SPECIAL MOBILITY STRAND

Influence of design parameters in fire safety of structural steel beams

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Dr. Endrit HOXHA
EPOKA University

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Plan of presentation

- Importance of structural fire safety analysis
- Design approaches
- Critical temperature method
- Case study
- Influence of design parameters
- Conclusion

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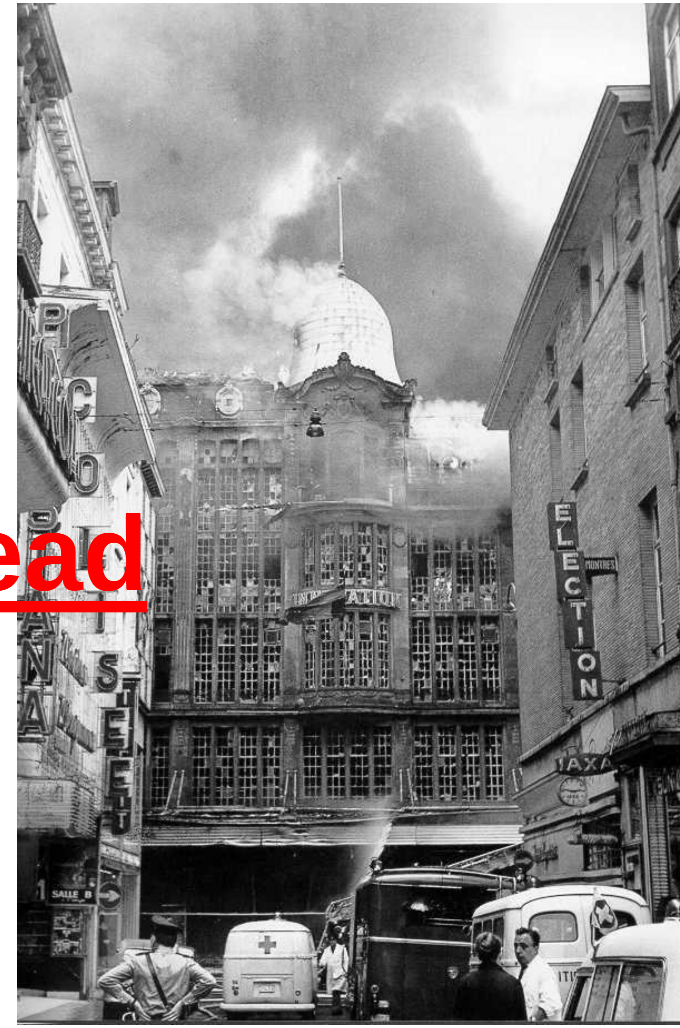
1. Importance of the problem

Why a fire design is important???

322 dead



Innovatin-Brussels, 1967

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1. Importance of the problem

Windsor tower on fire

Location:	Madrid, Spain
Fire Event:	12 February 2005 Fire started at the 21st Floor, spreading to all floors above the 2nd Floor. Fire duration: 18 ~ 20 hours
Fire Damage:	Extensive slab collapse above the 17th Floor. The building was totally destroyed by the fire.
Construction Type:	Reinforced concrete core with waffle slabs supported by internal RC columns and steel beams, with perimeter steel columns which were unprotected above the 17th Floor level at the time of the fire.
Fire Resistance:	Passive fire protection. No sprinklers.
Building Type:	106 m (32 storey). Commercial.

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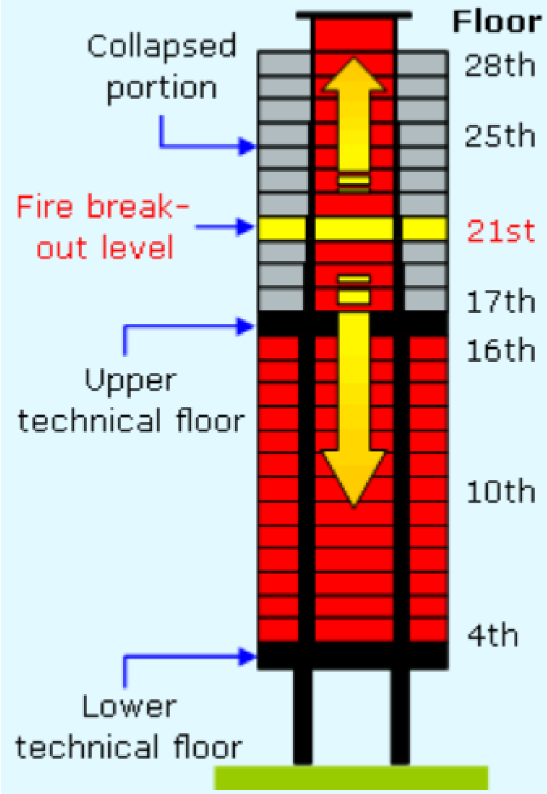
1. Importance of the problem

18 ~ 20 hours.

