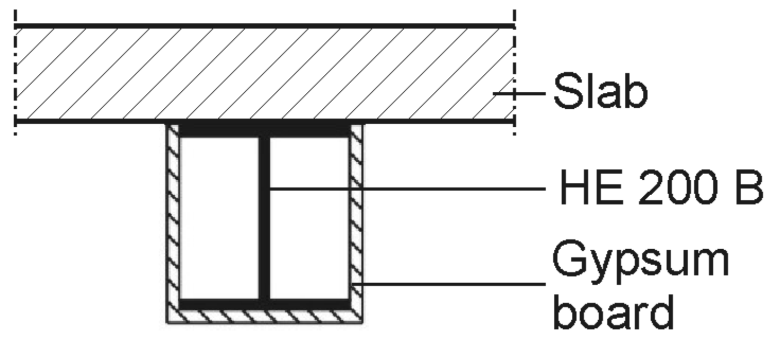
EN 1993-1-2: Section 4.2.3.5

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: $\Rightarrow \psi_{2,1} = 0.3$

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

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

Steel beam (N + M)

Maximum steel temperature

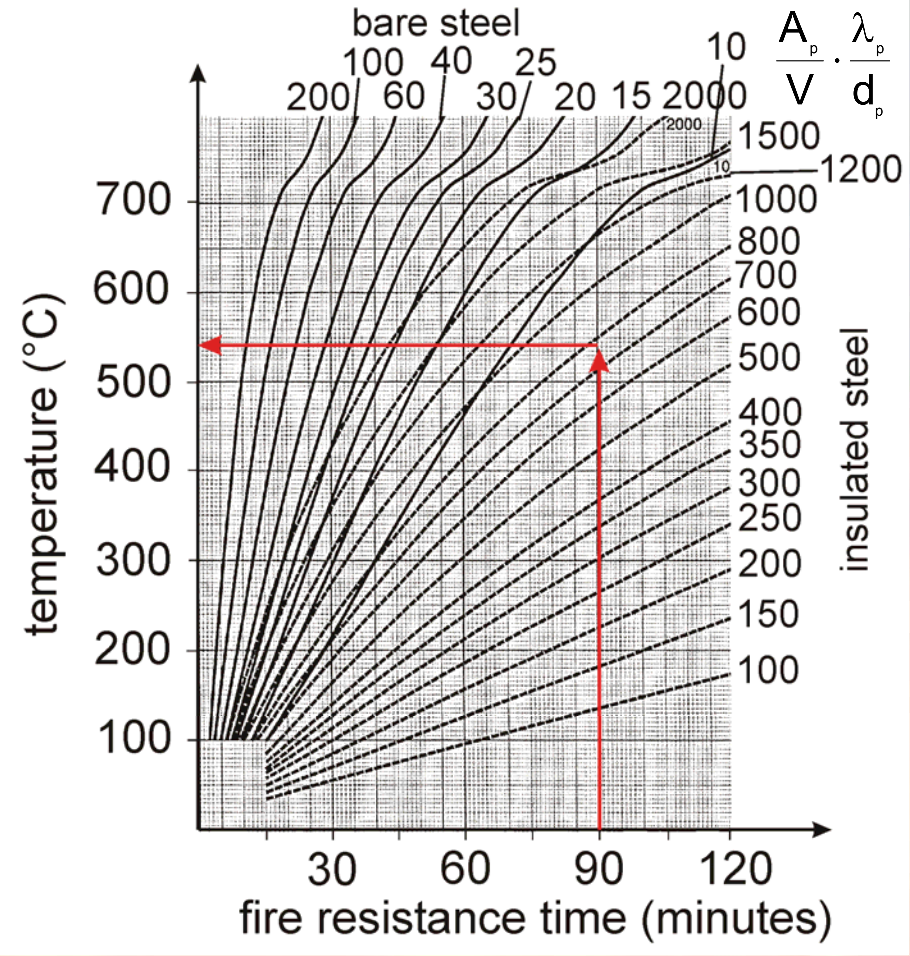
$$\frac{2 \cdot h + b}{A_a} \cdot \frac{\lambda_p}{d_p} = 770 \frac{W}{m^3 \cdot K}$$

Euro-Nomogram:

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

Reduction factors:

$\Rightarrow k_{y,\theta} = 0.656$
$k_{E,\theta} = 0.484$



Steel beam (N + M)
Reduction factors and verification

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

  Similar to example „Steel column“

- 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:

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

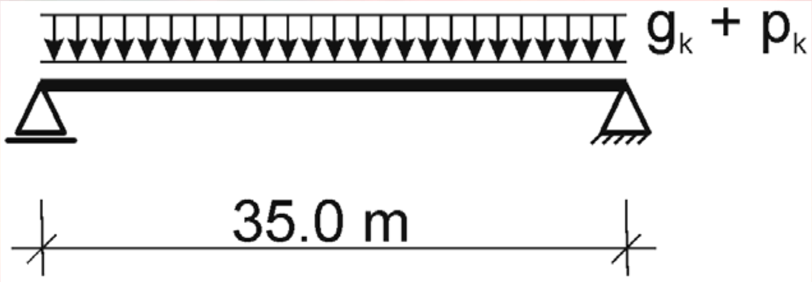
Worked examples - Overview

- 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

Steel beam (hollow section)

Task

Determination of the design bending resistance for the steel beam.



