Fire resistance assessment of steel structures

Basic design methods
Worked examples

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Basic design methods of EN1993-1-2

Fire part of Eurocode 3

Fire parts of Eurocodes 2 to 6 and 9

Following common layout to provide design rules for fire resistance of various types of structures:

→General

- Scope, application field, definitions, symbols and units

→Basic principles

- Performances requirements, design values of material properties and assessment approaches

→Material properties

- Mechanical and thermal properties at elevated temperatures

→Assessment methods for fire resistance

→Constructional details

→Annexes

- Additional information: common case - more detailed design rules

Fire resistance – European classes

Fire resistance is defined in terms of time as follows:

- Relevant time of fire exposure during which the corresponding fire resistance function of a structure is maintained despite fire actions

According to European standard, 3 criteria to define the fire resistance:

R – load bearing function

E – integrity separating function

I – thermal insulating separation function

Above criteria may be required individually or in combination:

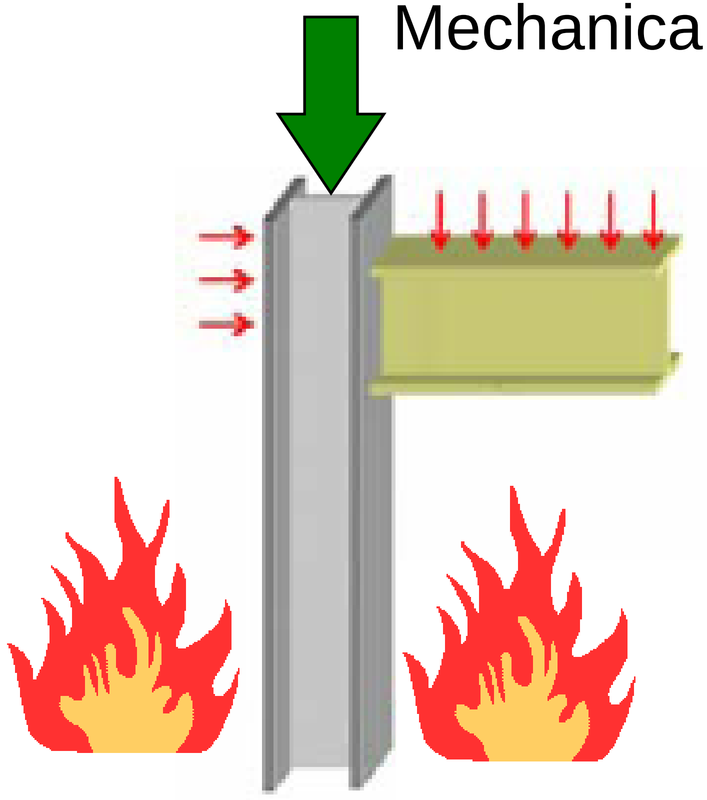
- separating only: integrity (criterion **E**) and, when requested, insulation (criterion **I**)
- load bearing only: mechanical resistance (criterion **R**)
- separating and load bearing: criteria **R**, **E** and, when requested **I**

Fire resistance – European classes

R – load bearing function

Capacity of a structure to maintain its required mechanical resistance in case of fire

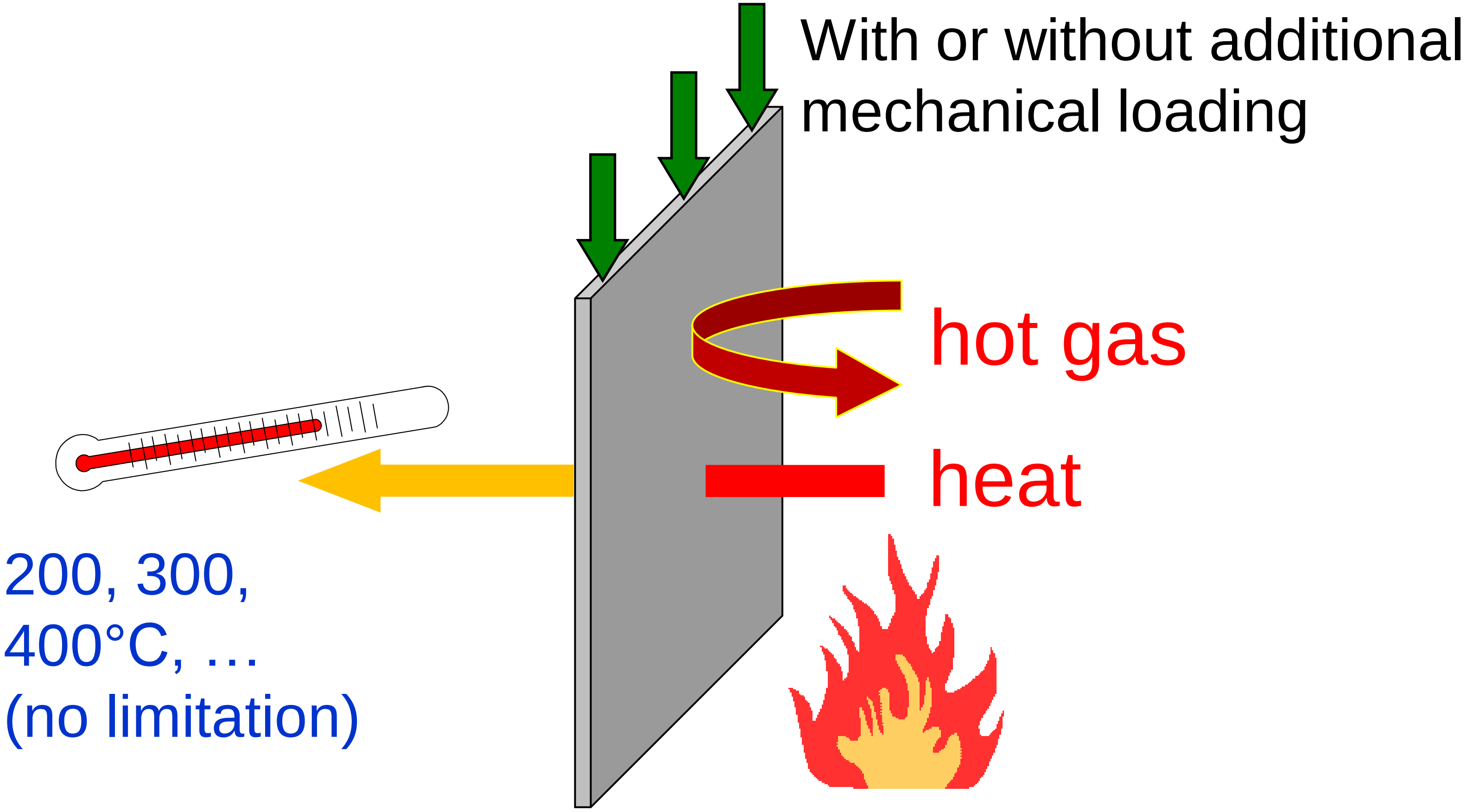
Mechanical loading



Fire resistance – European classes

E – integrity separating function

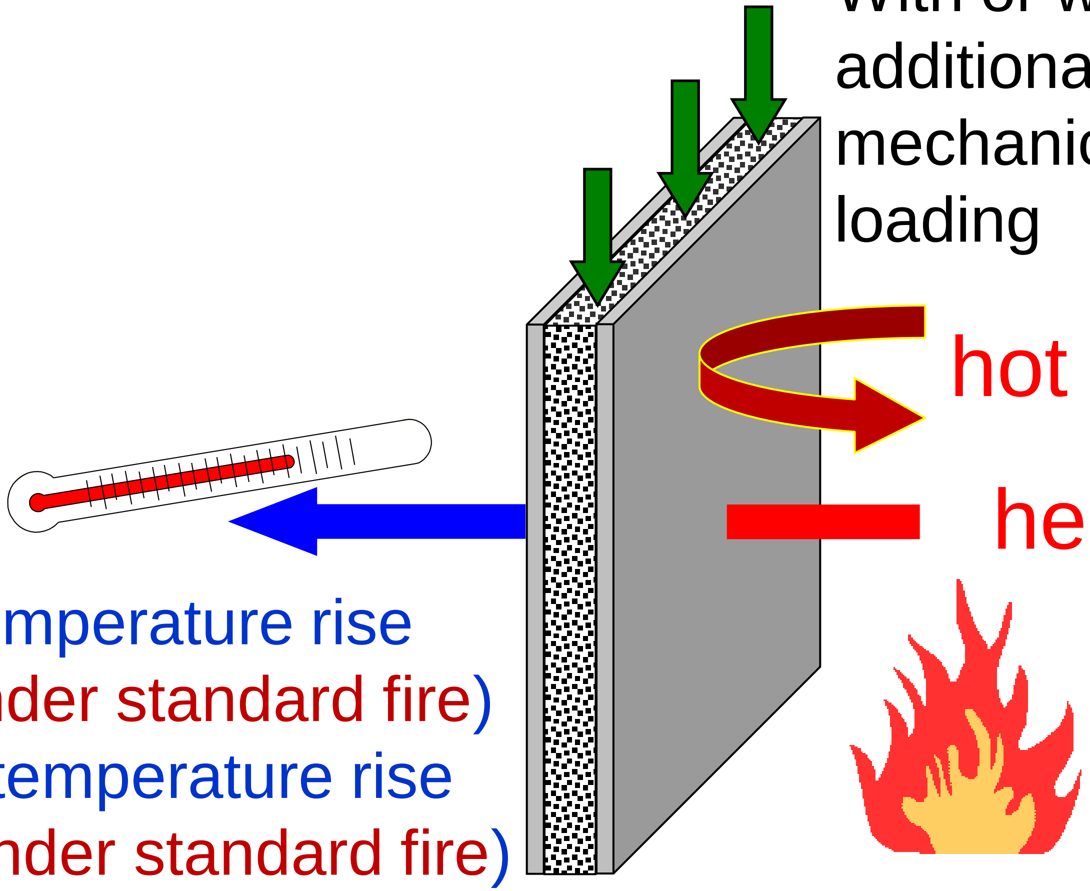
Capacity of a structure to maintain its required integrity separating function to hot gases in case of fire



Fire resistance – European classes

I – thermal insulation separating function

Capacity of a structure to maintain its required thermal insulation separating function in case of fire



Average temperature rise ≤140 K (under standard fire)

Maximum temperature rise ≤ 180 K (under standard fire)

Scope of fire part of Eurocode 3

Only load bearing function **R** of steel structures is covered by the design rules of the fire part of Eurocode 3

Load bearing function of a structure is satisfied only if during the relevant duration of fire exposure **t**

$$E_{fi,d,t} \leq R_{fi,d,t}$$

where

$E_{fi,d,t}$: design effect of actions (Eurocodes 0 and 1)

$R_{fi,d,t}$: corresponding design resistance of the structure at instant **t**

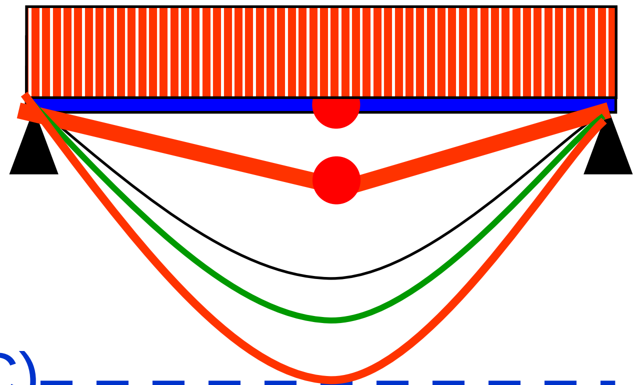
Scope of fire part of Eurocode 3

Covered field

- Carbon structural steel:
  - ✓ all types of structural members
  - ✓ grades in S235, S275, S355, S420 & S460
- Cold-formed carbon structural steel:
  - ✓ members in accordance with EN 1993-1-3
- Stainless structural steel:
  - ✓ 5 commonly used grades for building sector
  - ✓ no specific simple design rules
- Both internal and external steel structures

Load bearing function **R** in fire and ambiant temperature design

Constant room temperature (20 °C)

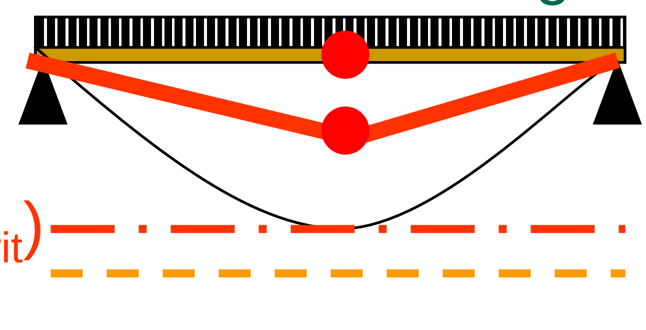


Load increase

Cold design

Fire design

Constant loading



Temperature increase until the collapse at instant **t**

Eurocodes allow fire resistance to be established in any of 3 "domains":

Time:	$t_{fi.d} \geq t_{fi.requ}$
Load resistance:	$R_{fi.d.t} \geq E_{fi.d.t}$
Temperature:	$\theta_{cr.d} \geq \theta_d$

- **Usually only <u>directly</u> feasible using advanced calculation models.**
- **Feasible by hand calculation. Find reduced resistance at required resistance time.**
- **Most usual simple EC3 method. Find critical temperature for loading, compare with design temperature.**

$t_{fi.d}$: design fire resistance time

$t_{fi.requ}$: required fire resistance time

Actions on structures exposed to fire

- Thermal actions
- Mechanical actions
- Load level in fire situation

} **Eurocodes 0 and 1**

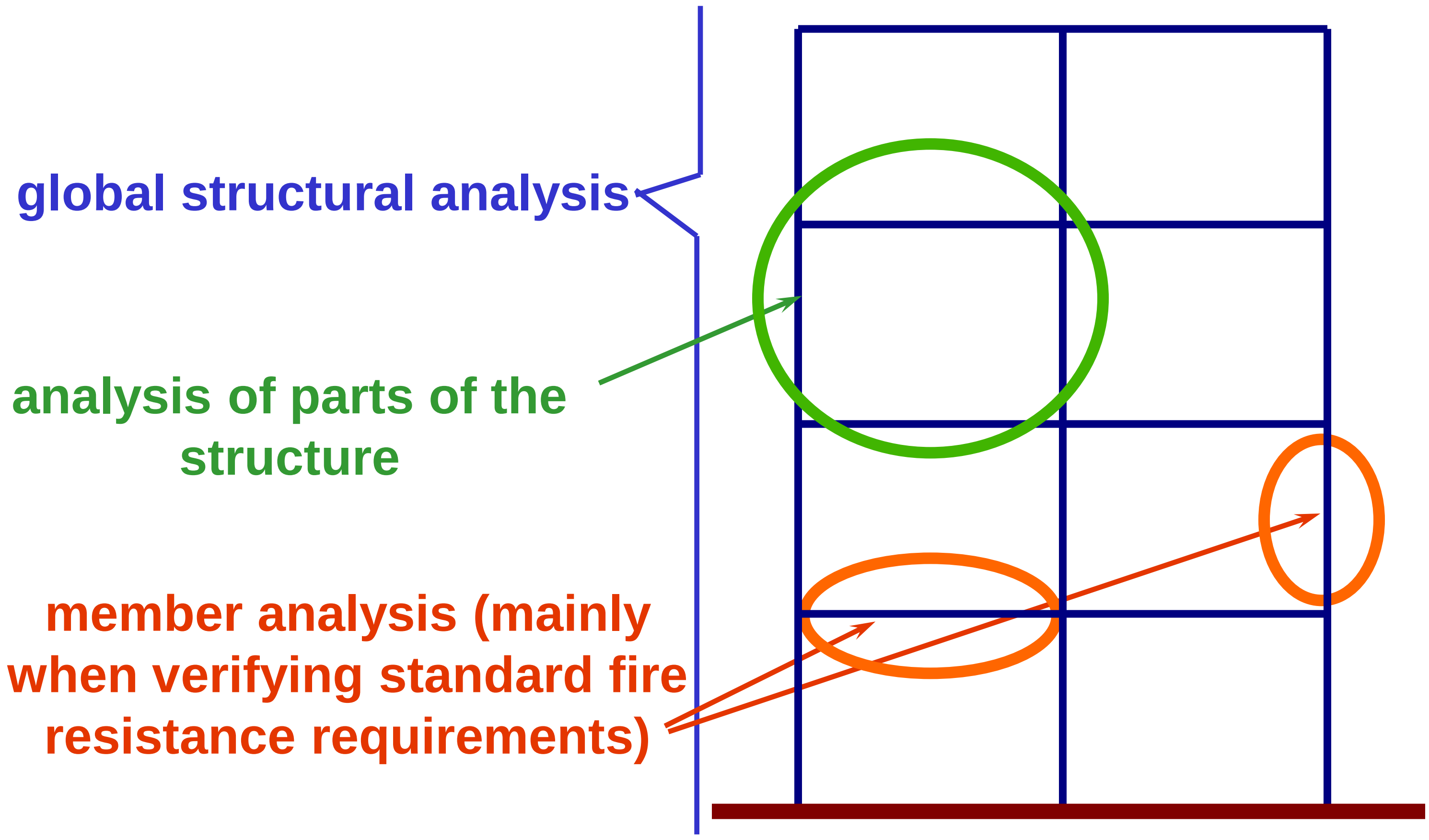
Design approaches

- Member analysis
- Analysis of parts of the structure
- Global structural analysis

Material properties at elevated temperatures

- Thermal properties of steel
- Mechanical properties of steel → Reduction factors for both strength and stiffness of steel
- Partial factors for fire design of steel structures

Different design approaches for mechanical response of structure in fire



Two types of design methods for assessing mechanical response of steel structures in fire

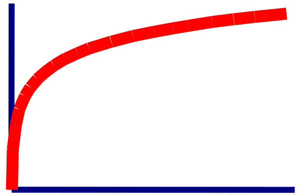
- **Simple calculation models**
  - **critical temperature**
  - **mechanical model of steel structural members**

→ **Ordinary structural fire design**

- **Advanced calculation models**
  - **all types of steel structures**
  - **numerical models based on:**
    - **finite element method**
    - **finite difference method**

→ **Advanced and specific structural fire design**

Application domain of different design methods for steel structures under fire situation

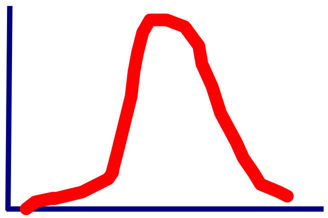


- **Thermal action defined under standard fire**

Type of analysis	Simple calculation methods	Critical temperature	Advanced calculation models
Member analysis	Yes	Yes	Yes
Analysis of parts of the structure	Not applicable	Not applicable	Yes
Global structural analysis	Not applicable	Not applicable	Yes

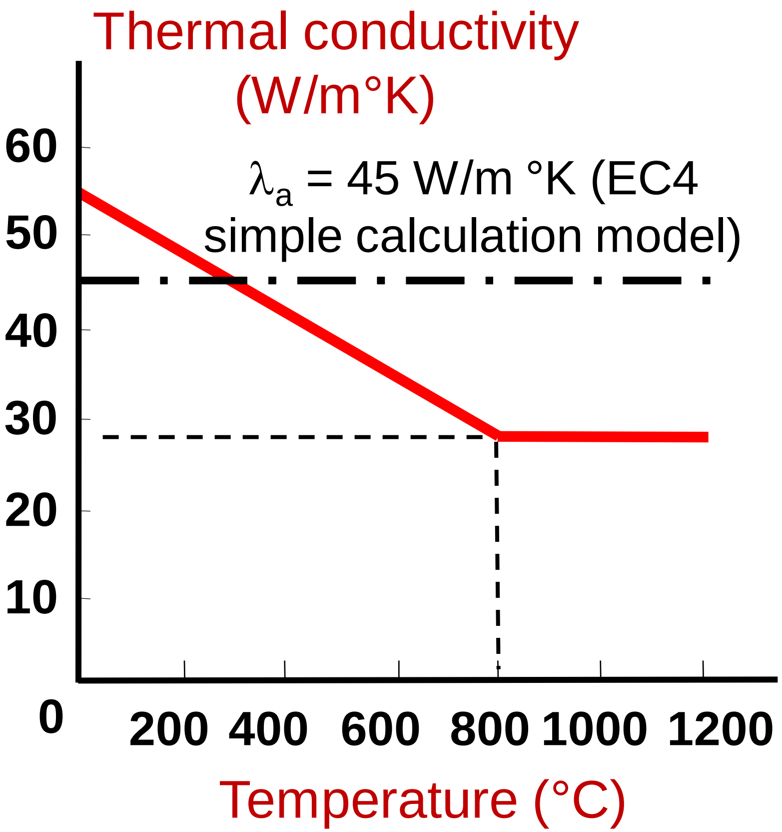
Application domain of different design methods for steel structures under fire situation

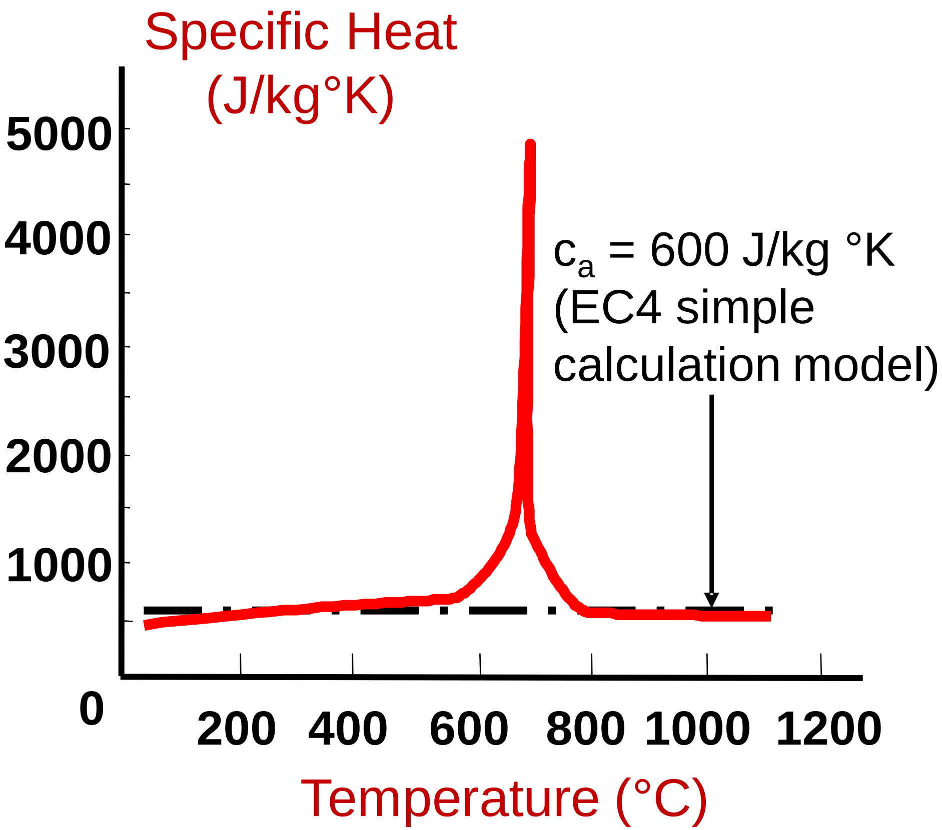
- **Thermal action defined under natural fire**



Type of analysis	Simple calculation methods	Critical temperature	Advanced calculation models
Member analysis	Yes (if available)	Yes (if available)	Yes
Analysis of parts of the structure	Not applicable	Not applicable	Yes
Global structural analysis	Not applicable	Not applicable	Yes

Thermal properties of steel at elevated temperatures

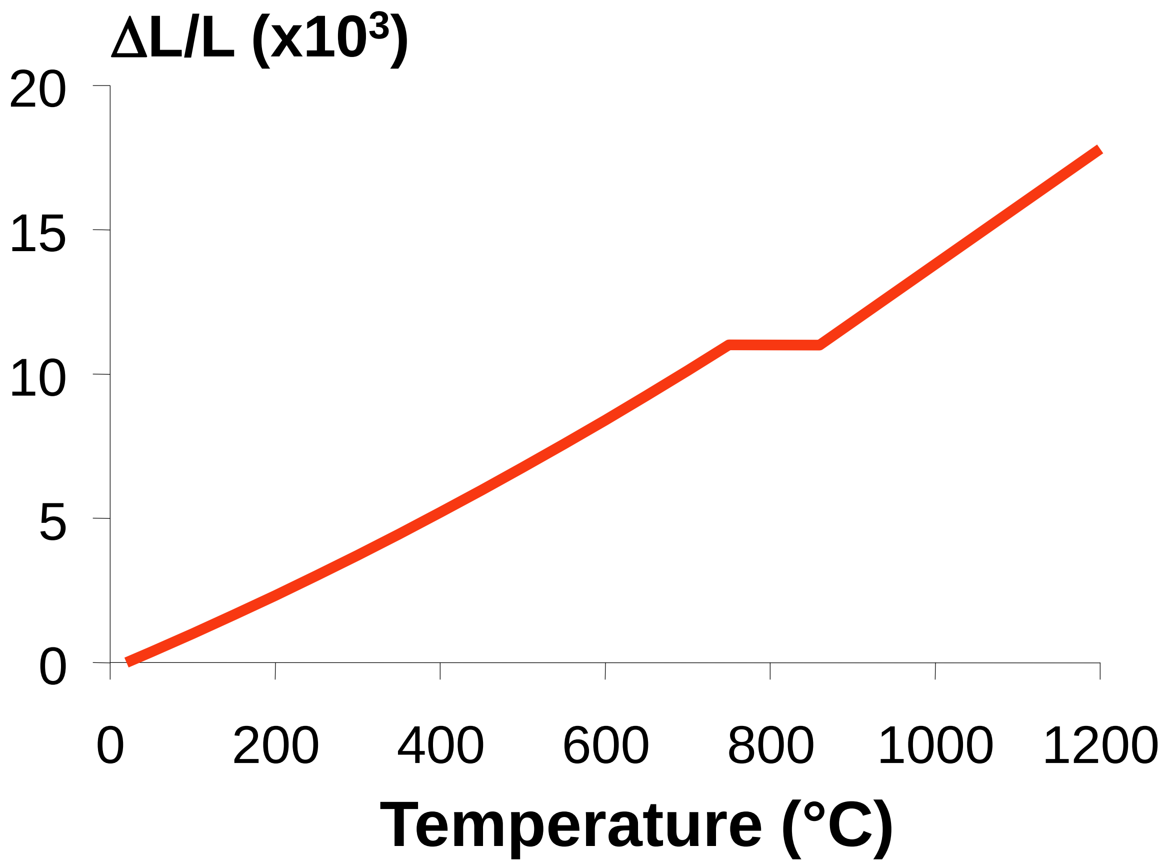




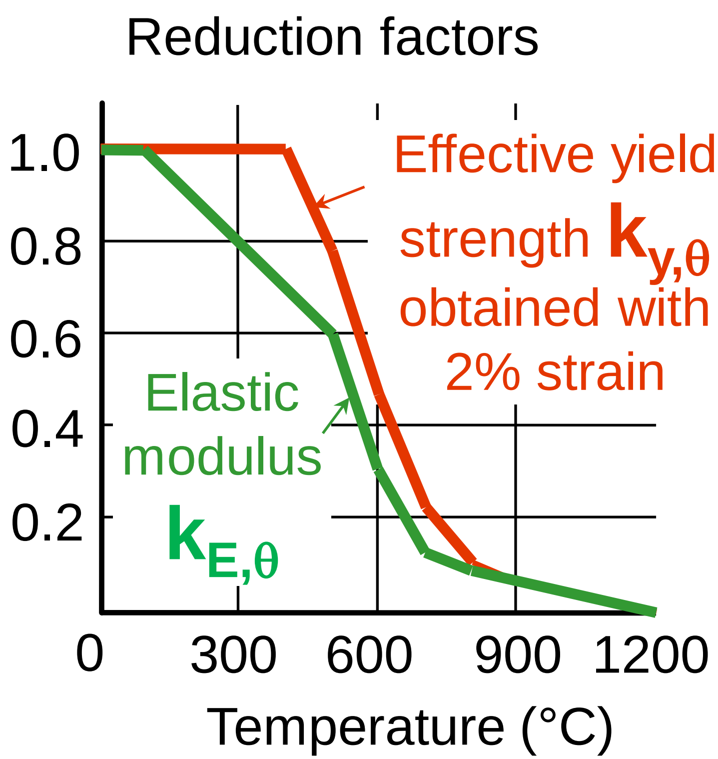
Density of steel: 7850 kg/m^3

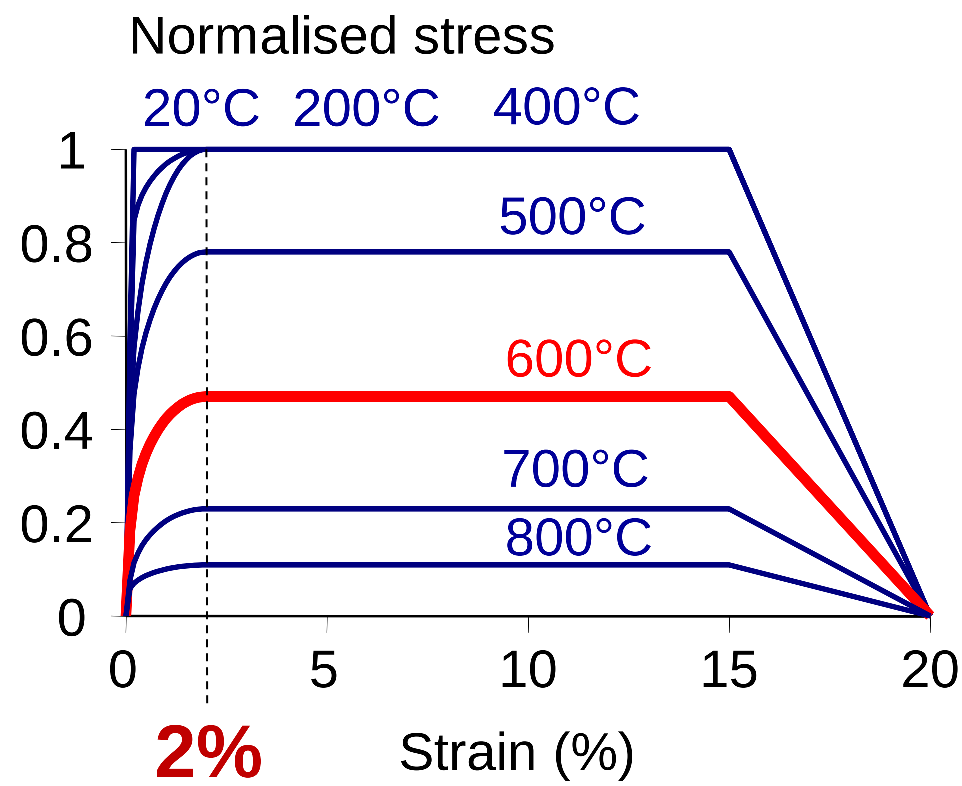
Thermal properties of steel at elevated temperatures

Thermal expansion of steel



Mechanical properties of steel at elevated temperatures





- **Elastic modulus at 600°C reduced by about 70%**
- **Yield strength at 600°C reduced by over 50%**

Partial factors of steel at elevated temperatures

Type of members	Ambient temperature design	Fire design
Cross-sections	$\gamma_{M0} = 1.0$	$\gamma_{M,fi} = 1.0$
Members with instability	$\gamma_{M1} = 1.0$	$\gamma_{M,fi} = 1.0$
Tension members to fracture	$\gamma_{M2} = 1.25$	$\gamma_{M,fi} = 1.0$
Joints	$\gamma_{M2} = 1.25$	$\gamma_{M,fi} = 1.0$

FIRE RESISTANCE

Action in fire situation $E_{fi.d.t}$

STEEL TEMPERATURE

Building regulations

$t_{fi.requ}$

Design load in fire situation

Either ….. $E_{fi,d,t} = \sum_{j \geq 1} G_{k,j} + \Psi_{2,1} Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i} Q_{k,i}$

Recommended, for practical application refer to each National Annex

Reduction factor

Or more usefully….. $E_{fi.d.t} = \eta_{fi} E_d$ **relative to ambient-temperature design load**

On the other hand, load level $\eta_{fi,t} = \dfrac{E_{fi,d,t}}{R_d}$ **relative to ambient-temperature design resistance**

Reduction factor for design load in fire situation

$$\eta_{fi} = \frac{\gamma_{GA} G_k + \psi_{2.1} Q_{k.1}}{\gamma_G G_k + \gamma_{Q.1} Q_{k.1}}$$

Ambient temperature strength design

γ_G **= 1.35** Permanent loads;