Time	Fire Development
23:00	Fire started at the 21st Floor
23:05 ~ 23:20	After receiving a fire signal, the security guards went to the 21st floor and attempting to fight the fire before giving up
23:21	Fire brigade was called
23:25	Fire brigade arrived
23:30	Fire brigade started to fight the fire (news report)
00:00	All floors above the 21st floor were in fire (news report)
00:30	Fire brigade retreated and adopted a defensive position, preventing fire spread to adjacent buildings
02:00	Fire spread below the 17th floor
02:15	Chunks of facade started falling off (news report)
03:30	Fire spread below 16th floor, crossing over the upper technical floor
04:00	Floors at upper level collapsed (news report)
05:30	Fire spread below the 12th floor (news report)
08:30	Fire spread below the 4th floor
13:30	Fire was under controlled
17:00	Fire brigade declared the put out of the fire (news report)

Cross Section



1. Importance of the problem

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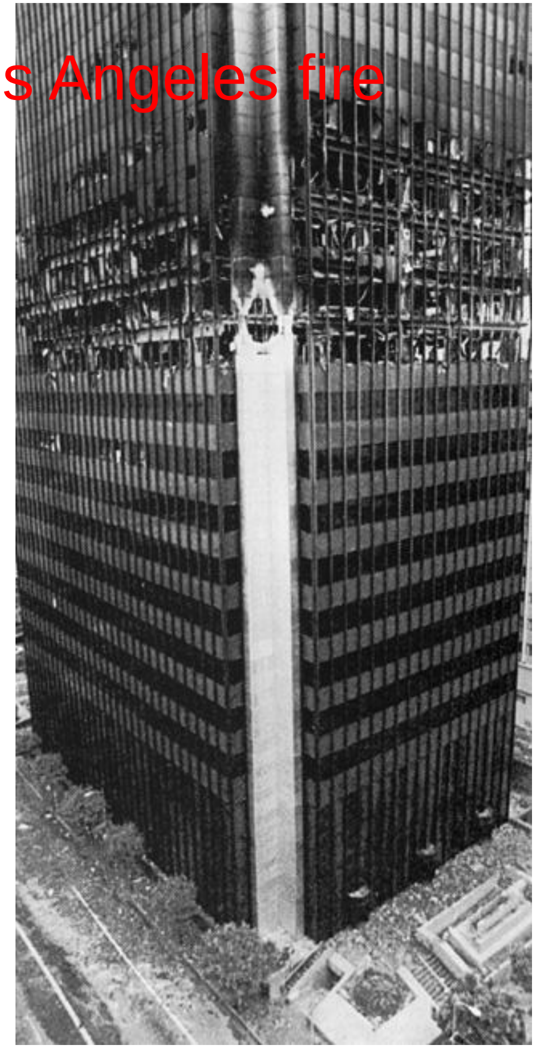
Interstate bank Los Angeles fire



1. Importance of the problem

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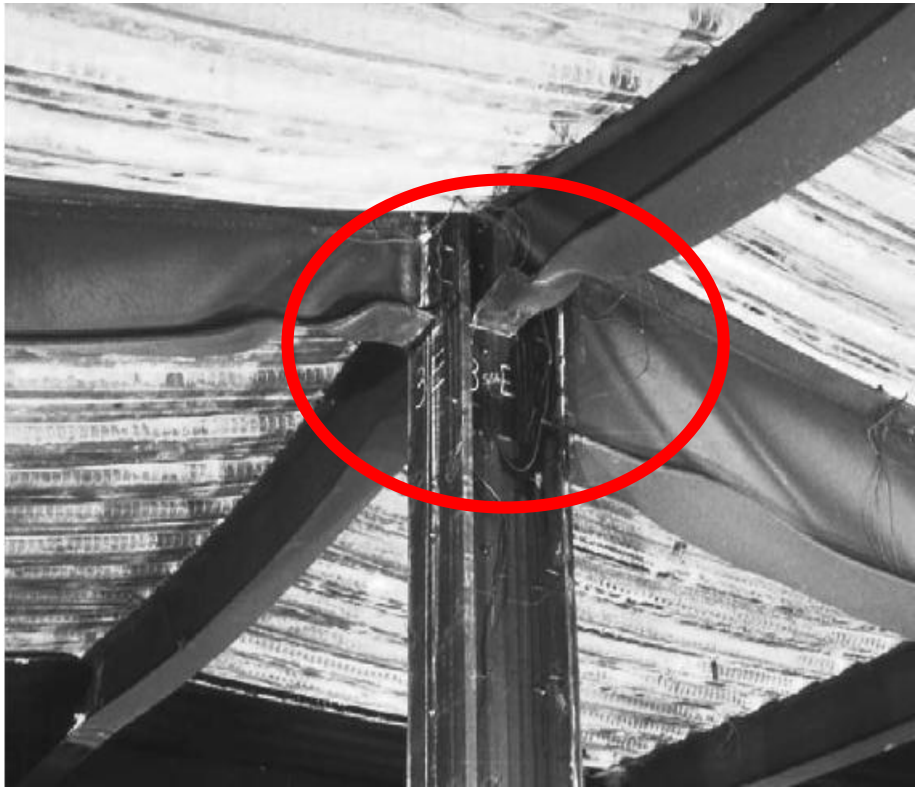

