9-3. Structural response in fire

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Education and Culture
Lifelong learning programme
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Objectives
Repetition
Mechanical load
Material properties
Assessment 1
Design tables
Simplified calculation
Advanced calculation
Design software
Assessment 2
Worked example
Assesment
Conclusions
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Objectives of the lecture

- The mechanical load in the fire design
- Response of the structure exposed to fire
- Levels of accuracy/complexity of fire design
- Avaliable worked examples and design softwares

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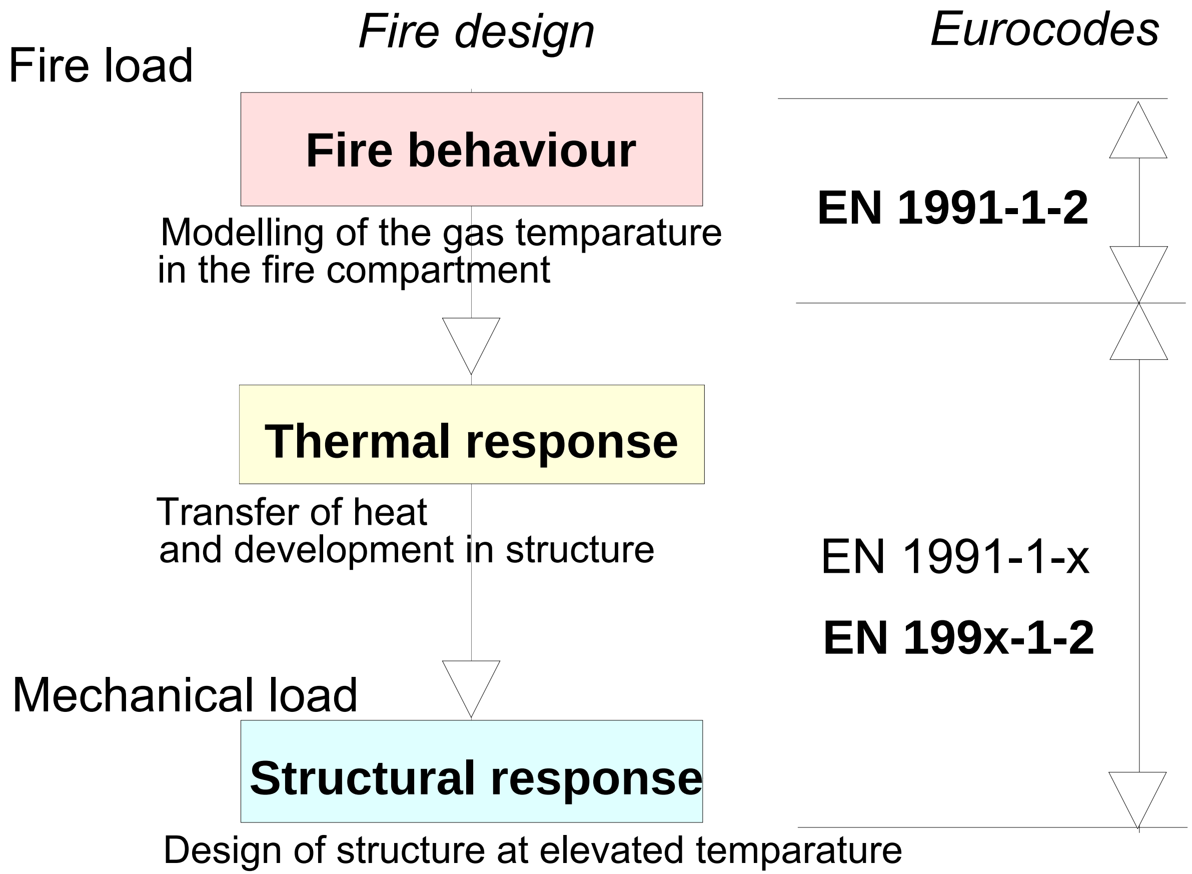
Repetition

- Three steps of fire design



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Repetition

- Structural response
  - Global analyses
    - At ambient temparature
    - At elevated temparature
  - The structure
    - Whole structure
    - Part of the structure
    - The structural element (beam, colum, connection)

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Mechanical load at fire situation

- Mechanical load at fire lower compare to maximum one at ambiet temparature
- Sorce of safety for structures exposed to fire
- Described in
  - EN 1990 the load combinations at accidental situation
  - EN 1991-1-2 procedure to aplly the load
  - EN 1991-1-x particular loading
    - pernament, wind, snow, etc.

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Mechanical load

- Combination rules for mechanical actions
  EN 1990: Basis of structural design
- **At fire conditions ≡ at the accidental situation**

$$E_{fi,d} = G + \psi_{1\text{ or }2,1} Q_1 + \sum_{i>1} \psi_{1\text{ or }2,i} Q_i$$

E.g. offices area with the imposed load *Q*,

as the leading variable action

$$E_{fi,d} = G + 0{,}5\ Q$$

E.g. offices area with the wind *W*,
as the leading variable action

$$E_{fi,d} = G + 0{,}2\ W + 0{,}3\ Q$$

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Values of ψ factors for buildings

Table A1.1 in EN 1990:2002

Action	ψ_0	ψ_1	ψ_2
Imposed loads in buildings, category (see EN 1991-1.1)			
Category A : domestic, residential areas	0,7	0,5	0,3
Category B : office areas	0,7	0,5	0,3
Category C : congregation areas	0,7	0,7	0,6
Category D : shopping areas	0,7	0,7	0,6
Category E : storage areas	1,0	0,9	0,8
Category F : traffic area vehicle weight $\leq$ 30kN	0,7	0,7	0,6
Category G : traffic area, 30 kN < vehicle weight $\leq$ 160kN	0,7	0,5	0,3
Category H : roofs	0	0	0
Snow loads on buildings (see EN1991-1.3)			
Finland, Iceland, Norway, Sweden	0,70	0,50	0,20
Remainder of CEN Member States, for sites located at altitude H > 1000 m a.s.l.	0,70	0,50	0,20
Remainder of CEN Member States, for sites located at altitude $H \leq$ 1000 m a.s.l.	0,50	0,20	0
Wind loads on buildings (see EN1991-1.4)	0,6	0,2	0
Temperature (non-fire) in buildings (see EN1991-1.5)	0,6	0,5	0