$\gamma_{Q.1}$ **= 1.50** Combination factor; variable loads

In structural fire design

γ_{GA} **= 1.0** Permanent loads; accidental design situations

$\psi_{2.1}$ **= 0.3** Combination factor; variable loads, offices

$Q_{k,1}/G_k$	1	2	3	4
η_{fi}	0.53	0.46	0.43	0.41

Establishing fire resistance of steel structures using simple process

FIRE RESISTANCE

Action in fire situation $E_{fi.d.t}$

↓

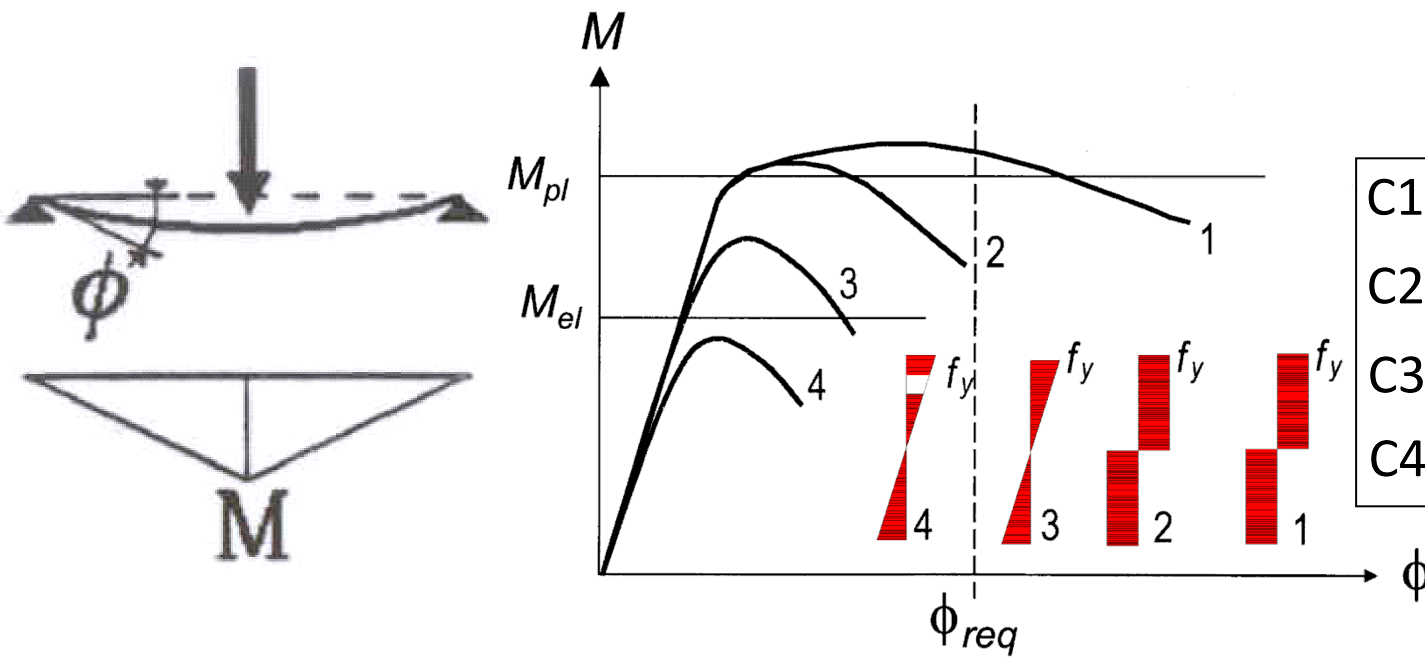
Classify member

STEEL TEMPERATURE

Building regulations

$t_{fi.requ}$

Classification of steel members in fire



$C1: M = M_{pl} \quad \phi > \phi_{req}$

$C2: M = M_{pl} \quad \phi < \phi_{req}$

$C3: M = M_{el}$

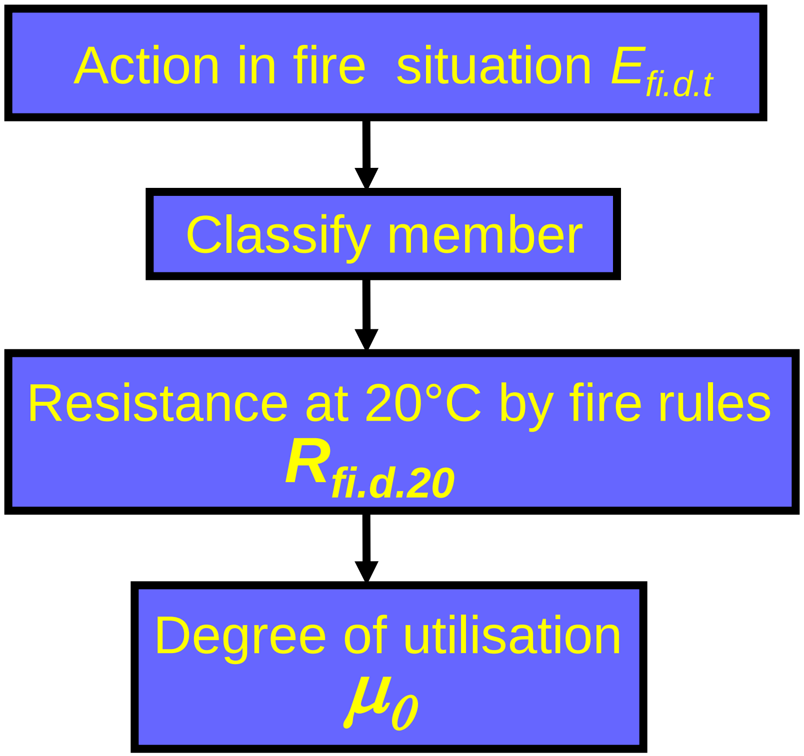
$C4: M = M_{eff,\,el}$

- classified as at ambient temperature
- however, different value of ε to take account of temperature influence

Temperature induced

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

FIRE RESISTANCE



STEEL TEMPERATURE

Building regulations $t_{fi.requ}$

The "Degree of Utilisation"

…is the **design loading** of a member in fire,

as a proportion of its **design resistance** at ambient temperature (t = 0) but including material partial factors for fire design.

$$\mu_0 = \frac{E_{fi.d}}{R_{fi.d.0}}$$

A simple version of Degree of Utilisation:

$$\mu_0 = \eta_{fi,t}\left(\frac{\gamma_{M,fi}}{\gamma_{M0}}\right)$$

- **can be used when no risk of overall or lateral-torsional buckling …**
- **conservative if $\eta_{fi,t}$ calculated as proportion of design loading at ambient temperature.**

FIRE RESISTANCE

Action in fire situation $E_{fi.d.t}$

↓

Classify member

↓

Resistance at 20°C by fire rules $R_{fi.d.20}$

↓

Degree of utilisation μ_0

↓

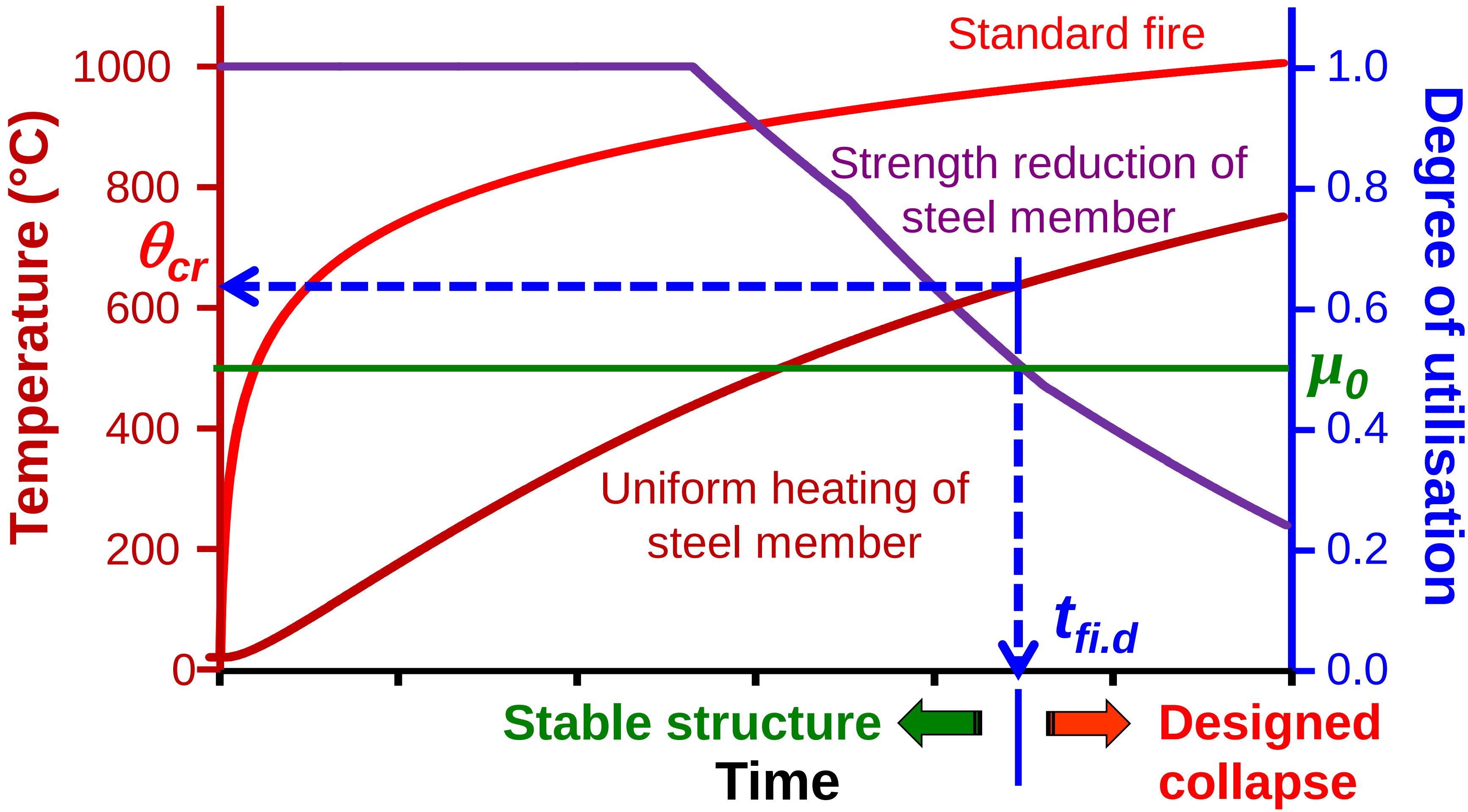
Critical temperature θ_{cr}

STEEL TEMPERATURE

Building regulations $t_{fi.requ}$

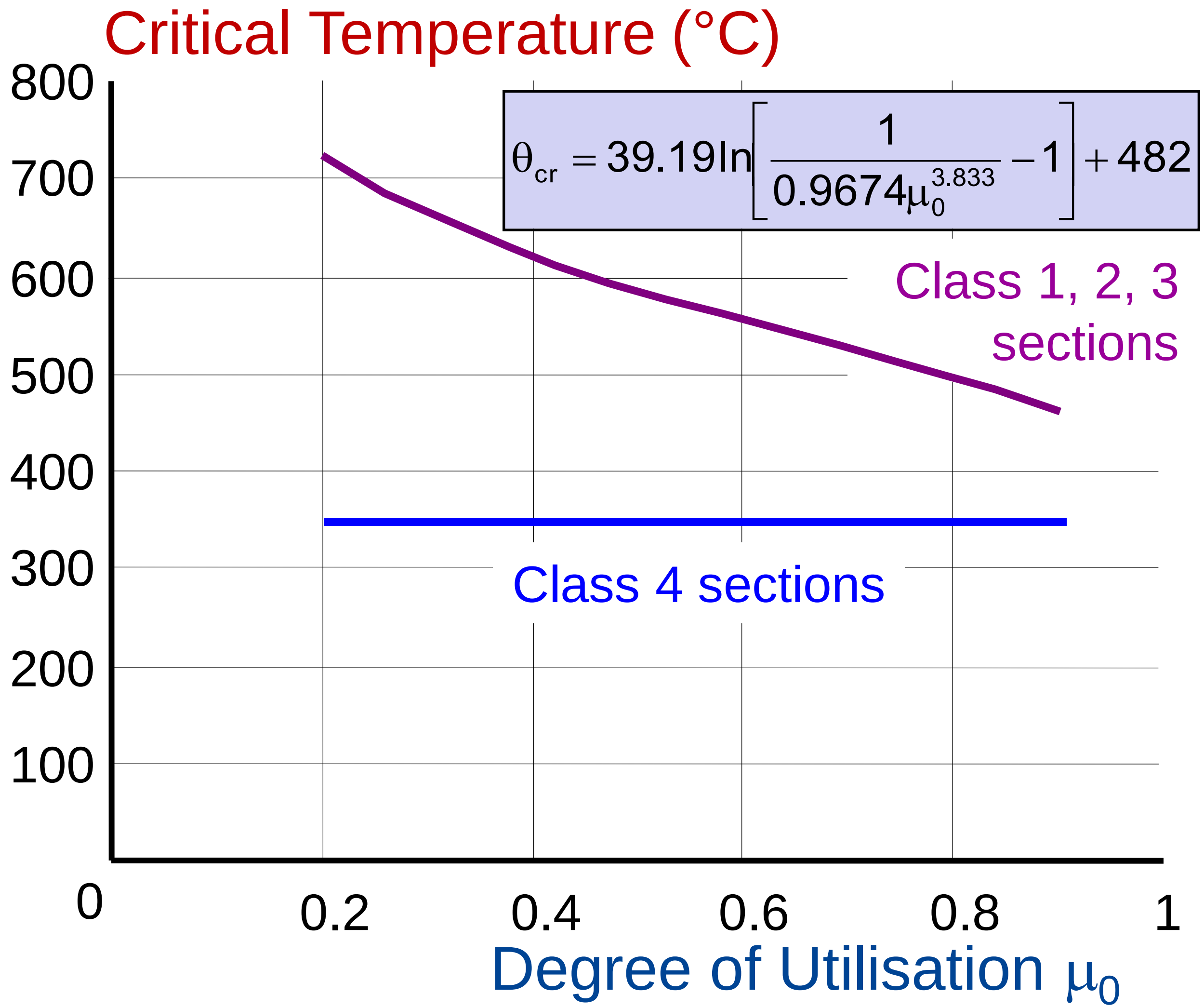
Critical temperature of steel members

- Basic assumption: uniform temperature of steel member



Critical temperature of steel members

- Based on standard fire tests. Simple members only.
- Non-slender sections without instability (Classes 1, 2, 3) treated the same.
- Slender (Class 4) sections treated conservatively (350°C) or Annex E for more detailed design rules



Critical temperature of steel members under instability using specific tabulated data based on:

- non-dimensional slenderness at instant 0 $\bar{\lambda}_{fi,0}$
- and a specific load level $\mu_0 = N_{fi,d,t} / N_{pl,fi,0}$
- each steel grade has its own tabulated data

$\bar{\lambda}_{fi,0}$	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
μ_0											
0.04	1000	977	949	913	880	839	787	742	696	678	659
0.06	900	885	866	837	795	756	700	679	656	630	602
0.08	860	839	811	785	749	697	674	647	616	588	564
0.10	820	797	780	752	703	677	648	614	585	557	527
0.12	792	777	755	719	685	656	622	588	559	526	474
0.14	775	757	730	694	668	636	597	567	533	487	373
0.16	758	737	705	681	652	615	580	546	507	408	
0.18	742	717	691	668	636	596	563	524	453		
0.20	725	698	680	655	619	582	545	503	384		
0.22	708	689	669	641	603	568	528	457			
0.24	696	679	658	628	591	554	511	406			
0.26	688	670	647	615	579	540	485				
0.28	679	660	636	602	568	526	446				

FIRE RESISTANCE

Action in fire situation $E_{fi.d.t}$

↓

Classify member

↓

Resistance at 20°C by fire rules $R_{fi.d.20}$

↓

Degree of utilisation μ_0

↓

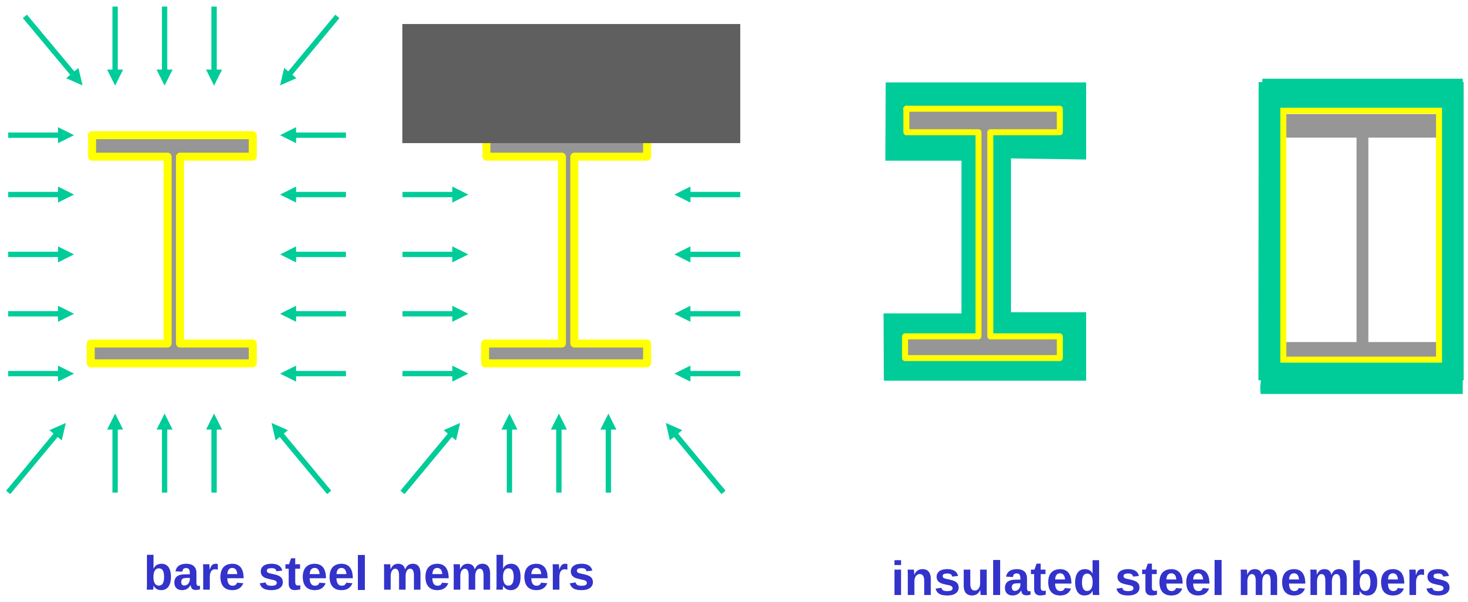
Critical temperature θ_{cr}

STEEL TEMPERATURE (UNPROTECTED)

Find Section Factor A_m/V and k_{sh}

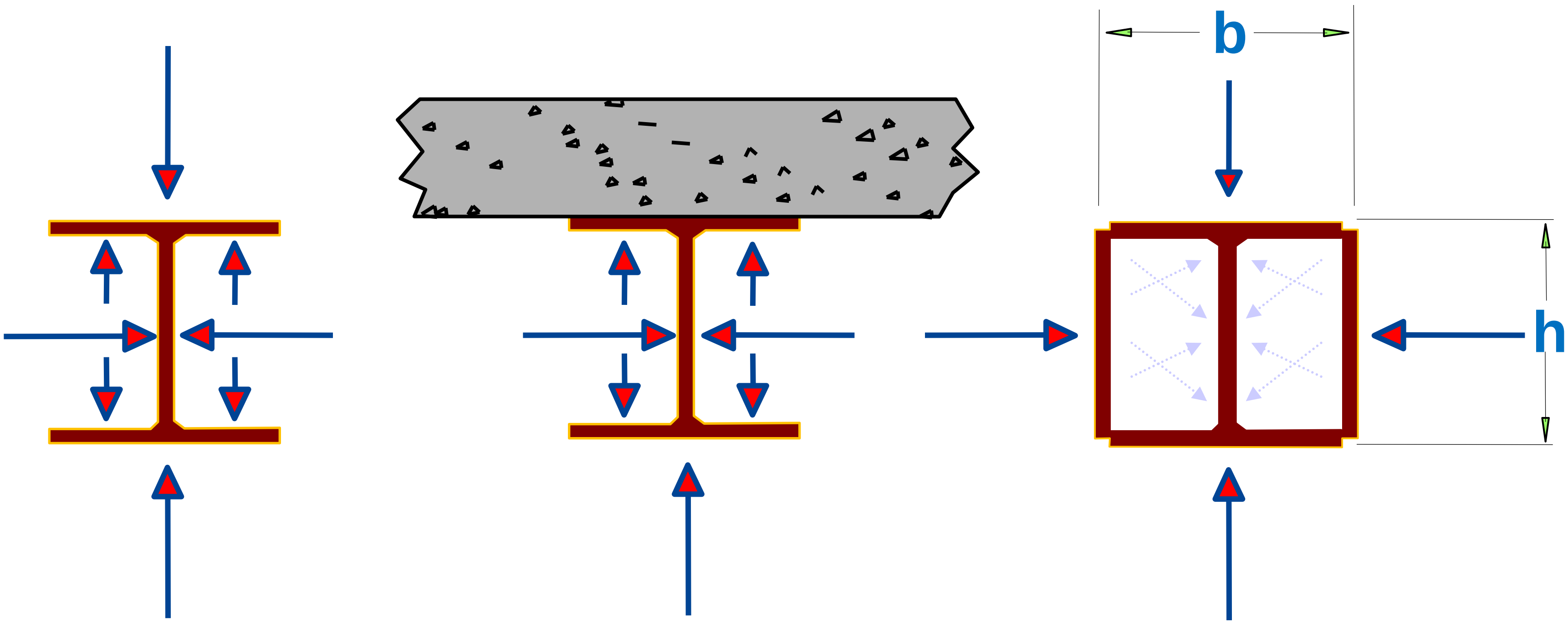
Building regulations $t_{fi.requ}$

Section factor:

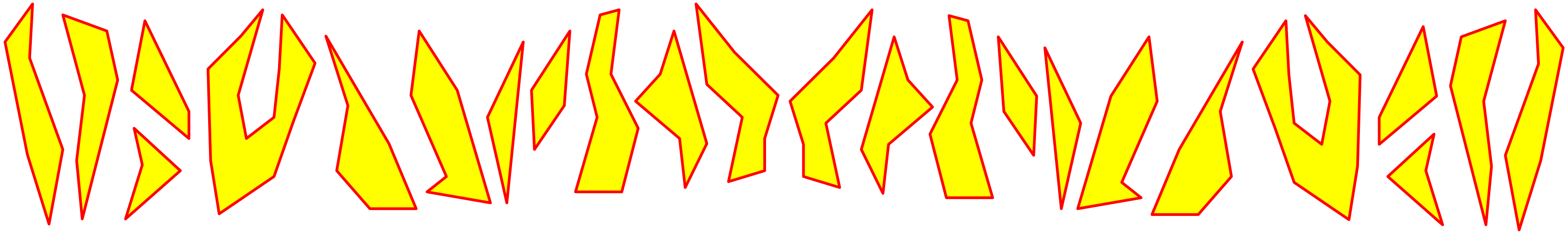


Definition: ratio between "perimeter through which heat is transferred to steel" and "steel volume"

Section factor A_m/V - unprotected steel members

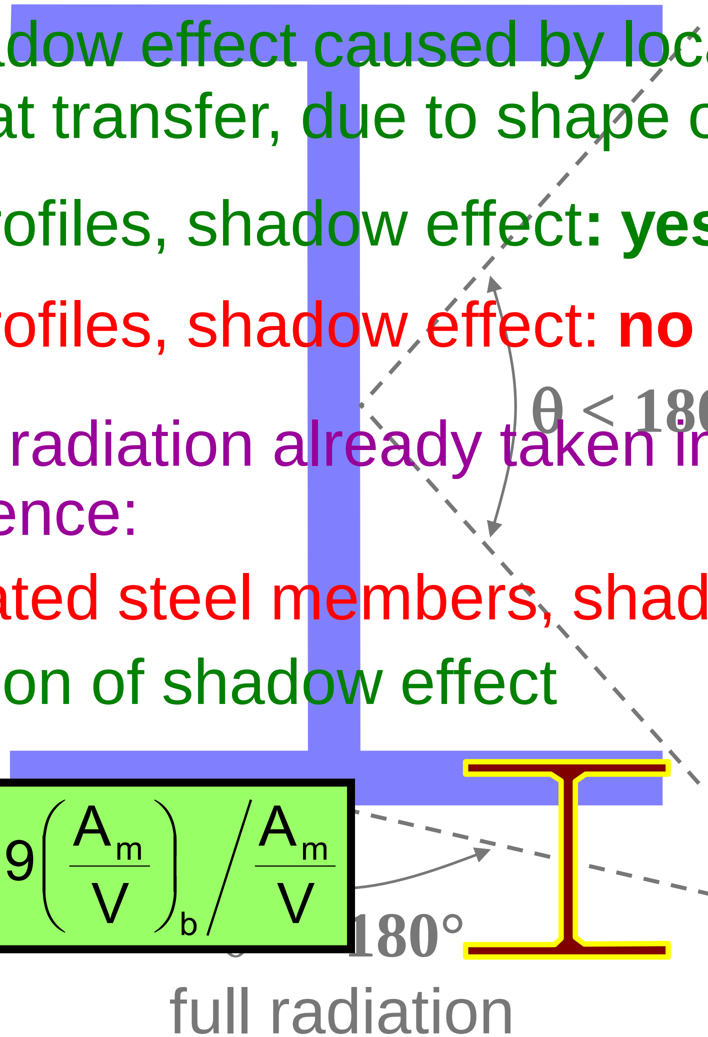


$\frac{\text{perimeter}}{\text{c/s area}}$ $\frac{\text{exposed perimeter}}{\text{c/s area}}$ $\frac{2(b+h)}{\text{c/s area}}$

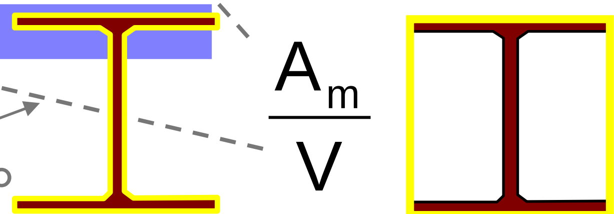


Temperature increase of unprotected steel – **shadow effect**

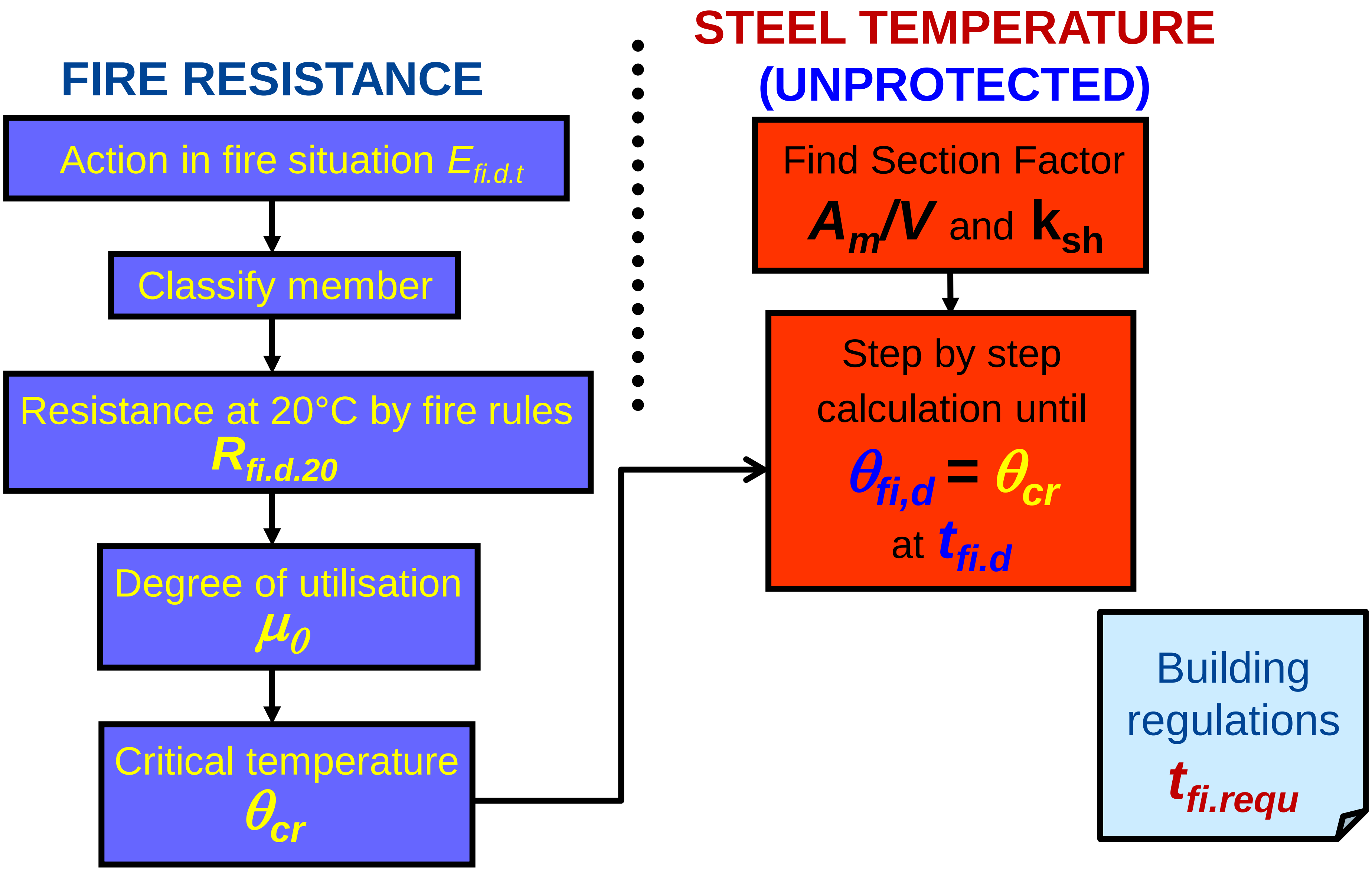
- **k_{sh}**: shadow effect caused by local shielding of radiative heat transfer, due to shape of steel profile, i.e.:
  - I profiles, shadow effect**: yes**
  - □ profiles, shadow effect: **no**
- Thermal radiation already taken into account, no shadow effect; hence:
  - Insulated steel members, shadow effect: **no**
- Calculation of shadow effect



$$k_{sh} = 0.9\left(\frac{A_m}{V}\right)_b \Big/ \frac{A_m}{V}$$



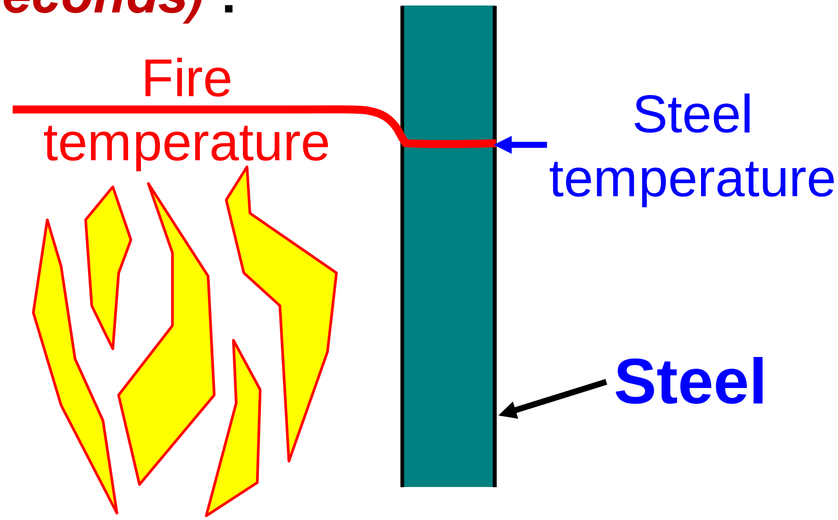
Establishing fire resistance of steel structures using simple process



Temperature increase of unprotected steel

Temperature increase in time step ***Δt (≤ 5 seconds)*** :

$$\Delta\theta_{a.t} = \frac{k_{sh}}{c_a \rho_a} \frac{A_m}{V} h_{net.d} \Delta t$$



Heat flux *$h_{net.d}$* has 2 parts:

Radiation:

$$h_{net,r} = 5.67 \times 10^{-8} \Phi \varepsilon_{res} \left((\theta_g + 273)^4 - (\theta_m + 273)^4 \right)$$