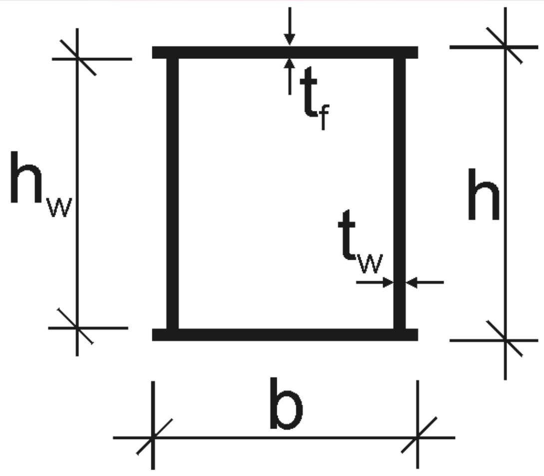
⇒ Simple calculation model:

- for members subjected with bending loads
- without stability problems

EN 1993-1-2: Section 4.2.3.3

Steel beam (hollow section)
Parameters

Building:	Hall roof structure
Fire resistance class:	R 30
Loads:	g_k = 9.32 kN/m
	p_k = 11.25 kN/m
Profile:	Welded section
	h / b = 70 cm / 45 cm
	$t_w = t_f$ = 25 mm
Fire protection:	none
Steel grade:	S 355



Steel beam (hollow section)
Mechanical actions during fire exposure

Accidental situation:

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

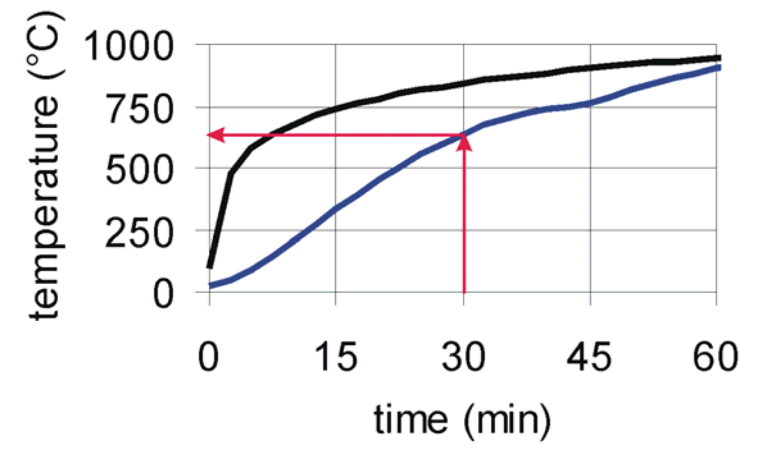
Combination factor for snow loads: $\Rightarrow \psi_{2,1} = 0.0$

$$\Rightarrow \quad M_{fi,d} = 1427.1 kNm$$

Steel beam (hollow section)
Maximum steel temperature

- Standard temperature – time curve:

$$\theta_g = 20 + 345 \cdot \log_{10}(8 \cdot t + 1)$$



- Steel temperature – time curve:

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

Section factor with equal thickness of flanges and web. $\Rightarrow$ $\frac{A_p}{V} = \frac{1}{t} = 40 \; \frac{1}{m}$

Steel beam (hollow section)
Verification

- Verification in the temperature domain:

$$\mu_0 = E_{fi,d} / R_{fi,d,0} = 0.31$$

$$\Rightarrow \theta_{a,cr} = 659\ °C$$

$$\frac{\theta_{a,max,30}}{\theta_{a,cr}} = 0.98 < 1$$

- Verification in the strength domain:

$$M_{fi,t,Rd} = M_{pl,Rd,20°C} \cdot k_{y,\theta} \cdot \frac{\gamma_{M,1}}{\gamma_{M,fi}} \cdot \frac{1}{\kappa_1 \cdot \kappa_2} = 1645.4\ kNm$$

where

$k_{y,\theta} = 0.360$

$\kappa_1 = 1.0$

$\kappa_2 = 1.0$

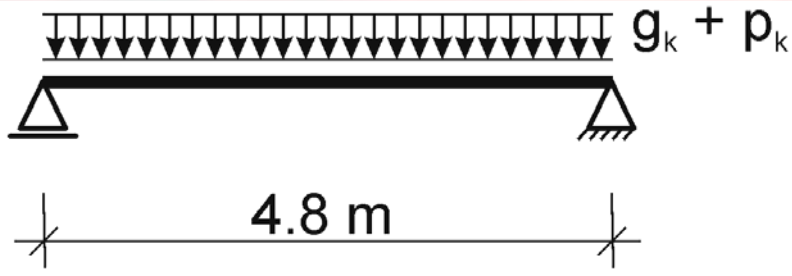
$$\frac{M_{fi,d}}{M_{fi,t,Rd}} = 0.87 < 1$$

