2C10
Fire Resistance of Steel Structures

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2) Fire load
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9) Fire resistance of timber and aluminium structures
10) Loading at explosion
11) Structural analysis at explosion
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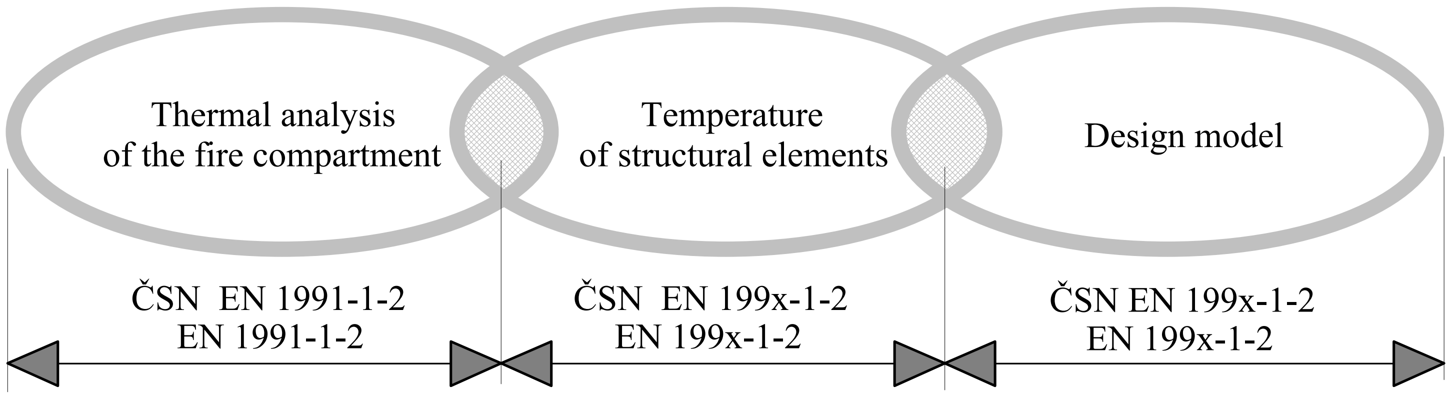
katedra ocelových a dřevěných konstrukcí

Design procedure



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Introduction

- Generally, the same method as for normal temperature is used
- The partial safety factor for steel at fire is

$$\gamma_{M,fi} = 1{,}0$$

- The change of material properties caused by high temperature is very important
- Slightly different formulas are used when resistance to buckling (compression) or lateral-torsional buckling (bending) needs to be evaluated
- Attention should be paid to structural detailing, design of joints and maintaining the structural integrity to prevent the progressive collapse of the structure

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- The critical temperature method
- Classification of cross-sections
- Elements in tension
- Beams
- Elements in compression
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- Combination of bending and compression
- Elements with class 4 sections
- Connections

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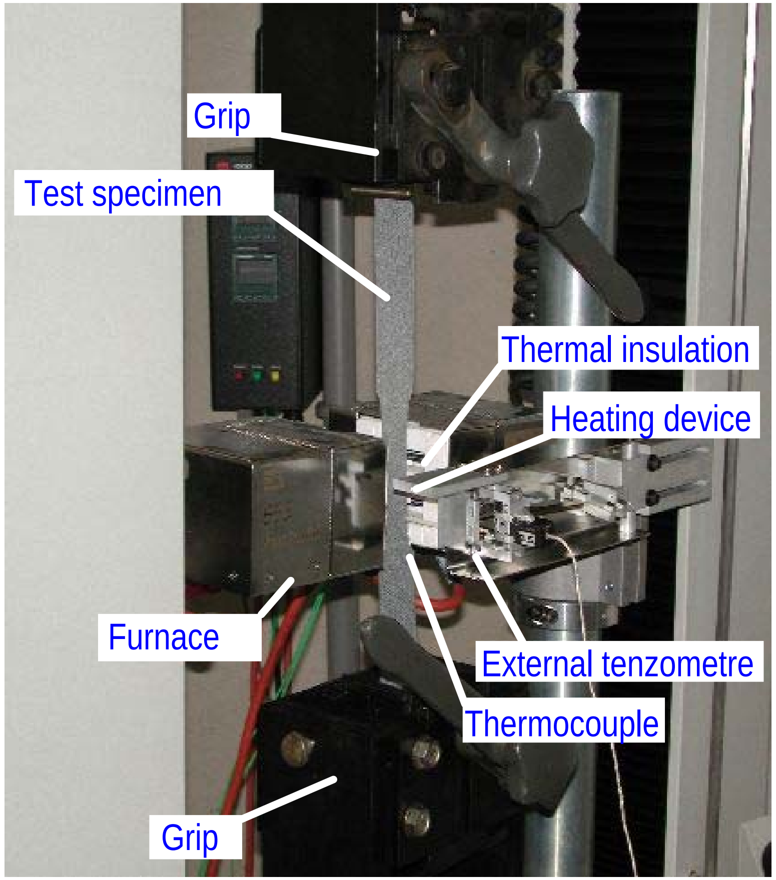
Material testing at high temperature



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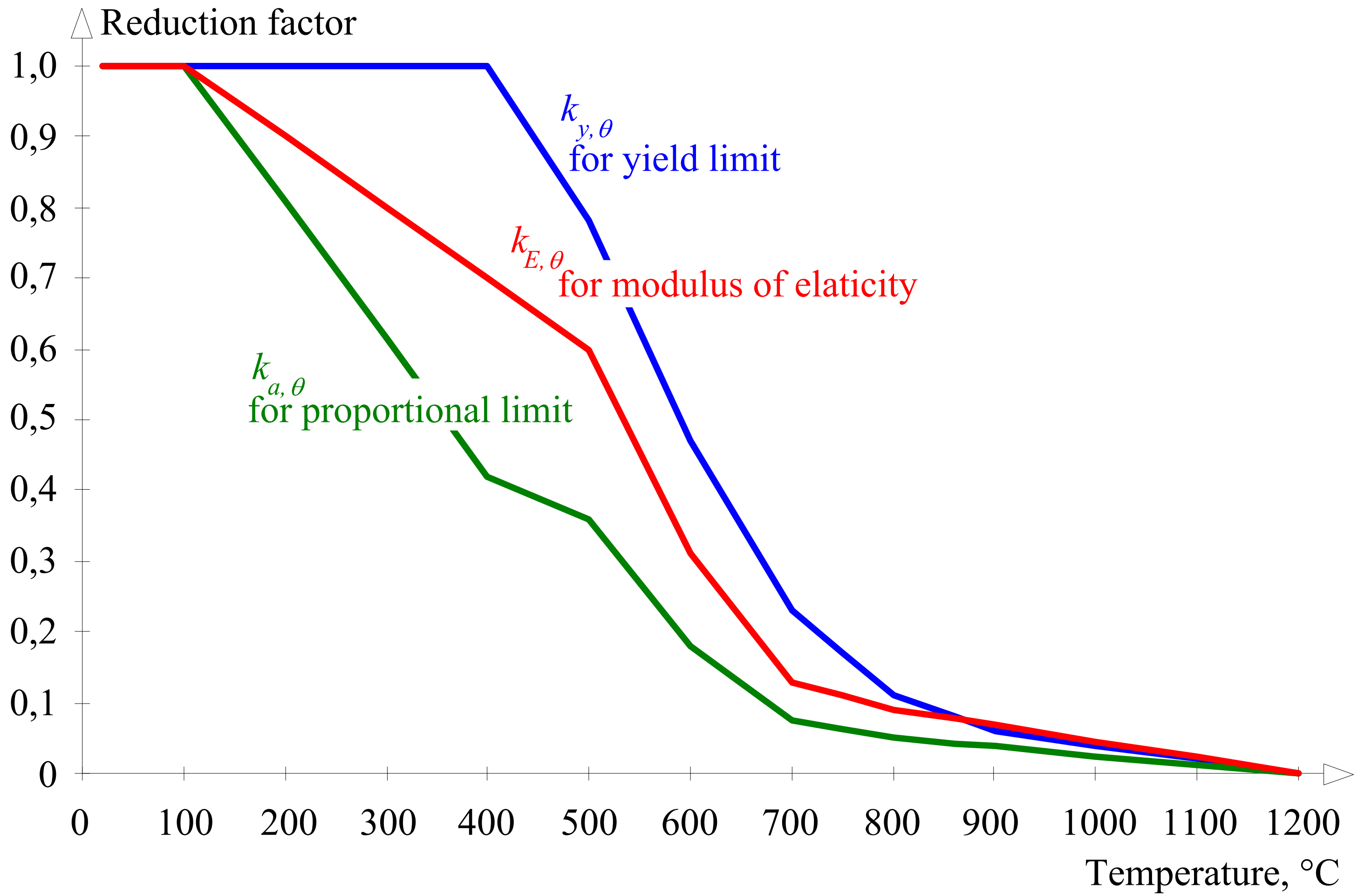
Properties of steel at high temperature