Convection:

$$h_{net,c} = \alpha_c (\theta_g - \theta_m)$$

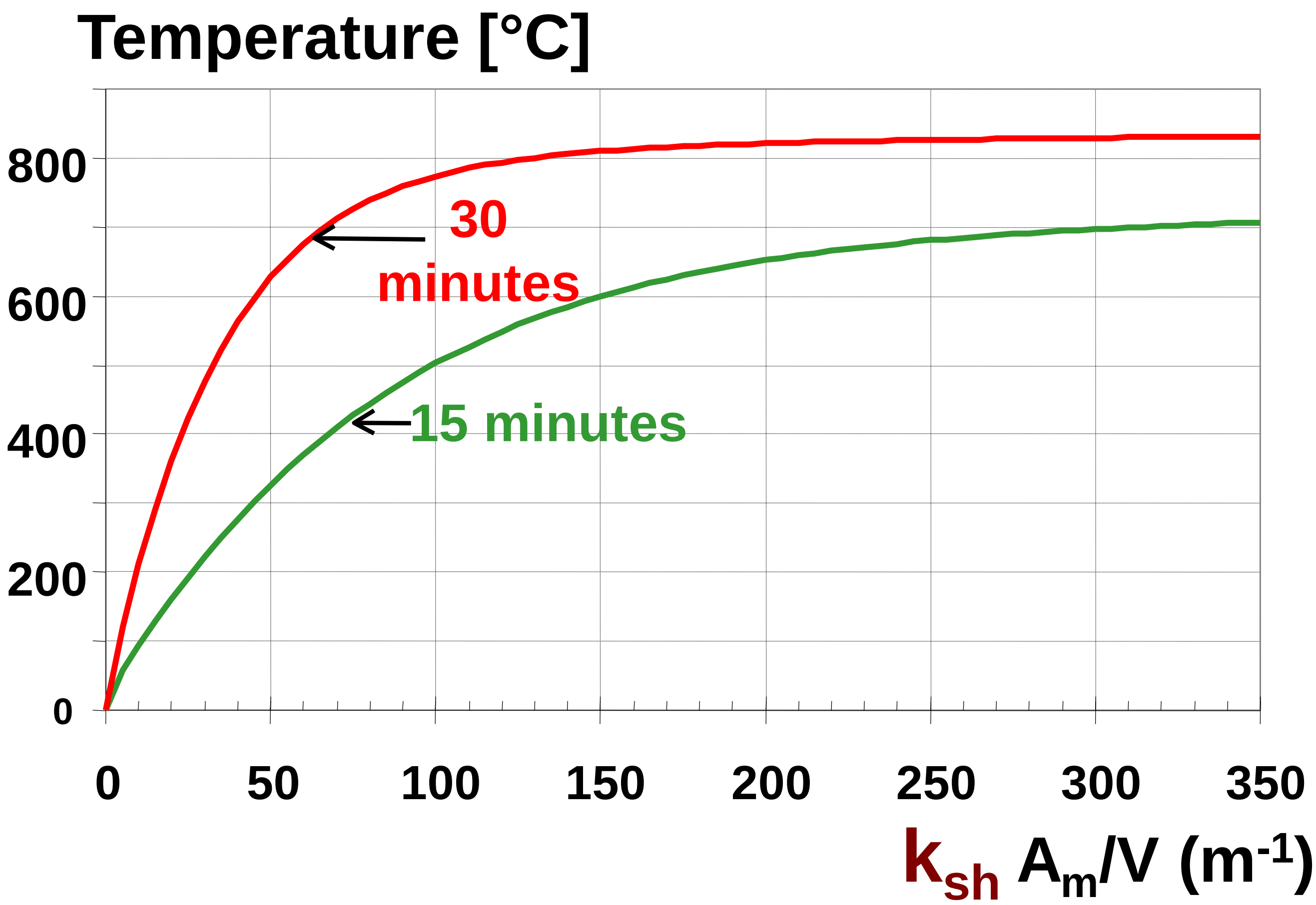
Under standard fire situation

$\varepsilon_{res} = \varepsilon_f \times \varepsilon_m = 0.7$ and $\phi = 1.0$

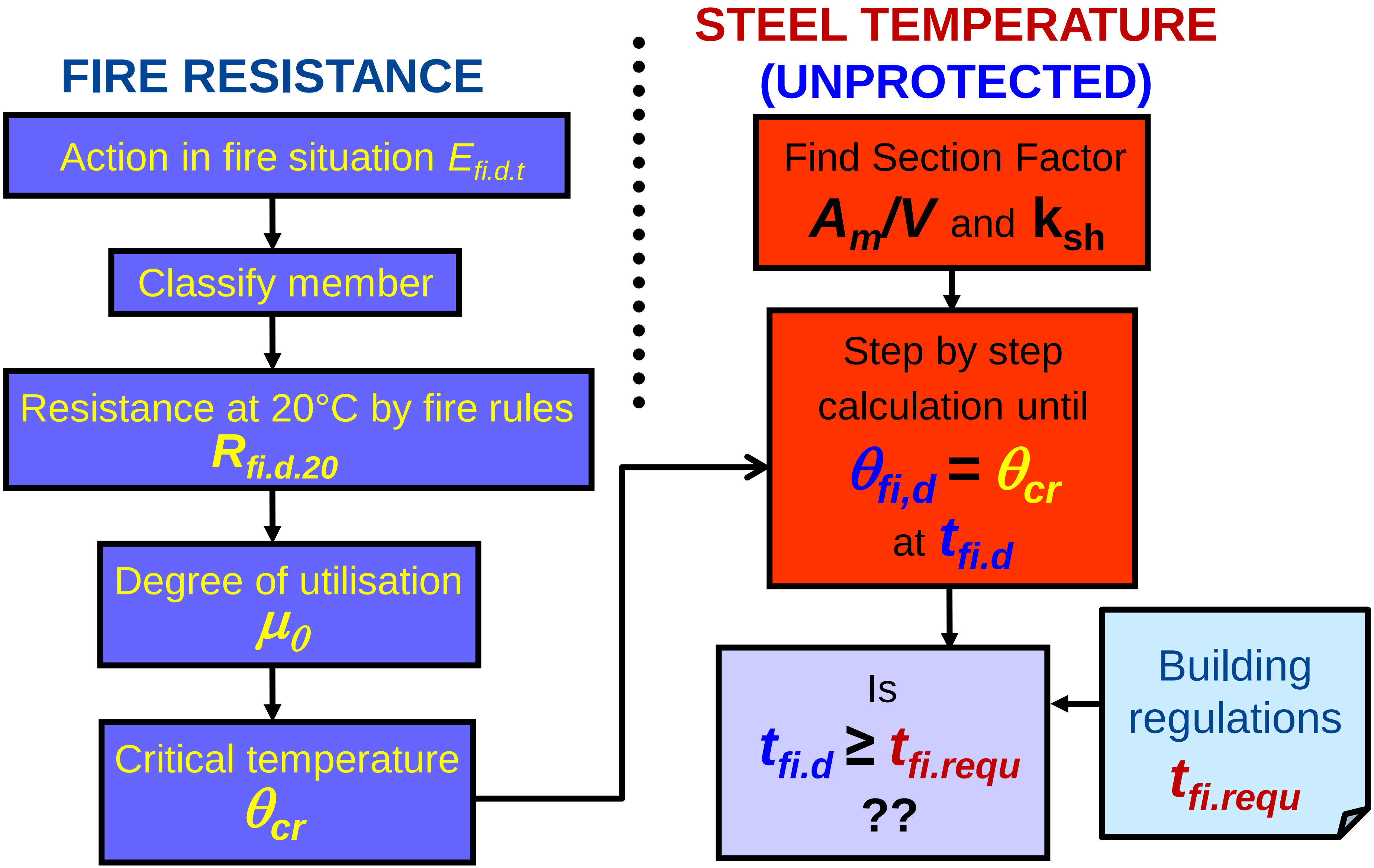
$\alpha_c = 25\ W/m^2K$

Steel temperature as function of Section Factor value

- Bare steel profiles



Establishing fire resistance of steel structures using simple process



Establishing fire resistance of steel structures using simple process

FIRE RESISTANCE

Action in fire situation $E_{fi.d.t}$

↓

Classify member

↓

Resistance at 20°C by fire rules
$R_{fi.d.20}$

↓

Degree of utilisation
μ_0

↓

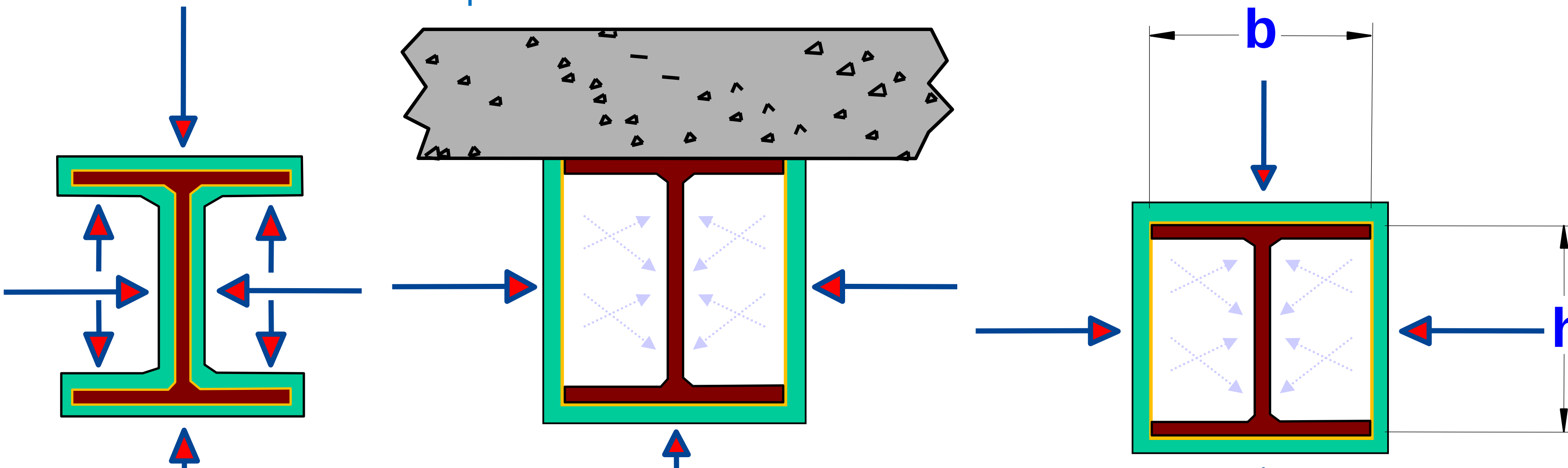
Critical temperature
θ_{cr}

STEEL TEMPERATURE (PROTECTED)

Find Section Factor
A_p/V

Building regulations
$t_{fi.requ}$

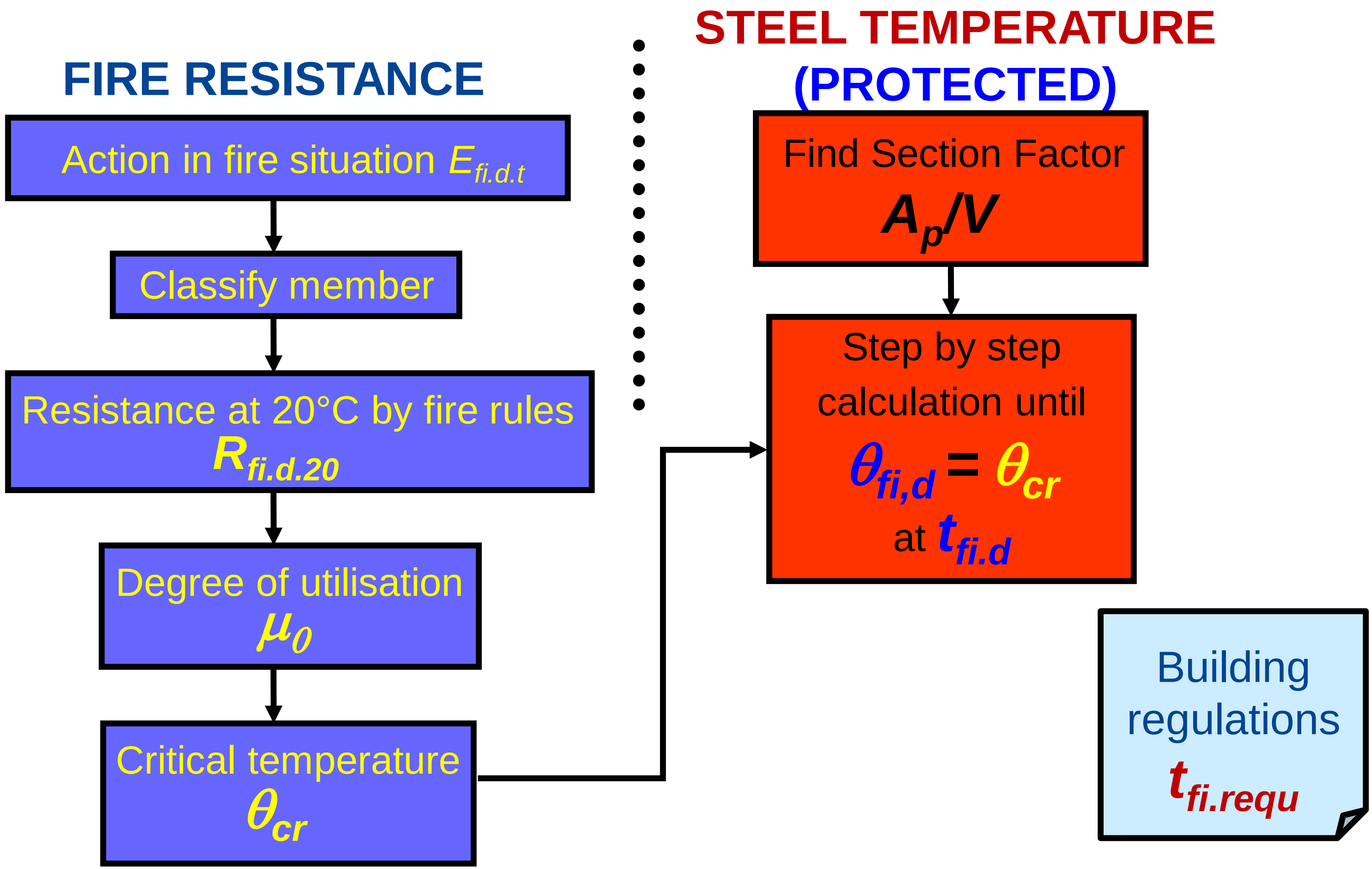
Section factor A_p/V - protected steel members



$\frac{\text{Steel perimeter}}{\text{steel c/s area}}$

$\frac{\text{inner perimeter of board}}{\text{steel c/s area}}$

$\frac{2(b+h)}{\text{c/s area}}$



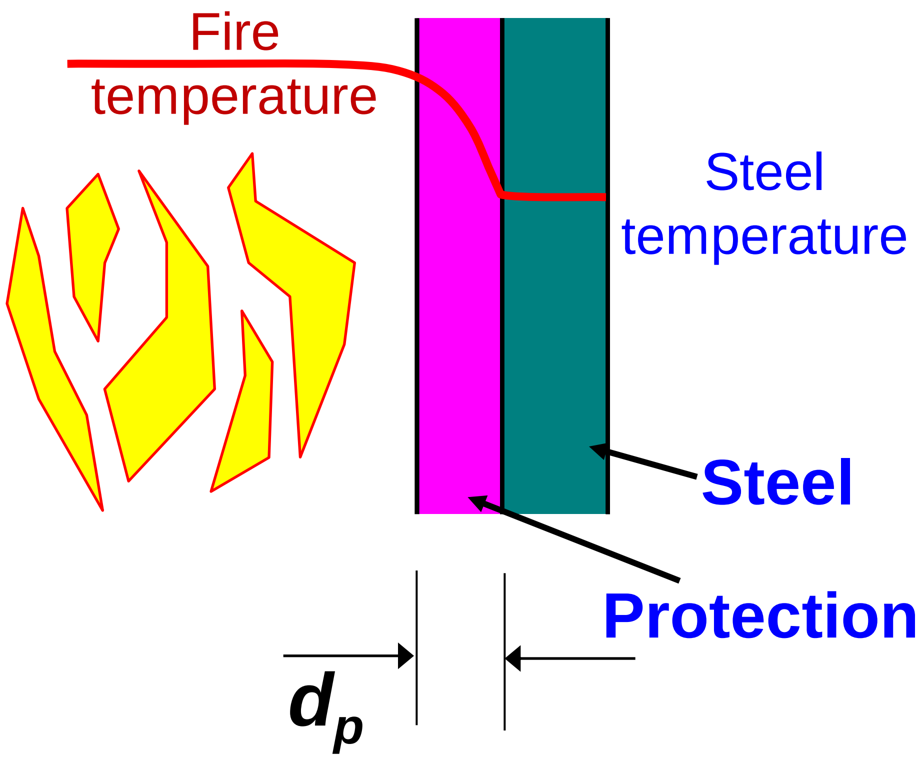
FIRE RESISTANCE
Action in fire situation $E_{fi.d.t}$
Classify member
Resistance at 20°C by fire rules
$R_{fi.d.20}$
Degree of utilisation
μ_0
Critical temperature
θ_{cr}
STEEL TEMPERATURE
(PROTECTED)
Find Section Factor
A_p/V
Step by step
calculation until
$\theta_{fi,d} = \theta_{cr}$
at $t_{fi.d}$
Building
regulations
$t_{fi.requ}$

Temperature increase of protected steel members

- Some heat stored in protection layer.
- Heat stored in protection layer relative to heat stored in steel

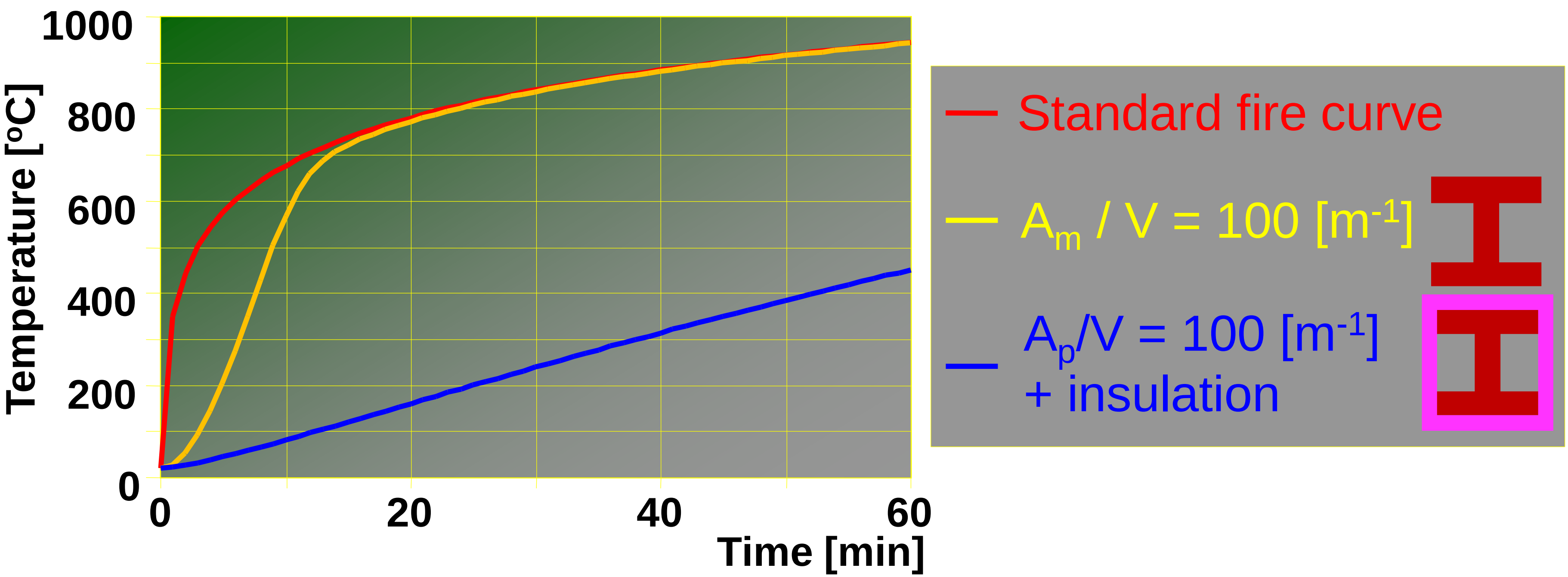
$$\phi = \frac{c_p \rho_p}{c_a \rho_a} d_p \frac{A_p}{V}$$

- Temperature rise of steel in time increment ***Δt (≤ 30 seconds)***

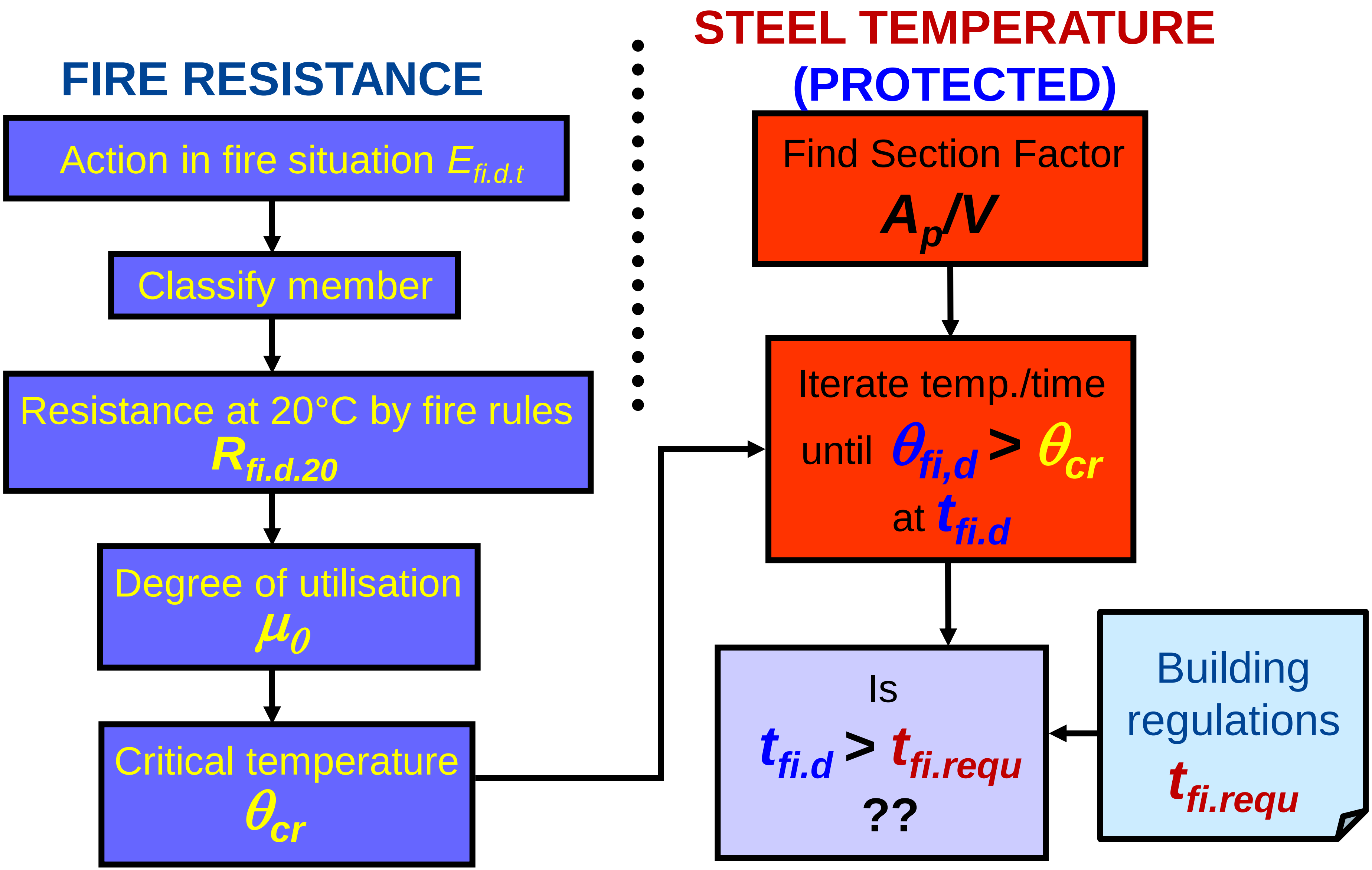


$$\Delta\theta_{a.t} = \frac{\lambda_p / d_p}{c_a \rho_a} \frac{A_p}{V} \left(\frac{1}{1 + \phi/3} \right) (\theta_{g,t} - \theta_{a,t}) \Delta t - \left(e^{\phi/10} - 1\right) \Delta\theta_{g,t}$$

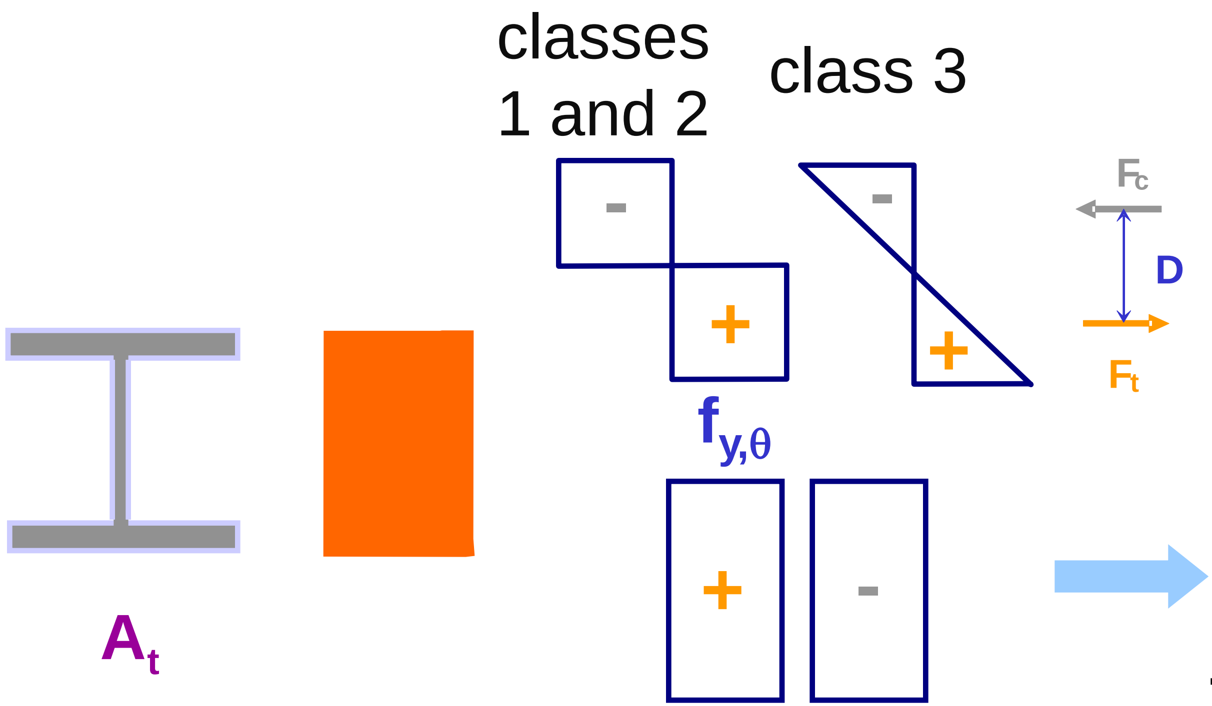
Examples of protected steel members



Establishing fire resistance of steel structures using simple process



Tension, simple bending and members under compression without instability behaviour (classes 1 to 3)



$$M_{fi,t,Rd} = F_t \times D$$

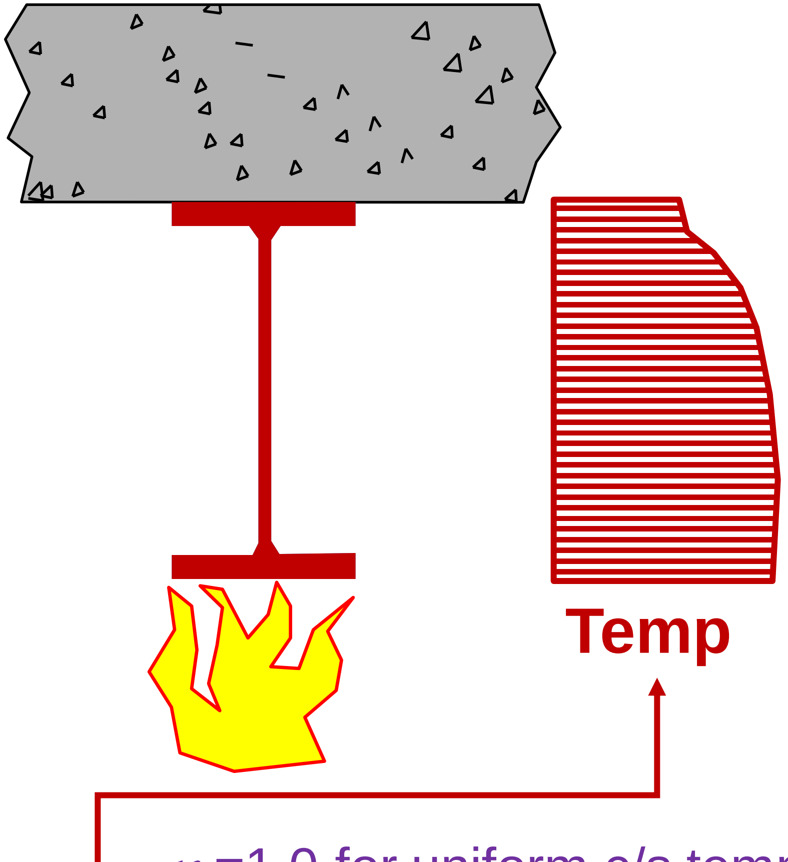
Simple bending

$$N_{fi,t,Rd} = A_t \times f_{y,\theta}$$

Tension or compression

Cross section | **Temperature Distibution** | **Stress** | **Load bearing capacity**

Adaptation factors - beam with concrete slab on top flange



Adaptation factors used to allow for non-uniform temperature distribution for both

Moment Resistance:

$$M_{fi,t,Rd} = M_{Rd} k_{y.\theta} \left(\frac{\gamma_{M,1}}{\gamma_{M,fi}} \right) \frac{1}{\kappa_1 \kappa_2}$$

Shear Resistance:

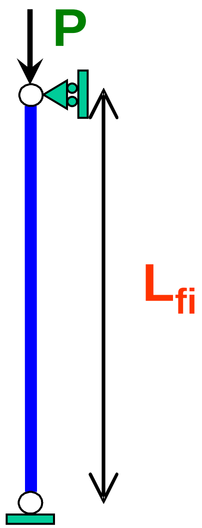
$$V_{fi,t,Rd} = V_{Rd} k_{y.\theta.max} \left(\frac{\gamma_{M,1}}{\gamma_{M,fi}} \right)$$

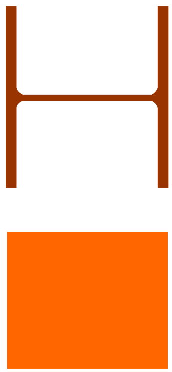
κ_1=1.0 for uniform c/s temperature, 0.7 or 0.85 for slab on top flange.

κ_2=0.85 at supports of statically indeterminate beam, 1.0 for all other cases (temperature distribution along beam).