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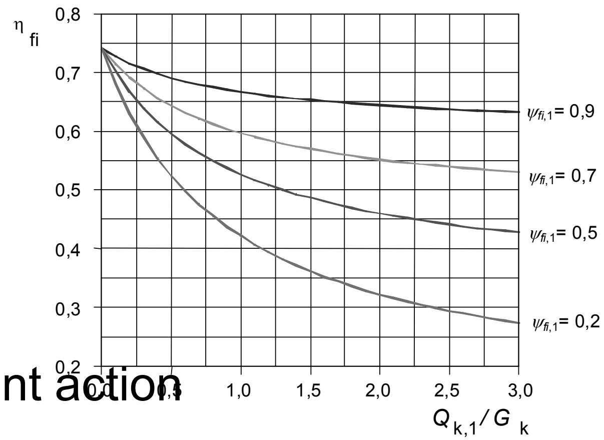
Reduction factor η_{fi}

for load combination

The design value at fire situation devided by design value at ultimate limit state at elevated temperature:

$$\eta_{fi} = \frac{G_k + \psi_{fi} Q_{k,l}}{\gamma_G G_k + \gamma_{Q,1} Q_{k,1}}$$



G_k is the characteristic value of a permanent action

$Q_{k,1}$ is characteristic value of the leading variable action

ψ_{fi} is the combination factor for values, given either by $\psi_{1,1}$ or $\psi_{2,1}$ (according to relevant National Annexes)

γ_G is the partial factor for permanent actions

$\gamma_{Q,1}$ is the partial factor for variable action

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Material properties

at elevated temparature

Design values of material properties at elevated temparature for structures exposed to fire are described by reduction factors of properties at ambient temperature

$$X_{d,fi} = k_\theta X_k / \gamma_{M,fi}$$

k_θ	is reduction factor for a mechanical property with respect to temperature
X_k	is characteristic value of a mechanical property for ambient temperature design to EN1993-1-1
$\gamma_{M,fi}$	is Partial material safety factor for fire situation**;** for thermal & mechanical properties recommended 1,0

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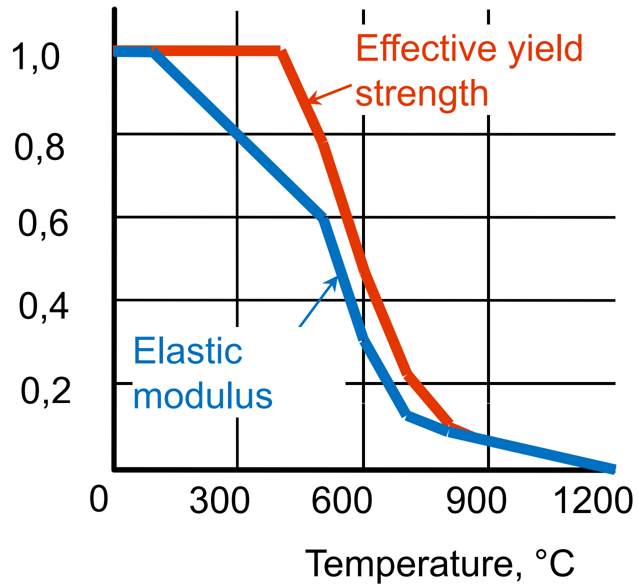
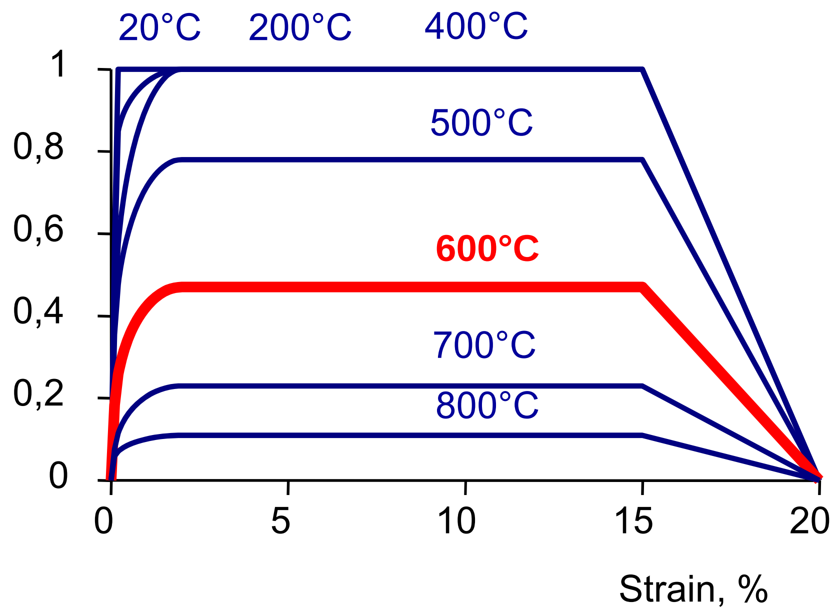
Structural steel
at elevated temperatures, EN 1993-1-2