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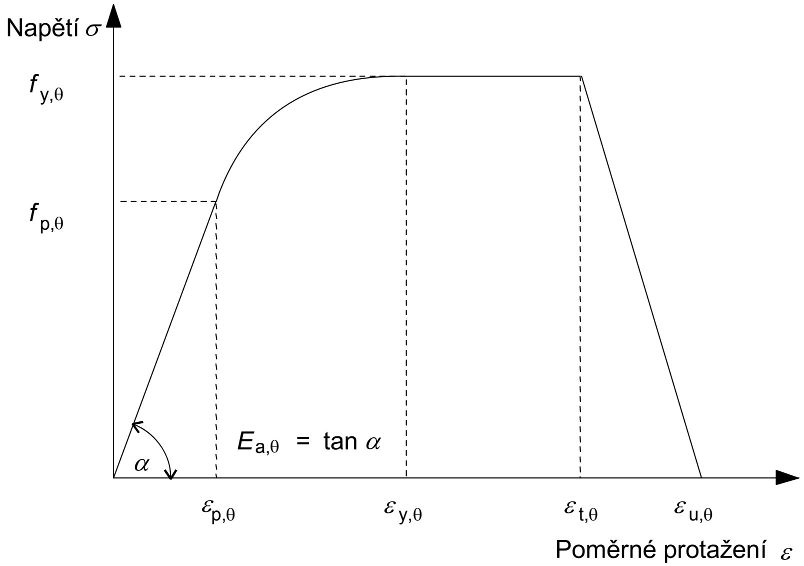
Stress-strain diagram at high temperature

Poměrné protažení	Napětí σ	Modul pružnosti
$\varepsilon \le \varepsilon_{p,\theta}$	$\varepsilon E_{a,\theta}$	$E_{a,\theta}$
$\varepsilon_{p,\theta} < \varepsilon < \varepsilon_{y,\theta}$	$f_{p,\theta} - c + (b/a)\left[a^2 - (\varepsilon_{y,\theta} - \varepsilon)^2\right]^{0,5}$	$\dfrac{b(\varepsilon_{y,\theta} - \varepsilon)}{a\left[a^2 - (\varepsilon_{y,\theta} - \varepsilon)^2\right]^{0,5}}$
$\varepsilon_{y,\theta} \le \varepsilon \le \varepsilon_{t,\theta}$	$f_{y,\theta}$	0
$\varepsilon_{t,\theta} < \varepsilon < \varepsilon_{u,\theta}$	$f_{y,\theta}\left[1 - (\varepsilon - \varepsilon_{t,\theta})/(\varepsilon_{u,\theta} - \varepsilon_{t,\theta})\right]$	-
$\varepsilon = \varepsilon_{u,\theta}$	0,00	-
Parametry	$\varepsilon_{p,\theta} = f_{p,\theta} / E_{a,\theta}$ $\quad \varepsilon_{y,\theta} = 0,02$ $\quad \varepsilon_{t,\theta} = 0,15$ $\quad \varepsilon_{u,\theta} = 0,20$	
Funkce	$a^2 = (\varepsilon_{y,\theta} - \varepsilon_{p,\theta})(\varepsilon_{y,\theta} - \varepsilon_{p,\theta} + c/E_{a,\theta})$ $b^2 = c\,(\varepsilon_{y,\theta} - \varepsilon_{p,\theta})E_{a,\theta} + c^2$ $c = \dfrac{(f_{y,\theta} - f_{p,\theta})^2}{(\varepsilon_{y,\theta} - \varepsilon_{p,\theta})E_{a,\theta} - 2(f_{y,\theta} - f_{p,\theta})}$	



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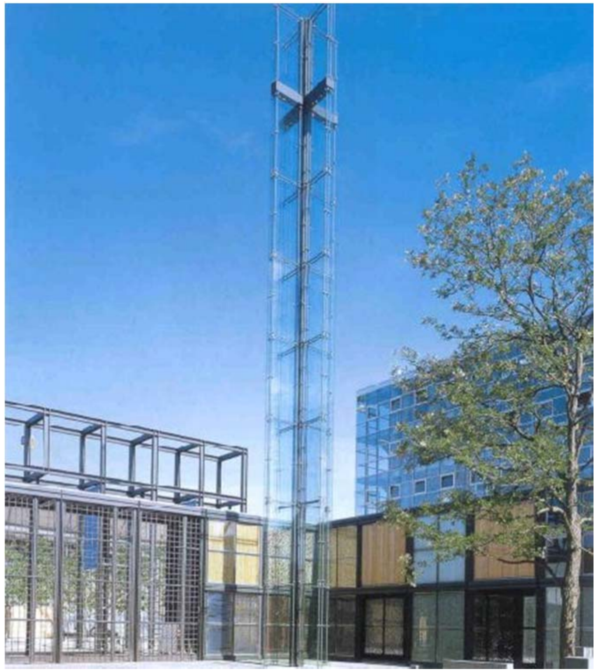
Fire resistant steel

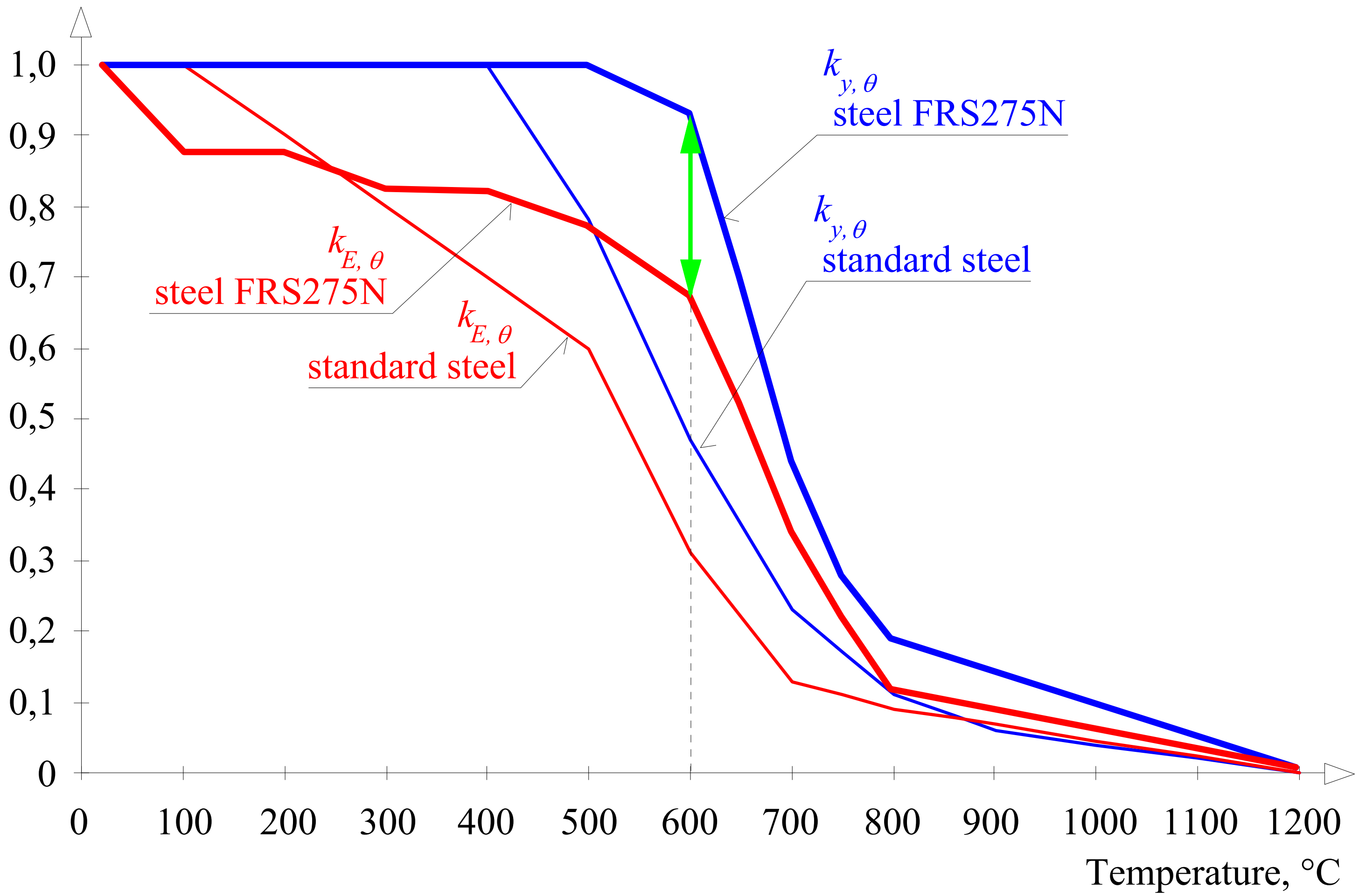
- Fire proof steel
  - For industrial structures (furnaces, etc.) exposed to 600 °C to 1200 °C
- Fire resistant steel
  - Fine crystal structure (reduced sulfur content)
  - Addition of molybdenum and niobium