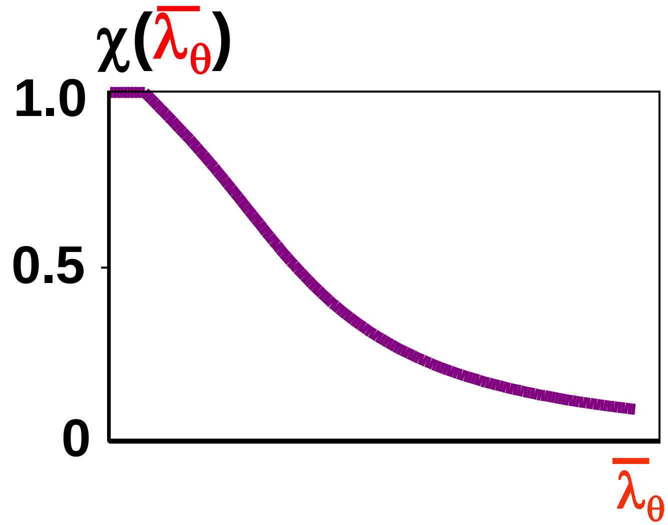
Simple load-bearing design rules

Members under bending or/and compression with instability behaviour (classes 1 to 3)





Section and temperature



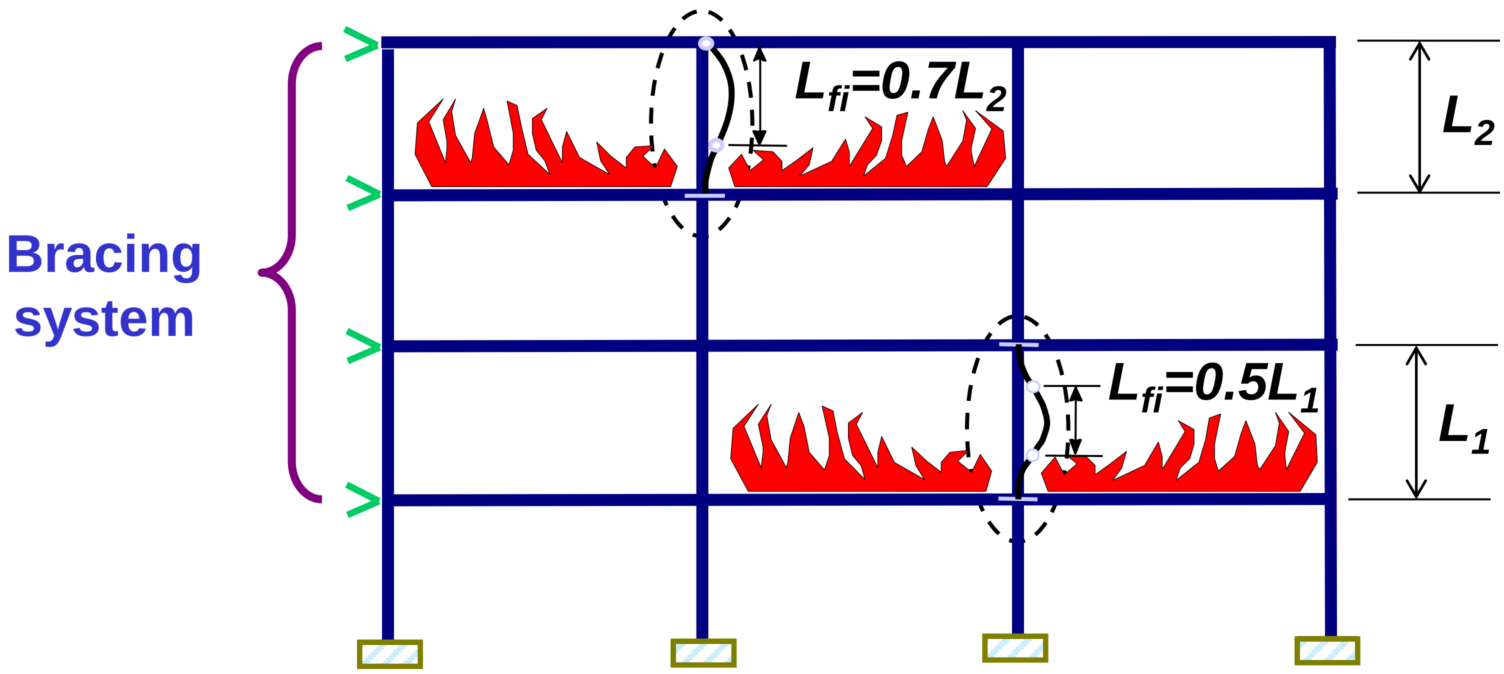
Specific buckling curve

Load bearing capacity: $N_{fi,t,Rd} = \chi(\bar{\lambda}_\theta)\, N_{fi,pl,Rd}$

$\chi(\bar{\lambda}_\theta) \Leftarrow$ **resistance and stiffness of cross section + buckling length L_{fi} and a specific buckling curve**

Design buckling length of steel columns in fire situation

- Braced structures
- Continued or ends maintained columns
- Same fire resistance R between columns and floor members



Design recommendations for steel joints

- Check of thermal resistance of steel joints

$$\left(\frac{d_f}{\lambda_f}\right)_c \text{ of steel joint} \geq \text{minimum value of} \left(\frac{d_f}{\lambda_f}\right)_m$$

of any of the connected members

- Check of utilisation of steel joints

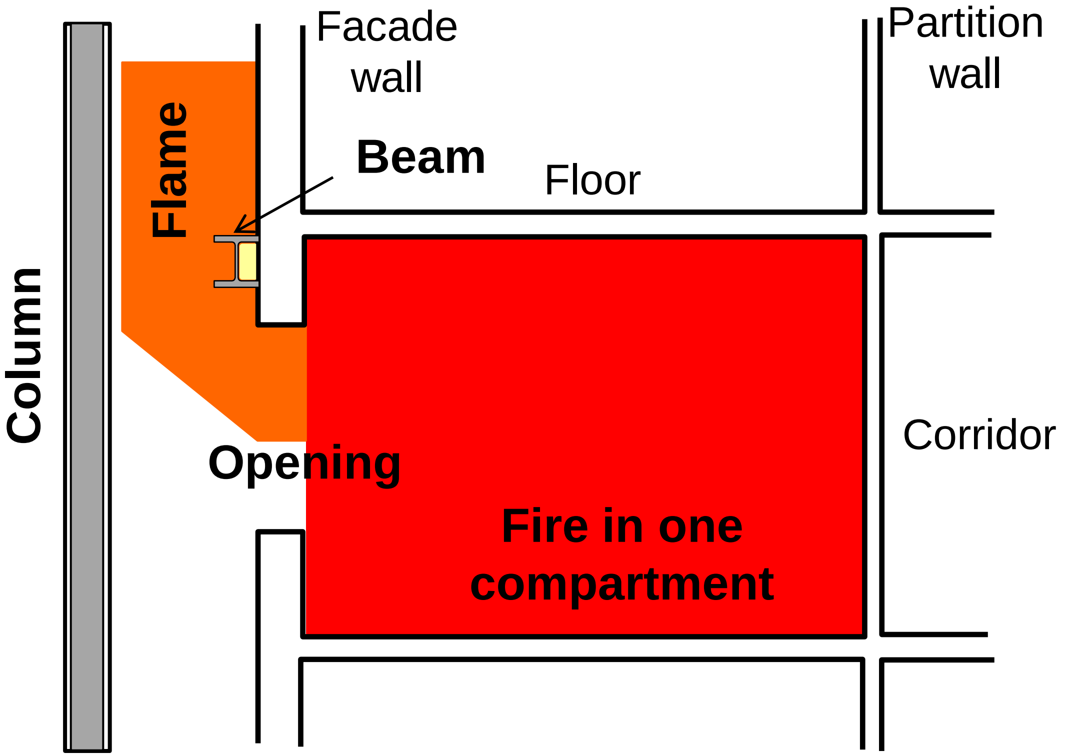
$\eta_{c,fi}$ of steel joint ≤ maximum value of $\eta_{m,fi}$ of any of the connected members

More detailed simple design rules for steel joints

- Annex D

Simple load-bearing design rules

Design rules for external steel works

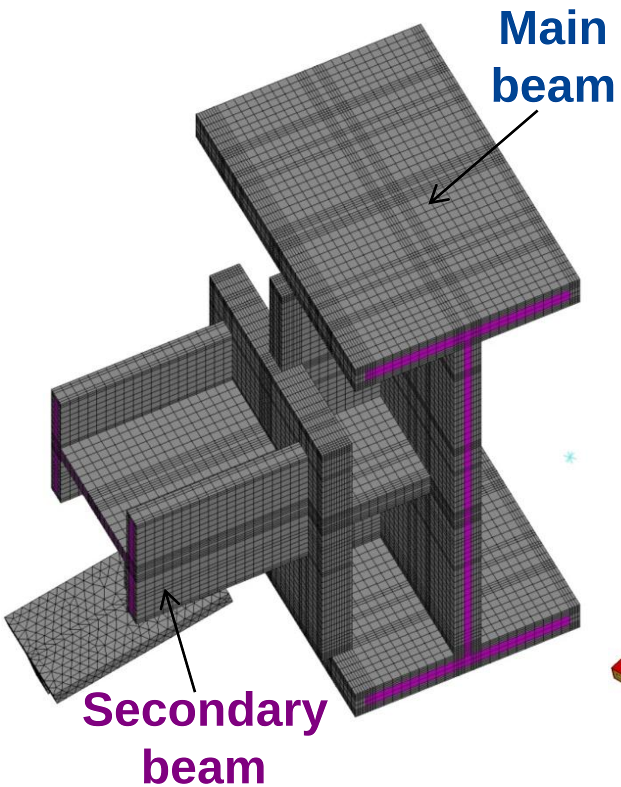


<u>Simple design rules</u>

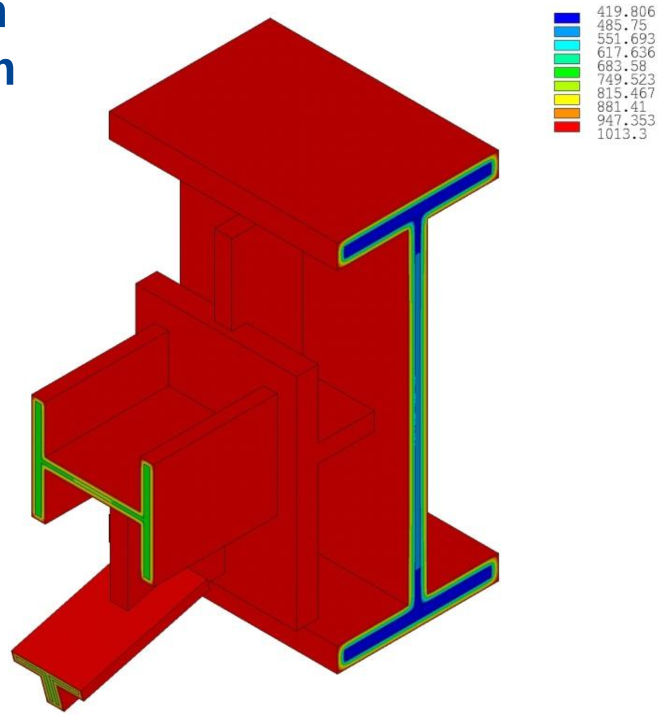
- Thermal action: annex B of EC1
- Heating of steel: annex B of EC3

Application example of advanced thermal analysis

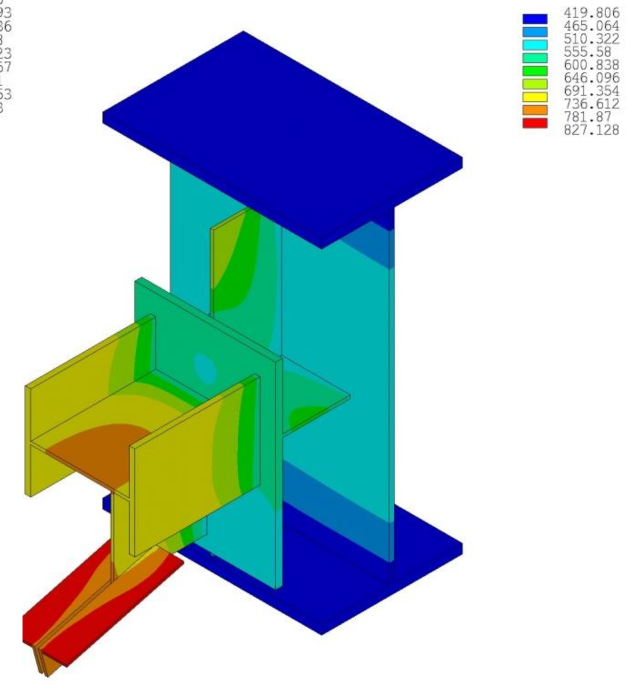
- Heating of fire insulated steel joint for R90



Numerical model of fire insulated joint



Temperature field of fire insulated joint



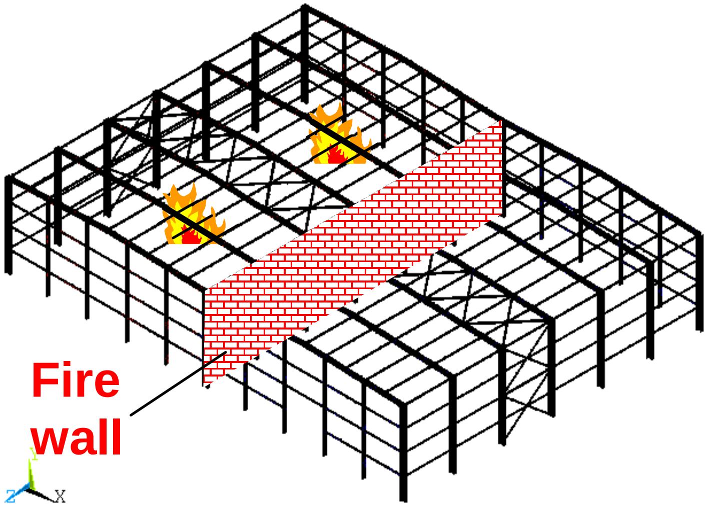
Temperature field of steel parts of the joint

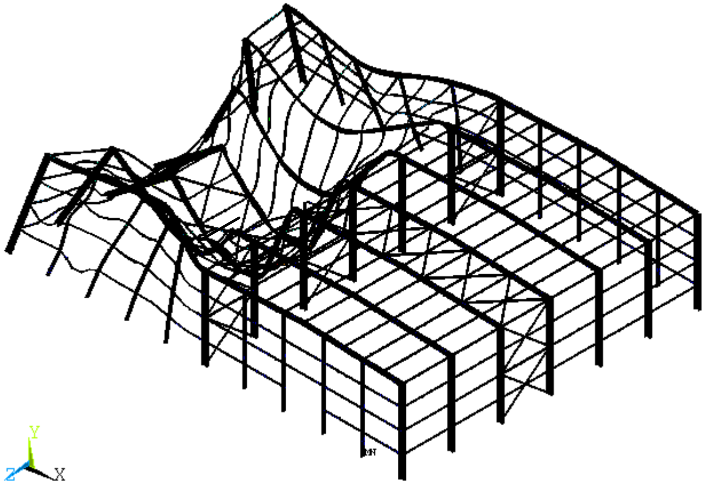
Advanced fire resistance design tools

Application example of advanced structural analysis

- failure mode of bare steel structures exposed to fire







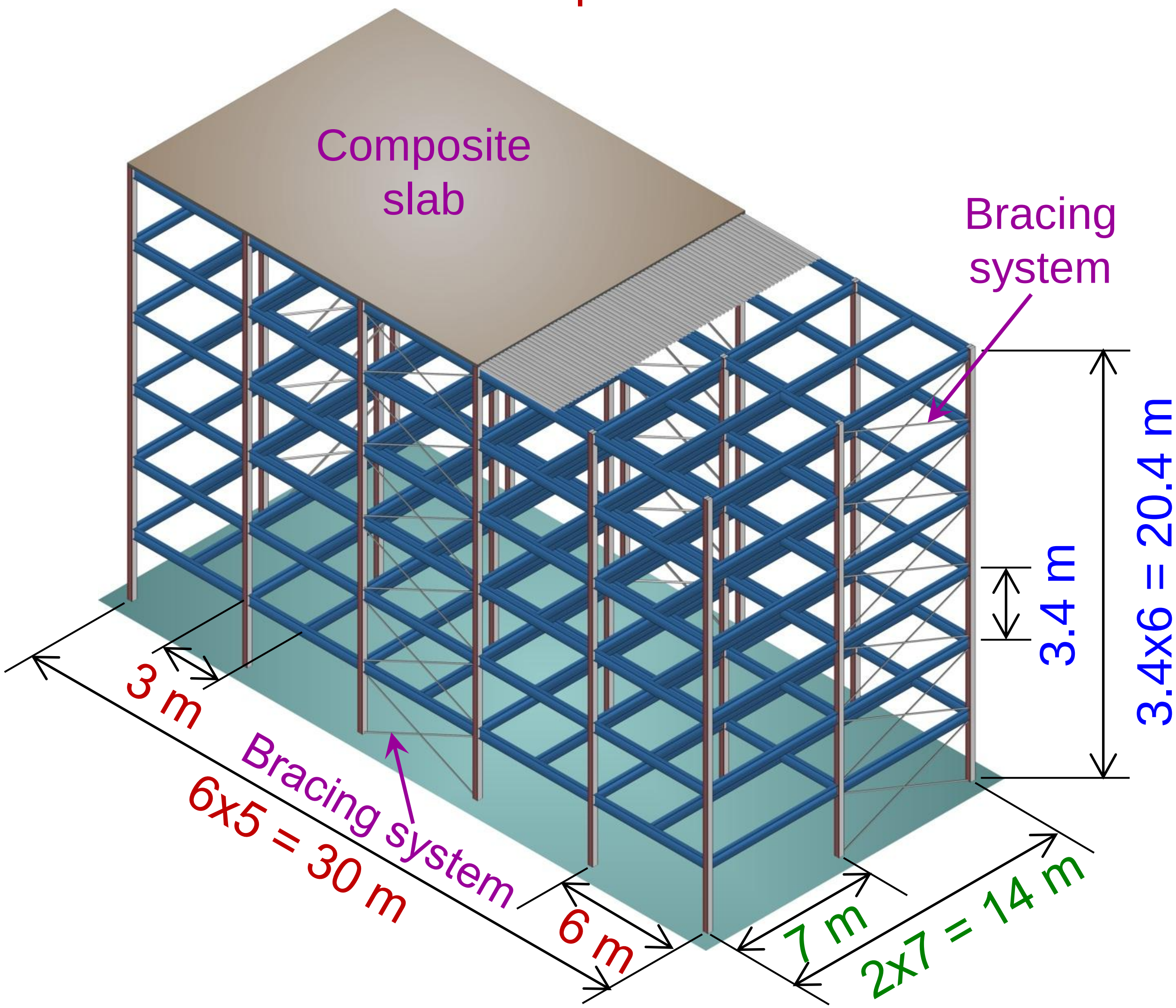
Worked examples

according to fire part of Eurocode 3

Building in steel structure

Office building with 6 levels of floor

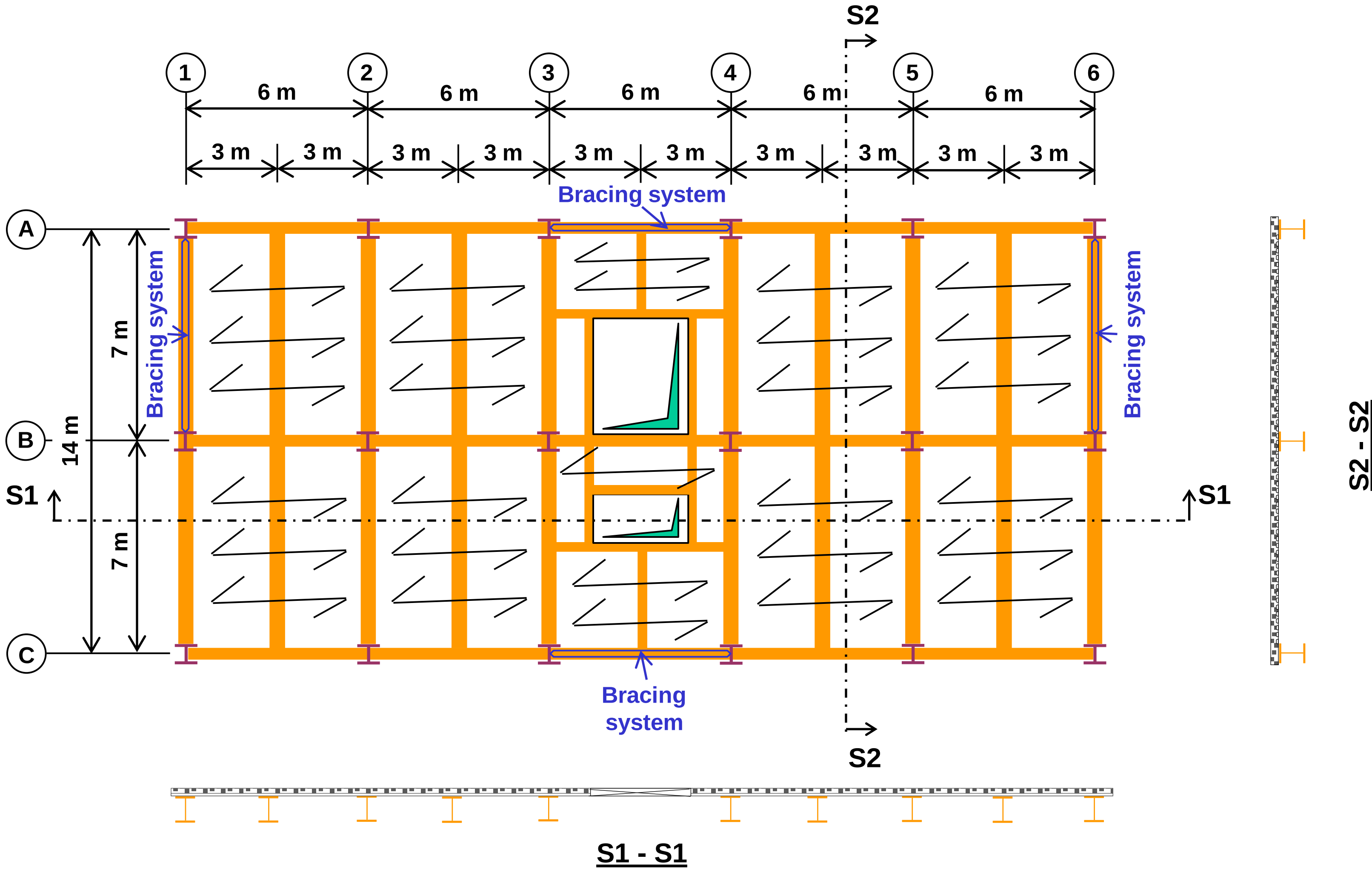
- Standard fire resistance requirement: R60



Structure grid of the steel building

Plan view of the steel structure

- two span continuous composite slab



Structural members

- Composite slab:
  - ✓ Total thickness: 12 cm
  - ✓ Steel deck: COFRAPLUS60
  - ✓ Thickness of steel deck: 0.75 mm
  - ✓ Continuous slab over 2 spans
- Common secondary beams:
  - ✓ IPE360 with steel grade of S275
- Internal main beams:
  - ✓ HEA360 with steel grade of S275
- Columns for ground level:
  - ✓ Edge columns (ground level): HEA300 with steel grade of S275
  - ✓ Central columns (ground level): HEB300 with steel grade of S275

Design loads of the steel structure

European Commission

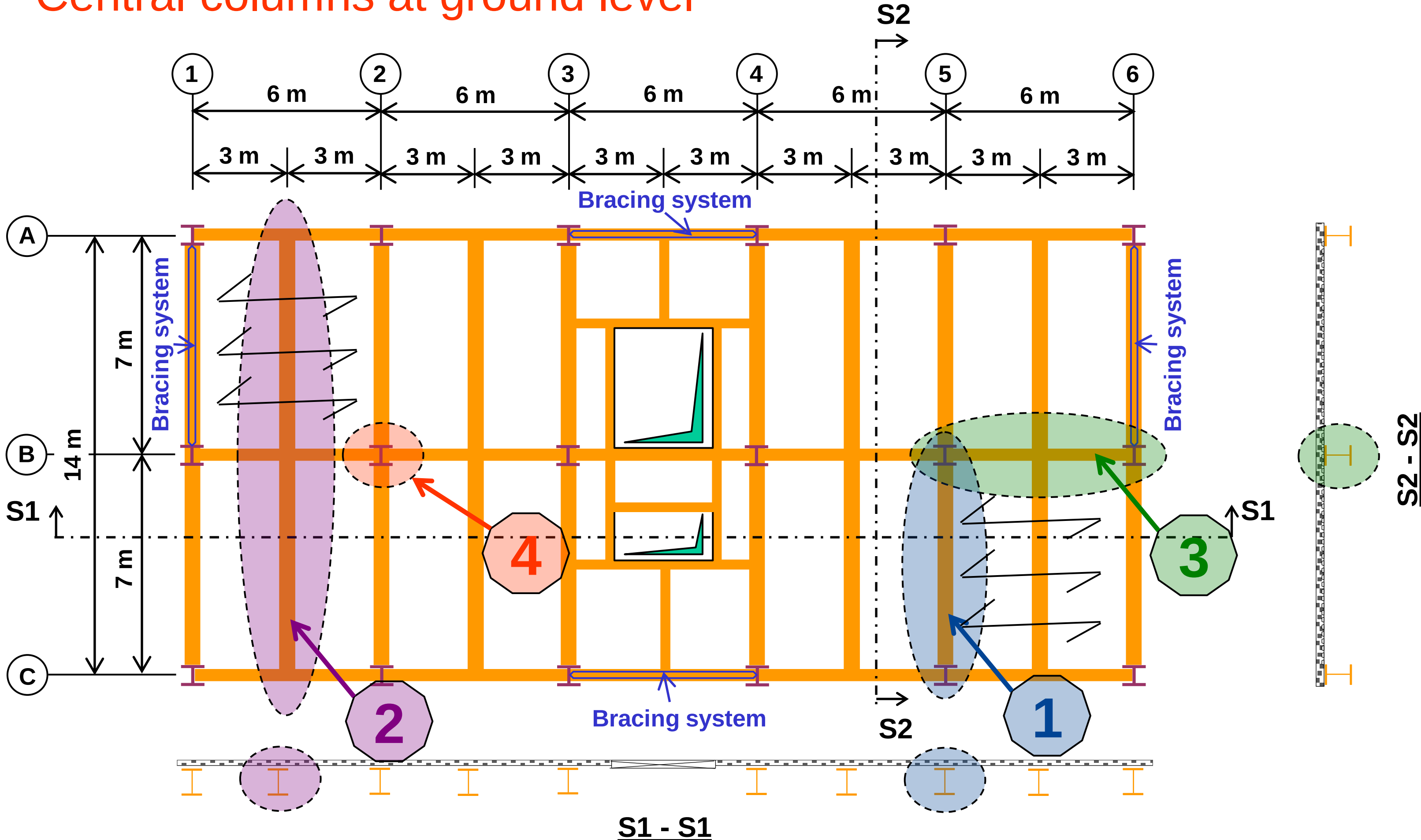
Actions (for all floor levels)

- Self weight G1:
  - ✓ composite slab unit weight: 2.12 kN/m²
  - ✓ steel structural members: according to their sizes
- Permanent load G2:
  - ✓ finishing, embedded services, partitions: 1.50 kN/m²
- Permanent load G3:
  - ✓ Façade cladding load: 2.00 kN/m
- Characteristic values of variable loads and ψ factors

Type	q_k	ψ_1	ψ_2
Live load on floors	4.0 kN/m²	0.7	**0.6**
Snow on roof	1.7 kN/m²	0.2	0.0

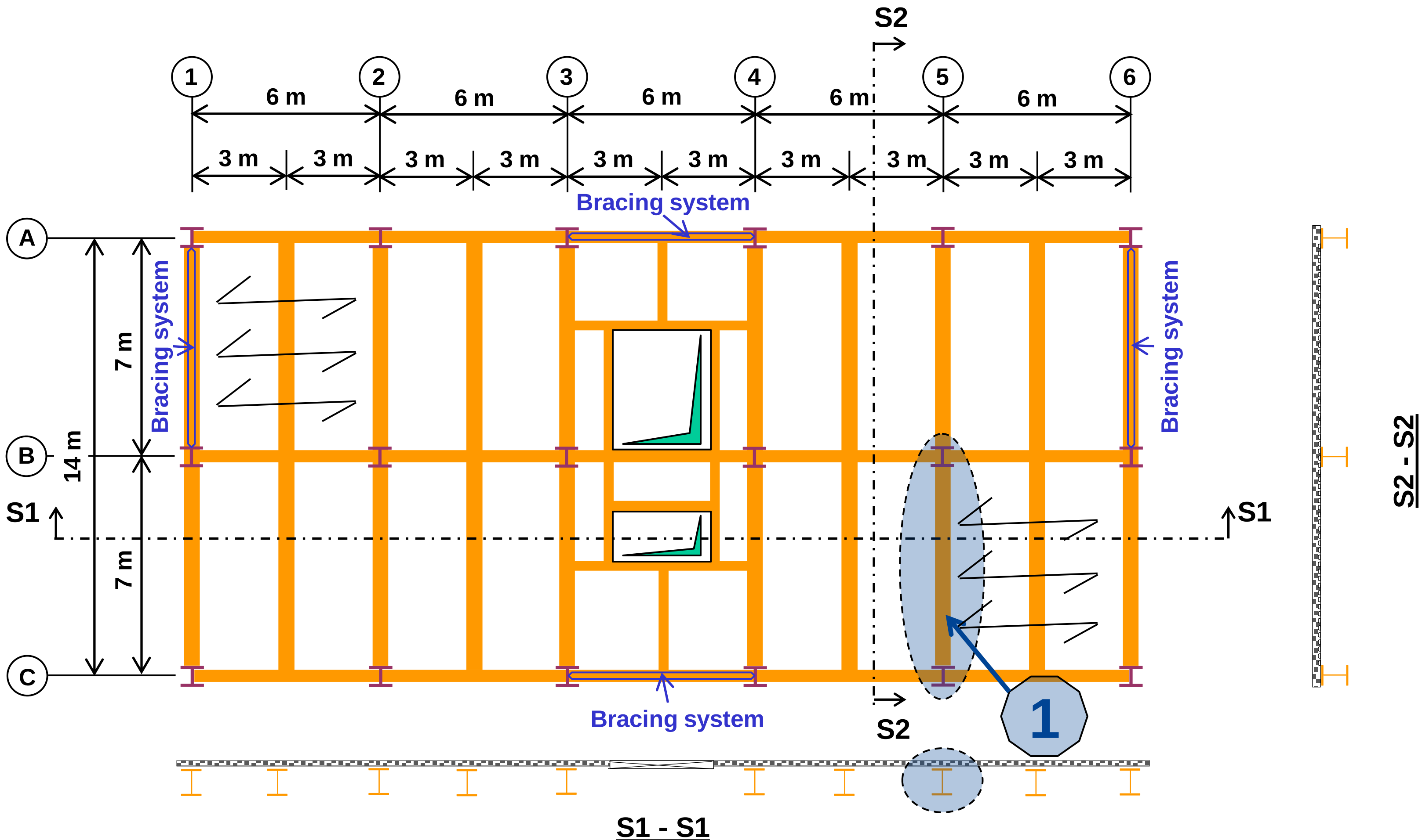
Selected worked examples

1. Secondary beams under end support of the continuous slabs
2. Secondary beams under central support of the continuous slabs
3. Simply supported central main beams
4. Central columns at ground level



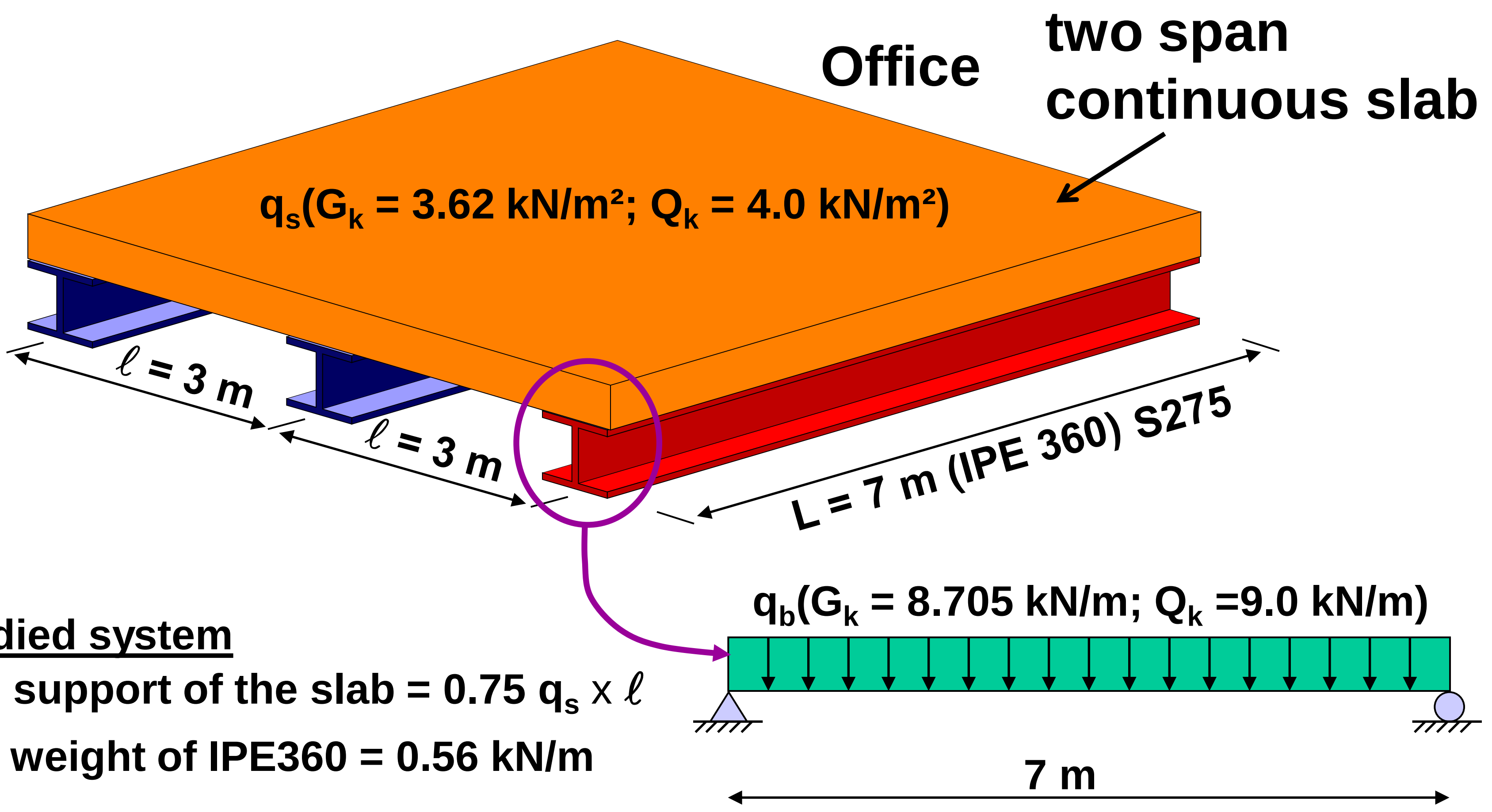
Worked example 1

Secondary beams under end support of the continuous slabs



Step 1: Design mechanical action in fire design

- Summary of input data



<u>Studied system</u>

End support of the slab = 0.75 $q_s \times \ell$

Self weight of IPE360 = 0.56 kN/m

Step 1: Design mechanical action in fire situation

- Design load in fire situation

$$E_{fi,d,t} = \sum_{j \geq 1} G_{k,j} + \Psi_{2,1} Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i} Q_{k,i}$$

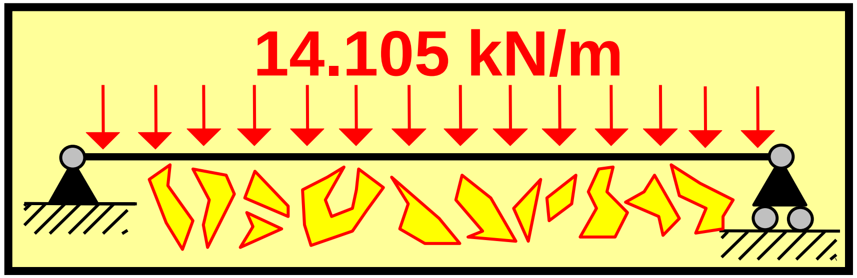
$$q_{fi,d,t} = G_b + 0.75 \times \left(G_{k,1} + \psi_{2,1} Q_{k,1}\right) \times \ell \approx 14.105 \text{ kN/m}$$

0.75 → end support of 2 span slab

$\psi_{2,1}$ → 0.6 (meeting area)

$$M_{fi,d,t} = \frac{q_{fi,d,t} L^2}{8} = 86.4 \text{ kNm}$$

$$V_{fi,d,t} = \frac{q_{fi,d,t} L}{2} = 49.4 \text{ kN}$$



1. Secondary beams under end support of the continuous slabs

Step 2: Classify member

- Bending member (**IPE360**)