Reduction factor, k_θ
strength % of normal value, k_θ



Normalised stress
for advanced modelling



Yield strength at 600°C reduced by over 50%

Elastic modulus at 600°C reduced by about 70%

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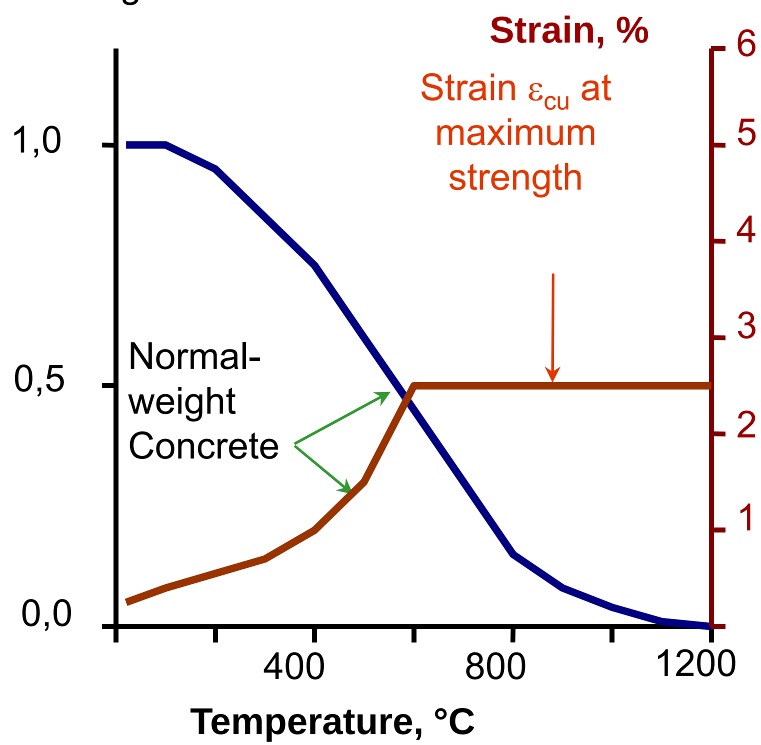
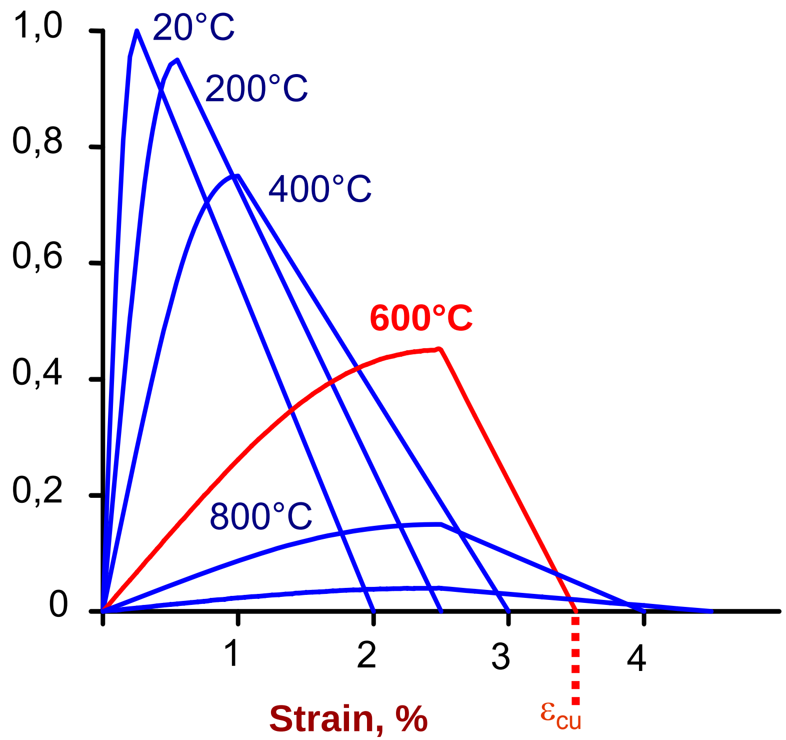
Concrete
at elevated temperatures, EN 1994-1-2

Reduction factor, k_θ
strength % of normal value



Normalised stress
for advanced modelling



Compressive strength at 600°C reduced by about 50 %

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Formative assessment question 1

- Where are formulated the combination rules for mechanical actions?
- How is defined the redaction factor for load combinations?
- How is reduced the yield strength of structural steel at 600°C?
- How is reduced the compressive strength of concrete at 600°C?
- How is defined the reduction of the material properties at elevated temperature during fire in standards?

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Procedure

for assessing mechanical response in fire

- Tabulated data
  - Composite structural members
- Simple calculation models
  - Critical temperature method
  - Steel and composite structural members

→ Classic and traditional fire design

- Advanced calculation models
  - All types of structures
  - Numerical models based FE

→ Advanced fire design

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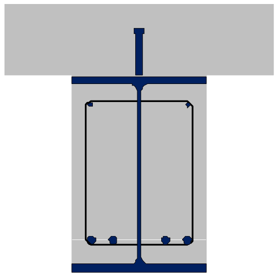
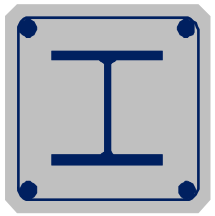
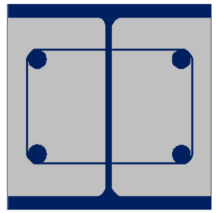
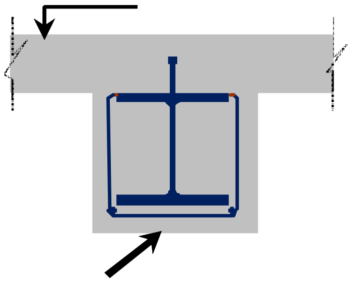
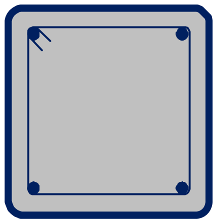
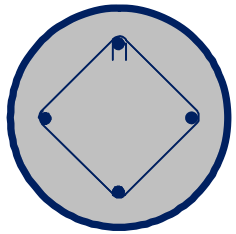
Tabulated data

for steel and concrete composite members

Composite beams	Composite columns	
		
		