Used at EXPO 2000 in Hannover - The Christ Pavilion



Fire resistant steel FRS275N

Increased yield limit at temperature 600˚C



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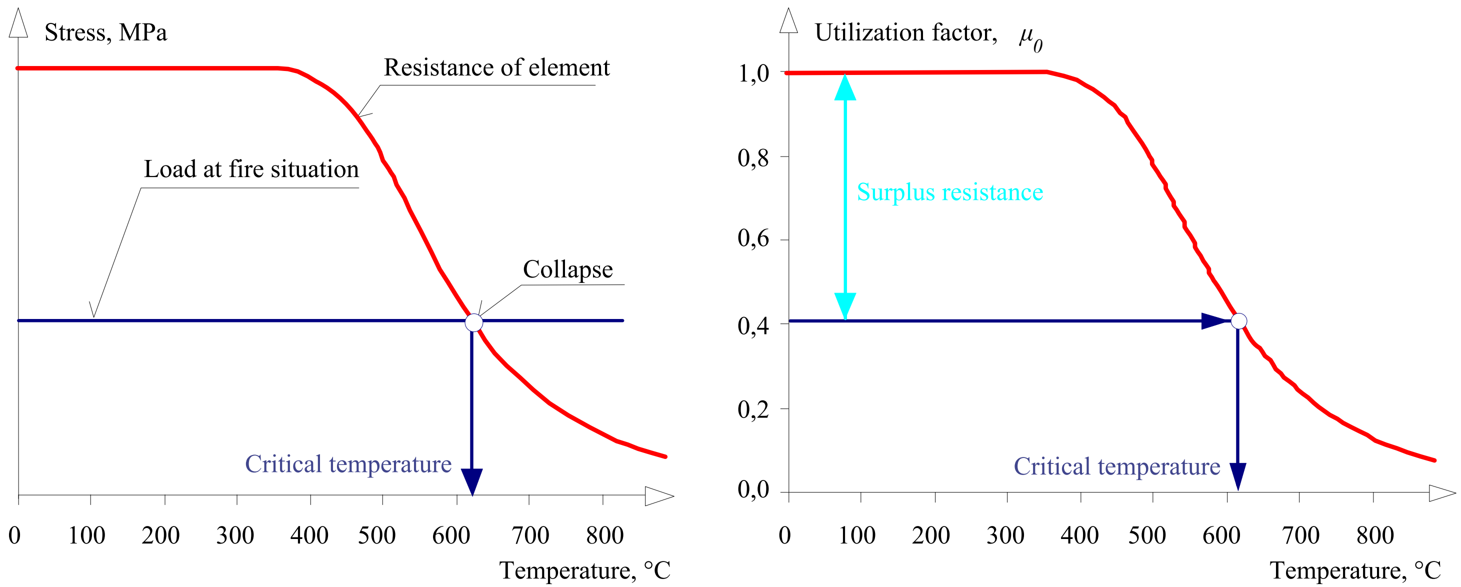
Critical temperature



Critical temperature

- Attention!
- The formula is applicable only to elements whose resistance depends on the yield limit only (no stability effects)

$$\theta_{a,cr} = 39{,}19\, ln\left(\frac{1}{0{,}9674\,\mu_0^{\;3{,}833}} - 1\right) + 482$$

Utilization factor μ_0

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

$E_{fi,d}$ — Load at fire

$R_{fi,d,0}$ — Resistance at fire at temperature 20˚C

Classification at normal temperature

… at normal temperature

where

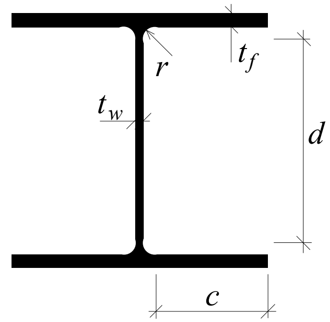
$$\varepsilon = \sqrt{\frac{235}{f_y}}$$

Element	Class 1	Class 2	Class 3
Flange	$c/t_f=10\ \varepsilon$	$c/t_f=11\ \varepsilon$	$c/t_f=15\ \varepsilon$
Web in bending	$d/t_w=72\ \varepsilon$	$d/t_w=83\ \varepsilon$	$d/t_w=124\ \varepsilon$
Web in compression	$d/t_w=33\ \varepsilon$	$d/t_w=38\ \varepsilon$	$d/t_w=42\ \varepsilon$

Classification

The slenderness

$$\bar{\lambda}_p = \frac{b}{28{,}4\ t\ \varepsilon\ \sqrt{k_\sigma}}$$



The general formula

$$\bar{\lambda}_p = \frac{\frac{b}{t}}{\sqrt{\frac{\pi^2\ E}{12\cdot 235\cdot\left(1-\mu^2\right)}}\ \varepsilon\ \sqrt{k_\sigma}}$$

both values depend on the temperature

after simplification

$$\bar{\lambda}_p = \frac{\frac{b}{t}}{\sqrt{\frac{\pi^2\ E}{12\cdot 235\cdot\left(1-\mu^2\right)}}\ \sqrt{\frac{235}{f_y}}\ \sqrt{k_\sigma}} = \frac{\frac{b}{t}}{\sqrt{\frac{\pi^2}{12\cdot\left(1-\mu^2\right)}}\ \sqrt{\frac{E}{f_y}}\ \sqrt{k_\sigma}} = \frac{\frac{b}{t}}{0{,}904\ \sqrt{\frac{E}{f_y}}\ \sqrt{k_\sigma}}$$

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Classification

The factor ε is used at normal temperature

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

It needs to be modified at high temperature

$$\sqrt{\frac{E_\theta}{f_{y,\theta}}} = \sqrt{\frac{k_{E,\theta}\;E}{k_{y,\theta}\;f_y}} = \sqrt{\frac{k_{E,\theta}}{k_{y,\theta}}}\sqrt{\frac{E}{f_y}}$$

Simplified approach is used in standards

$$\varepsilon = 0{,}85\sqrt{\frac{235}{f_y}}$$

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Classification at high temperature

… at high temperature

reduced ε

$$\varepsilon = 0{,}85\sqrt{\frac{235}{f_y}}$$

Element	Class 1	Class 2	Class 3
Flange	$c/t_f = 10\ \varepsilon$	$c/t_f = 11\ \varepsilon$	$c/t_f = 15\ \varepsilon$
Web in bending	$d/t_w = 72\ \varepsilon$	$d/t_w = 83\ \varepsilon$	$d/t_w = 124\ \varepsilon$
Web in compression	$d/t_w = 33\ \varepsilon$	$d/t_w = 38\ \varepsilon$	$d/t_w = 42\ \varepsilon$

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Elements in tension

Elements with uniform temperature distribution in the cross-section

$$N_{fi,t,Rd} = \frac{A\,k_{y,\theta}\;f_y}{\gamma_{M,fi}}$$

Non-uniform temperature distribution

$$N_{fi,t,Rd} = \frac{\sum_{i=1}^{n} A_i\;k_{y,\theta,i}\;f_y}{\gamma_{M,fi}}$$

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Laterally restrained beams, Class 1 and 2

Uniform temperature distribution (constant temperature)

$$M_{fi,t,Rd} = \frac{W_{pl,y}\, k_{y,\theta}\, f_y}{\gamma_{M,fi}}$$

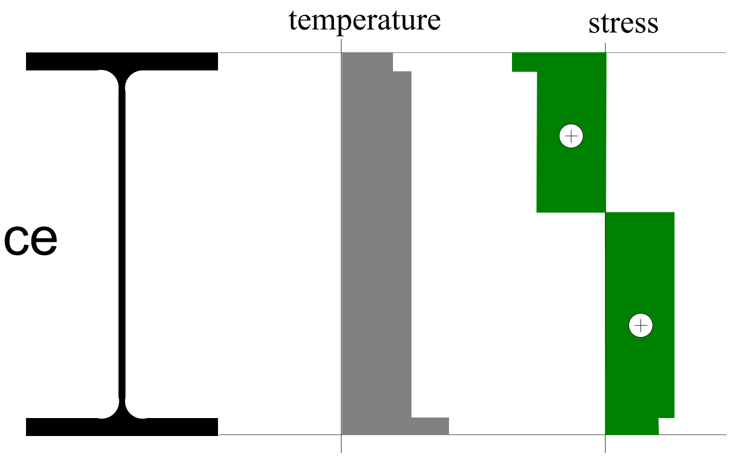
Non-uniform temperature distribution (general method)

– neutral axis

$$N^+ = N^-$$

– bending moment resistance

$$M_{fi,t,Rd} = \frac{\sum_{i=1}^{n} A_i\, k_{y,\theta,i}\, z_i\, f_y}{\gamma_{M,fi}}$$



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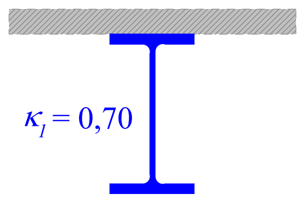
Laterally restrained beams, Class 1 and 2

Non-uniform temperature distribution (alternative method)

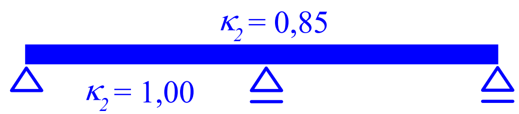
$$M_{fi,t,Rd} = \frac{1}{\kappa_1 \, \kappa_2} \frac{W_{pl,y} \, k_{y,\theta} \, f_y}{\gamma_{M,fi}}$$

Adaptation factors

- Factor κ_1 to take into account non-uniform temperature of the cross-section
  - κ_1 = 1,00 for beams exposed on four sides
  - κ_1 = 0,70 for beams exposed on three sides with concrete slab on the fourth side



- Factor κ_2 to take into account non-uniform temperature of the beam
  - κ_2 = 0,85 for intermediate supports of statically indetermined beams
  - κ_2 = 1,00 in other cases