Relation 4.2 of Eurocode 3 part 1-2

$$\varepsilon = 0.85\sqrt{235/f_y} = 0.786$$

f_y: *S275*

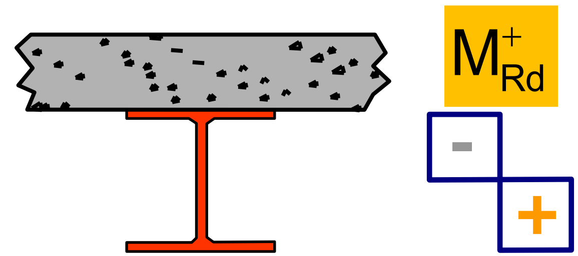
Table 5.2 of Eurocode 3 part 1-1

$$c/t_w \leq 72\varepsilon \rightarrow \textit{Web class 1}$$

c/t_w *= 37.3*; 72ε *= 56.6*

$$c/t_f \leq 9\varepsilon \rightarrow \textit{Flange class 1}$$

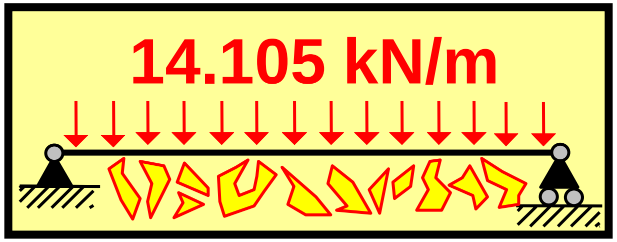
c/t_f *= 4.96*; 9ε *= 7.07*



Pure bending

→ **Section class 1**

Step 3: Design resistance at ambient temperature



- Design resistance at ambient temperature according to §6.2.5 and §6.2.6 of Eurocode 3 part 1-1

➢ **Moment resistance (relation 6.13)**

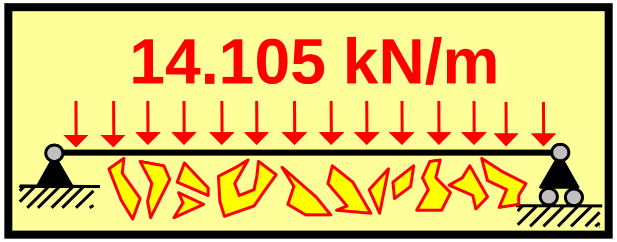
$$M_{Rd} = M_{pl,Rd} = \frac{W_{pl,y} f_y}{\gamma_{M0}} = 280.3 \ \text{kNm}$$

IPE360	
$W_{pl,y}$ (cm^3)	1019.15
A_v (cm^2)	35.14

➢ **Vertical shear resistance (relation 6.18)**

$$V_{Rd} = V_{pl,Rd} = \frac{A_v \left(f_y / \sqrt{3} \right)}{\gamma_{M0}} = 557.9 \ \text{kN}$$

$\gamma_{M0} = 1$



Step 4: Degree of utilisation

- with respect to two resistances
- without consideration of adaptation factors κ_1 and κ_2

➢ **Relative to moment resistance (relation 4.24)**

$$\mu_{0,M} = \eta_{fi,M} \frac{\gamma_{M0}}{\gamma_{M,fi}} = \frac{M_{fi,d,t}}{M_{Rd}} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 0.308$$

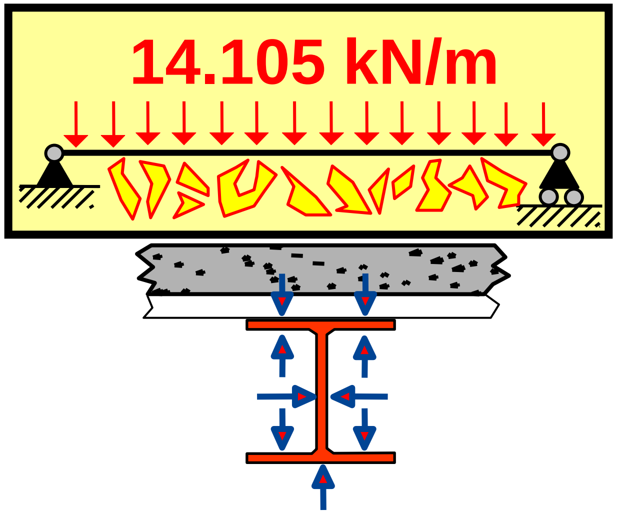
➢ **Relative to vertical shear resistance (relation 4.24)**

$$\mu_{0,V} = \eta_{fi,V} \frac{\gamma_{M0}}{\gamma_{M,fi}} = \frac{V_{fi,d,t}}{V_{Rd}} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 0.088$$

$$\gamma_{M0} = \gamma_{M,fi} = 1$$

1. Secondary beams under end support of the continuous slabs

Step 4: Degree of utilisation (bare beam)



- modification with consideration of adaptation factors κ_1 and κ_2 for bare steel beams

➢ **On the basis of relation 4.10**

four sides exposed (see 4.1(16) of EN1994-1-2)

$$\left.\begin{array}{l}\kappa_1 = 1.0 \\ \kappa_2 = 1.0\end{array}\right\} \Rightarrow \mu_{0,M,\kappa} = \mu_{0,M} \times (\kappa_1 \kappa_2) = 0.308$$

$$\mu_{0,V,\kappa} = \mu_{0,V} = 0.088$$

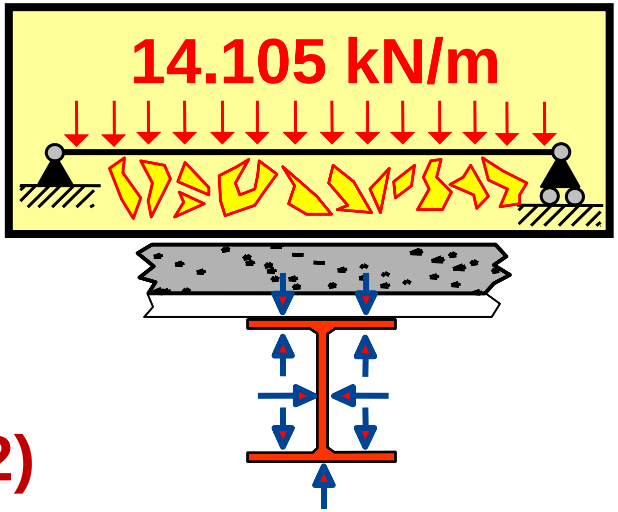
no adaptation factors for vertical shear

➢ **Design value of degree of utilisation**

$$\mu_0 = \max(\mu_{0,M,\kappa}, \mu_{0,V,\kappa}) = 0.308$$

Step 5: Critical temperature (bare beam)

- with simple calculation rule
- with accurate reduction factor table



➢ **Simple calculation rule (relation 4.22)**

$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 \approx 660 \;\; °C$$

➢ **Linear interpolation of the reduction factor $k_{y,\theta}$ (table 3.1)**

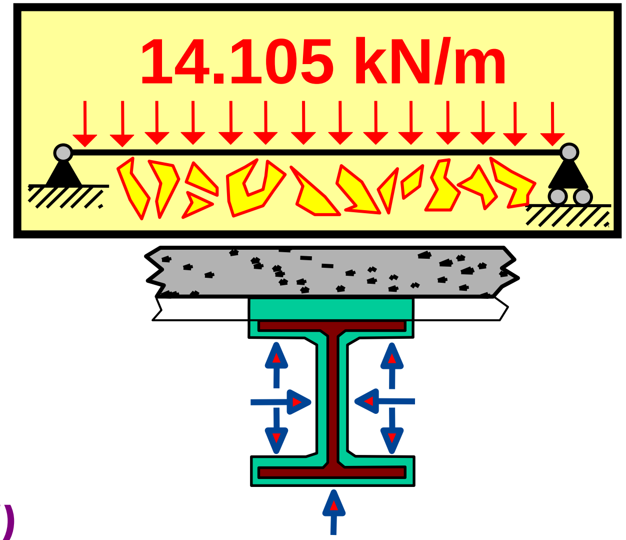
at 600 °C: $k_{y,\theta} = 0.47$

at 700 °C: $k_{y,\theta} = 0.23$

$$\theta_{cr} \approx 667 \;\; °C$$

Step 4b: Degree of utilisation (insulated beam)

•modification with consideration of adaptation factors κ_1 and κ_2 for insulated steel beams



➢ **On the basis of relation 4.10**

three sides exposed (insulated)

$$\left.\begin{array}{l}\kappa_1 = 0.85\\ \kappa_2 = 1.0\end{array}\right\} \Rightarrow \mu_{0,M,\kappa} = \mu_{0,M} \times (\kappa_1 \kappa_2) = 0.262$$

$$\mu_{0,V,\kappa} = \mu_{0,V} = 0.088$$

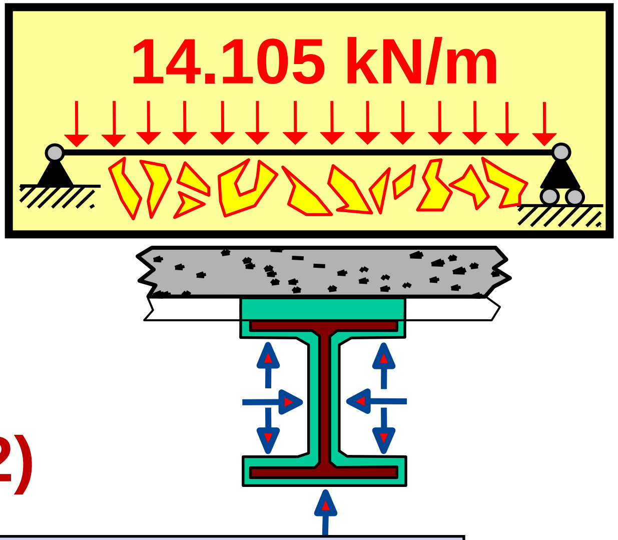
no adaptation factors for vertical shear

➢ **Design value of degree of utilisation**

$$\mu_0 = \max(\mu_{0,M,\kappa}, \mu_{0,V,\kappa}) = 0.262$$

Step 5b: Critical temperature (insulated beam)

- with simple calculation rule
- with accurate reduction factor table



➢ **Simple calculation rule (relation 4.22)**

$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 \approx 684 \ \ °C$$

➢ **Linear interpolation of the reduction factor $k_{y,\theta}$ (table 3.1)**

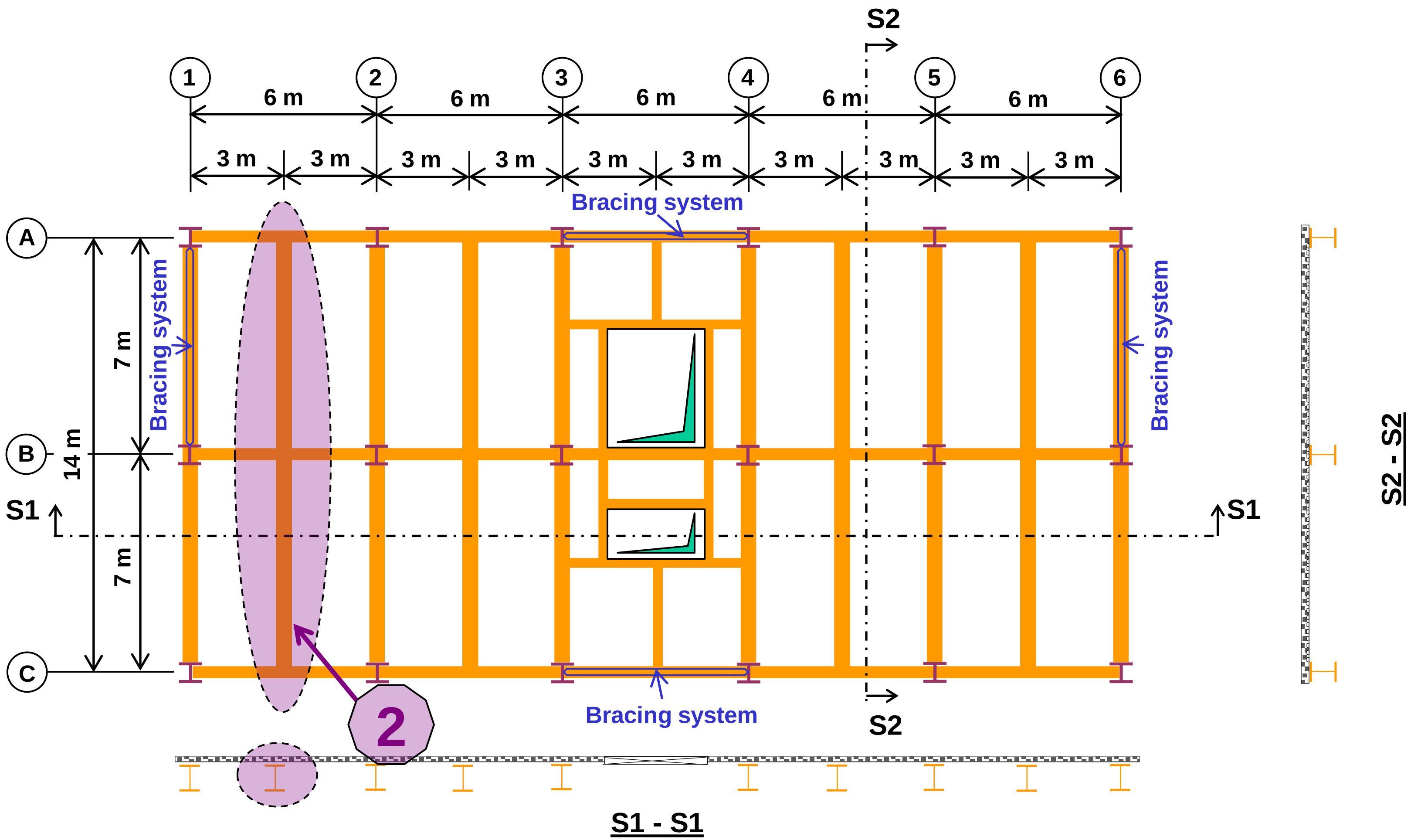
at 600 °C: $k_{y,\theta} = 0.47$

at 700 °C: $k_{y,\theta} = 0.23$

$$\theta_{cr} \approx 687 \ \ °C$$

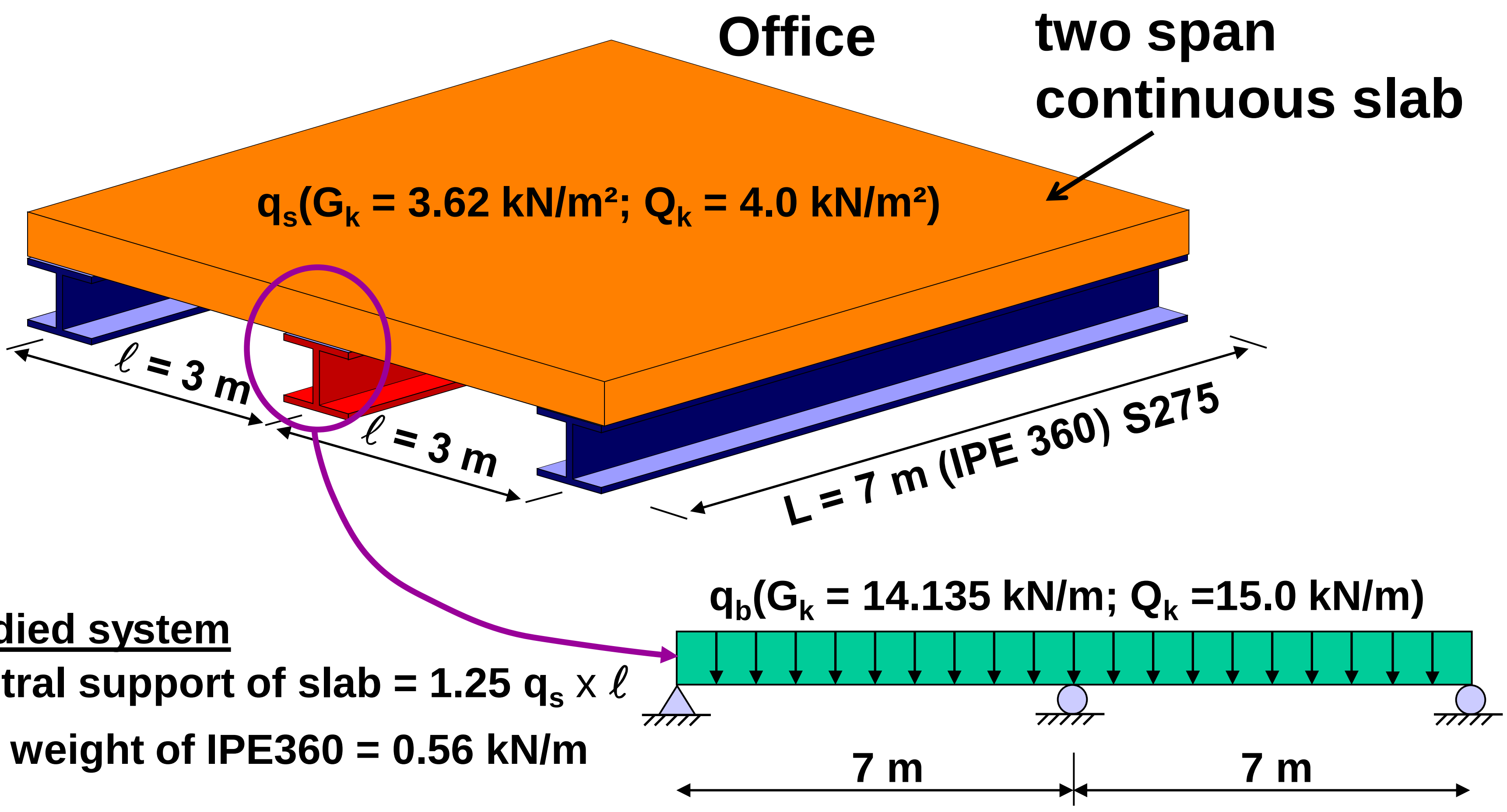
Worked example 2

Secondary beams under central support of the continuous slabs



Step 1: Design mechanical action in fire design

- Summary of input data



<u>Studied system</u>

Central support of slab = 1.25 q_s x ℓ

Self weight of IPE360 = 0.56 kN/m

2. Secondary beams under central support of the continuous slab

Step 1: Design mechanical action in fire situation

- Design load in fire situation

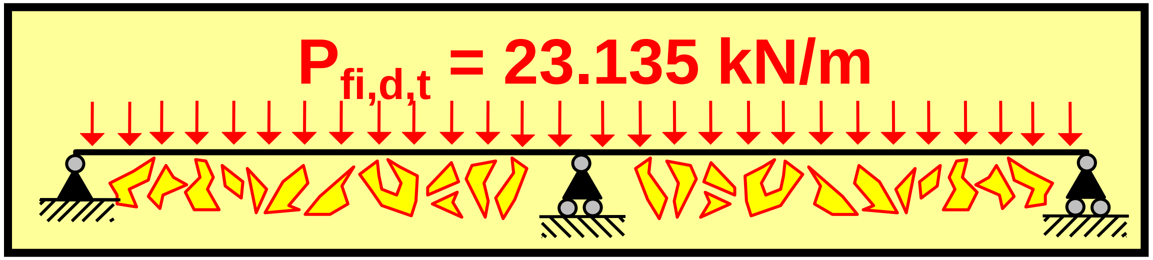
$$E_{fi,d,t} = \sum_{j \geq 1} G_{k,j} + \Psi_{2,1} Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i} Q_{k,i}$$

$$q_{fi,d,t} = 1.25 \times \left(G_{k,1} + \psi_{2,1} Q_{k,1}\right) \times \ell = 23.135 \text{ kN/m}$$

1.25 → **central support of 2 span slab**

$\psi_{2,1}$ → **0.6**

Two span continuous beam



Step 2: Classify member

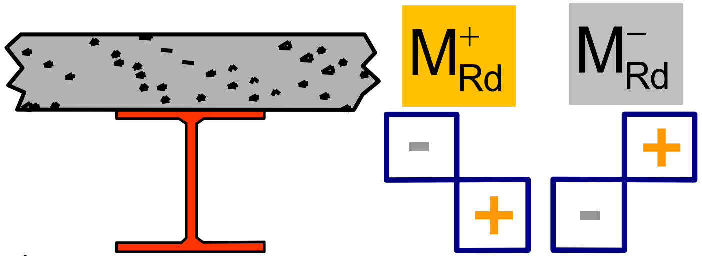
- Bending member (**IPE360**)

Relation 4.2 of Eurocode 3 part 1-2

$$\varepsilon = 0.85\sqrt{235/f_y} = 0.786$$

S275

Table 5.2 of Eurocode 3 part 1-1



$c/t_w \le 72\varepsilon$ → ***Web class 1***

= 37.3 *= 56.6*

$c/t_f \le 9\varepsilon$ → ***Flange class 1***

= 4.96 *= 7.07*

Pure bending

Section class 1

2. Secondary beams under central support of the continuous slab

Step 3: Design resistance at ambient temperature

- two equal span continuous beam

➢ Plastic load-bearing capacity

- Moment resistance ratio

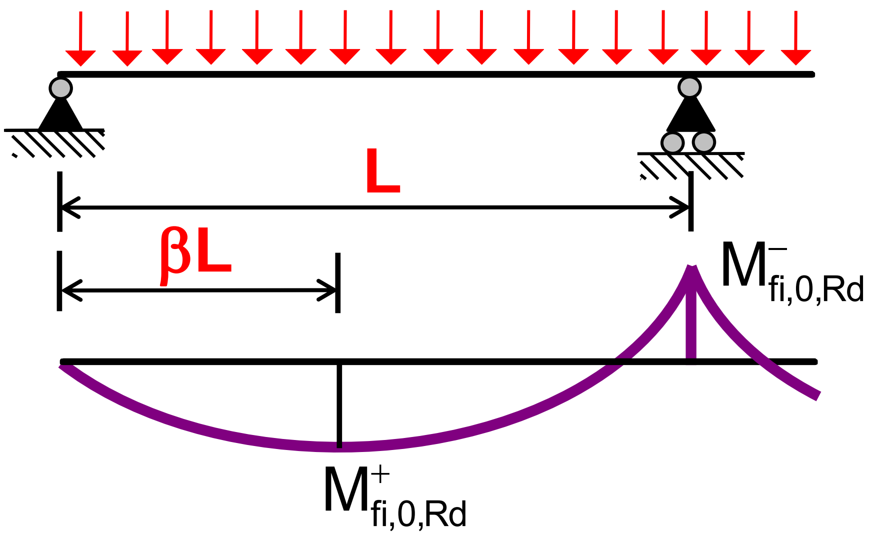
$$n = \left| M^{-}_{fi,0,Rd} \big/ M^{+}_{fi,0,Rd} \right|$$

- Plastic hinge position

$$\beta = \sqrt{1+n} - 1/n$$

- Load-bearing capacity

$$q_{fi,0,Rd} = 2M^{+}_{fi,0,Rd} \big/ (\beta L)^2$$



- Necessary vertical shear resistance at central support

$$V^{(n)}_{fi,0,Rd} = q_{fi,0,Rd}\, L/2 + M^{+}_{fi,0,Rd} \big/ L$$

Step 3: Design resistance at ambient temperature

- Design resistance at ambient temperature according to Eurocode 3 part 1-1

IPE360	
$W_{pl,y}$ (cm³)	1019.15
A_v (cm²)	35.14

➢ **Moment resistance (relation 6.13)**

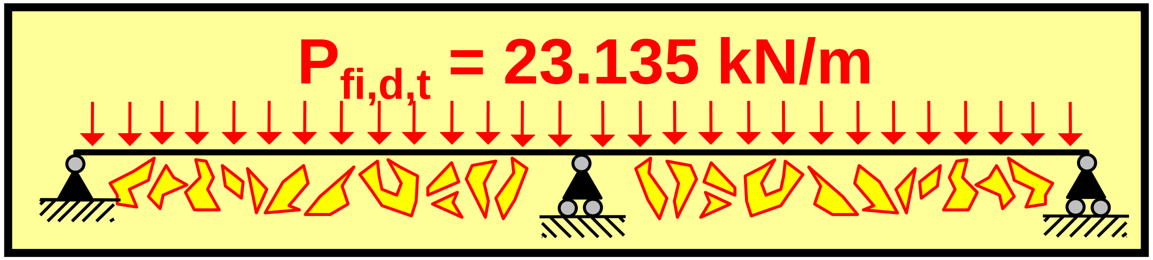
$$M_{Rd} = M_{pl,Rd} = \frac{W_{pl,y} f_y}{\gamma_{M0}} = 280.3 \ \text{kNm}$$

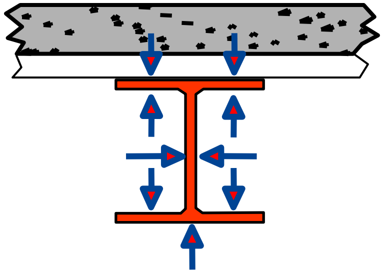
➢ **Vertical shear resistance (relation 6.18)**

$$V_{Rd} = V_{pl,Rd} = \frac{A_v \left(f_y / \sqrt{3}\right)}{\gamma_{M0}} = 557.9 \ \text{kN}$$

$\gamma_{M0} = 1$

Step 3a: Design resistance at ambient temperature (bare beam and **four sides exposed**)





- **Modify sagging moment resistance at 20°C (relation 4.10)**
  - refer to Step 3 for M_{Rd}

$$\left.\begin{array}{l}\kappa_1 = 1.0\\ \kappa_2^{+} = 1.0\end{array}\right\} \Rightarrow M^{+}_{fi,0,Rd} = \frac{M_{Rd}}{\kappa_1 \kappa_2^{+}} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 280.3\ \text{kNm}$$

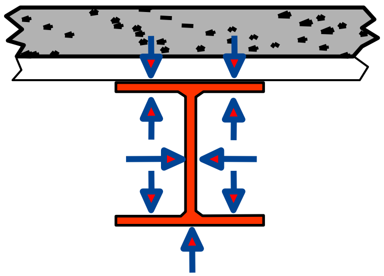
- **Modify hogging moment resistance at 20°C (relation 4.10)**

$$\left.\begin{array}{l}\kappa_1 = 1.0\\ \kappa_2^{-} = 0.85\end{array}\right\} \Rightarrow M^{-}_{fi,0,Rd} = \frac{M_{Rd}}{\kappa_1 \kappa_2^{-}} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 329.7\ \text{kNm}$$

Step 3a: Design resistance at ambient temperature (bare beam)

•two equal span continuous beam and four sides exposed section

- **Plastic load-bearing capacity**



$$n = \left| M_{Rd}^{-} / M_{Rd}^{+} \right| = \kappa_2^{+} / \kappa_2^{-} = 1.176$$

$$\beta = \sqrt{1+n} - 1/n = 0.404$$

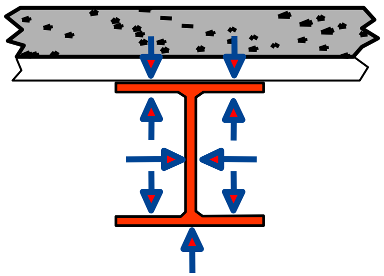
$$q_{fi,0,Rd} = 2M_{Rd}^{+} / (\beta L)^2 = 70.1\ \text{kN/m}$$

Step 4a: Degree of utilisation (bare beam)

$$\mu_0 = q_{fi,d,t} / q_{fi,0,Rd} = 0.330$$

2. Secondary beams under central support of the continuous slab

Step 4a: Degree of utilisation (bare beam)



- two equal spans continuous beam and four sides exposed section

➢ Check of vertical shear resistance at central support

- Necessary vertical shear resistance at central support

$$V_{fi,0,Rd}^{(n)} = q_{fi,0,Rd} L/2 + M_{fi,0,Rd}^{+}/L = 292.4 \ \text{kN}$$

- Vertical shear resistance of the beam at central support

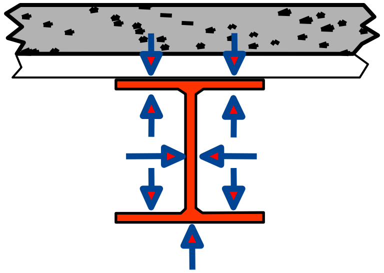
$$V_{fi,0,Rd} = V_{Rd} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 557.9 \ \text{kN} > V_{fi,0,Rd}^{(n)}$$

no adaptation factors for vertical shear

- **As $V_{fi,0,Rd} > V_{fi,0,Rd}^{(n)}$ no further calculation is needed to modify the degree of utilisation**

Step 5a: Critical temperature (bare beam)

- with simple calculation rule (relation 4.22)
- with accurate reduction factor table (Table 3.1)



➢ **Simple calculation rule (relation 4.22)**

$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 = 649 \quad °C$$

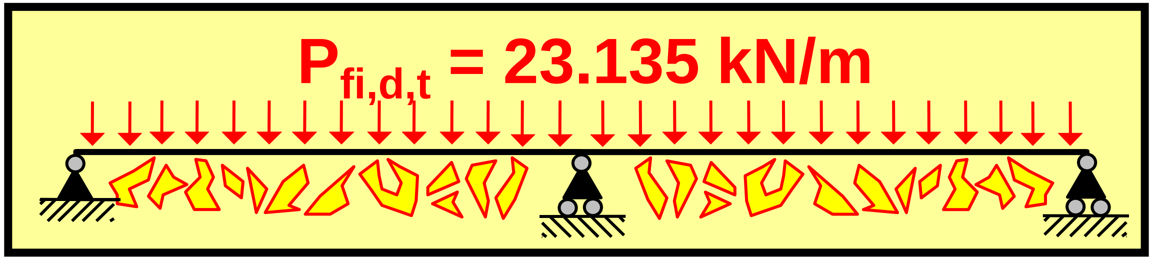
➢ **Linear interpolation of the reduction factor $k_{y,\theta}$ (Table 3.1)**

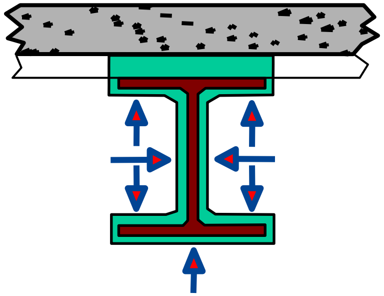
at 600 °C: $k_{y,\theta} = 0.47$

at 700 °C: $k_{y,\theta} = 0.23$

$$\theta_{cr} = 658 \quad °C$$

Step 3b: Design resistance at ambient temperature (insulated beam – 3 sides exposed)





- **Modify sagging moment resistance at 20°C (relation 4.10)**
  - refer to **Step 3** for M_{Rd}

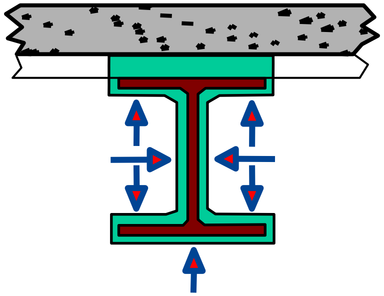
$$\left.\begin{array}{l}\kappa_1 = 0.85 \\ \kappa_2^+ = 1.0\end{array}\right\} \Rightarrow M^+_{fi,0,Rd} = \frac{M_{Rd}}{\kappa_1^+ \kappa_2^+} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 329.7 \text{ kNm}$$

- **Modify hogging moment resistance at 20°C (relation 4.10)**

$$\left.\begin{array}{l}\kappa_1 = 0.85 \\ \kappa_2^- = 0.85\end{array}\right\} \Rightarrow M^-_{fi,0,Rd} = \frac{M_{Rd}}{\kappa_1^- \kappa_2^-} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 387.9 \text{ kNm}$$

2. Secondary beams under central support of the continuous slab

Step 3a: Design resistance at ambient temperature (insulated beam – **3 sides exposed**)



➢ **Plastic load-bearing capacity**

$$n = \left| M_{Rd}^{-} / M_{Rd}^{+} \right| = \kappa_2^{+} / \kappa_2^{-} = 1.176$$

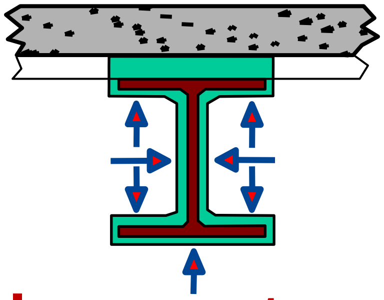
$$\beta = \sqrt{1+n} - 1/n = 0.404$$

$$q_{fi,0,Rd} = 2M_{Rd}^{+} / (\beta L)^2 = 82.5 \ \text{kN/m}$$

Step 4b: Degree of utilisation (insulated beam – **3 sides exposed**)

$$\mu_0 = q_{fi,d,t} / q_{fi,0,Rd} = 0.281$$

Step 4b: Degree of utilisation (insulated beam – **3 sides exposed**)



- Two equal spans continuous beam

➢ **Check of vertical shear resistance at central support**

- Necessary vertical shear resistance at central support

$$V^{(n)}_{fi,0,Rd} = q_{fi,0,Rd}\, L/2 + M^{+}_{fi,0,Rd}/L = 344.0 \text{ kN}$$

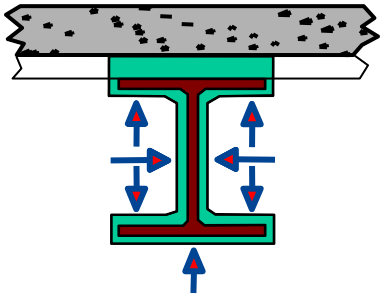
- Vertical shear resistance of the beam at central support

$$V_{fi,0,Rd} = V_{Rd}\,\frac{\gamma_{M0}}{\gamma_{M,fi}} = 557.9 \text{ kN} > V^{(n)}_{fi,0,Rd}$$

no adaptation factors for vertical shear

- **As** $V_{fi,0,Rd} > V^{(n)}_{fi,0,Rd}$ **no further calculation is needed to modify the degree of utilisation**