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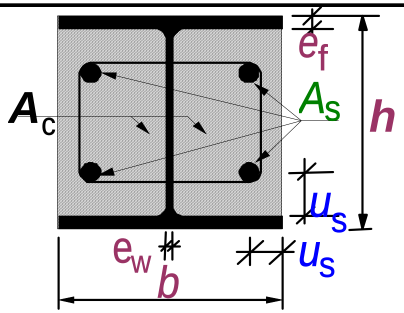
Tabulated data

parameters for composite columns EN 1994-1-2



		Standard Fire Resistance			
		R30	R60	R90	R120
	Minimum ratio of web to flange thickness e_w/e_f	0,5			
1	Minimum cross-sectional dimensions for load level	$\eta_{fi,t} \le 0{,}28$			
1.1	minimum dimensions *h* and *b* [mm]	160	200	300	400
1.2	minimum axis distance of reinforcing bars u_s [mm]	-	50	50	70
1.3	minimum ratio of reinforcement $A_s/(A_c+A_s)$ in %	-	4	3	4
2	Minimum cross-sectional dimensions for load level	$\eta_{fi,t} \le 0{,}47$			
2.1	minimum dimensions *h* and *b* [mm]	160	300	400	-
2.2	minimum axis distance of reinforcing bars u_s [mm]	-	50	70	-
2.3	minimum ratio of reinforcement $A_s/(A_c+A_s)$ in %	-	4	4	-
3	Minimum cross-sectional dimensions for load level	$\eta_{fi,t} \le 0{,}66$			
3.1	minimum dimensions *h* and *b* [mm]	160	400	-	-
3.2	minimum axis distance of reinforcing bars u_s [mm]	40	70	-	-
3.3	minimum ratio of reinforcement $A_s/(A_c+A_s)$ in %	1	4	-	-

Standard fire rating

Load level

Section dimension

Reinforcing steel

Concrete cover

Application of tabulated data

Verification

Design resitance at ambient temparature: R_d

Acting forces at elevated temparature: $E_{fi,d}$

Reduction factor for load combination: $\eta_{fi} = E_{fi,d} / R_d$

↓

Section dimension
Reinforcing steel
Concrete cover

↓

Rating
for nominal standard fire curve

Simple calculations models

- The Eurocode for fire design of steel structures EN 1993-1-2 based on global analyses at ambient temperature:
  - Limits of use
  - Classification of sections
  - Procedure for evaluation of member resistance
    - for evaluation of the members in time or resistance domain
    - Beams
    - Columns
  - Critical temperature procedure
    - for evaluation of the members in temperature domain

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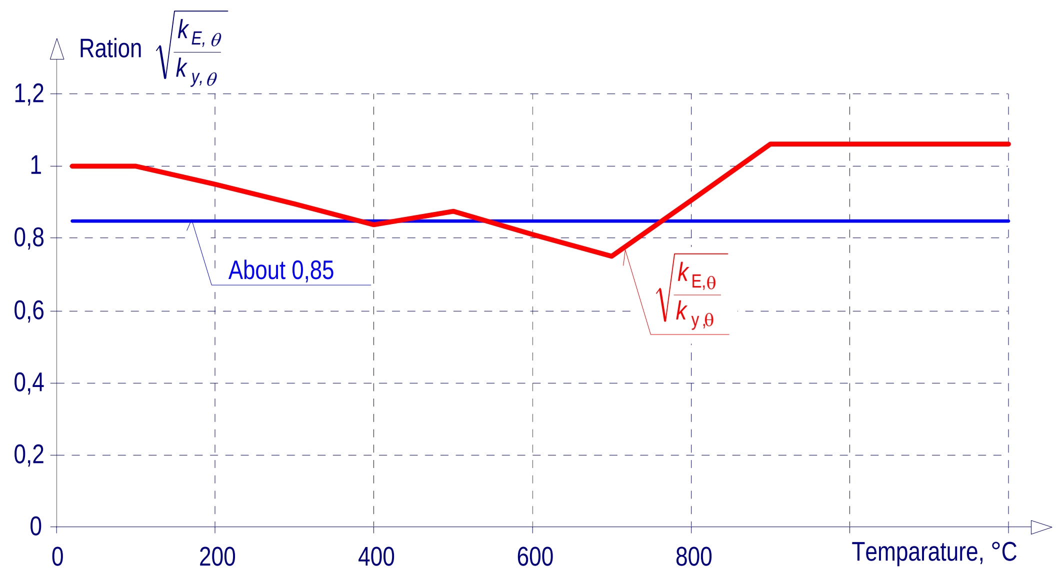
Classification of cross-sections

For the purpose of the simplified rules the cross-sections may be classified as for ambient temperature design with a reduced value for

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

where:

f_y is the yield strength at ambient temperature



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Beams

Class 1 and 2, laterally restrained

The **design moment resistance**
of a Class 1 or Class 2 cross-section
with a uniform temperature θ_a should be determined from

$$M_{fi,\theta,Rd} = k_{y,\theta} [\gamma_{M,0} / \gamma_{M,fi}] M_{Rd}$$

where:

$k_{y,\theta}$ is the reduction factor for the effective yield strength of steel at temperature θ_a

M_{Rd} is the plastic moment resistance of the cross-section $M_{pl,Rd}$ for ambient temperature design

$\gamma_{M,0} / \gamma_{M,fi}$ is the ratio of partial safety factors at ambient and fire situation

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Beams

Non-uniform temperature distribution

- Simplified solution

The design moment resistance at time *t*
of a Class 1 or 2 cross-section in a member
with a **non-uniform temperature distribution**

$$M_{fi,t,Rd} = M_{fi,\theta,Rd} / (\kappa_1 \kappa_2)$$

where:

$M_{fi,\theta,Rd}$ is the **design moment resistance** of the cross-section for a uniform temperature θ_a

κ_1 and κ_2 are the **adaptation factors** of non-uniform temperature distribution

- Complex solution

Based on reduction of material properties along the cross-section hight and distance from the plastic neutral axis

Beams

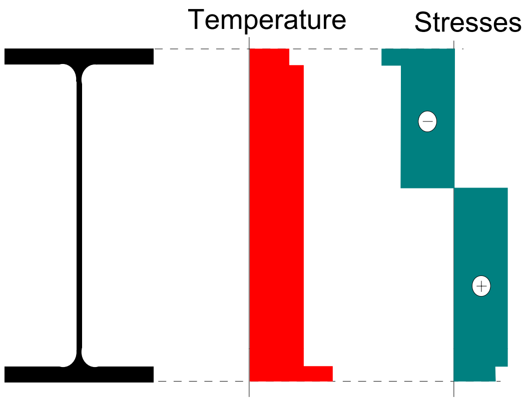
Adaptation factor for non-uniform temperature distribution **across**