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

Composite slab
Task

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

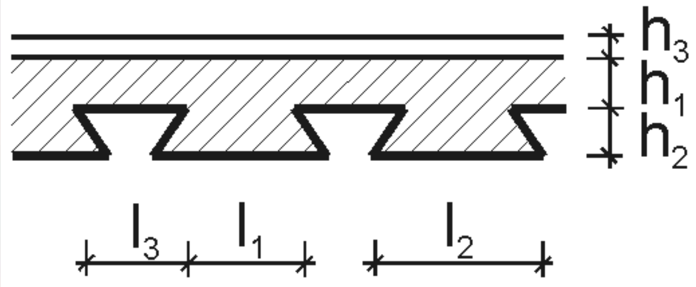


$\Rightarrow$ Simple calculation model for composite slabs exposed to fire

EN 1994-1-2: Annex D

Composite slab
Parameters

Building:	Shopping centre
Fire resistance class:	R 90
Loads:	g_k = 4.62 kN/m²
	p_k = 5.0 kN/m²
Heigth of slab:	h = 14.0 cm
Strength class:	C 25/30
Steel sheet:	Re-entrant
	h_2 = 5.1 cm
Yield stress:	f_y = 350 N/mm²

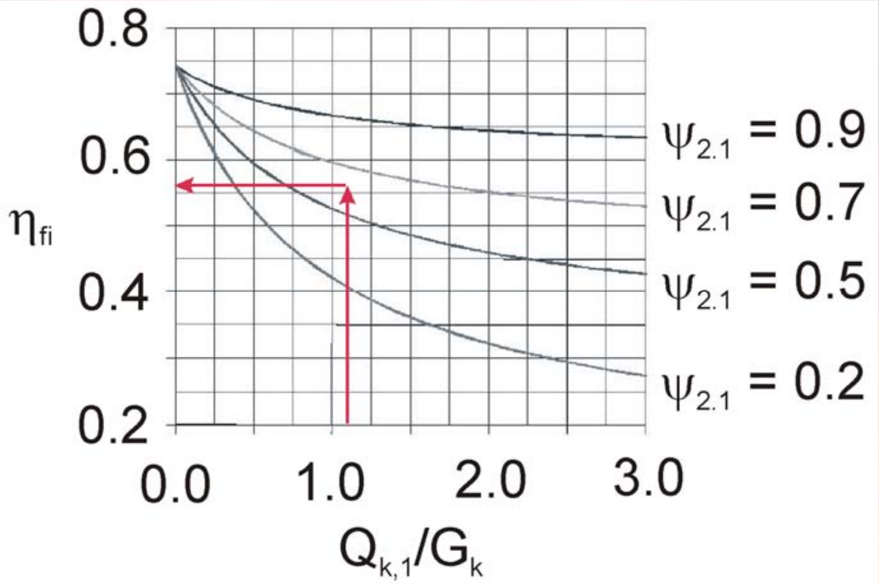


Composite slab
Mechanical actions during fire exposure

Accidental situation:

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

$$\frac{Q_{k,1}}{G_k} = \frac{q_{k,1}}{g_k} = 1.1$$

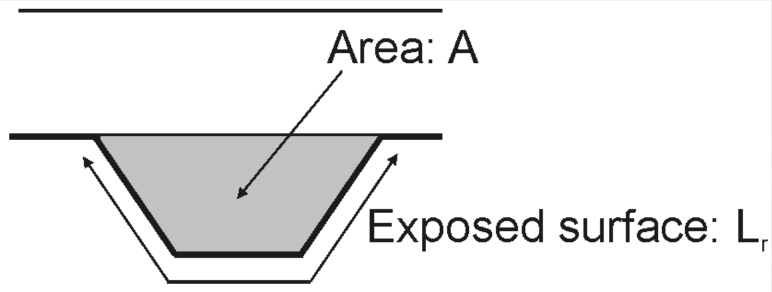


Bending moment
in fire situation:

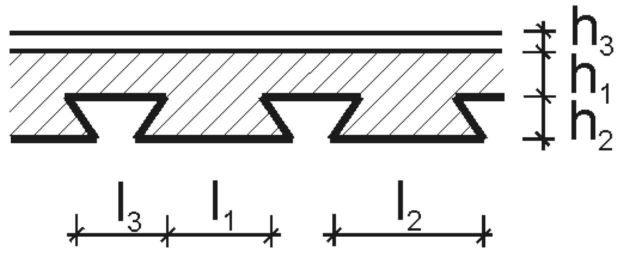
$$M_{fi,d} = \eta_{fi} \cdot M_{sd} = 21.76 \text{ kNm/m}$$

Composite slab
Rib geometry factor

Rib geometry factor considers positive effects of mass and height of the rib.