Step 5b: Critical temperature (insulated beam – **3 sides exposed**)



- with simple calculation rule (relation 4.22)
- with accurate reduction factor table (Table 3.1)

➢ **Simple calculation rule (relation 4.22)**

$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 = 674 \quad °C$$

➢ **Linear interpolation of the reduction factor $k_{y,\theta}$ (Table 3.1)**

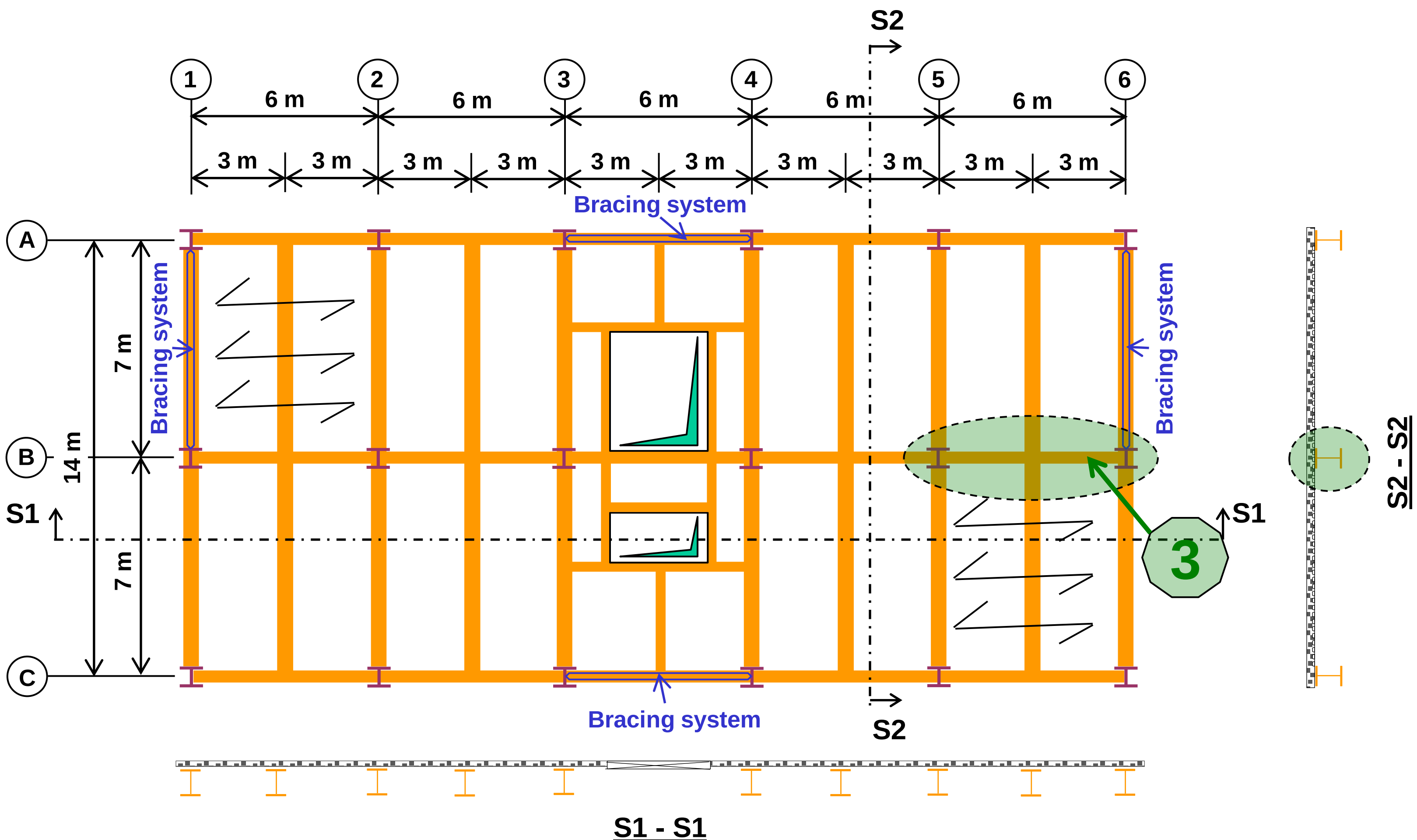
at 600 °C: $k_{y,\theta} = 0.47$

at 700 °C: $k_{y,\theta} = 0.23$

$$\theta_{cr} = 679 \quad °C$$

Worked example 3

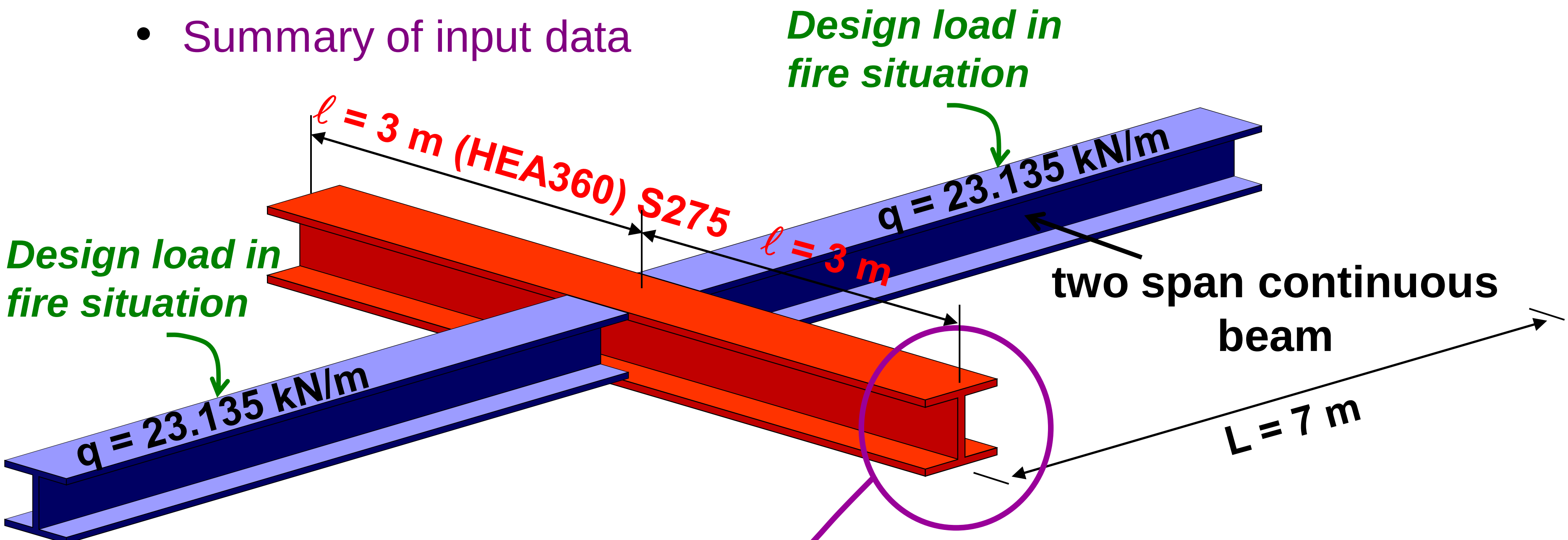
Simply supported central main beams



3. Simply supported central main beams

Step 1: Design mechanical action in fire design

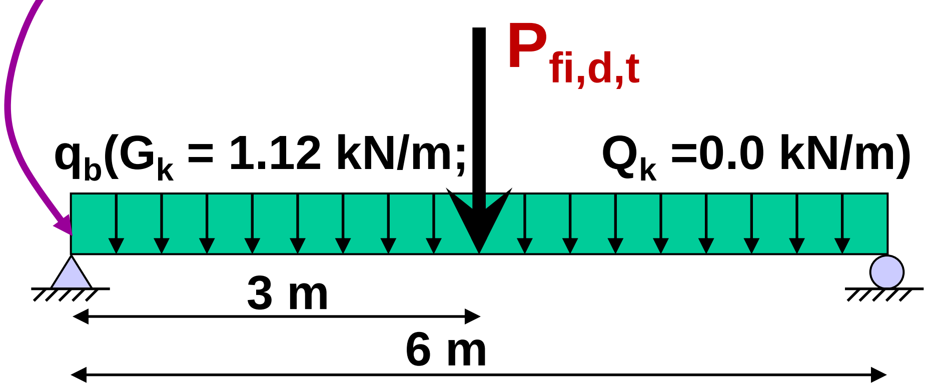
- Summary of input data



<u>**Studied system**</u>

Central support of secondary beam = 1.25 q x L

Self weight of HEA360 = 1.12 kN/m



3. Simply supported central main beams

Step 1: Design mechanical action in fire situation

- Design load in fire situation

$$E_{fi,d,t} = \sum_{j \geq 1} G_{k,j} + \Psi_{2,1} Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i} Q_{k,i}$$

➢ **Uniformely distributed load**

$$q_{fi,d,t} = G_{k,1} + \psi_{2,1} Q_{k,1} = 1.12 \text{ kN/m}$$

Self weight ($G_{k,1}$); **0.6** ($\psi_{2,1}$)

➢ **Concentrated load from continuous secondary beam**

$$P_{fi,d,t} = 1.25 \times (G_{k,1} + \psi_{2,1} Q_{k,1}) \times L$$

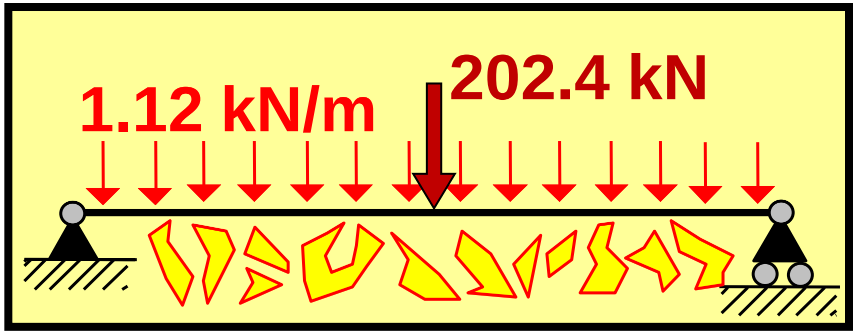
$$= 1.25 \times 23.135 \times 7 = 202.4 \text{ kN/m}$$

design load of secondary beam in fire situation (23.135)

Step 1: Design mechanical action in fire situation

- both uniform and concentrated loads

➢ Design loading conditions in fire situation



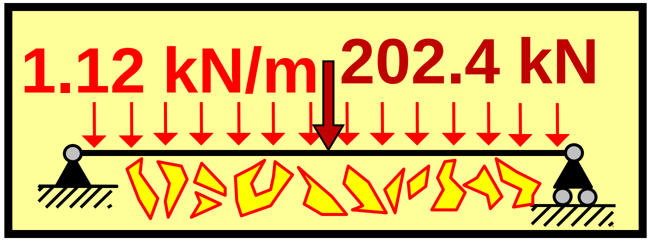
➢ Applied bending moment and vertical shear

$$M_{fi,d,t} = \frac{q_{fi,d,t}\ell^2}{2} + \frac{P_{fi,d,t}\ell}{2} = 308.6 \text{ kNm}$$

$$V_{fi,d,t} = q_{fi,d,t}\ell + \frac{P_{fi,d,t}}{2} = 104.5 \text{ kN}$$

$$\ell = 3 \text{ m}$$

3. Simply supported central main beams



Step 2: Classify member

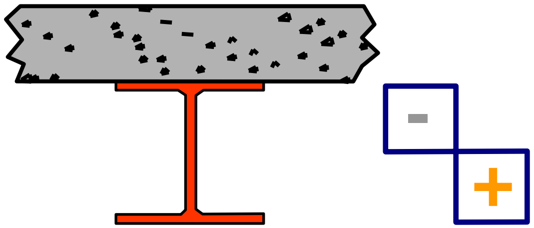
- Bending member (**HEA360**)

Relation 4.2 of Eurocode 3 part 1-2

$$\varepsilon = 0.85\sqrt{235/f_y} = 0.786$$

S275

Table 5.2 of Eurocode 3 part 1-1



Pure bending

$$c/t_w \le 72\varepsilon \rightarrow \textit{Web class 1}$$

= 26.1 = 56.6

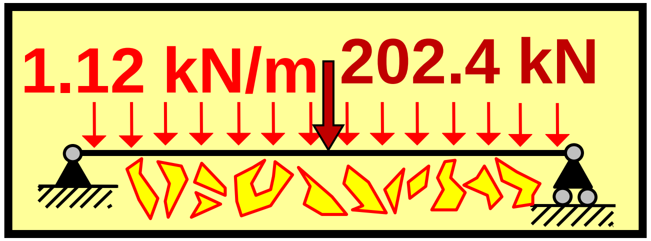
$$c/t_f \le 9\varepsilon \rightarrow \textit{Flange class 1}$$

= 6.74 = 7.07

Section class 1

3. Simply supported central main beams

Step 3: Design resistance at ambient temperature



- Design resistance at ambient temperature according to Eurocode 3 part 1-1

➢ **Moment resistance (relation 6.13)**

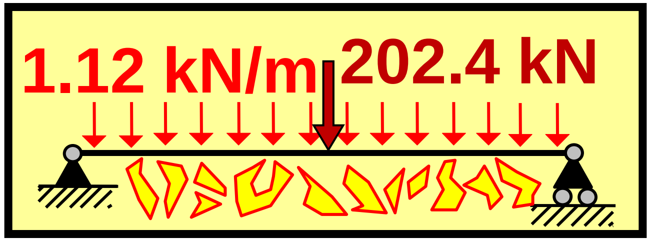
HEA360	
$W_{pl,y}$ (cm^3)	**2088.47**
A_v (cm^2)	**48.96**

$$M_{Rd} = M_{pl,Rd} = \frac{W_{pl,y} f_y}{\gamma_{M0}} = 574.3 \text{ kNm}$$

➢ **Vertical shear resistance (relation 6.18)**

$\gamma_{M0} = 1$

$$V_{Rd} = V_{pl,Rd} = \frac{A_v \left(f_y / \sqrt{3}\right)}{\gamma_{M0}} = 777.3 \text{ kN}$$



Step 4: Degree of utilisation

- with respect to two resistance forces
- without consideration of adaptation factors κ_1 and κ_2

➢ **Relative to moment resistance (relation 4.24)**

$$\mu_{0,M} = \eta_{fi,M}\frac{\gamma_{M0}}{\gamma_{M,fi}} = \frac{M_{fi,d,t}}{M_{Rd}}\frac{\gamma_{M0}}{\gamma_{M,fi}} = 0.537$$

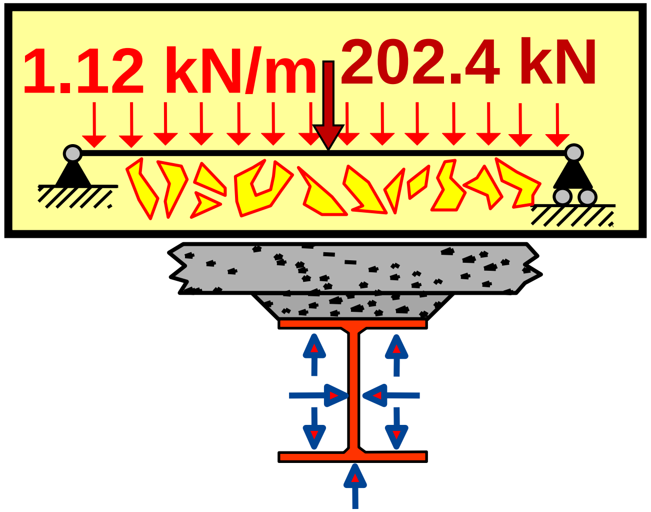
➢ **Relative to vertical shear resistance (relation 4.24)**

$$\mu_{0,V} = \eta_{fi,V}\frac{\gamma_{M0}}{\gamma_{M,fi}} = \frac{V_{fi,d,t}}{V_{Rd}}\frac{\gamma_{M0}}{\gamma_{M,fi}} = 0.134$$

$$\gamma_{M0} = \gamma_{M,fi} = 1$$

Step 4: Degree of utilisation

- modification with consideration of adaptation factors κ_1 and κ_2 for bare steel beams



➤ **On the basis of relation 4.10**

three sides exposed (bare)

$$\left.\begin{aligned}\kappa_1 &= 0.70\\ \kappa_2 &= 1.0\end{aligned}\right\} \Rightarrow \begin{aligned}\mu_{0,M,\kappa} &= \mu_{0,M} \times (\kappa_1 \kappa_2) = 0.376\\ \mu_{0,V,\kappa} &= \mu_{0,V} = 0.134\end{aligned}$$

no adaptation factors for vertical shear

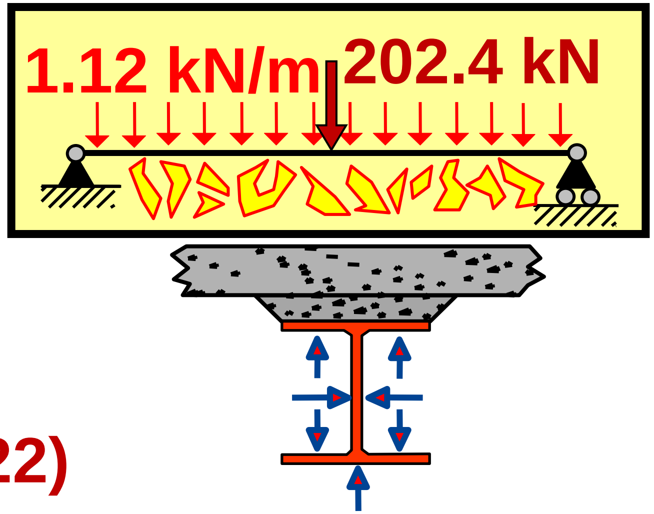
➤ **Design value of degree of utilisation**

$$\mu_0 = \max(\mu_{0,M,\kappa}, \mu_{0,V,\kappa}) = 0.376$$

3. Simply supported central main beams

Step 5: Critical temperature (bare beams)

- with simple calculation rule
- with accurate reduction factor table



➢ **Simple calculation rule (relation 4.22)**

$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 \approx 629 \ \ ^\circ C$$

➢ **Linear interpolation of the reduction factor $k_{y,\theta}$ (table 3.1)**

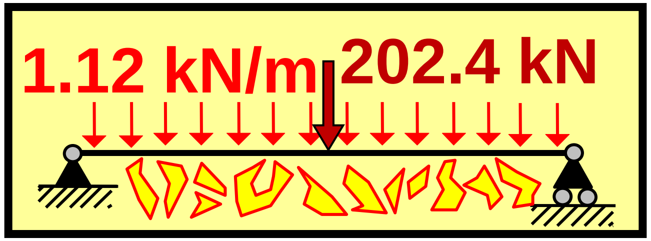
at 600 °C: $k_{y,\theta} = 0.47$

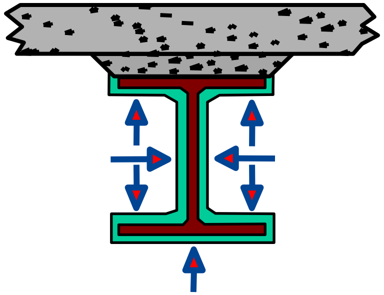
at 700 °C: $k_{y,\theta} = 0.23$

$$\theta_{cr} \approx 639 \ \ ^\circ C$$

Step 4b: Degree of utilisation

•modification with consideration of adaptation factors κ_1 and κ_2 for insulated steel beams





➢ **On the basis of relation 4.10**

three sides exposed (insulated)

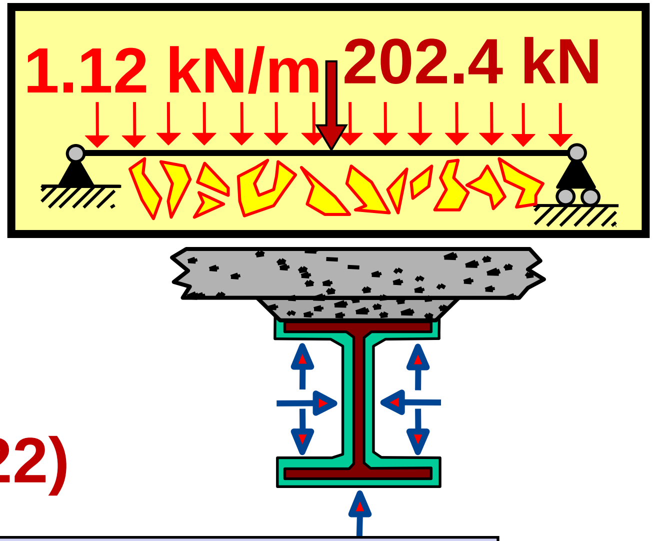
$$\left.\begin{aligned}\kappa_1 &= 0.85\\ \kappa_2 &= 1.0\end{aligned}\right\} \Rightarrow \begin{aligned}\mu_{0,M,\kappa} &= \mu_{0,M} \times (\kappa_1 \kappa_2) = 0.457\\ \mu_{0,V,\kappa} &= \mu_{0,V} = 0.134\end{aligned}$$

no adaptation factors for vertical shear

➢ **Design value of degree of utilisation**

$$\mu_0 = \max(\mu_{0,M,\kappa}, \mu_{0,V,\kappa}) = 0.457$$

3. Simply supported central main beams



Step 5b: Critical temperature (insulated beam)

- with simple calculation rule
- with accurate reduction factor table

➢ **Simple calculation rule (relation 4.22)**

$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 \approx 599 \ \text{°C}$$

➢ **Linear interpolation of the reduction factor $k_{y,\theta}$ (table 3.1)**

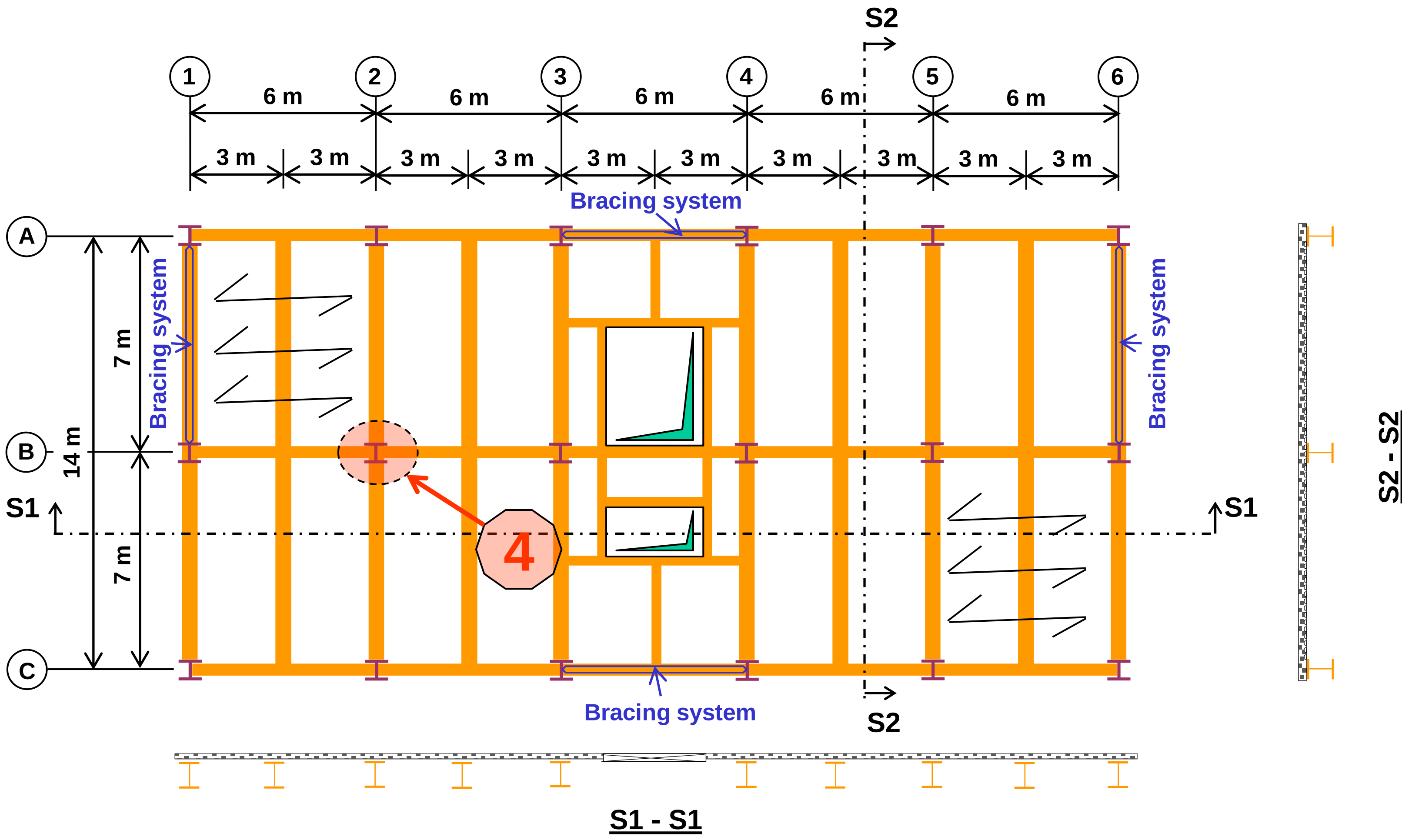
at 600 °C: $k_{y,\theta} = 0.47$

at 700 °C: $k_{y,\theta} = 0.23$

$$\theta_{cr} \approx 606 \ \text{°C}$$

Worked examples

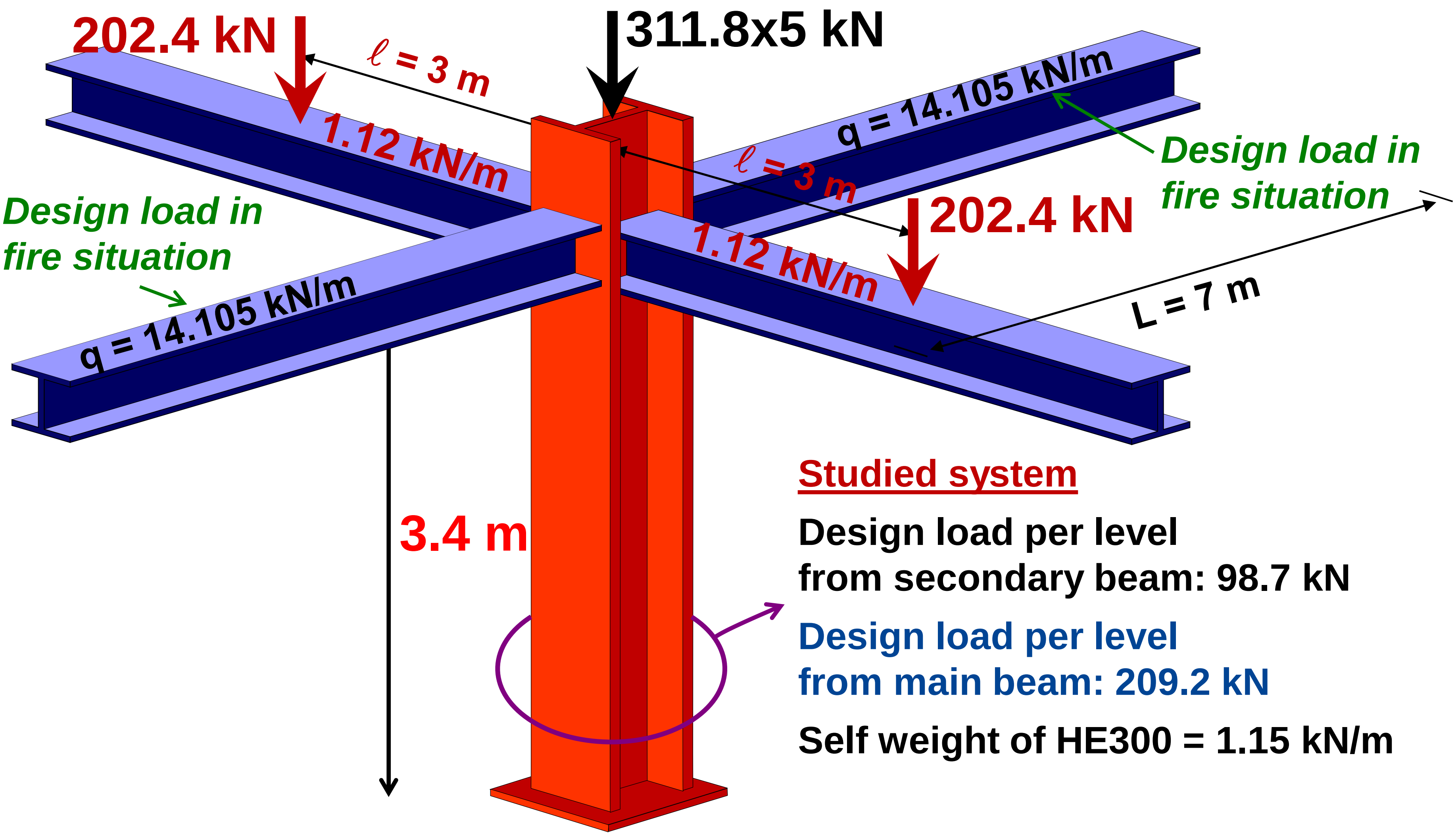
Central columns at ground level



4. Central column at ground level

Step 1: Design mechanical action in fire design

- Summary of input data



Studied system

Design load per level from secondary beam: 98.7 kN

Design load per level from main beam: 209.2 kN

Self weight of HE300 = 1.15 kN/m

Step 1: Design mechanical action in fire situation

- Design load in fire situation

$$E_{fi,d,t} = \sum_{j \geq 1} G_{k,j} + \Psi_{2,1} Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i} Q_{k,i}$$

➢ **Self weight of the column**

$$q_{fi,d,t} = 1.148 \times 3.4 \approx 3.9 \text{kN/m}$$

➢ **Total concentrated axial load from steel beams**

$$P_{fi,d,t} = \sum \left(G_{k,1} + \psi_{2,1} Q_{k,1} \right)$$

$$= \underbrace{14.105 \times 7}_{\text{secondary beam}} + \underbrace{202.4 + 1.12 \times 6}_{\text{main beam}} \approx 307.9 \text{ kN}$$

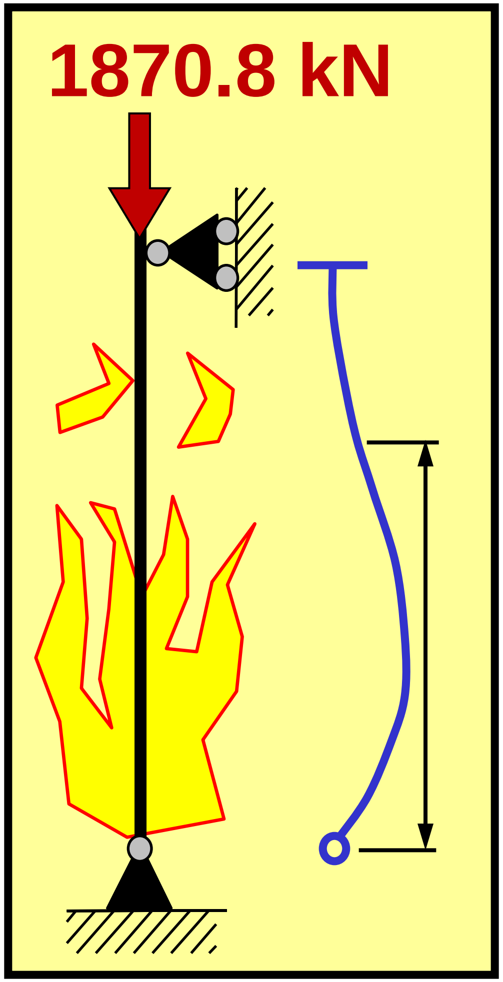
Step 1: Design mechanical action in fire situation

- **Total design loading conditions in fire situation**

$$N_{fi,d,t} = (307.9 + 3.9) \times 6 = 1870.8 \text{ kN}$$

- **Buckling length in fire situation**
  - pinned column base

$$L_{fi} = 0.7L = 0.7 \times 3.4 = 2.38 \text{ m}$$



4. Central column at ground level

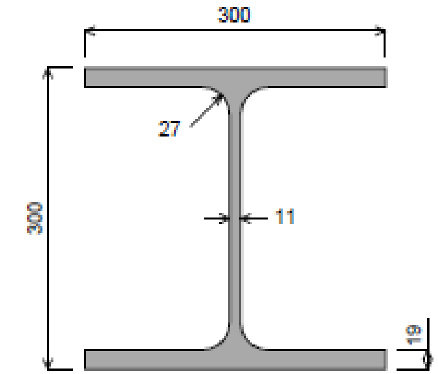
Step 2: Classify member

- Bending member

Relation 4.2 of Eurocode 3 part 1-2

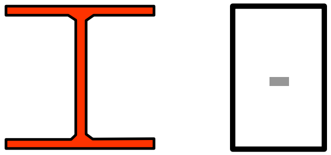
$$\varepsilon = 0.85\sqrt{235/f_y} = 0.786$$

f_y → *S275*



HEB300

Table 5.2 of Eurocode 3 part 1-1



Compression

$$c/t_w \leq 33\varepsilon$$ → ***Web class 1***

c/t_w *= 18.9*; 33ε *= 25.9*

$$c/t_f \leq 9\varepsilon$$ → ***Flange class 1***

c/t_f *= 6.2*; 9ε *= 7.07*

→ **Section class 1**

Step 3: Design resistance **at instant 0** (ambient temperature)