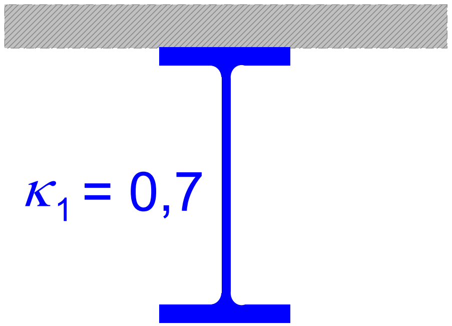
- For non-uniform temperature distribution across a cross-section

  - for a beam exposed on all four sides $\kappa_1 = 1,0$

  - for an unprotected beam exposed on three sides, with a composite or concrete slab on side four $\kappa_1 = 0,70$

  - for an protected beam exposed on three sides, with a composite or concrete slab on side four $\kappa_1 = 0,85$





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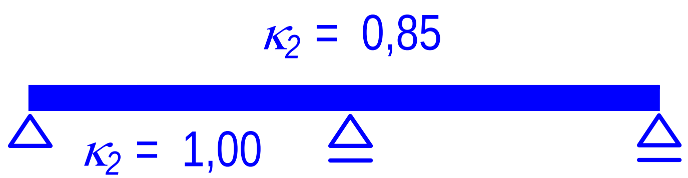
Beams

Adaptation factor for non-uniform temperature distribution **along**

- For a non-uniform temperature distribution along a
  - at the supports of a statically indeterminate beam $\kappa_2 = 0,85$
  - in all other cases $\kappa_2 = 1,0$



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Critical temperature method

According to simple calculation models, for uniformly heated steel members $R_{fi,d,t} = k_{y,\theta} R_{fi,d,0}$

On the other hand, fire resistance should satisfy:

$$R_{fi,d,t} \geq E_{fi,d} = \frac{E_{fi,d}}{R_{fi,d,0}} R_{fi,d,0} = \mu_0 R_{fi,d,0} \Rightarrow k_{y,\theta} \geq \mu_0$$

In particular, when $k_{y,\theta} = \mu_0$ the corresponding temperature is defined as critical temperature θ_{cr}

In EN 1993-1-2 a formula is given to determine critical temperature

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

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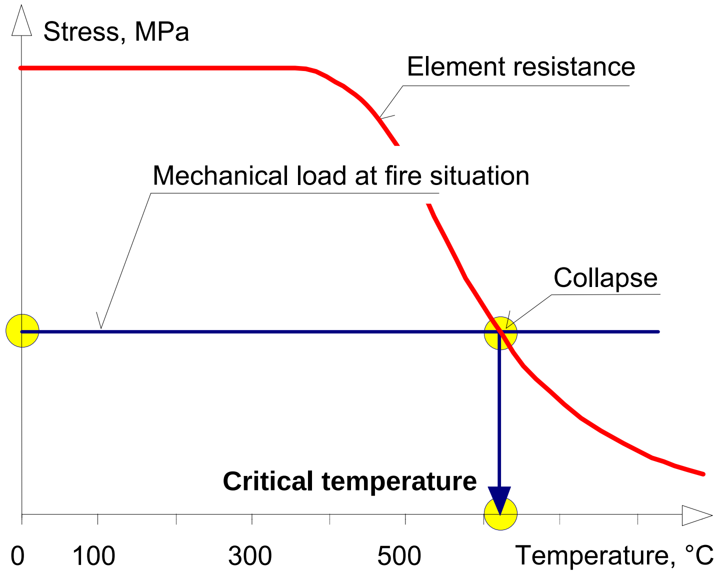
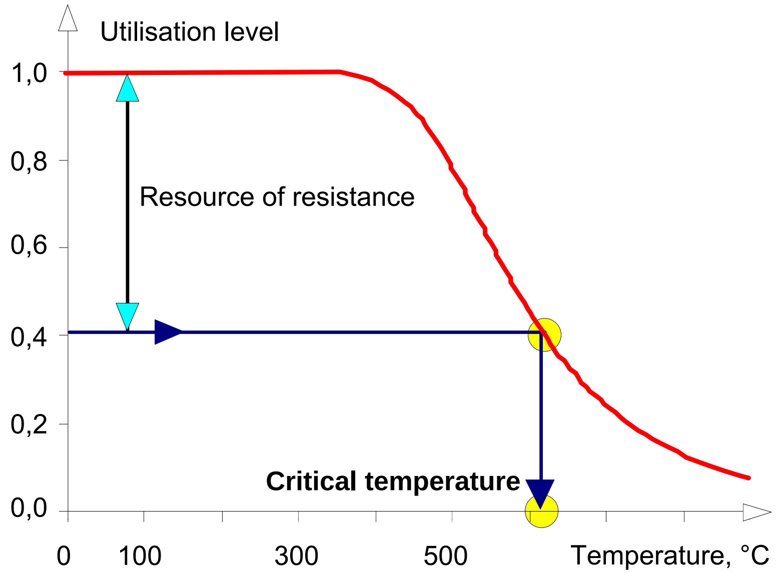
Verification in the time domain

- The metod is handly for stress driven resistance, e.g. bending
- For stability problem is more efficient to check the resistance at certain level of temperature





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Application
of critical temperature method

Action in fire $E_{fi,d}$

Design resistance at ambient temperature R_d
or design action at ambient temperature E_d