Laterally restrained beams, Class 3

Uniform temperature distribution (constant temperature)

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

Non-uniform temperature distribution

the maximum temperature of the cross-section should be used for evaluation of moment resistance

$$M_{fi,t,Rd} = \frac{1}{\kappa_1\, \kappa_2} \frac{W_{pl,y}\, k_{y,\theta,max}\, f_y}{\gamma_{M,fi}}$$

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Beams (shear resistance)

All sections

$$V_{fi,t,Rd} = k_{y,\theta,web} \frac{A_{V,z} \, f_y}{\sqrt{3} \, \gamma_{M,fi}}$$

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Design models for structural elements

Design models for joints

Conclusion

Buckling resistance

For sections of class 1, 2 and 3

- the maximum temperature should be used for non-uniform temperature
- only one buckling curve with the imperfection factor *α*

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

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

Slenderness

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

Buckling reduction factor

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

where

$$\varphi_\theta = \frac{1 + \alpha \, \bar{\lambda}_\theta + \bar{\lambda}_\theta^{\,2}}{2}$$

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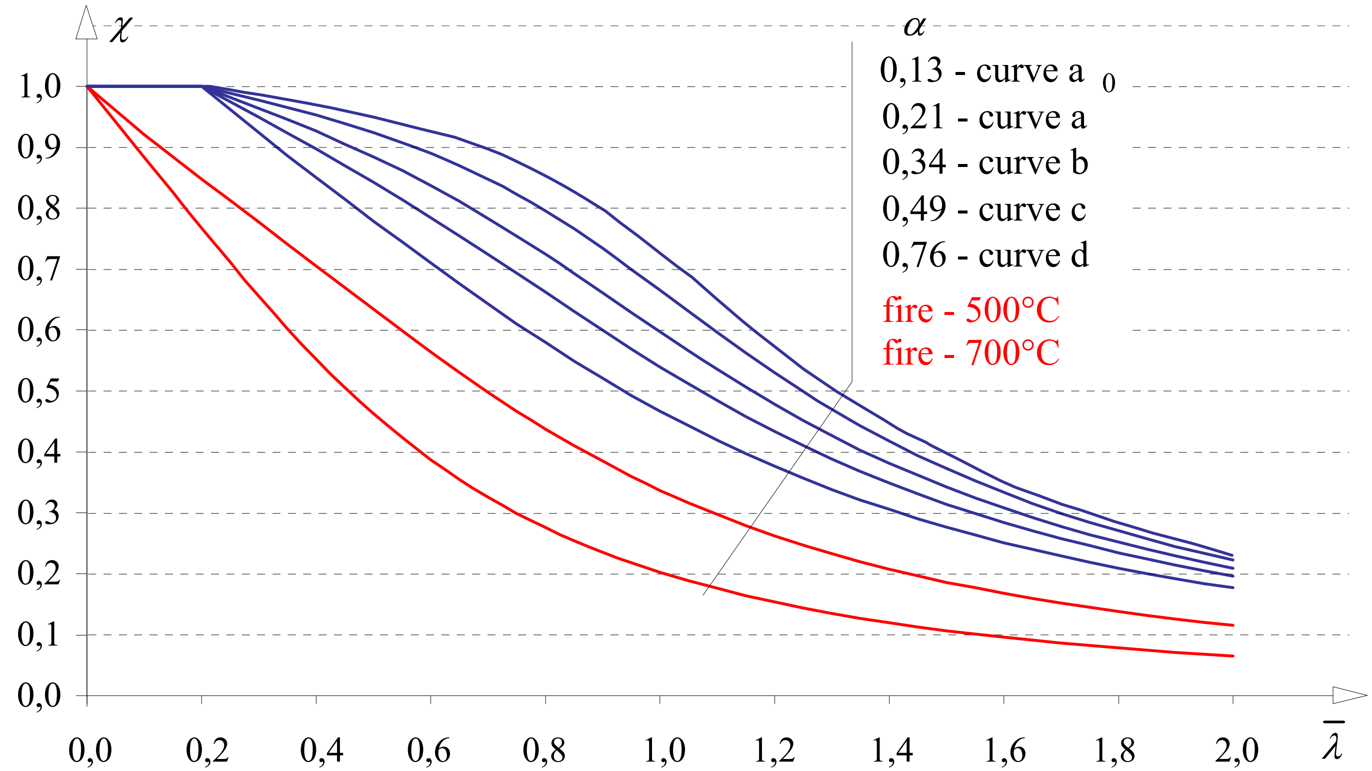
Buckling reduction factors



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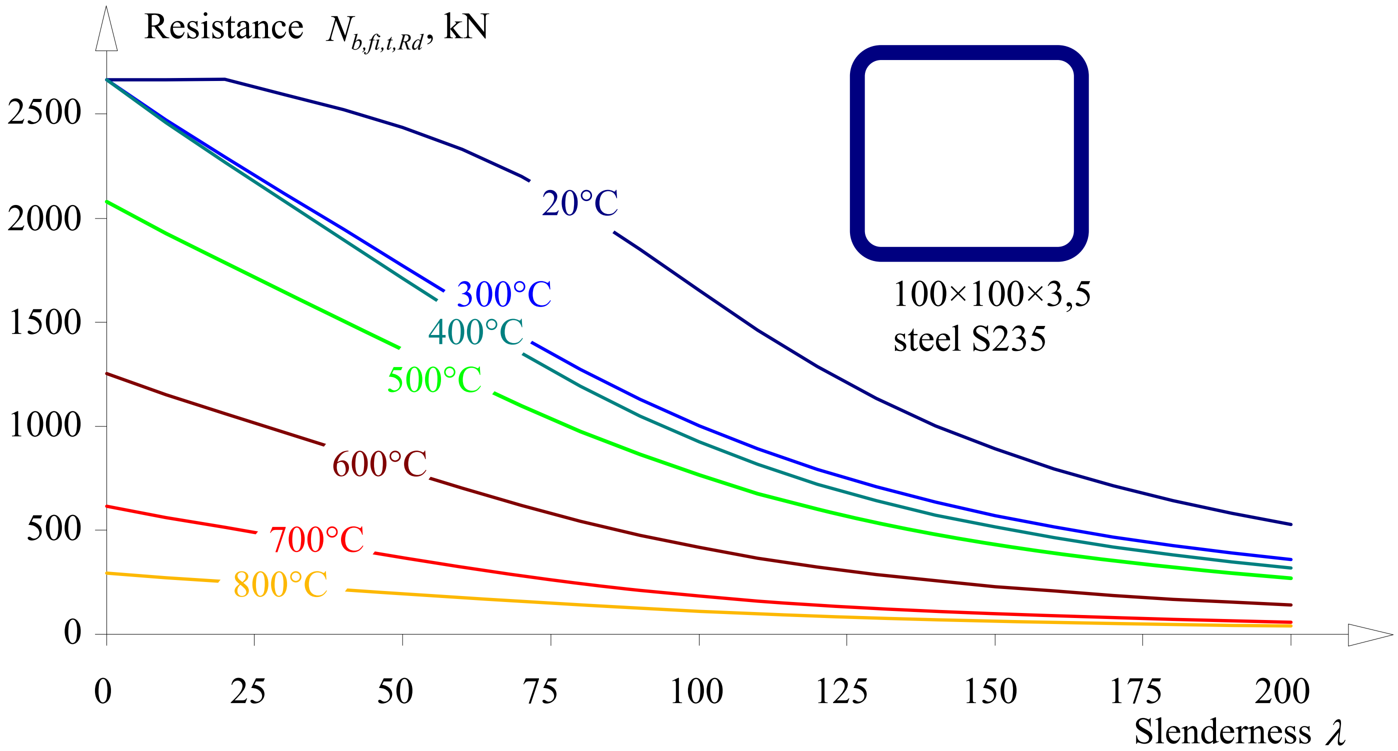
Buckling resistance of element



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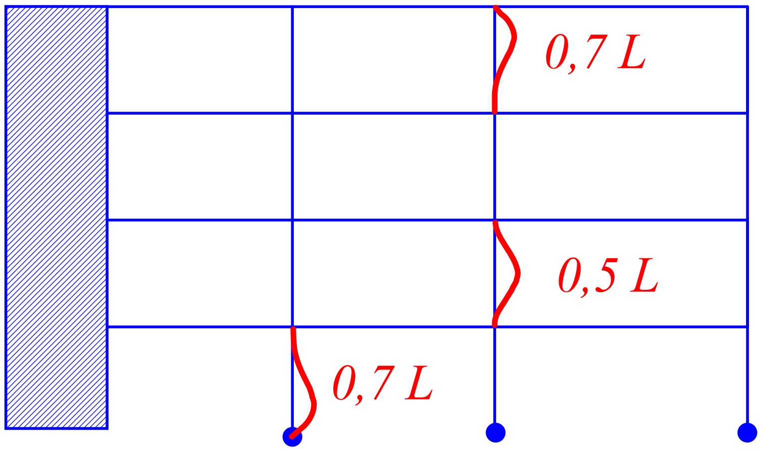
Reduction of buckling length of columns

- Generally, the buckling lengths at fire are the same as those at normal temperature
- The buckling lengths for multi-storey buildings can be reduced, when
  - it is non-sway structure
  - there are separate fire compartments in each storey
  - the floors have the same or higher fire resistance than the columns