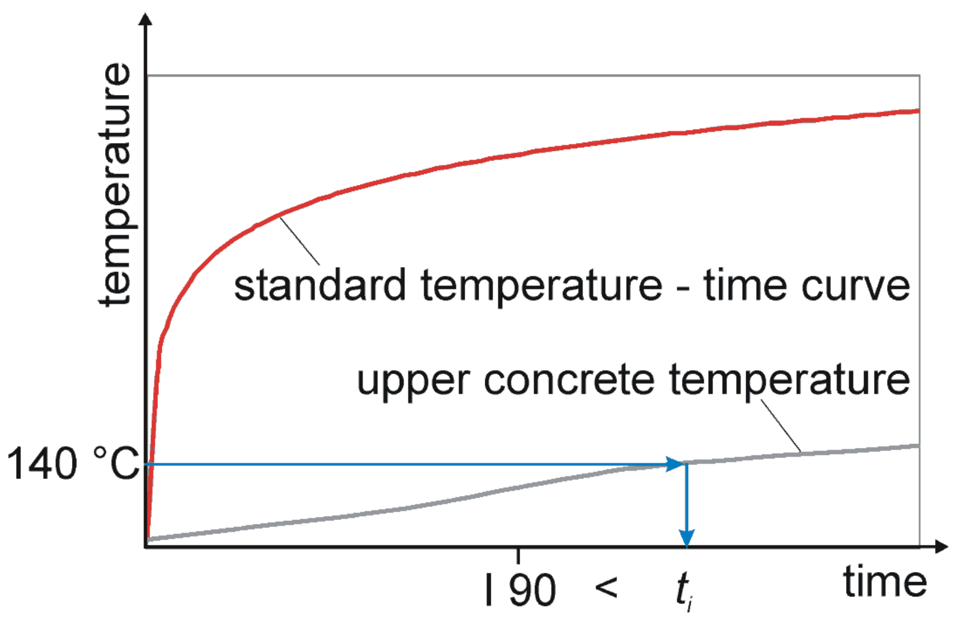
$$\frac{A}{L_r} = \frac{h_2 \cdot \left(\frac{l_1 + l_2}{2}\right)}{l_2 + 2 \cdot \sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}} = 27\ \text{mm}$$



Composite slab
Thermal insulation

The temperature on top of the slab should not exceed 140 °C in average and 180 °C at its maximum.

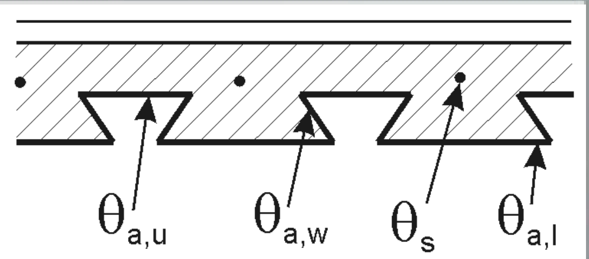
$$t_i = 131.48 \text{ min} > 90 \text{ min}$$



Composite slab

Maximum steel temperatures and verification

- Calculation of the steel temperatures:



Steel sheet

$$\theta_{a,i} = b_{0,i} + b_{1,i} \cdot \frac{1}{l_3} + b_{2,i} \cdot \frac{A}{L_r} + b_{3,i} \cdot \Phi + b_{4,i} \cdot \Phi^2$$

Reinforcement bars

$$\theta_s = c_0 + c_1 \cdot \frac{u_3}{h_2} + c_2 \cdot z + c_3 \cdot \frac{A}{L_r} + c_4 \cdot \alpha + c_5 \cdot \frac{1}{l_3}$$

- Verification:

$$M_{fi,t,Rd} = \sum A_i \cdot z_i \cdot k_{y,\theta,i} \cdot \left(\frac{f_{y,i}}{\gamma_{M,fi}} \right) + \alpha_{slab} \cdot \sum A_j \cdot z_j \cdot k_{c,\theta,j} \cdot \left(\frac{f_{c,j}}{\gamma_{M,fi,c}} \right)$$

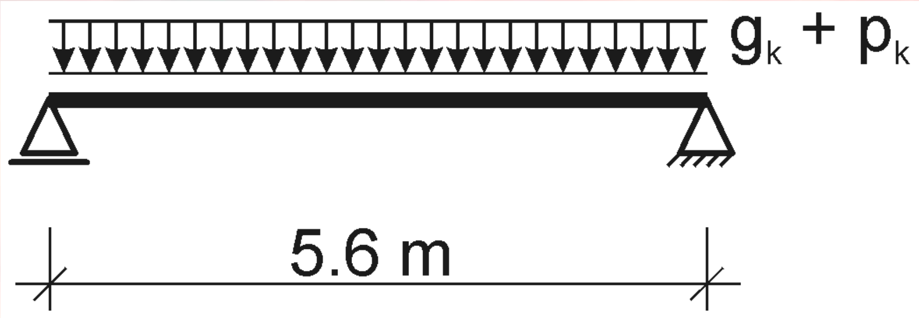
$$= 25.00 \text{ kNm/m} > 21.76 \text{ kNm/m}$$

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

Composite beam (steel beam)
Task

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



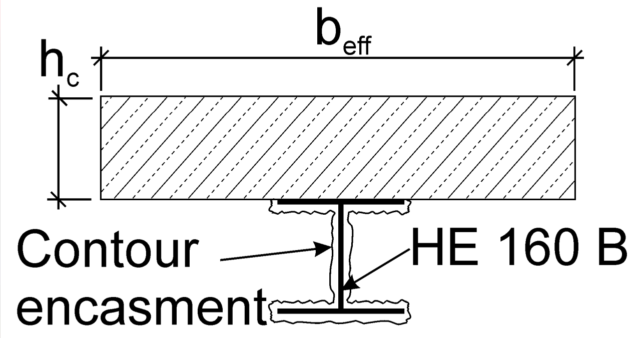
⇒ Simple calculation model for composite beams exposed to fire