Load level in fire $\eta_{fi,t} = \dfrac{E_{fi,d}}{R_d}$

Utilisation level $\mu_0 = \eta_{fi,t} \dfrac{\gamma_{M,fi}}{\gamma_M}$

Critical temperature θ_{cr}

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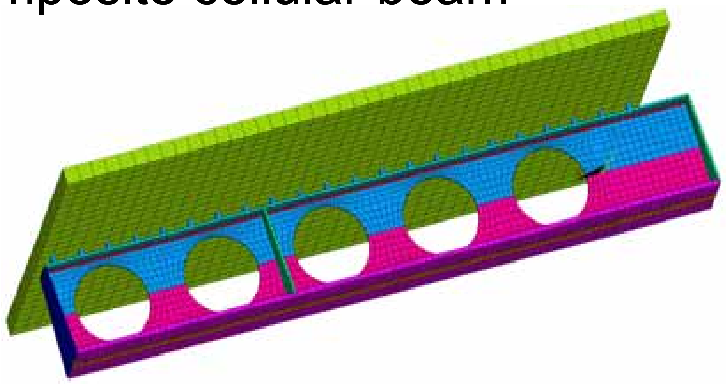
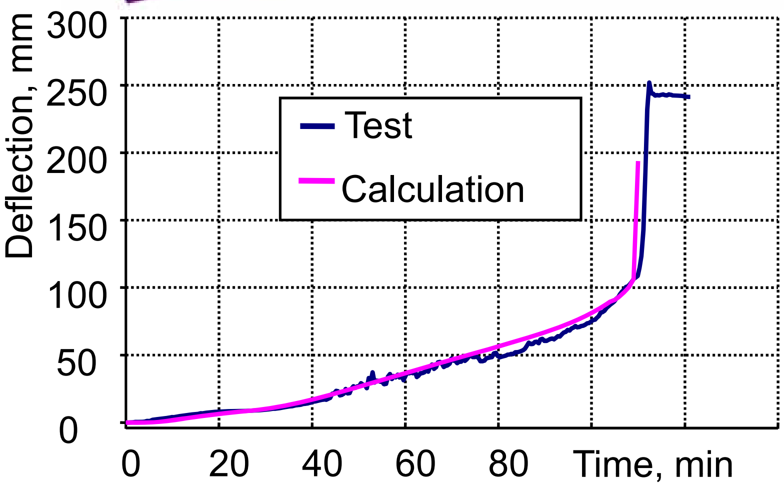
Advanced calculation model

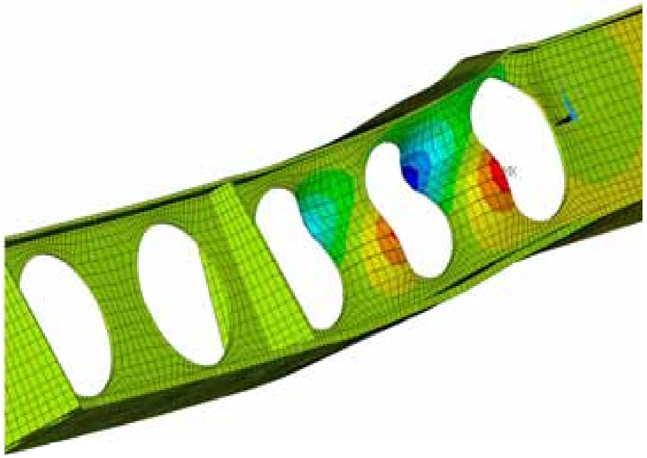
Example
composite cellular beam





Calculation vs test

Tested failure mode



Simulated failure mode

Acording to DIFISEK⁺ O. Vassart, ArcelorMittal

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Examples of the tools

General / Commerical codes

Examples
- Abaqus
- Ansys
- Others

Dedicated Codes

Examples
- Vulcan
- Adaptic
- Safir
- Others

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Pros and Cons of the tools

General/Commerical codes

- **Pros**
  - Fast
  - Reliable
  - Very general
  - Support
- **Cons**
  - (Very) expensive
  - Black-box

Dedicated codes

- **Pros**
  - Good price
  - Access to source
  - Focussed on fire
- **Cons**
  - Struggle with large problems
  - Not support
  - Credibility

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Formative assessment question 2

- What is the difference of classification of cross-sections at ambient and elevated temperatures?
- Describe the evaluation of the design moment resistance of a beam of a Class 1 or Class 2 cross-section at elevated temperature with a uniform temperature?
- How may be treated the non-uniform temperature of a cross-section?
- What is the principle of the critical temperature method?
- Pros of dedicated codes for advanced fire design?

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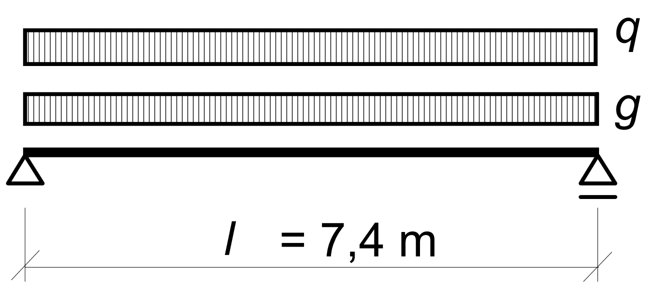
Worked example

Fire design of an unprotected beam using graphs

- This worked example covers the fire design of a **hot-rolled IPE section** forming part of floor structure of an office building.
- The beam is **uniformly loaded** and **restrained** against lateral torsional buckling by the presents of a **concrete slab on the top flange**.
- The beam is to be designed to achieve **R15 fire resistance** without the use of fire protection material.



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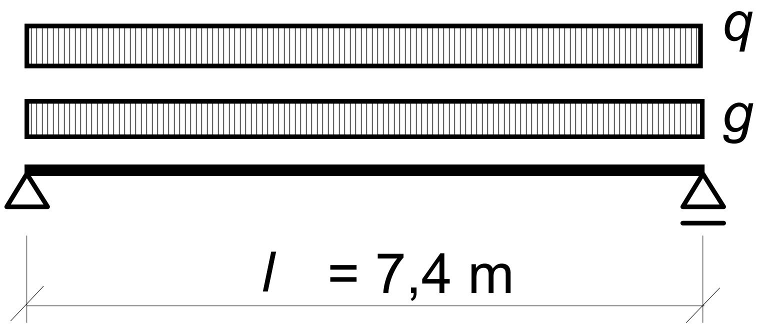
Basic data