- Design resistance at instant 0 (ambient temperature) according to **Eurocode 3 part 1-2**

> **Plastic axial resistance**

$$N_{pl,fi,0} = A \times f_y / \gamma_{M,fi} = 4099.7 \ \text{kNm}$$

> **Non-dimensional slenderness**

$$\bar{\lambda}_{fi,0} = \sqrt{\frac{Af_y}{N_{cr}}} = \frac{L_{fi}}{i_z} \frac{1}{93.9\varepsilon} = 0.362$$

HEB300	
A (cm²)	149.08
i_z (cm)	7.58

4. Central column at ground level

Step 4: Degree of utilisation for tabulated data

$$\mu_0 = \frac{N_{fi,d,t}}{N_{pl,fi,0}} = 0.456$$

Step 5: Critical temperature

- With $\bar{\lambda}_{fi,0} = 0.362$ and **linear interpolation of tabulated data**

$\bar{\lambda}_{fi,0}$	0.0	**0.2**	**0.4**	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
μ_0											
…	…	…	…	…	…	…	…	…	…	…	…
0.40	629	603	578	544	499						
0.42	621	595	569	535	477						
0.44	613	**588**	**561**	525	455						
0.46	604	**581**	**553**	516	433						
0.48	597	573	545	506	411						
0.50	590	566	536	494	367						
0.52	584	559	528	477							

$$\theta_{cr} \approx 560\ ^{\circ}C$$

Critical temperatures of all calculated steel members

- Bare and insulated

Steel members		Critical temperatures (°C)	
		Bare	Insulated
1	Secondary beams under end support of continuous slab	667	687
2	Secondary beams under central support of continuous slab	658	679
3	Simply supported central main beam	639	606
4	Central column at ground level	560	560

Step 6: Heating of bare steel members under standard fire

Change of steel temperature in time Δt (Section 4.2.5.1 of EN1993-1-2):

$$\Delta\theta_{a.t} = k_{sh} / (c_a \rho_a)\, A_m/V\, h_{net.d}\, \Delta t$$

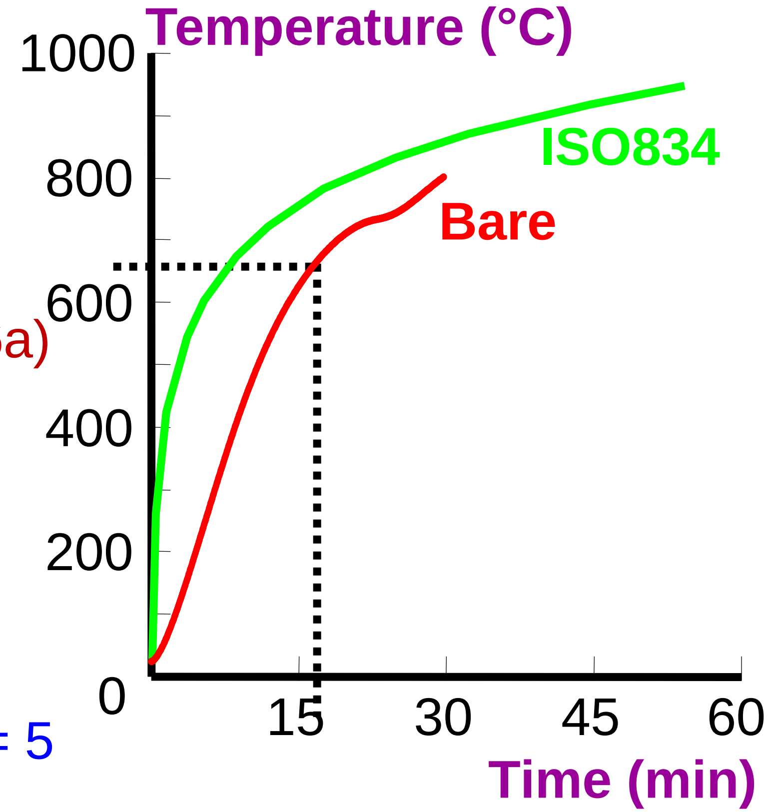
Four sides exposed:

- $\theta_{cr} = 667$ °C
- Section factor: $A_m/V = 186\ m^{-1}$ (IPE360)
- $k_{sh} = 0.9 \times 146/186 = 0.706$ (relation 4.26a)

Net heat flux/unit area $h_{net.d}$ for ISO834 Standard Fire (EN1991-1-2):

- Using $\varepsilon_f = 1.0$ et $\varepsilon_m = 0.7$ (Section 3.1)
- Using $\alpha_c = 25$ W/m²K (Section 3.2.1)

By calculation using Excel sheet with $\Delta t = 5$ seconds …. (4.2.5.1(5) of EN1993-1-2)



Time for bare steel to reach critical temperature = 17 min 00 sec

Step 6: Heating of bare steel members under standard fire

Change of steel temperature in time Δt (Section 4.2.5.1 of EN1993-1-2)**:**

$$\Delta\theta_{a.t} = k_{sh} / (c_a \rho_a) A_m/V h_{net.d} \Delta t$$

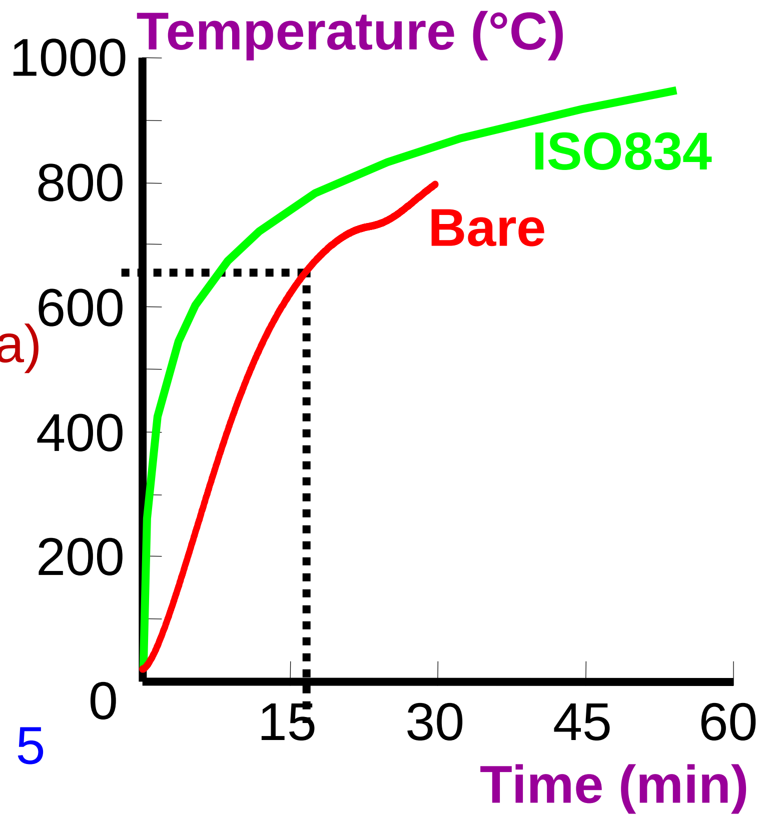
Four sides exposed:

- $\theta_{cr} = 658$ °C
- Section factor: $A_m/V = 186$ m^{-1} (IPE360)
- $k_{sh} = 0.9 \times 146/186 = 0.706$ (relation 4.26a)

Net heat flux/unit area $h_{net.d}$ for ISO834 Standard Fire (EN1991-1-2):

- Using $\varepsilon_f = 1.0$ et $\varepsilon_m = 0.7$ (Section 3.1)
- Using $\alpha_c = 25$ W/m²K (Section 3.2.1)

By calculation using Excel sheet with $\Delta t = 5$ seconds …. (4.2.5.1(5) of EN1993-1-2)



<u>Time for bare steel to reach critical temperature = 16 min 30 sec</u>

Step 6: Heating of bare steel members under standard fire

Change of steel temperature in time Δt (Section 4.2.5.1 of EN1993-1-2)**:**

$$\Delta\theta_{a.t} = k_{sh} / (c_a\, \rho_a)\; A_m/V\; h_{net.d}\; \Delta t$$

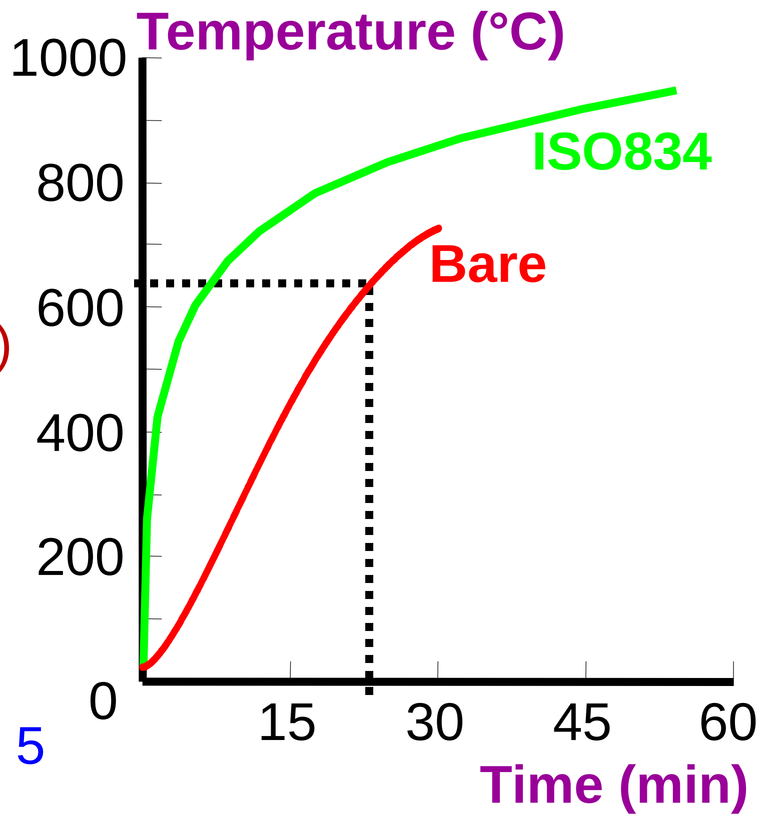
Three sides exposed:

- θ_{cr} = 639 °C
- Section factor: A_m/V = 107 m^{-1} (HEA360)
- k_{sh} = 0.9 x70/107 = 0.589 (relation 4.26a)

Net heat flux/unit area $h_{net.d}$ for ISO834 Standard Fire (EN1991-1-2):

- Using ε_f = 1.0 et ε_m = 0.7 (Section 3.1)
- Using α_c = 25 W/m²K (Section 3.2.1)

By calculation using Excel sheet with Δt = 5 seconds …. (4.2.5.1(5) of EN1993-1-2)



<u>**Time for bare steel to reach critical temperature = 23 min 10 sec**</u>

Step 6: Heating of bare steel members under standard fire

Change of steel temperature in time Δt (Section 4.2.5.1 of EN1993-1-2)**:**

$$\Delta\theta_{a.t} = k_{sh} / (c_a \rho_a) A_m/V h_{net.d} \Delta t$$

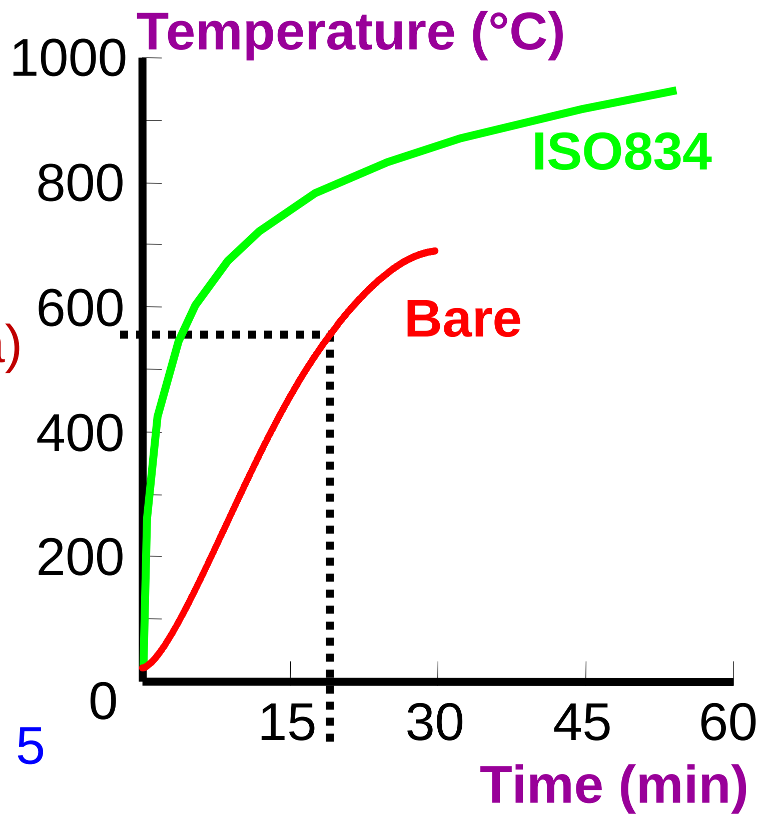
Four sides exposed:

- $\theta_{cr} = 560$ °C
- Section factor: $A_m/V = 116$ m^{-1} (HEB300)
- $k_{sh} = 0.9 \times 80/116 = 0.621$ (relation 4.26a)

Net heat flux/unit area $h_{net.d}$ for ISO834 Standard Fire (EN1991-1-2):

- Using $\varepsilon_f = 1.0$ et $\varepsilon_m = 0.7$ (Section 3.1)
- Using $\alpha_c = 25$ W/m²K (Section 3.2.1)

By calculation using Excel sheet with $\Delta t = 5$ seconds …. (4.2.5.1(5) of EN1993-1-2)



<u>**Time for bare steel to reach critical temperature = 17 min 50 sec**</u>

Summary of standard fire resistance of bare steel members

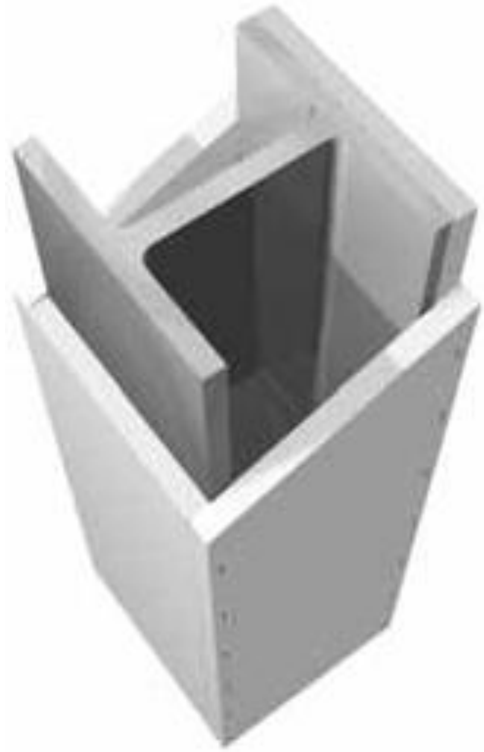
Steel members	θ_{cr} (°C)	$k_{sh}A_m/V$ (m^{-1})	Fire resistance R
Secondary beams under end support of continuous slab	667	131	17 min 00 sec
Secondary beams under central support of continuous slab	658	131	16 min 30 sec
Simply supported central main beam	639	63	23 min 10 sec
Central column at ground level	560	72	17 min 50 sec

Fire resistance of bare members depends on critical temperature, section factor and shadow effect

- Fire resistance of R15
- **Fire protection is needed for R60**

Different fire protection solutions for steel members

- Steel beams: sprayed vermiculite cement – 10 mm and 15 mm
- Steel columns: one layer plasterboard encasement – 12.5 mm



Step 7: Heating of insulated steel members under standard fire

- fire resistance requirement: R60 (60 min)

Temperature increase of steel in time Δt (Section 4.2.5.2 of EN1993-1-2):

$$\Delta\theta_{a.t} = \lambda_p/(d_p c_a \rho_a)\ A_p/V\ [1/(1+\phi/3)]\ (\theta_{g.t}-\theta_{a.t})\Delta t - (e^{\phi/10}-1)\ \Delta\theta_{g.t}$$

Encasement with 10 mm sprayed insulation:

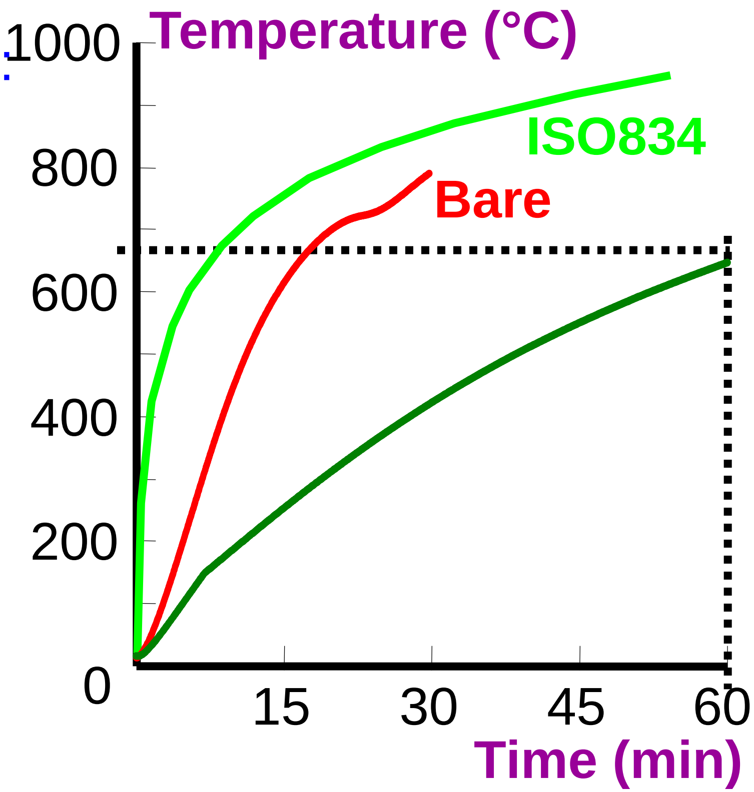
Density	ρ_p	= 350 kg/m³
Specific heat	c_p	= 1200 J/kg°K
Th. conductivity	λ_p	= 0.12 W/m°K

Three sides exposed:

- θ_{cr} = 687 °C and 679 °C
- Section factor: A_p/V = 163 m^{-1} (IPE360)

$$\phi = (c_p \rho_p d_p / c_a \rho_a)\ A_p/V = 0.145$$

At 60 min steel temperature θ_a=643 °C (< θ_{cr} = 687 °C and 679 °C)



Step 7: Heating of insulated steel members under standard fire

•fire resistance requirement: R60 (60 min)

Temperature increase of steel in time Δt (Section 4.2.5.2 of EN1993-1-2):

$$\Delta\theta_{a.t} = \lambda_p/(d_p c_a \rho_a)\ A_p/V\ [1/(1+\phi/3)]\ (\theta_{g.t}-\theta_{a.t})\Delta t - (e^{\phi/10}-1)\ \Delta\theta_{g.t}$$

Encasement with 10 mm sprayed insulation:

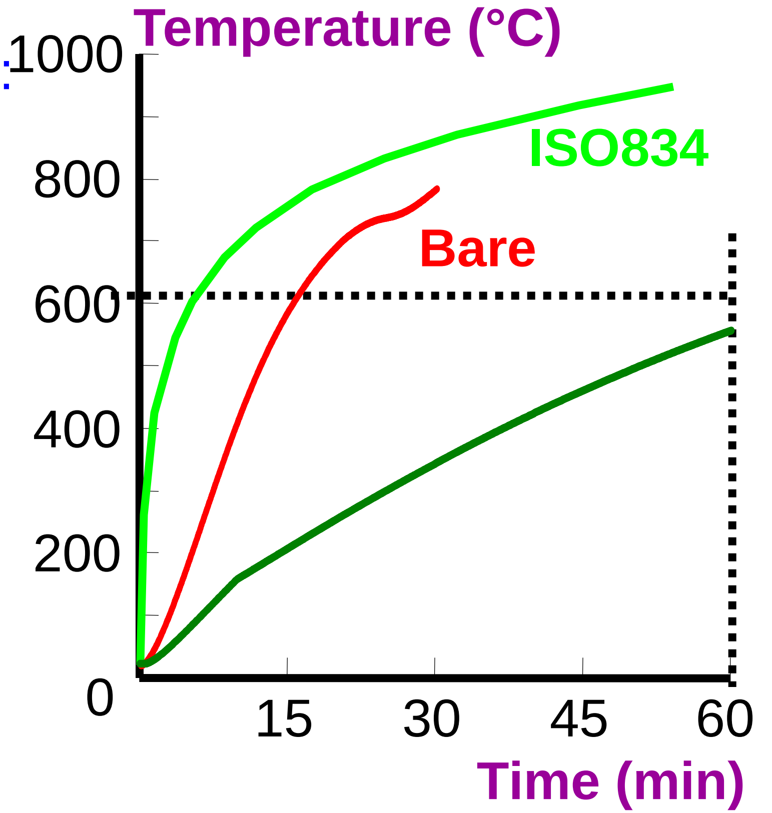
Density	ρ_p	= 350 kg/m^3
Specific heat	c_p	= 1200 J/kg°K
Th. conductivity	λ_p	= 0.12 W/m°K

Three sides exposed:

- $\theta_{cr} = 606$ °C
- Section factor: $A_p/V = 107\ m^{-1}$ (HEA360)

$$\phi = (c_p \rho_p d_p / c_a \rho_a)\ A_p/V = 0.0954$$

At 60 min steel temperature θ_a=514 °C (< θ_{cr} = 606 °C)



Step 7: Heating of insulated steel members under standard fire

- fire resistance requirement: R60 (60 min)

Temperature increase of steel in time Δt (Section 4.2.5.2 of EN1993-1-2):

$$\Delta\theta_{a.t} = \lambda_p/(d_p c_a \rho_a)\ A_p/V\ [1/(1+\phi/3)]\ (\theta_{g.t}-\theta_{a.t})\Delta t - (e^{\phi/10}-1)\ \Delta\theta_{g.t}$$

Encasement with 12.5 mm plasterboard:

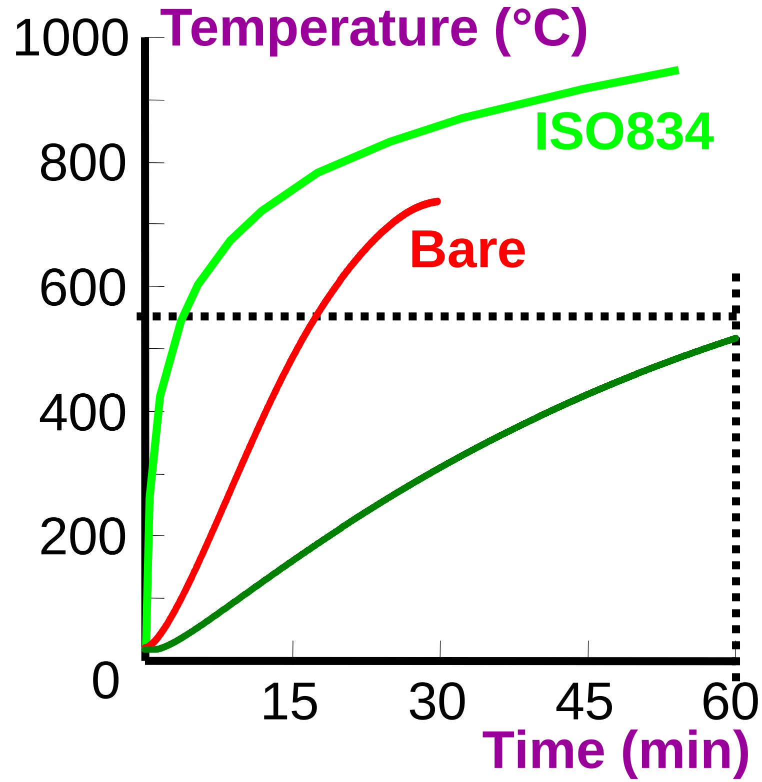
Density	ρ_p	= 800 kg/m^3
Specific heat	c_p	= 1700 J/kg°K
Th. conductivity	λ_p	= 0.20 W/m°K

Three sides exposed:

- $\theta_{cr} = 560$ °C
- Section factor: $A_p/V = 80\ m^{-1}$ (HEB300)

$$\phi = (c_p \rho_p d_p / c_a \rho_a)\ A_p/V = 0.289$$

At 60 min steel temperature θ_a=487 °C (< θ_{cr} = 560 °C)



Summary of passive fire protection of steel members

Steel members	θ_{cr} (°C)	Type of protection	Thickness (mm)
Secondary beams under end support of continuous slab	687	Contour encasement	10
Secondary beams under central support of continuous slab	679	Contour encasement	10
Simply supported central main beam	606	Contour encasement	10
Central column at ground level	560	Hollow encasement	12.5

Optimized solution:

- **Use of continuous secondary beams allows only one protection thickness for all beams – 10 mm**

Thank you for attention

Questions ?

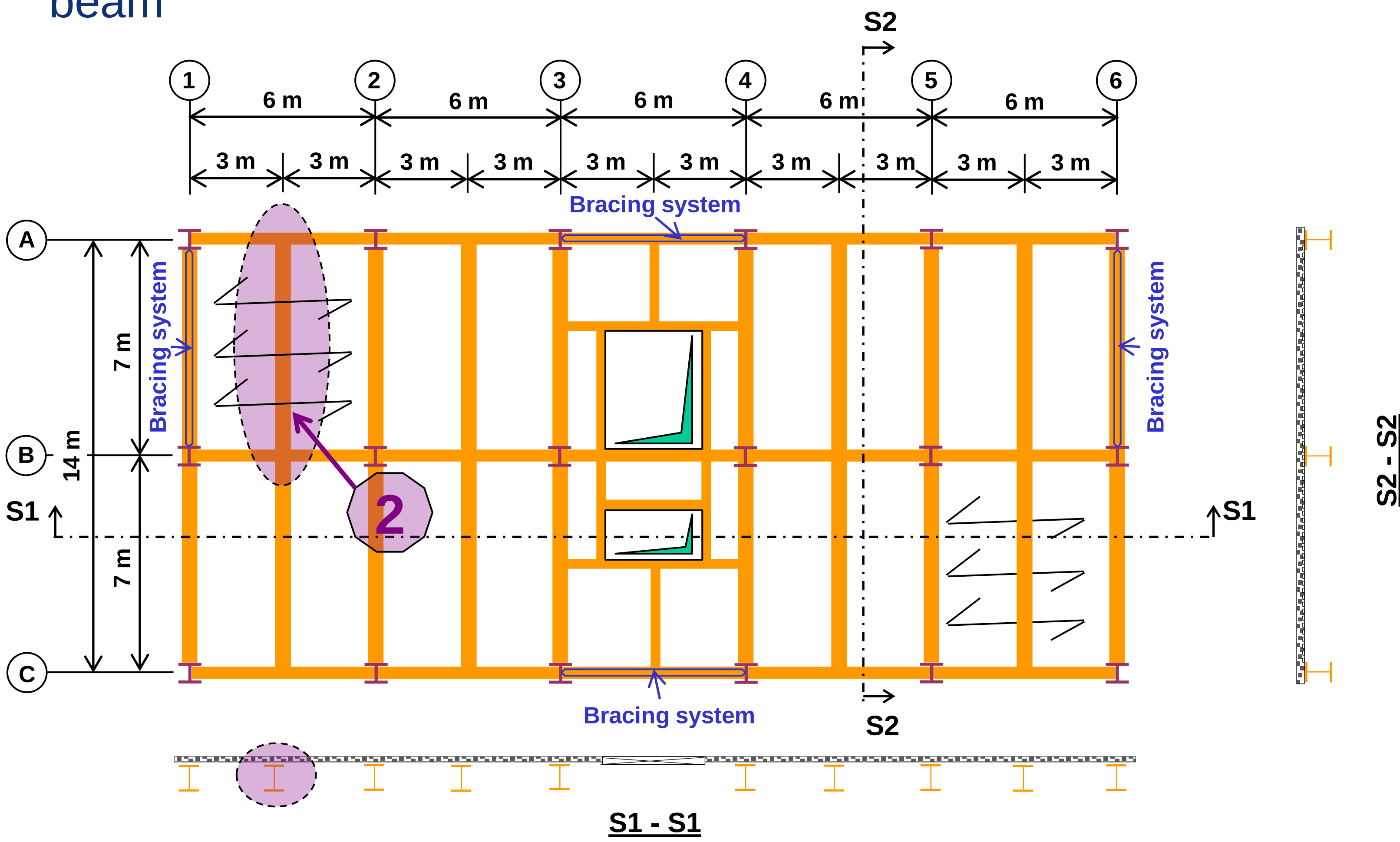
Additional worked examples

according to fire part of Eurocode 3

Option of worked example 2

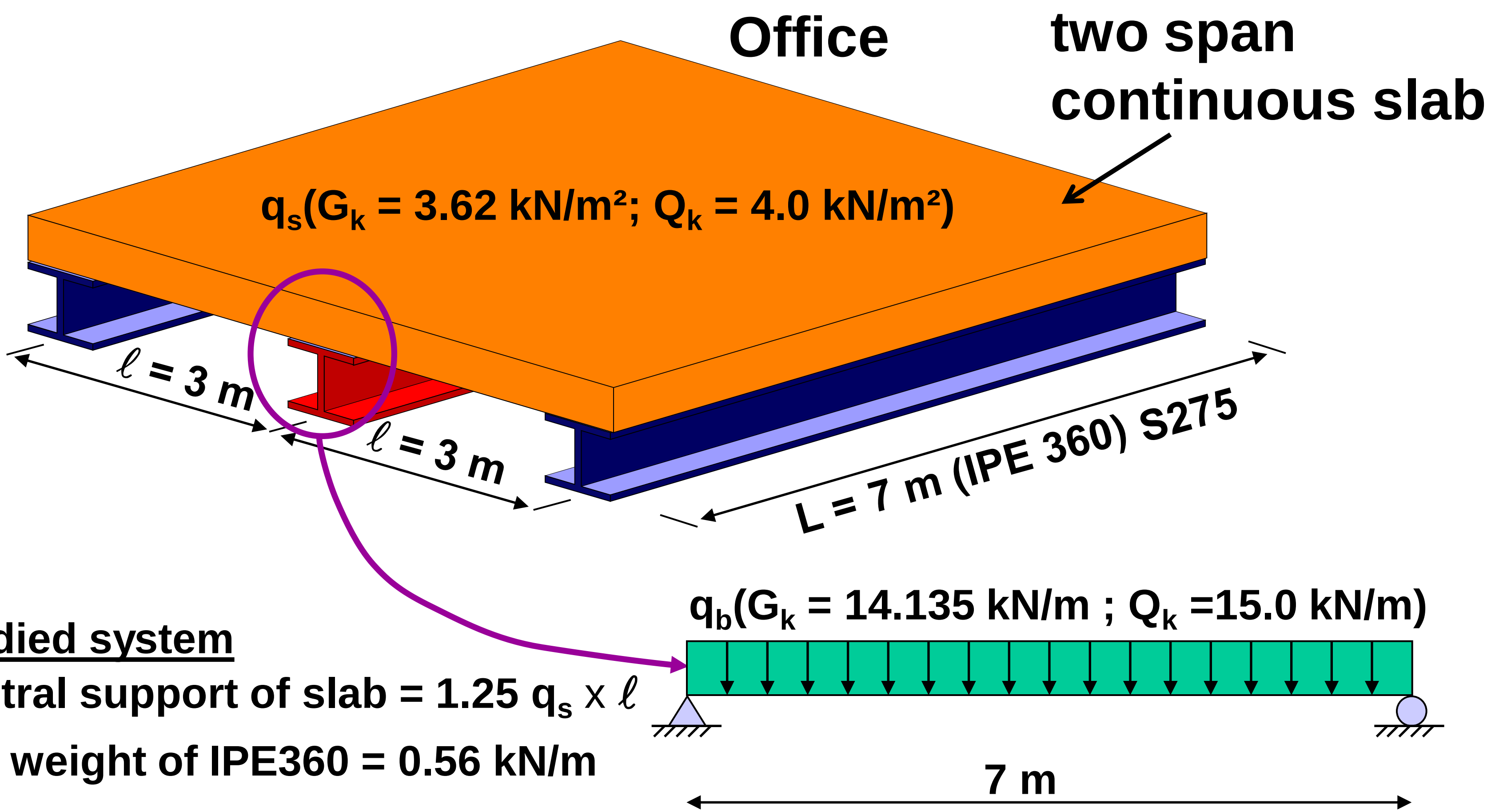
Secondary beams under central support of the continuous slabs

- The beam is considered as simply supported in stead of continuous beam



Step 1: Design mechanical action in fire design

- Summary of input data (***simply supported beam***)



Studied system

Central support of slab = 1.25 q_s x ℓ

Self weight of IPE360 = 0.56 kN/m

Step 1: Design mechanical action in fire situation

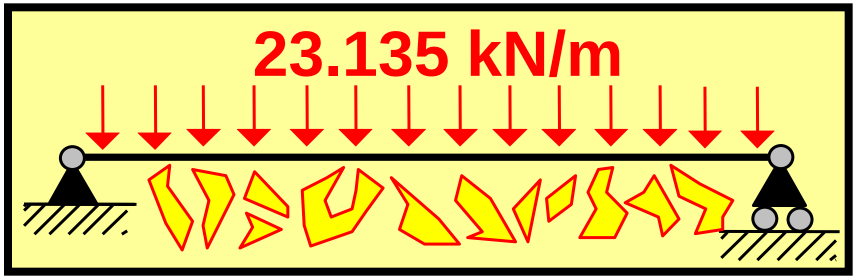
- Design load in fire situation

$$E_{fi,d,t} = \sum_{j \geq 1} G_{k,j} + \Psi_{2,1} Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i} Q_{k,i}$$