Unrestrained beams

- Beams with class 1 and class 2 sections
  - reduction of the yield limit is based on the temperature of the compressed flange
  - the maximum temperature can be also used (conservative approach)

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

- Beams with class 3 sections

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

Imperfection factor

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

Slenderness

$$\bar{\lambda}_{LT,\theta} = \bar{\lambda}_{LT}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}}$$

Buckling reduction factor

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

where

$$\varphi_{LT,\theta} = \frac{1 + \alpha\,\bar{\lambda}_{LT,\theta} + \bar{\lambda}_{LT,\theta}^{2}}{2}$$

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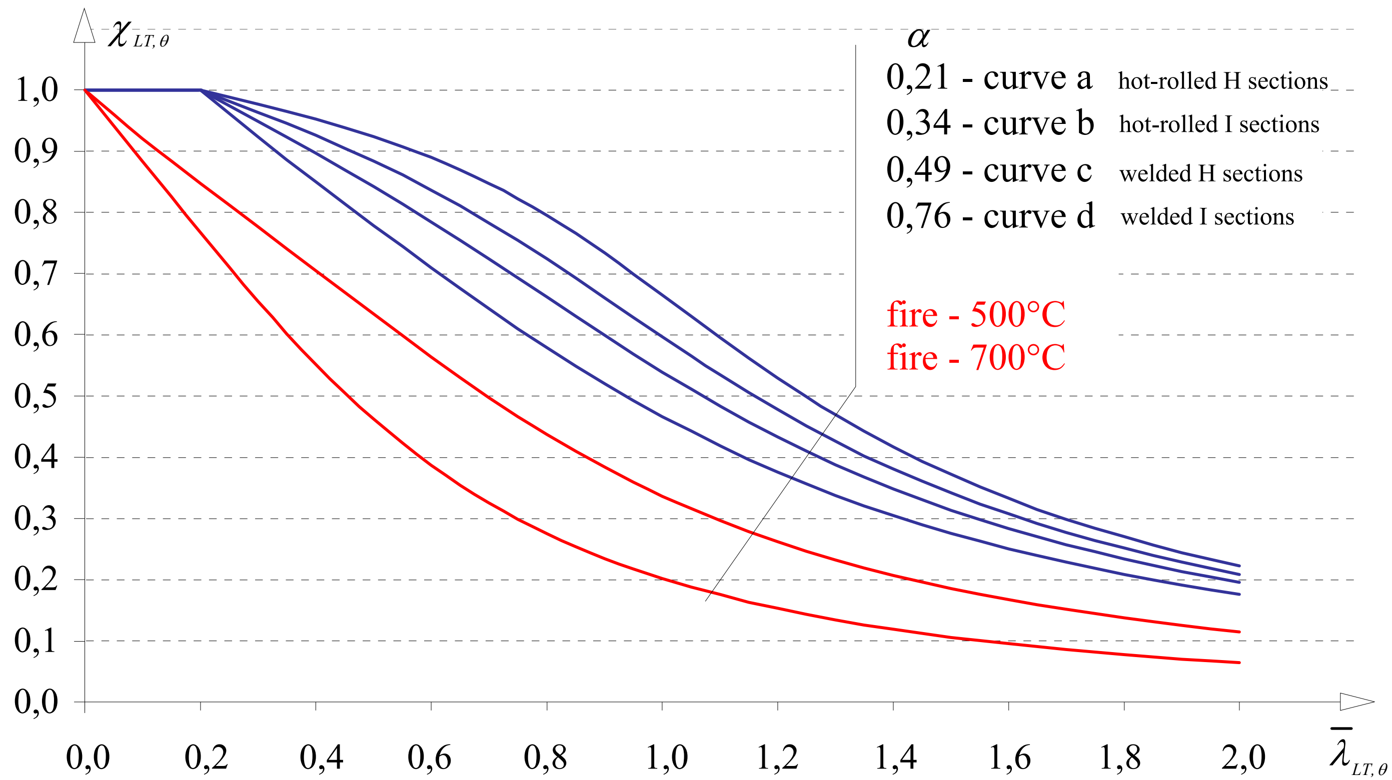
Buckling reduction factor (lateral torsional instability)



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Bending and compression

- For class 1 and class 2 sections
  - restrained elements (no lateral torsional instability)

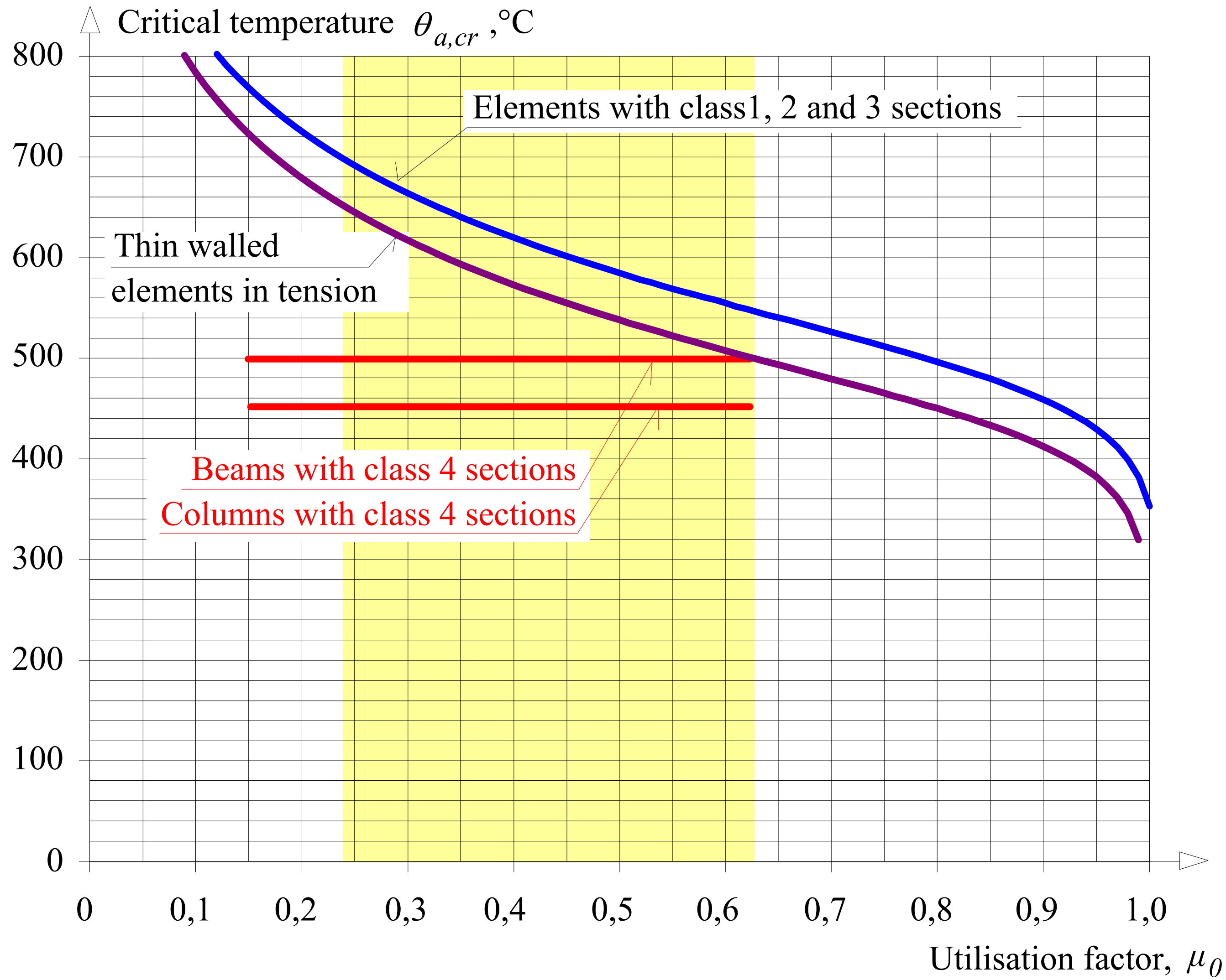
$$\frac{N_{Ed}}{\chi_{min,fi} \dfrac{A\, k_{y,\theta}\, f_y}{\gamma_{M,fi}}} + \frac{k_y\, M_{y,Ed}}{\dfrac{W_{pl,y}\, k_{y,\theta}\, f_y}{\gamma_{M,fi}}} + \frac{k_z\, M_{z,Ed}}{\dfrac{W_{pl,z}\, k_{y,\theta}\, f_y}{\gamma_{M,fi}}} \leq 1$$

  - unrestrained elements (with lateral torsional instability)

$$\frac{N_{Ed}}{\chi_{z,fi} \dfrac{A\, k_{y,\theta}\, f_y}{\gamma_{M,fi}}} + \frac{k_{LT}\, M_{y,Ed}}{\chi_{LT,fi} \dfrac{W_{pl,y}\, k_{y,\theta}\, f_y}{\gamma_{M,fi}}} + \frac{k_z\, M_{z,Ed}}{\dfrac{W_{pl,z}\, k_{y,\theta}\, f_y}{\gamma_{M,fi}}} \leq 1$$