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: $\Rightarrow \psi_{2,1} = 0.3$

$$\Rightarrow \quad M_{fi,d} = 127.4 \text{ kNm}$$

Composite beam (steel beam)
Maximum steel temperature

Upper flange:

$\theta_{a,max,u} \approx 390\ °C$

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

Web:

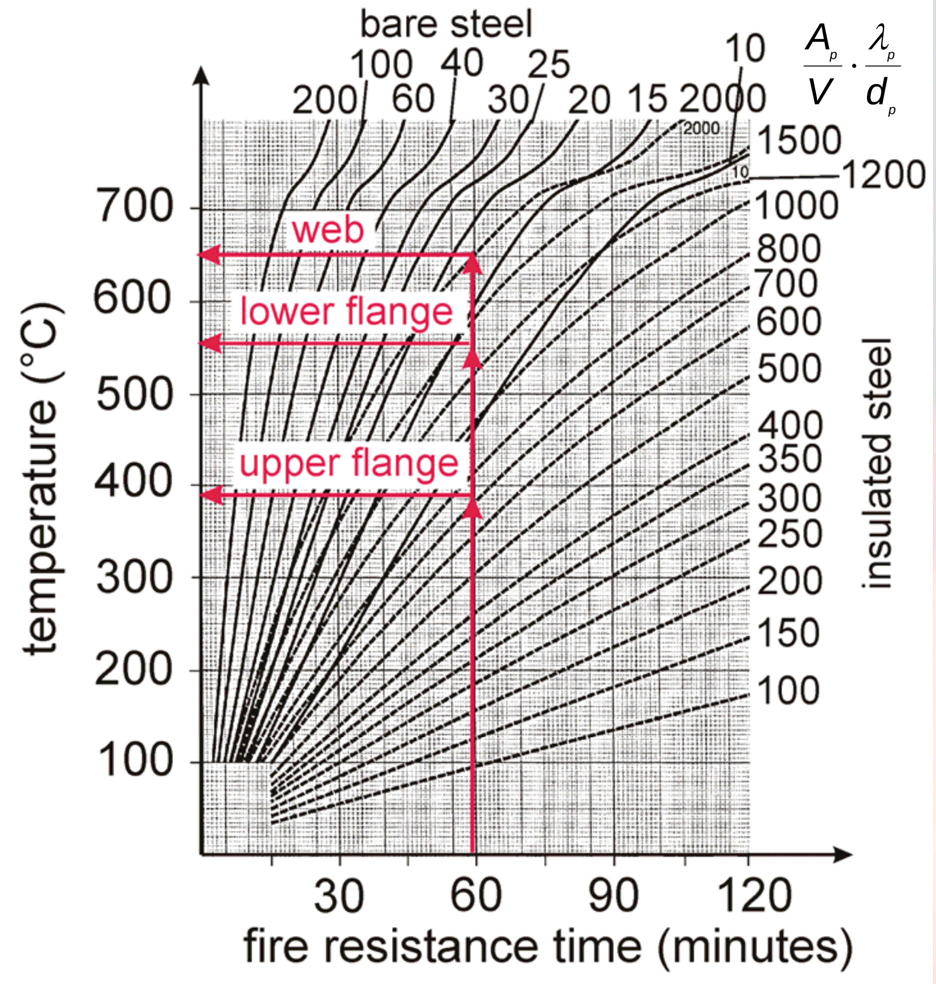
$\theta_{a,max,w} \approx 650\ °C$

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

Lower flange:

$\theta_{a,max,l} \approx 550\ °C$

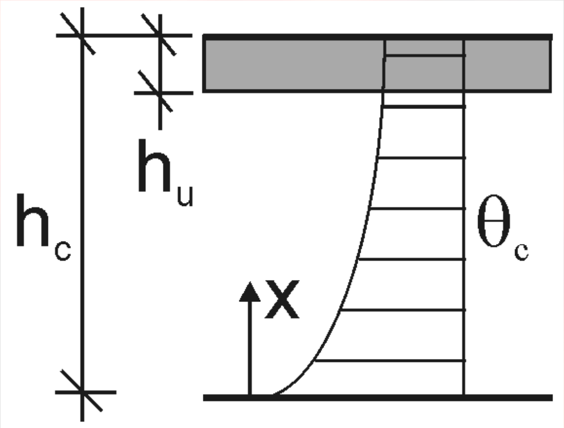
$\Rightarrow k_{y,\theta} = 0.625$



Composite beam (steel beam)
Temperatures of the concrete compression zone

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

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



⇒ Concrete compression strength is not reduced.