Material properties

Steel grade S 275

Yield stress f_y = 275 N/mm²

Density: ρ_a = 7850 kg/m³



Loads

Permanent action:

g_k = 4,8 kNm^{-1}

Variable action:

q_k = 7,8 kNm^{-1}

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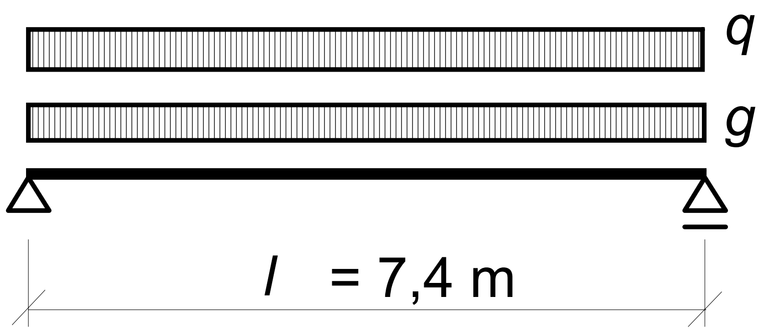
Mechanical actions at ambient temperature



The characteristic value of the load is

$$v_k = g_k + q_k = 4{,}8 + 7{,}2 = 12{,}6 \text{ kN/m}$$

The design value of the load is

$$v_d = g_k\, \gamma_G + q_k\, \gamma_Q = 4{,}8 \cdot 1{,}35 + 7{,}2 \cdot 1{,}5 = 18{,}18 \text{ kN/m}$$

The applied bending moment is given by

$$M_{Ed} = \frac{1}{8} v_d\; l^2 = \frac{1}{8} \cdot 18{,}18 \cdot 7{,}4^2 = 124{,}4\ kNm$$

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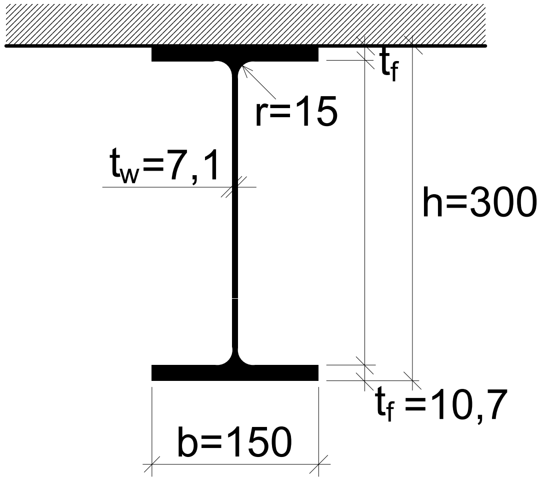
Design at ambient temperature

The IPE 300 section is a Class 1 section in bending.



The section is checked at ULS at ambient temperature.

The concrete slab is assumed to provide full lateral restraint to the beam; therefore, lateral-torsional instability does not need to be taken into account.

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Mechanical actions for the fire design situation

The **reduction factor** for the design load level is equal to

$$\eta_{\mathrm{fi}} = \frac{g_{\mathrm{k}} + \psi_{1,1}\, q_{\mathrm{k}}}{g_{\mathrm{k}}\, \gamma_{\mathrm{G}} + q_{\mathrm{k}}\, \gamma_{Q}} = \frac{4{,}8 + 0{,}3 \cdot 7{,}8}{4{,}8 \cdot 1{,}35 + 7{,}8 \cdot 1{,}5} = 0{,}393$$

where for office buildings is taken the ψ factor as $\psi_{1,1}$ = 0,3

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Design at ambient temperature

Bending moment resistance

$$M_{\text{pl,Rd}} = \frac{W_{\text{pl,y}}\, f_{\text{y}}}{\gamma_{\text{M0}}} = \frac{628{,}4 \cdot 10^3 \cdot 275}{1{,}0} = 172{,}8 \text{ kNm} > 124{,}4 \text{ kNm} = M_{\text{Sd}}$$

OK

Serviceability Limit State

Deflection limits are given either in a national annex or in other national documents. This limit is a typical value.

$$\delta = \frac{5}{384}\,\frac{v_{\text{k}}\, l^4}{E\, I_{\text{y}}} = \frac{5}{384}\,\frac{12{,}60 \cdot 7\,400^4}{210\,000 \cdot 83{,}56 \cdot 10^6} = 28{,}0 \text{ mm} < 29{,}6 \text{ mm} = \frac{l}{250}$$

OK

The section is satisfactory at ambient temperature.

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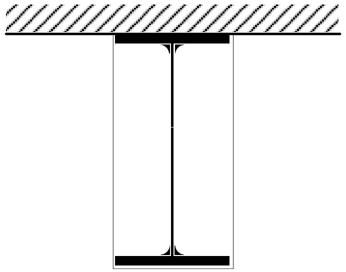
Design in the fire situation

Section factor

The section factor for the hot-rolled section is taken from tables. The box section factor for an unprotected beam exposed on three sides is equal to



$$\left(\frac{A_m}{V}\right)_b = 139\ \mathrm{m}^{-1}$$

The exposed perimeter is indicated by the dashed line on figure.

The shadow effect is considered by modifying the section factor as follows.

$$\left(\frac{A_m}{V}\right)_{sh} = 0{,}9 \cdot \left(\frac{A_m}{V}\right)_b = 0{,}9 \cdot 139 = 125\ \mathrm{m}^{-1}$$

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Degree of utilization

The **adaptation factor**

$\kappa_1 = 0{,}7$

is used for an unprotected beam exposed to fire on three sides

The **adaptation factor**

$\kappa_2 = 1{,}0$

is used for simply supported beam.