- For class 3 sections
  - similarly, but elastic section modulus is used

Class 4 sections

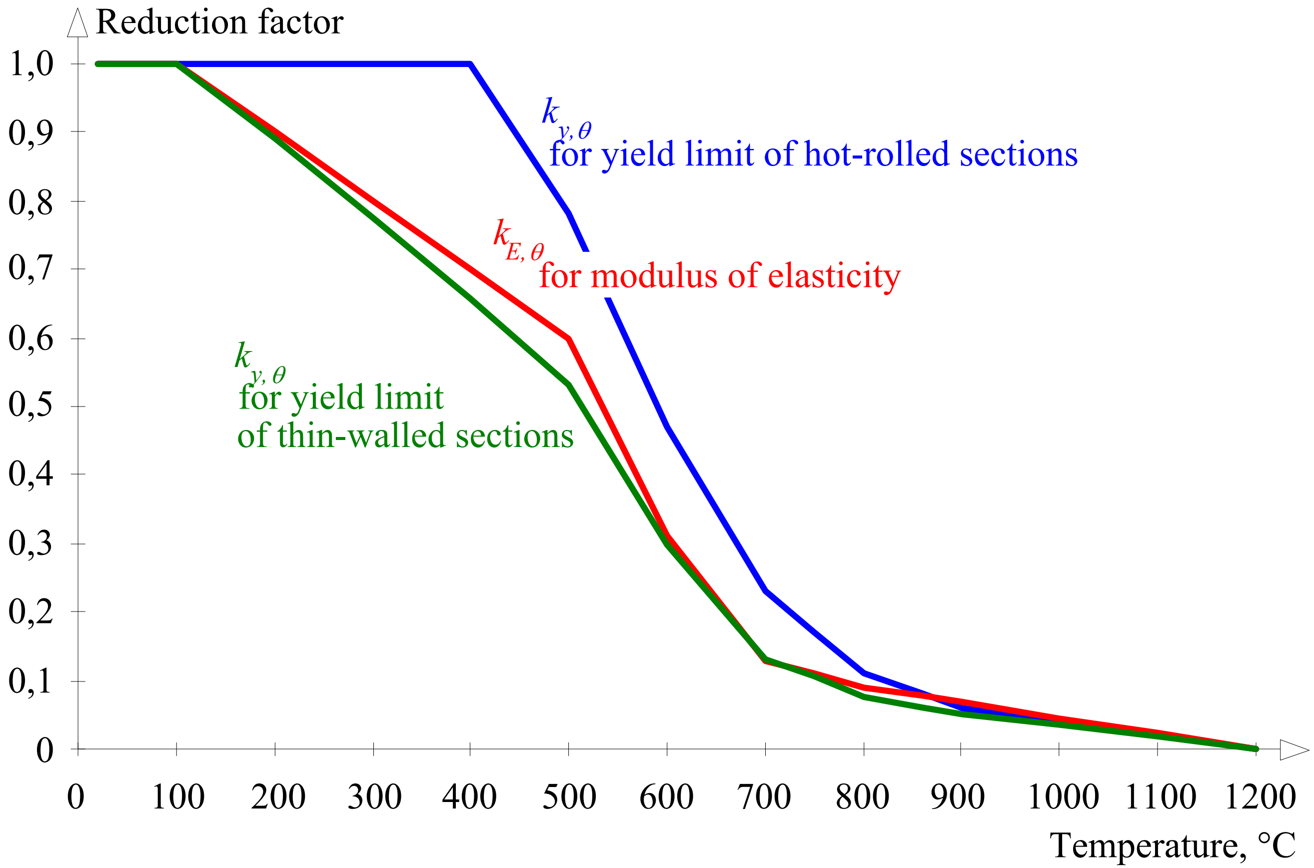


Class 4 sections

- As an alternative method, the resistance of thin-walled elements can be evaluated the same way as for class 3 sections, but effective section properties should be used
- The effective section properties can be evaluated at normal temperature
- The reduction factor for thin-walled sections (both, hot-rolled and cold-formed) is different from the factor for hot-rolled sections

Reduction factors for thin-walled sections

- The reduction factors are used for thin-walled sections
  - cold-formed
  - hot-rolled, welded



Joints

- The joints are usually not the critical part of the structure, as the temperature is lower than the temperature of the connected elements
- There are requirements for structural integrity

To check resistance of the joints:

- The temperature is the most important
- The methods:
  - simplified models for temperature
  - calculation using step by step method with *A/V* ratio for the joint
- The resistance calculation can be based on component method adopted for high temperatures

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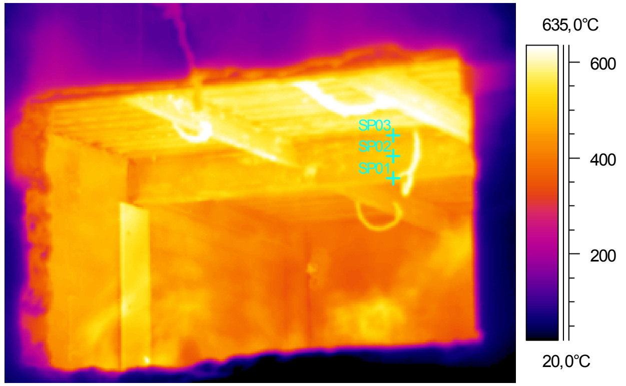
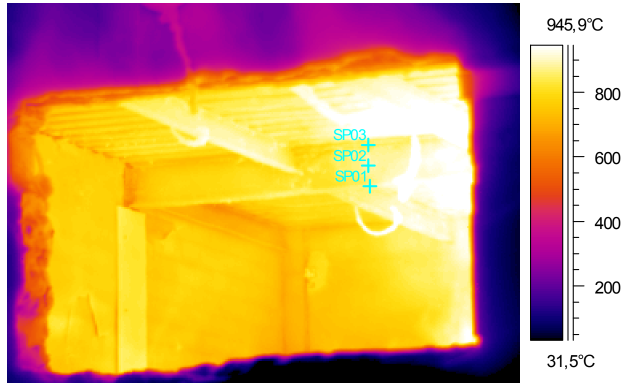
Temperature of the joints

Pictures from thermo cameras used to measure the beam to beam and beam to column connections

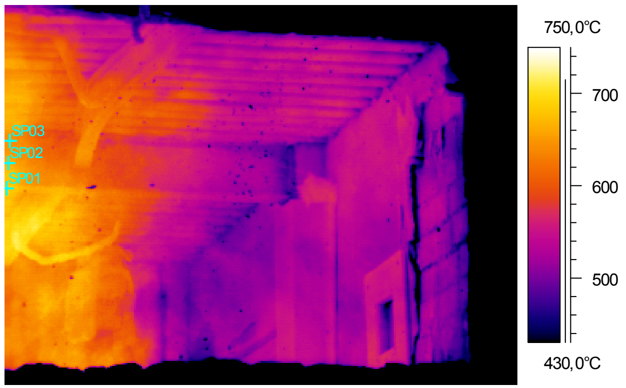
a) Heating phase (30 min)



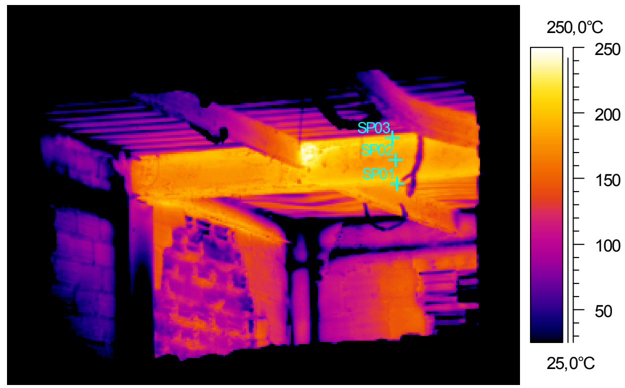
b) The maximum temperature (54 min)



c) Cooling phase (69 min)



d) The end (240 min)



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Simplified model for temperature

Temperature of the beam supporting the concrete slab is based on beam temperature in the mid span

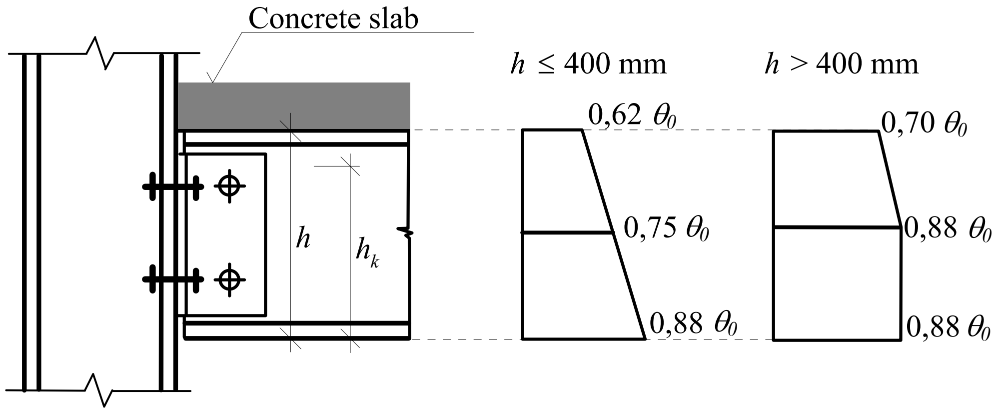
h < 400 mm

$$\theta_h = 0{,}88\,\theta_0 \left[1 - 0{,}3\left(\frac{h_k}{h}\right)\right]$$

h > 400 mm

$$\theta_h = 0{,}88\,\theta_0 \qquad \text{pro} \quad h_k \le \frac{h}{2}$$

$$\theta_h = 0{,}88\,\theta_0 \left[1 + 0{,}2\left(1 - 2\,\frac{h_k}{h}\right)\right] \qquad \text{pro} \quad h_k > \frac{h}{2}$$