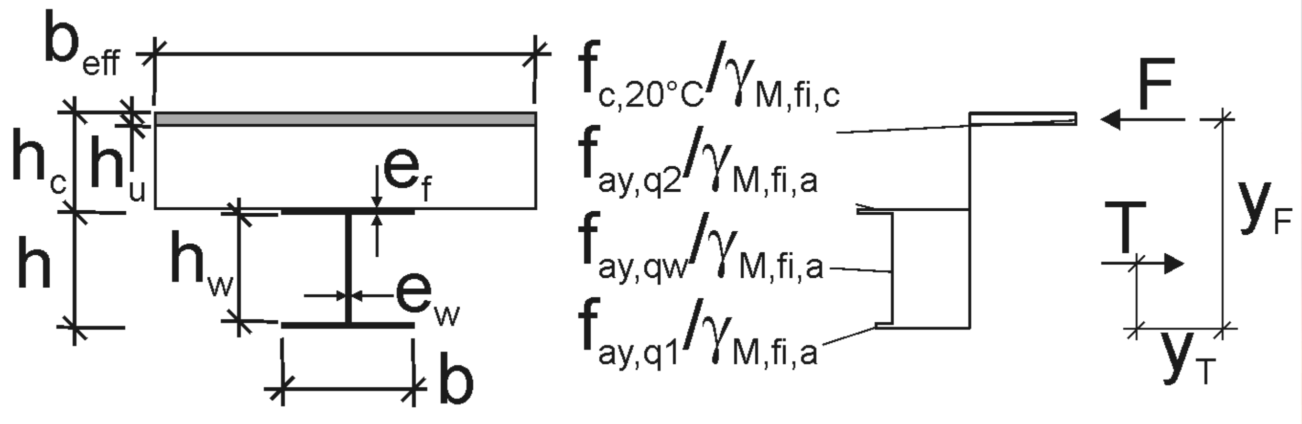
where

x: Concrete zone with temperatures θ_c > 250 °C
h_u: Height of the compression zone

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:

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

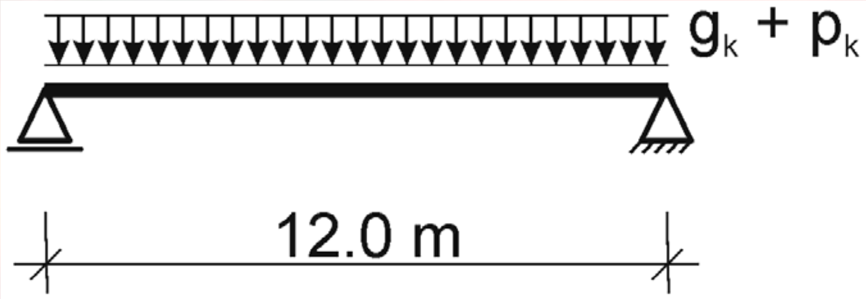
Worked examples - Overview

- 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

Composite beam (partially encased beam)

Task

Determination of the design sagging moment resistance for the composite beam



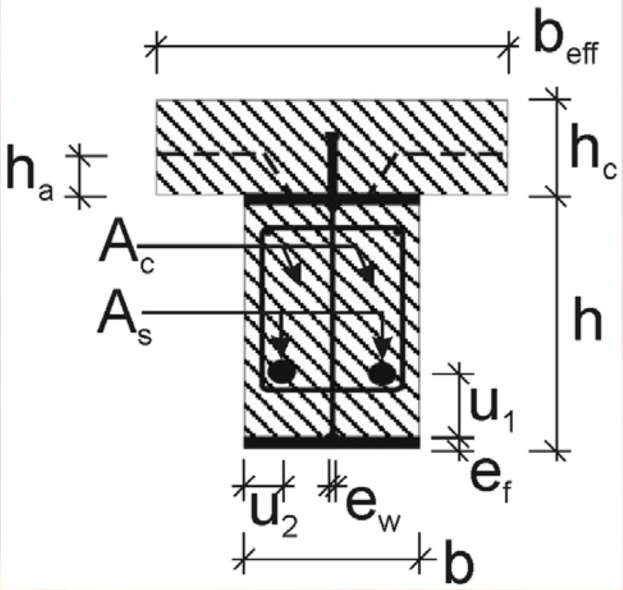
⇒ Simple calculation model for composite beams comprising steel beam with partial concrete encasement exposed to fire.

EN 1994-1-2: Annex F

Composite beam (partially encased beam)

Parameters

Building:	Storehouse
Fire resistance class:	R 90
Loads:	g_k = 21.0 kN/m
	p_k = 30.0 kN/m
Height of slab:	h_c = 16 cm
Strength category:	C 25/30
Width of encasement:	b_c = b = 20 cm
Strength class:	C 25/30
Profile:	Rolled section
	IPE 500
Steel grade:	S 355



Composite beam (partially encased beam)
Mechanical actions during fire exposure

Accidental situation:

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

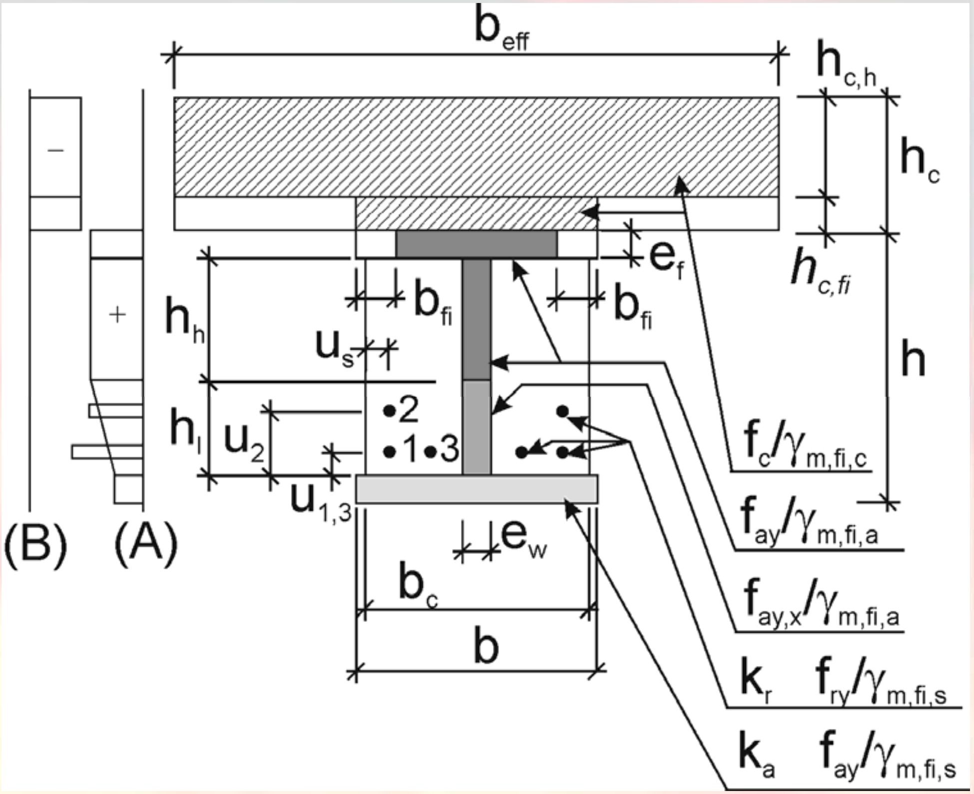
Combination factor for storage areas: $\Rightarrow \psi_{2,1} = 0.8$

$$\Rightarrow \quad M_{fi,d} = 810.0 \text{ kNm}$$

Composite beam (partially encased beam)

Reduction of the cross-section in the fire situation

- Concrete slab
  - Height reduction
- Upper flange
  - Width reduction
- Web
  - Determination of height without strength reduction
- Lower flange
  - Strength reduction
- Reinforcements
  - Strength reduction



Composite beam (partially encased beam)
Design sagging moment resistance and verification

- Design sagging moment resistance:

$$M_{fi,Rd} = \sum T_i \cdot z_i = 942.7 \text{ kNm}$$

where
T_i: tension force of part of the cross-section
z_i: distance from compression force to the tension force

- Verification:

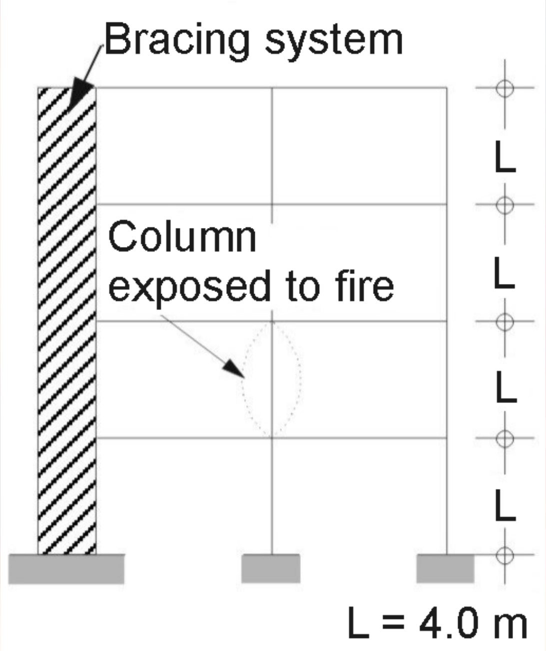
$$\frac{M_{fi,d}}{M_{fi,Rd}} = 0.86 < 1$$

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**

Composite column
Task

Determination of the design axial compression resistance for the composite column.



$\Rightarrow$ Simple calculation model

for composite columns exposed

to fire and tabulated data method

EN 1994-1-2: Annex G

EN 1994-1-2: Section 4.2.3.3

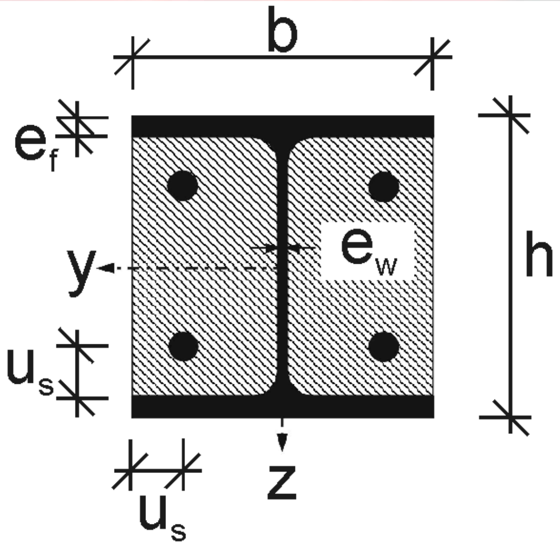
Composite column
Parameters

Building: Office building
Fire resistance class: R 60

Loads: G_k = 960.0 kN
P_k = 612.5 kN

Concrete strength class: C 25/30

Profile: Rolled section HE 300 B
Steel grade: S 235



Composite column
Mechanical actions during fire exposure

Accidental situation:

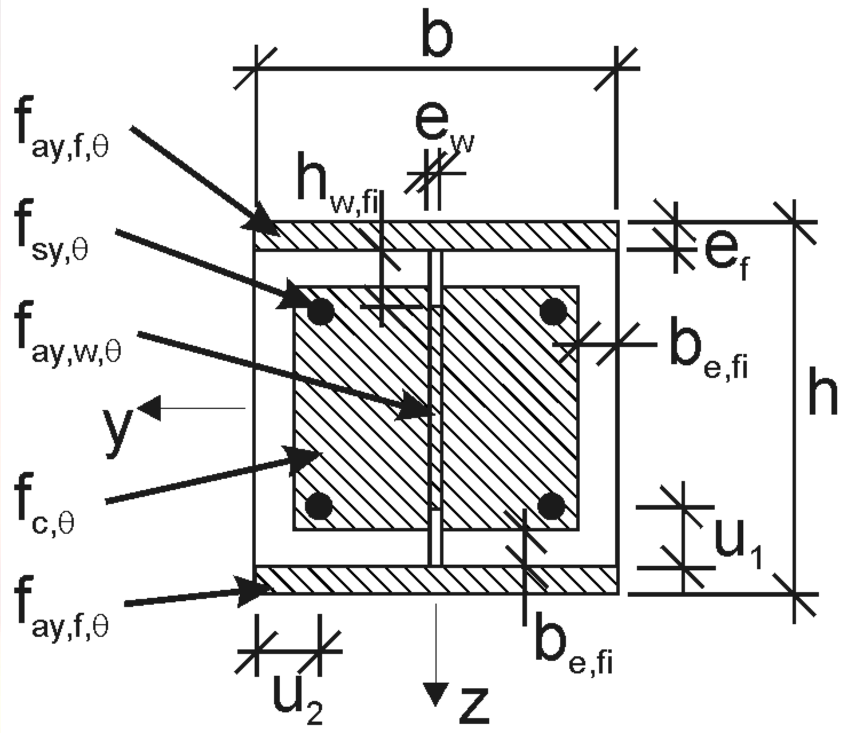
$$E_{dA} = E \cdot \left(\sum G_k + A_d + \sum \psi_{2,i} \cdot Q_{k,i} \right)$$

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

$$\Rightarrow \quad N_{fi,d} = 1143.8\,\text{kN}$$

Composite column
Reduction of the cross-section in fire situation

- Flanges
  - Strength reduction
  - Stiffness reduction
- Web
  - Heigth reduction
  - Strength reduction
  - Stiffness reduction
- Reinforcements
  - Strength reduction
  - Stiffness reduction
- Concrete
  - Thickness reduction
  - Strength reduction
  - Stiffness reduction



Composite column

Design axial resistance and verification

- Calculation of the axial design resistance:

$$N_{fi,pl,Rd} = \sum N_{fi,pl,Rd,i} = 2659.8\,\text{kN}$$

where

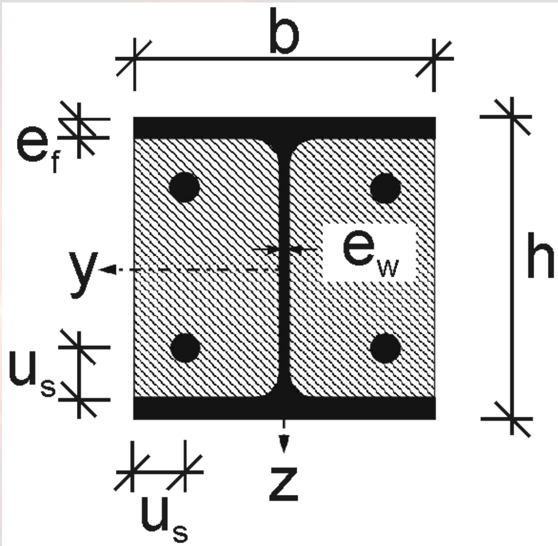
$N_{fi,pl,Rd,i}$ plastic design resistances of the several parts

- Flexural buckling:

$$\frac{N_{fi,d}}{\chi_{z,fi} \cdot N_{fi,pl,Rd}} = 0.50 \leq 1$$

$\chi_{z,fi}$ is determined similar to example „Steel column“

Composite column
Tabulated data method



Existing parameters:

$$b = h = 300 \text{ mm}$$

$$e_w / e_f = 0.58$$

$$u_s = 50 \text{ mm}$$

$$\eta_{fi,t} = 0.28$$

$$\frac{A_s}{A_c + A_s} = 3\%$$

		R30	R60
	Minimum ratio of web to flange thickness e_w/e_f	*0,5*	*0,5*
1	Minimum cross-sectional dimensions for load level $\eta_{fi,t} \leq$ **0,28**		
1.1	minimum dimensions h and b [mm]	*160*	*200*
1.2	minimum axis distance of reinforcing bars u_S [mm]	-	*50*
1.3	minimum ratio of reinforcement $A_s/(A_c+A_s)$ in %	-	*4*