The **degree of utilization** for the beam with non-uniform temparature distruibution is given by

$$\mu_0 = \eta_{\text{fi}}\ \kappa_1\ \kappa_2 = 0{,}393 \cdot 0{,}7 \cdot 1{,}0 = 0{,}275$$

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Critical temparature

The critical temparature can be evaluated for the degree of utilization

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

$$= 39{,}19 \cdot \ln\left(\frac{1}{0{,}9674 \cdot 0{,}275^{3{,}833}} - 1\right) + 482 = 677°C$$

EQUESTA

Electronic Quality Assured Steel Training & Assessment

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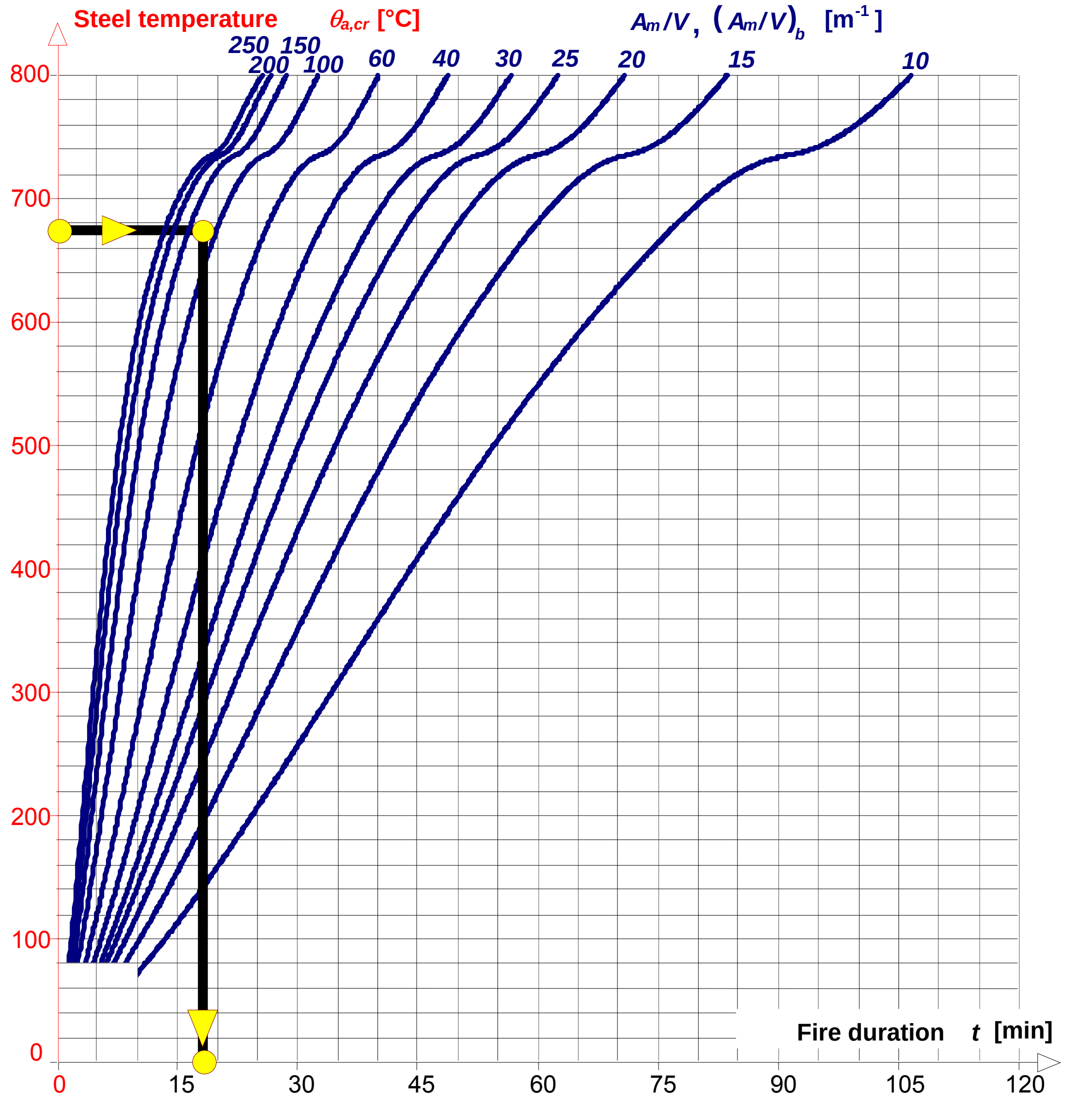
Transfer of heat by graph

The step-by-step procedure may be replaced by reading on the graph, as reproduced in Figure.



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Verification in the time domain

The fire resistance period predicted using Figure is equal to 17 min.

This exceeds the required fire resistance R15.

Therefore, **the fire resistance of the section is satisfactory without applied protection**.

For detailed explanation and another worked examples with more precised procedure see worked examples in www.access-steel.com

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Assessment

- What is the difference between the load level and the utilisation level?
- For what cases is useful the critical temperature method?
- In which domain is recommended to evaluate the resistance in case of stability?

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Conclusions

- There are tree levels of accuracy/complexity of fire design
- For simple worked examples please consult AcceesSteel
- For complex worked examples and software please consult DIFISEK^{+}
- New models for composite slab, connections and coldformed elements are finalised

Thank you
for your attention

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Notes to users of the lecture

- This session is a basic information about the mechanical load of structures exposed to fire and its modeling requires about 60 min lecturing and 60 min for tutorial session.
- Further readings on the relevant documents from website of www.access-steel.com and www.difisek.eu.
- The use of relevant standards of national standard institutions are recommended.
- Formative questions should be well answered before the summative questions completed within the tutorial session.
- Keywords for the lecture:

  fire design, mechanical loading, mechanical response at elevated temperature, simple calculation methods, Eurocodes.

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Notes to users of the lecture

Worked examples for mechanical response

- The application of the graph is in AccessSteel example
    - Fire design of an unprotected beam using graphs
- The description of step by step procedure for heat transfer is in AccessSteel examples
    - Fire design of an unprotected IPE section beam exposed to the standard time temperature curve
    - Fire design of a protected HEB section column exposed to the standard temperature time curve

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Notes for lecturers

- Subject: Fire modelling and transfer of heat to structure.
- Lecture duration: 60 min plus 60 min tutorial
- Keywords: fire design, mechanical loading, mechanical response at elevated temperature, simple calculation methods, Eurocodes.
- Aspects to be discussed: recources of fire safety at fire, start of reduction of material properties, advanced models.
- Within the lecturing, the procedure of Eurocode fire design is explained.
- Further reading: relevant documents from website of www.access-steel.com and www.difisek.eu.