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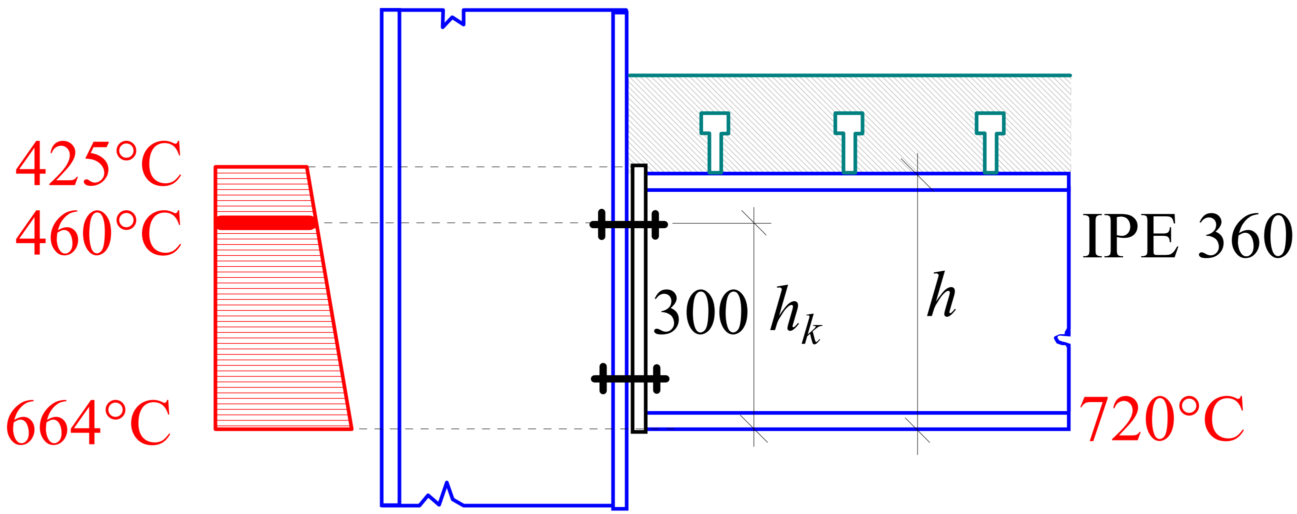
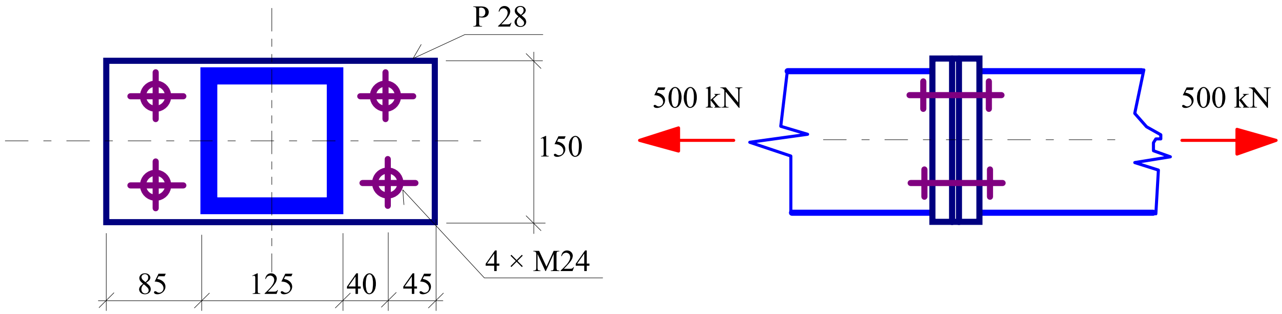
Temperature of the joint

Temperature of the joint depends on the location of the elements (bolts, weld, etc.)



Temperature by step by step method

Splice connection of the lower chord of the truss, R45 required



Unprotected connection

$$\frac{A_m}{V} = \frac{54{,}0}{1{,}24} = 43{,}18\ \mathrm{m}^{-1}$$

the fire resistance is 44 min 45 sec (standard curve)

Protected connection (protection thickness 15 mm)

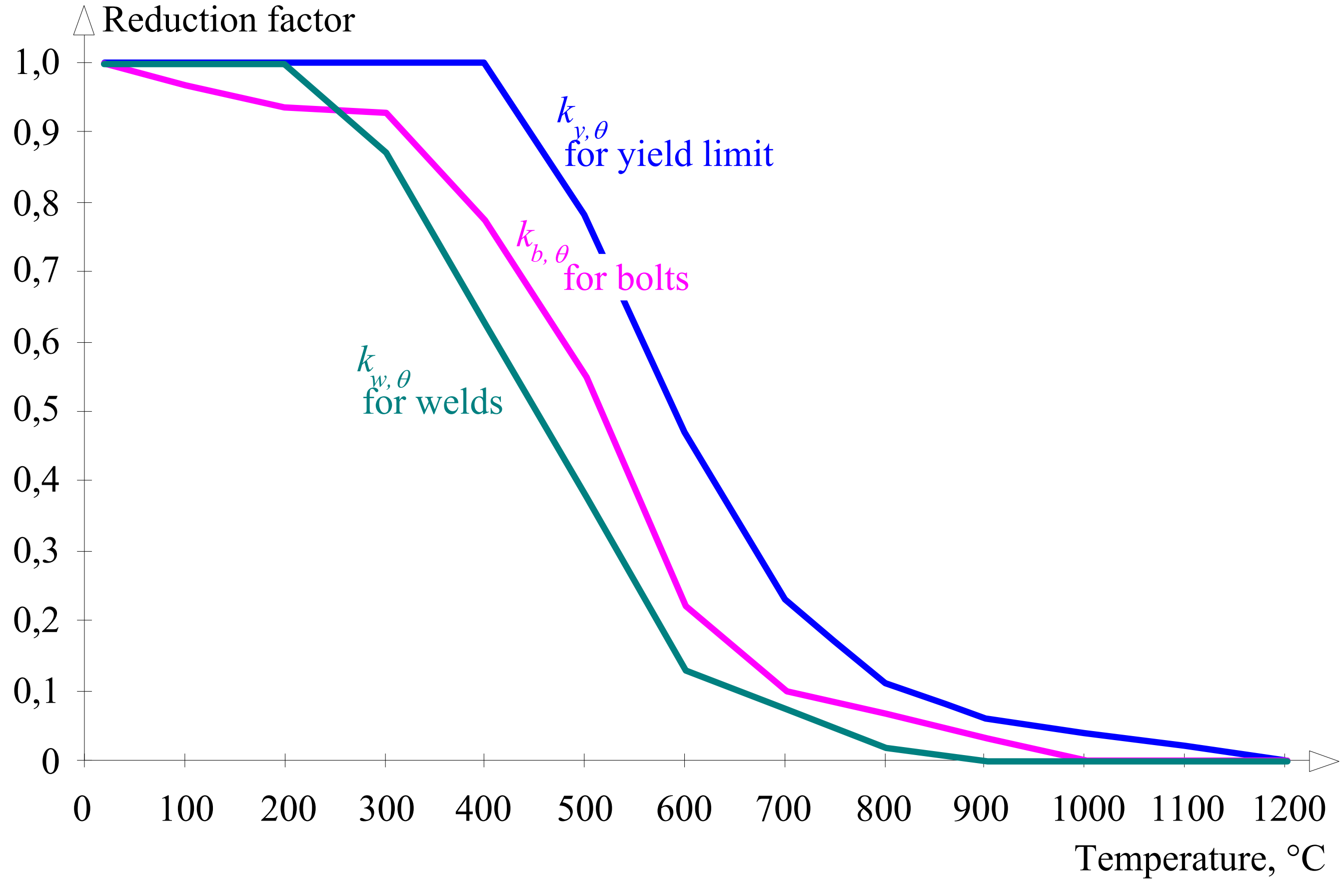
$$\frac{A_p}{V}\frac{\lambda_p}{d_p} = \frac{54{,}0}{1{,}24}\,\frac{0{,}1}{0{,}015} = 288\ \mathrm{W m^{-3} K^{-1}}$$

the fire resistance is 112 min (standard curve)

Reduction factors

EN 1993-1-2 gives the reduction factors for

- bolts
- welds



Component method

Components

– Resistance

$$F_{i,\theta} = k_{y,\theta}\, F_i$$

– Stiffness

$$k_{i,\theta} = k_{E,\theta}\, k_i$$

– Deformation

$$\delta_{i,\theta} = \frac{F_{i,\theta}}{k_{i,\theta}} = \frac{k_{y,\theta}}{k_{E,\theta}}\, \delta_i$$