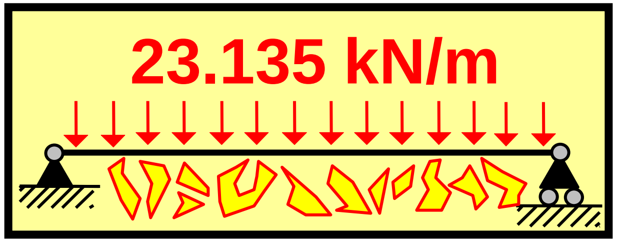
$$q_{fi,d,t} = 1.25 \times \left(G_{k,1} + \psi_{2,1} Q_{k,1}\right) \times \ell = 23.135 \text{ kN/m}$$

1.25 → central support of 2 span slab

$\psi_{2,1}$ → 0.6



$$\begin{cases} M_{fi,d,t} = \dfrac{q_{fi,d,t} L^2}{8} = 141.7 \text{ kNm} \\ V_{fi,d,t} = \dfrac{q_{fi,d,t} L}{2} = 81.0 \text{ kN} \end{cases}$$



Step 2: Classify member

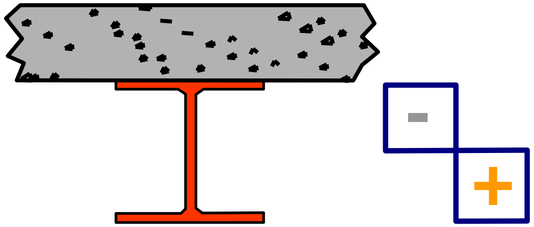
- Bending member (**IPE360**)

Relation 4.2 of Eurocode 3 part 1-2

$$\varepsilon = 0.85\sqrt{235/f_y} = 0.786$$

S275

Table 5.2 of Eurocode 3 part 1-1



Pure bending

$c/t_w \leq 72\varepsilon$ → ***Web class 1***

c/t_w ***= 37.3***; 72ε ***= 56.6***

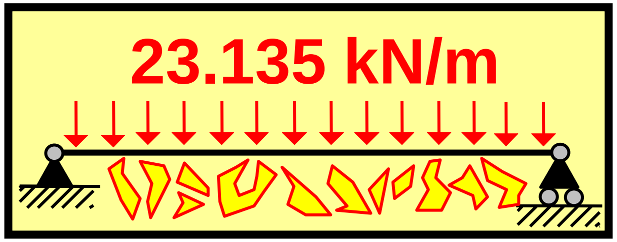
$c/t_f \leq 9\varepsilon$ → ***Flange class 1***

c/t_f ***= 4.96***; 9ε ***= 7.07***

→ **Section class 1**

Step 3: Design resistance at ambient temperature

- Design resistance at ambient temperature according to Eurocode 3 part 1-1



➢ **Moment resistance (relation 6.13)**

$$M_{Rd} = M_{pl,Rd} = \frac{W_{pl,y} f_y}{\gamma_{M0}} = 280.3 \ \text{kNm}$$

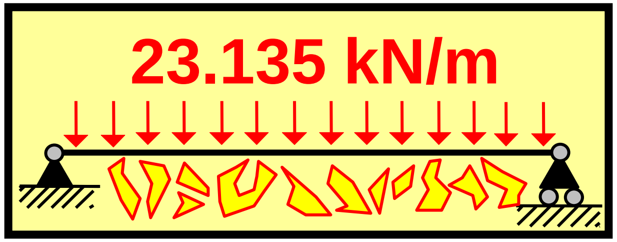
IPE360	
$W_{pl,y}$ (cm^3)	**1019.15**
A_v (cm^2)	**35.14**

➢ **Vertical shear resistance (relation 6.18)**

$$V_{Rd} = V_{pl,Rd} = \frac{A_v \left(f_y / \sqrt{3}\right)}{\gamma_{M0}} = 557.9 \ \text{kN}$$

$\gamma_{M0} = 1$

2b. Secondary beams under central support of the continuous slab



Step 4: Degree of utilisation

- with respect to two resistance forces
- without consideration of adaptation factors κ_1 and κ_2

➢ **Relative to moment resistance (relation 4.24)**

$$\mu_{0,M} = \eta_{fi,M} \frac{\gamma_{M0}}{\gamma_{M,fi}} = \frac{M_{fi,d,t}}{M_{Rd}} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 0.506$$

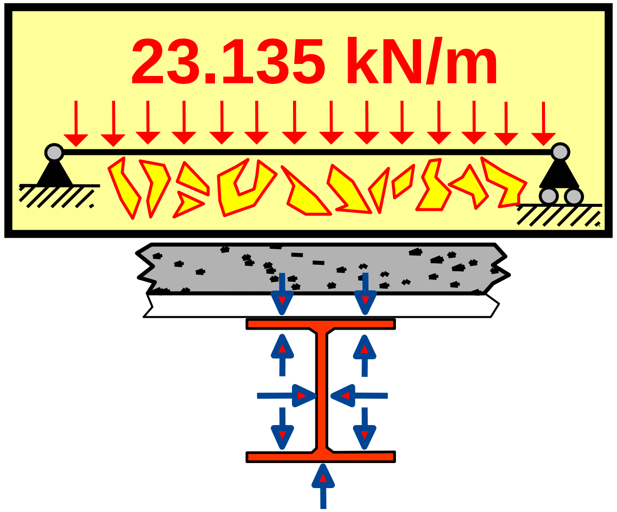
➢ **Relative to vertical shear resistance (relation 4.24)**

$$\mu_{0,V} = \eta_{fi,V} \frac{\gamma_{M0}}{\gamma_{M,fi}} = \frac{V_{fi,d,t}}{V_{Rd}} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 0.145$$

$$\gamma_{M0} = \gamma_{M,fi} = 1$$

Step 4: Degree of utilisation

•modification with consideration of adaptation factors κ_1 and κ_2 for bare steel beams



- **On the basis of relation 4.10**

four sides exposed (see 4.1(16) of EN1994-1-2)

$$\left.\begin{aligned}\kappa_1 &= 1.0\\ \kappa_2 &= 1.0\end{aligned}\right\} \Rightarrow \mu_{0,M,\kappa} = \mu_{0,M} \times (\kappa_1 \kappa_2) = 0.506$$

$$\mu_{0,V,\kappa} = \mu_{0,V} = 0.145$$

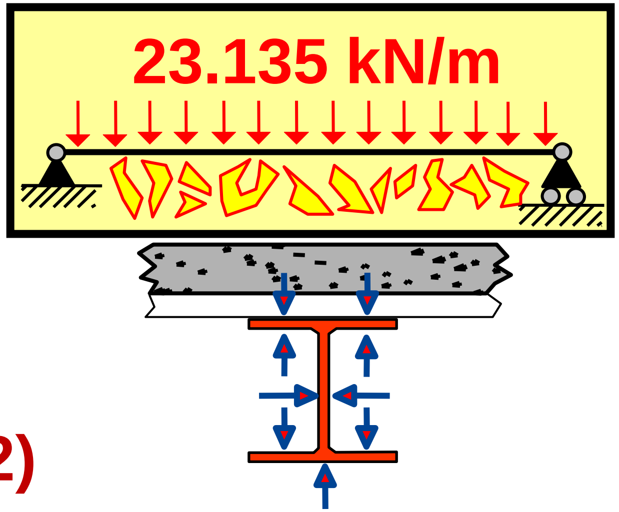
no adaptation factors for vertical shear

- **Design value of degree of utilisation**

$$\mu_0 = \max(\mu_{0,M,\kappa}, \mu_{0,V,\kappa}) = 0.506$$

Step 5: Critical temperature (bare beams)

- with simple calculation rule
- with accurate reduction factor table



➢ **Simple calculation rule (relation 4.22)**

$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 \approx 583 \;\; °C$$

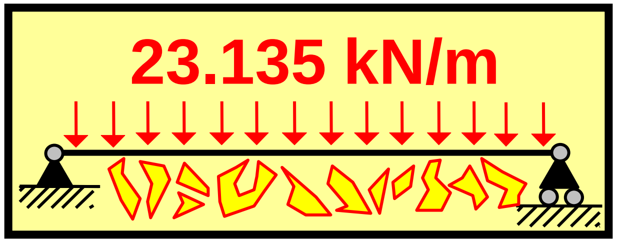
➢ **Linear interpolation of the reduction factor $k_{y,\theta}$ (table 3.1)**

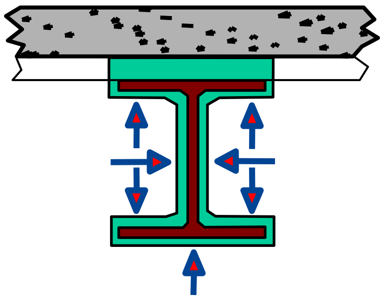
at 500 °C: $k_{y,\theta} = 0.78$

at 600 °C: $k_{y,\theta} = 0.47$

$$\theta_{cr} \approx 589 \;\; °C$$

2b. Secondary beams under central support of the continuous slab





Step 4b: Degree of utilisation

- modification with consideration of adaptation factors κ_1 and κ_2 for insulated steel beams

➢ **On the basis of relation 4.10**

three sides exposed (insulated)

$$\left.\begin{array}{l}\kappa_1 = 0.85 \\ \kappa_2 = 1.0\end{array}\right\} \Rightarrow \begin{array}{l}\mu_{0,M,\kappa} = \mu_{0,M} \times (\kappa_1 \kappa_2) = 0.430 \\ \mu_{0,V,\kappa} = \mu_{0,V} = 0.145\end{array}$$

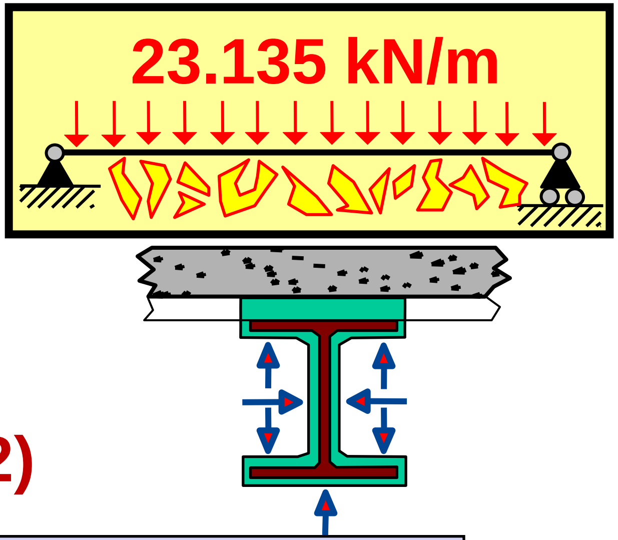
no adaptation factors for vertical shear

➢ **Design value of degree of utilisation**

$$\mu_0 = \max(\mu_{0,M,\kappa}, \mu_{0,V,\kappa}) = 0.430$$

Step 5b: Critical temperature (insulated beam)

- with simple calculation rule
- with accurate reduction factor table



➢ **Simple calculation rule (relation 4.22)**

$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 \approx 608 \quad °C$$

➢ **Linear interpolation of the reduction factor $k_{y,\theta}$ (table 3.1)**

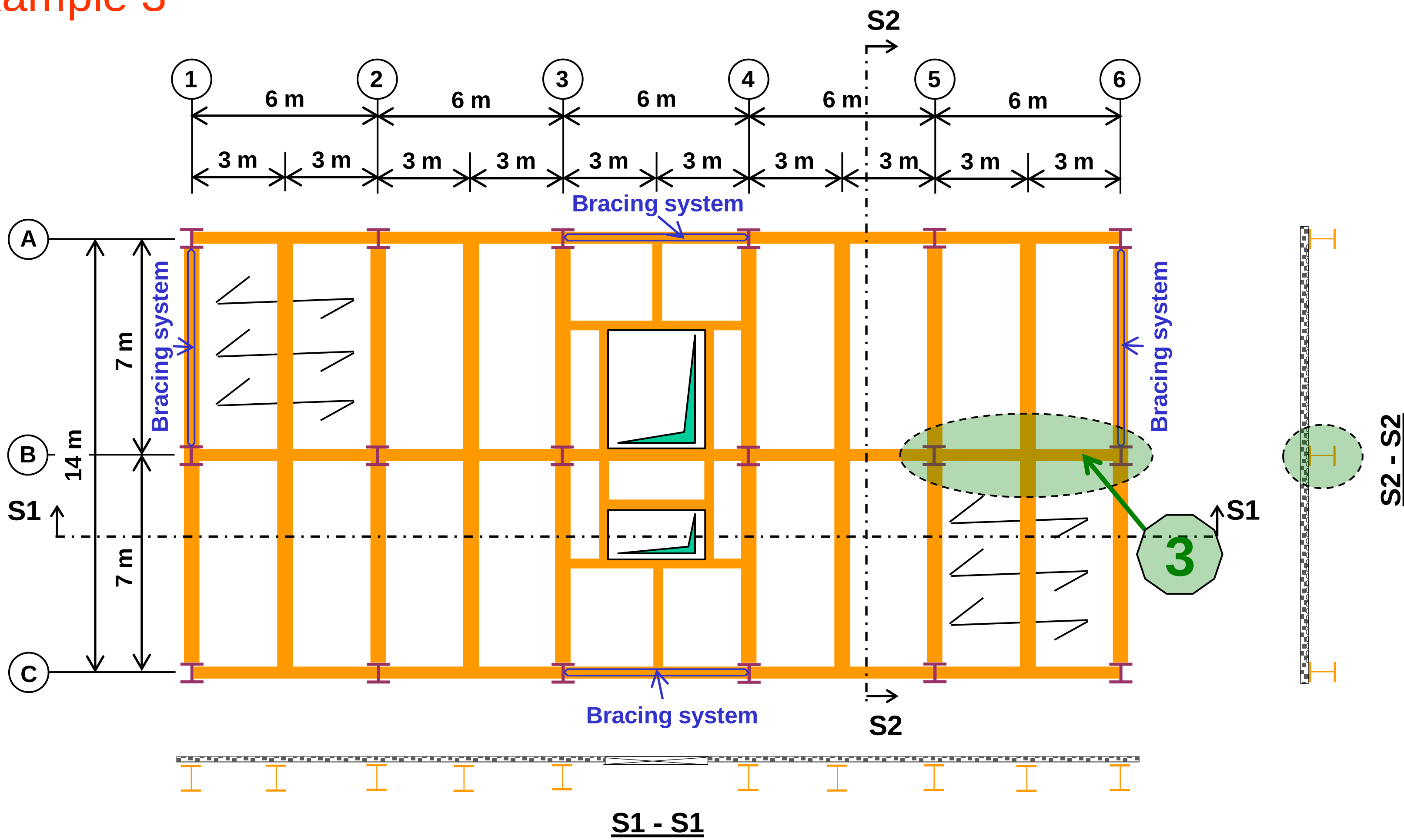
at 600 °C: $k_{y,\theta} = 0.47$

at 700 °C: $k_{y,\theta} = 0.23$

$$\theta_{cr} \approx 617 \quad °C$$

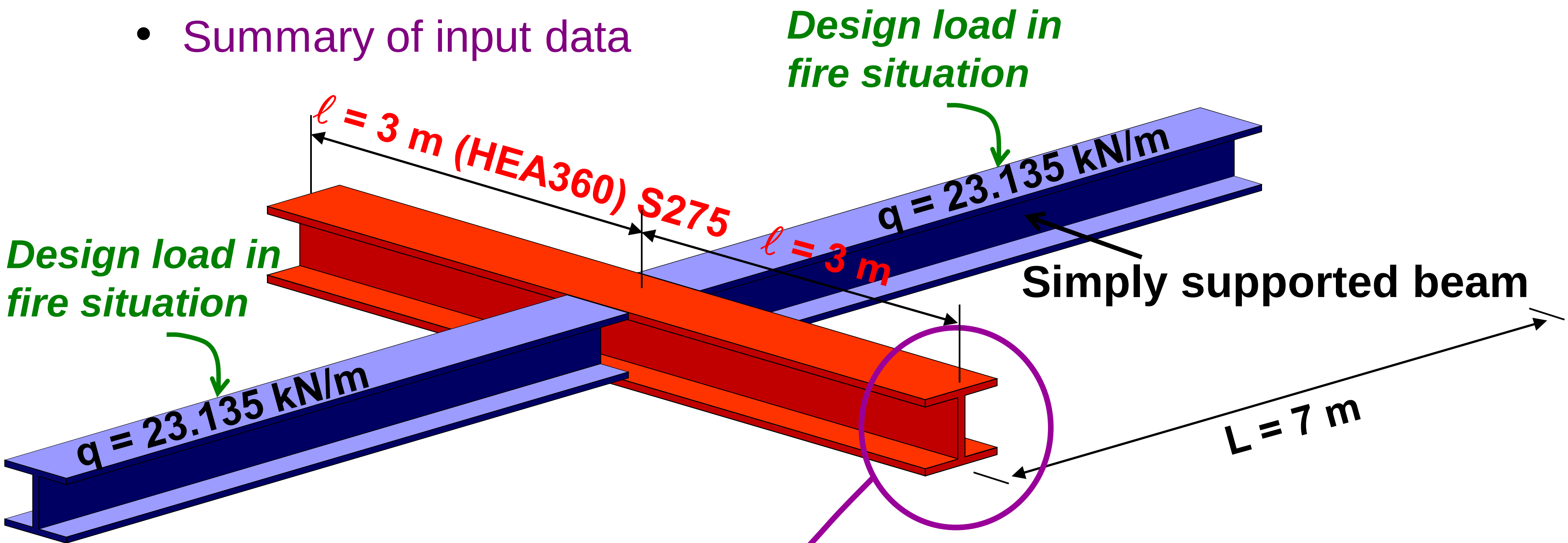
Simply supported central main beams

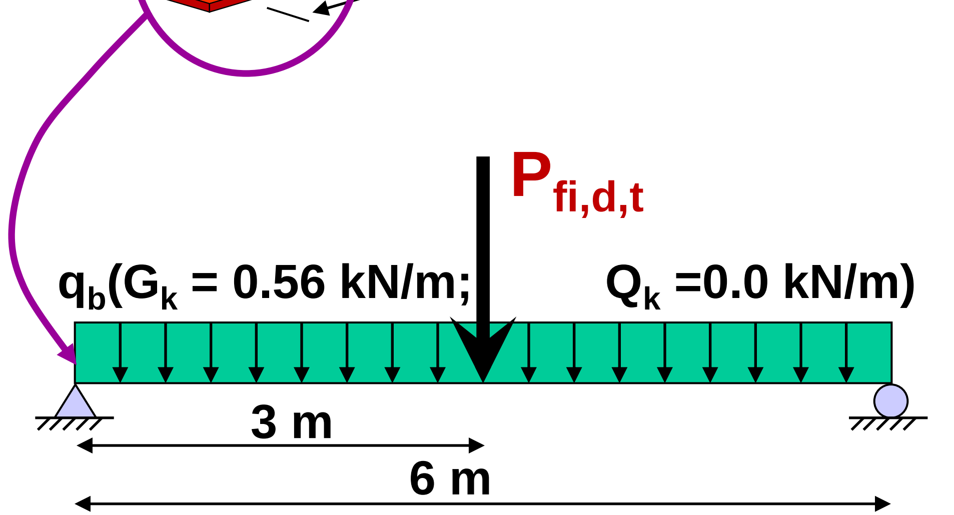
- The modification of worked example 2 will lead to modification of worked example 3



Step 1: Design mechanical action in fire design

- Summary of input data





Studied system

End support of secondary beam
= q x L

Self weight of HEA360 = 1.12 kN/m

Step 1: Design mechanical action in fire situation

- Design load in fire situation

$$E_{fi,d,t} = \sum_{j \geq 1} G_{k,j} + \Psi_{2,1} Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i} Q_{k,i}$$

➢ **Uniformely distributed load**

$$q_{fi,d,t} = G_{k,1} + \psi_{2,1} Q_{k,1} = 1.12 \text{ kN/m}$$

Self weight ($G_{k,1}$)

0.6 ($\psi_{2,1}$)

➢ **Concentrated load from simply supported secondary beam**

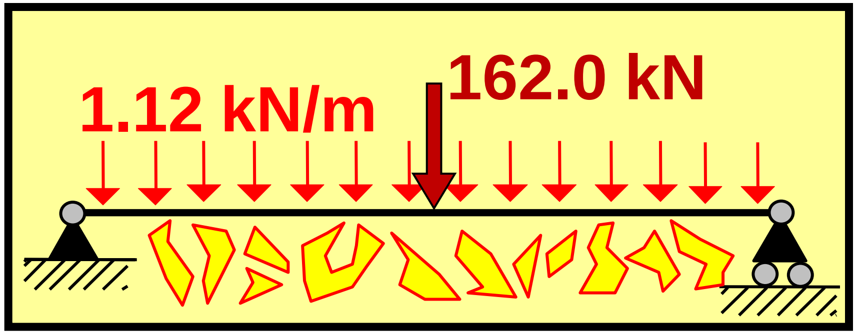
$$P_{fi,d,t} = \left(G_{k,1} + \psi_{2,1} Q_{k,1}\right) \times L = 23.135 \times L = 162.0 \text{ kN/m}$$

design load of secondary beam in fire situation

Step 1: Design mechanical action in fire situation

- both uniform and concentrated loads

➢ Design loading conditions in fire situation

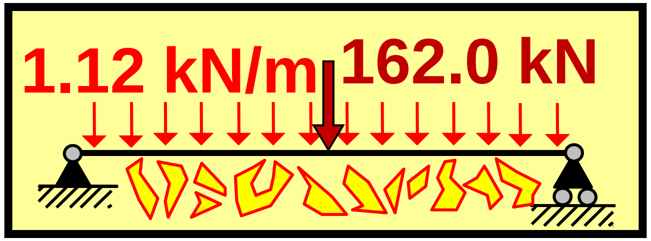


➢ Applied bending moment and vertical shear

$$M_{fi,d,t} = \frac{q_{fi,d,t}\ell^2}{2} + \frac{P_{fi,d,t}\ell}{2} = 248.0 \ \text{kNm}$$

$$V_{fi,d,t} = q_{fi,d,t}\ell + \frac{P_{fi,d,t}}{2} = 84.3 \ \text{kN}$$

3b. Simply supported central main beams



Step 2: Classify member

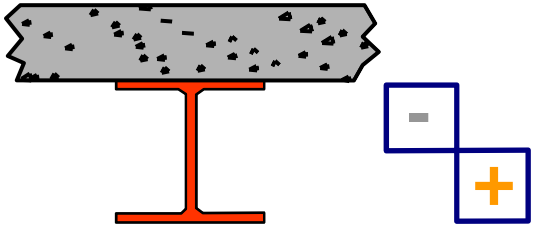
- Bending member (**HEA360**)

Relation 4.2 of Eurocode 3 part 1-2

$$\varepsilon = 0.85\sqrt{235/f_y} = 0.786$$

f_y → *S275*

Table 5.2 of Eurocode 3 part 1-1



Pure bending

$c/t_w \le 72\varepsilon$ → ***Web class 1***

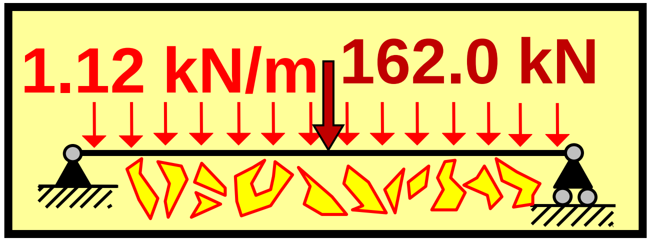
c/t_w = 37.3; 72ε = 56.6

$c/t_f \le 9\varepsilon$ → ***Flange class 1***

c/t_f = 4.96; 9ε = 7.07

→ **Section class 1**

Step 3: Design resistance at ambient temperature



- Design resistance at ambient temperature according to Eurocode 3 part 1-1

➢ **Moment resistance (relation 6.13)**

$$M_{Rd} = M_{pl,Rd} = \frac{W_{pl,y} f_y}{\gamma_{M0}} = 574.3 \text{ kNm}$$

HEA360	
$W_{pl,y}$ (cm^3)	2088.47
A_v (cm^2)	48.96

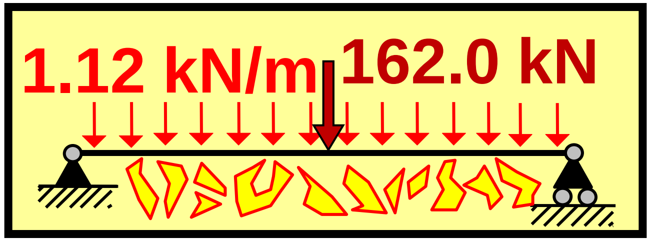
$\gamma_{M0} = 1$

➢ **Vertical shear resistance (relation 6.18)**

$$V_{Rd} = V_{pl,Rd} = \frac{A_v \left(f_y / \sqrt{3}\right)}{\gamma_{M0}} = 777.3 \text{ kN}$$

Step 4: Degree of utilisation

- with respect to two resistance forces
- without consideration of adaptation factors κ_1 and κ_2



➢ **Relative to moment resistance (relation 4.24)**

$$\mu_{0,M} = \eta_{fi,M} \frac{\gamma_{M0}}{\gamma_{M,fi}} = \frac{M_{fi,d,t}}{M_{Rd}} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 0.432$$

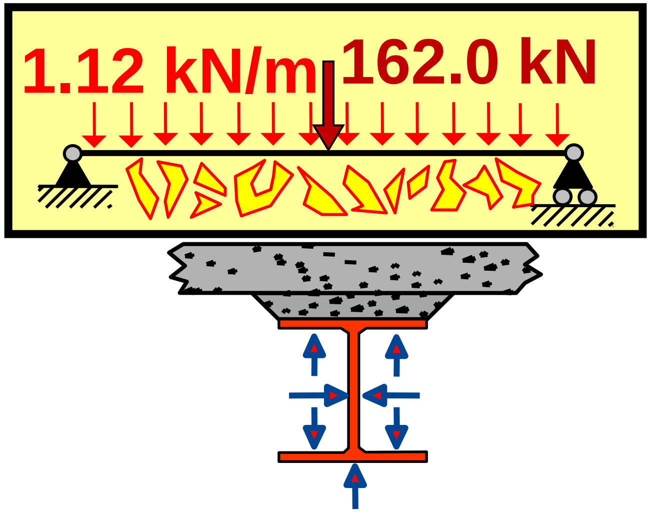
➢ **Relative to vertical shear resistance (relation 4.24)**

$$\mu_{0,V} = \eta_{fi,V} \frac{\gamma_{M0}}{\gamma_{M,fi}} = \frac{V_{fi,d,t}}{V_{Rd}} \frac{\gamma_{M0}}{\gamma_{M,fi}} = 0.108$$

$$\gamma_{M0} = \gamma_{M,fi} = 1$$

Step 4: Degree of utilisation

•modification with consideration of adaptation factors κ_1 and κ_2 for bare steel beams



➢ **On the basis of relation 4.10**

three sides exposed (bare)

$$\left.\begin{array}{l}\kappa_1 = 0.70\\ \kappa_2 = 1.0\end{array}\right\} \Rightarrow \mu_{0,M,\kappa} = \mu_{0,M} \times (\kappa_1 \kappa_2) = 0.302$$

$$\mu_{0,V,\kappa} = \mu_{0,V} = 0.108$$

no adaptation factors for vertical shear

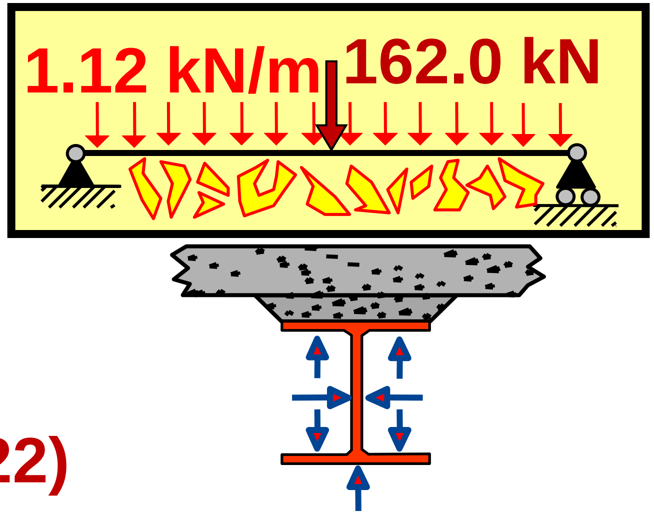
➢ **Design value of degree of utilisation**

$$\mu_0 = \max(\mu_{0,M,\kappa}, \mu_{0,V,\kappa}) = 0.302$$

3b. Simply supported central main beams

Step 5: Critical temperature (bare beams)

- with simple calculation rule
- with accurate reduction factor table



➢ **Simple calculation rule (relation 4.22)**

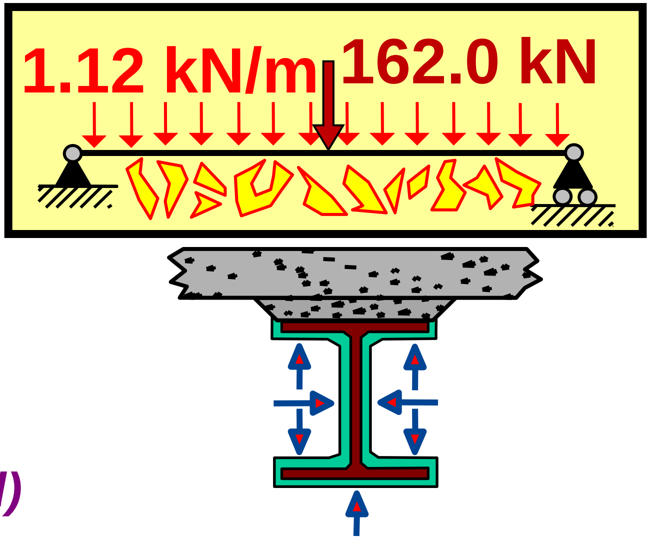
$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 \approx 663 \quad °C$$

➢ **Linear interpolation of the reduction factor $k_{y,\theta}$ (table 3.1)**

at 600 °C: $k_{y,\theta} = 0.47$

at 700 °C: $k_{y,\theta} = 0.23$

$$\theta_{cr} \approx 670 \quad °C$$



Step 4b: Degree of utilisation

•modification with consideration of adaptation factors κ_1 and κ_2 for insulated steel beams

- **On the basis of relation 4.10**

three sides exposed (insulated)

$$\kappa_1 = 0.85, \quad \kappa_2 = 1.0 \;\Rightarrow\; \mu_{0,M,\kappa} = \mu_{0,M} \times (\kappa_1 \kappa_2) = 0.367$$

$$\mu_{0,V,\kappa} = \mu_{0,V} = 0.108$$

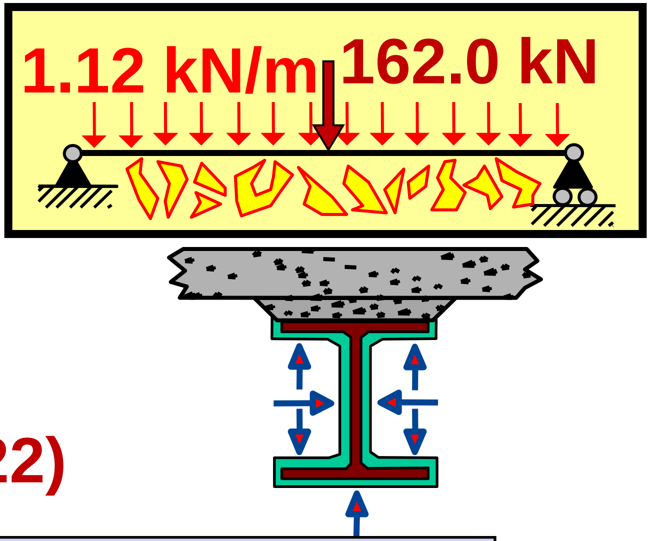
no adaptation factors for vertical shear

- **Design value of degree of utilisation**

$$\mu_0 = \max(\mu_{0,M,\kappa}, \mu_{0,V,\kappa}) = 0.367$$

Step 5b: Critical temperature (insulated beam)

- with simple calculation rule
- with accurate reduction factor table



➢ **Simple calculation rule (relation 4.22)**

$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 \approx 633 \ \ °C$$

➢ **Linear interpolation of the reduction factor $k_{y,\theta}$ (table 3.1)**

at 600 °C: $k_{y,\theta} = 0.47$

at 700 °C: $k_{y,\theta} = 0.23$

⇒ $\theta_{cr} \approx 643 \ \ °C$

Summary of passive fire protection of steel members (alternative solution)

With simply supported beam design for all secondary beams

Steel members	θ_{cr} (°C)	Type of protection	Thickness (mm)
Secondary beams under end support of continuous slab	687	Contour encasement	10
Secondary beams under central support of continuous slab	617	Contour encasement	15
Simply supported central main beam	643	Contour encasement	10
Central column at ground level	>560	Hollow encasement	12.5

Unoptimized solution:

- **Use of different protection thicknesses for steel beams**