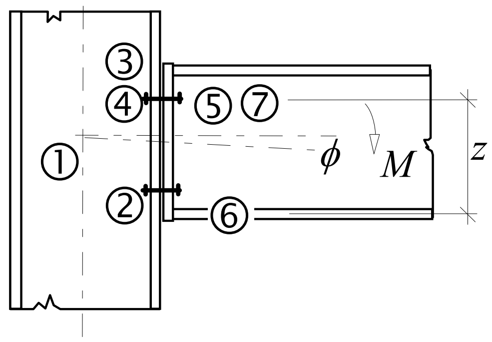
Joint

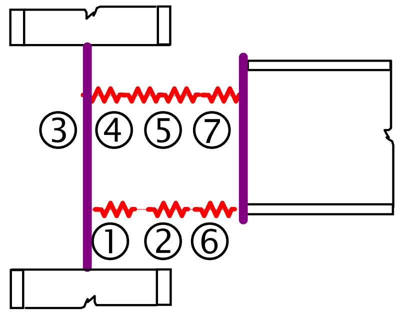
– Resistance

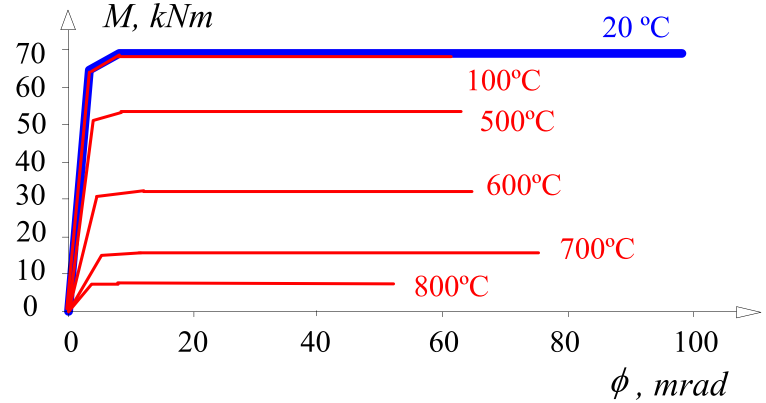
$$M_{j,\theta,Rd} = k_{y,\theta}\, M_{j,Rd}$$

– Stiffness

$$S_{j,ini,\theta} = \frac{E_\theta\, z^2}{\sum_i \frac{1}{k_{i,\theta}}}$$







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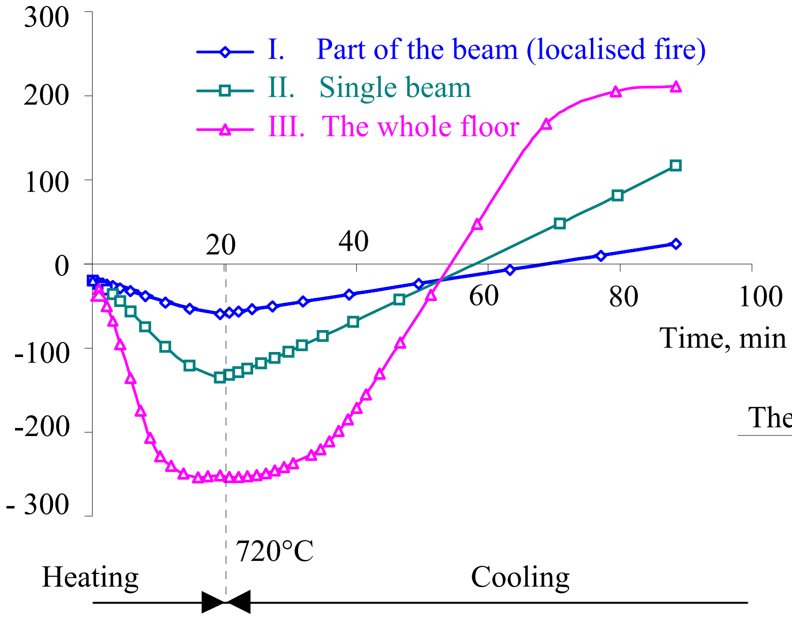
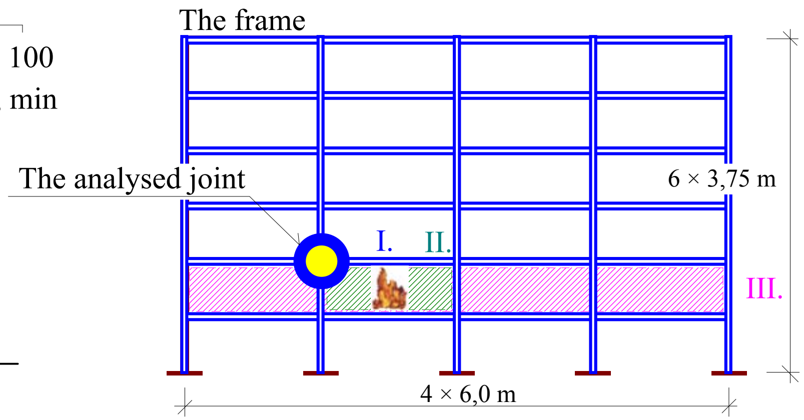
Structural integrity

Axial force in the joint for various fire scenarios





katedra ocelových a dřevěných konstrukcí

Introduction

Properties of steel at high temperatures

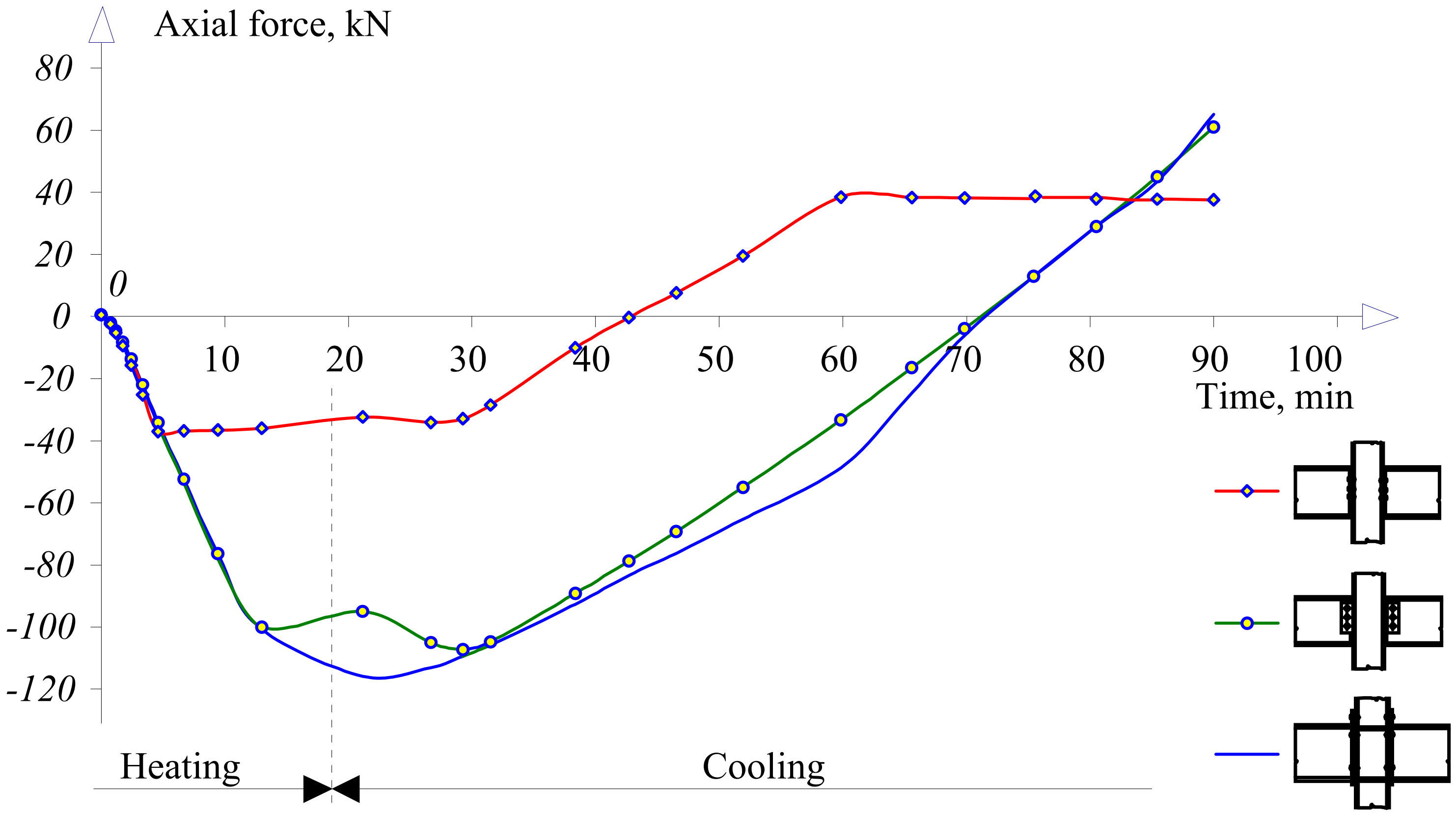
Design models for structural elements

Design models for joints

Conclusion

katedra ocelových a dřevěných konstrukcí

Comparison of different joints



Conclusion

- Simple design models for steel structures
- Based on design at ambient temperature
- Knowledge of material behaviour at high temperature is necessary

- Joints usually do not represent critical part of the structure, no specialised check is necessary
- Simple temperature model for joints is available

- Proper detailing of joints ensuring structural integrity is very important

Thank you for your attention

URL: www.ocel-drevo.fsv.cvut.cz

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