1. Importance of the problem

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1. Importance of the problem

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The key objective of fire protection is to limit, to acceptable levels the probability of death injury, property loss and environmental damage in an unwanted fire.

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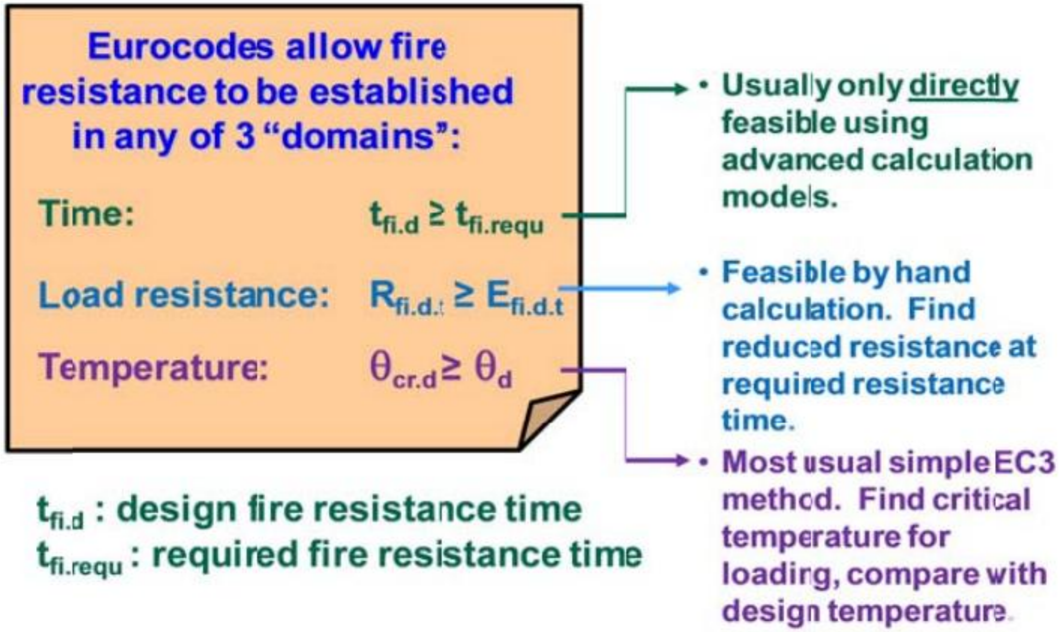
2. Design approaches

Fire resistance of steel building structures can be assessed:

- In terms of time duration obtained
- In terms of fire resistance capacity
- In terms of critical temperature

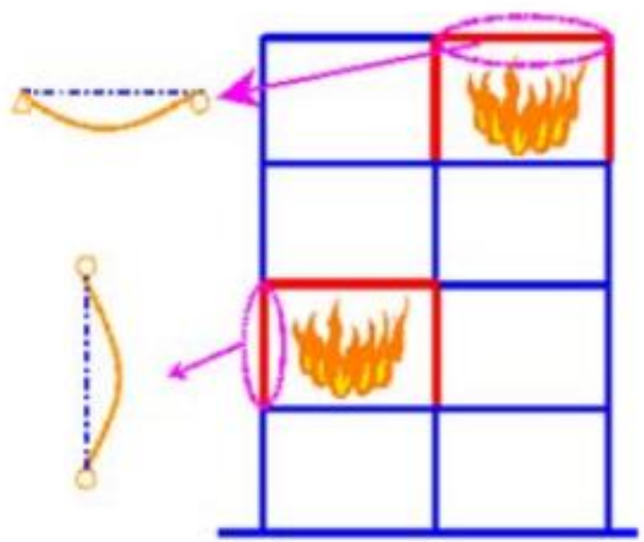


2. Design approaches

Fire resistance design of steel structures:

- Member analysis

Member analysis

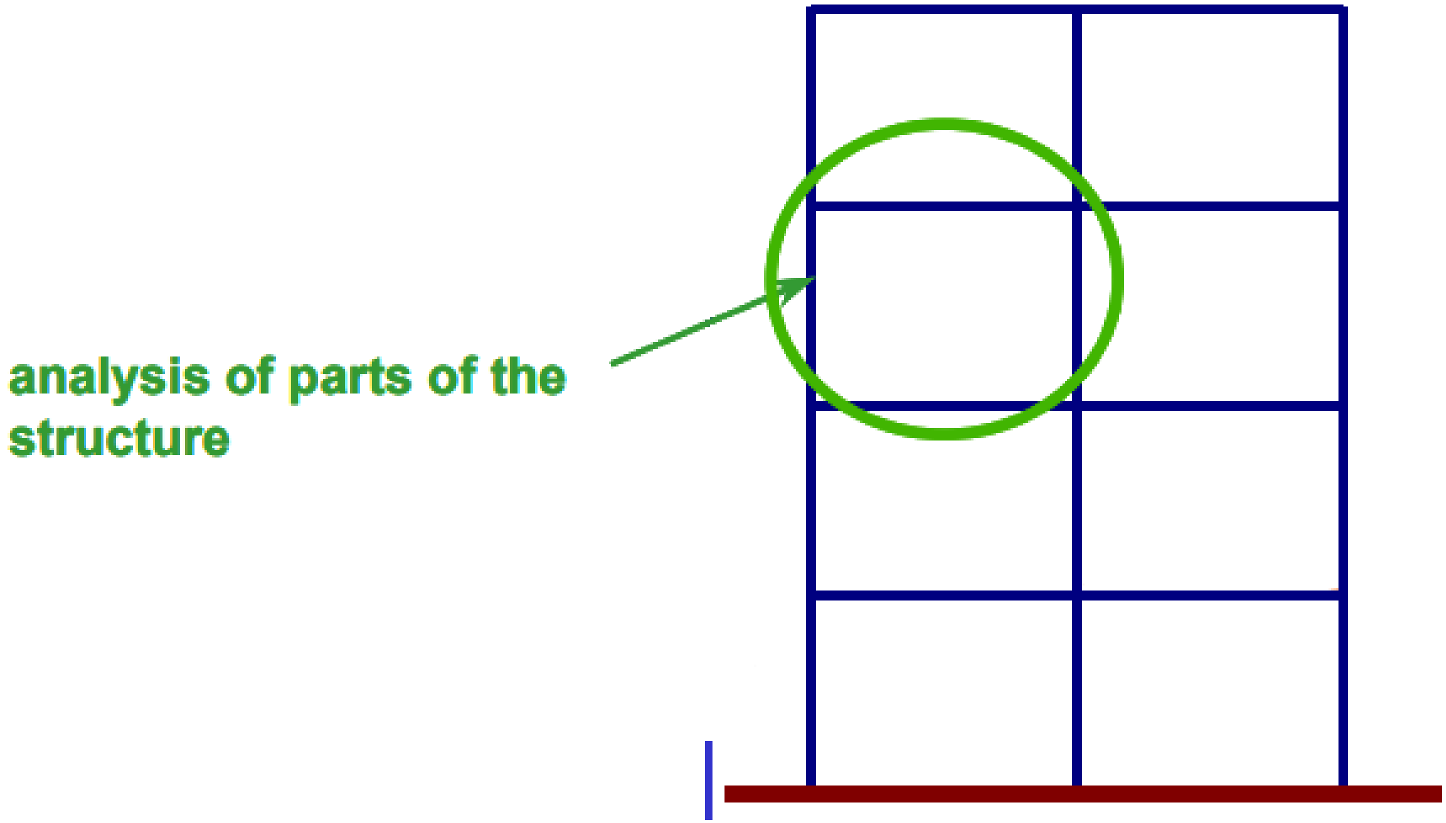


- ➢ independent structural element analysis
- ➢ simple to apply
- ➢ generally for nominal fire condition

2. Design approaches

Fire resistance design of steel structures:

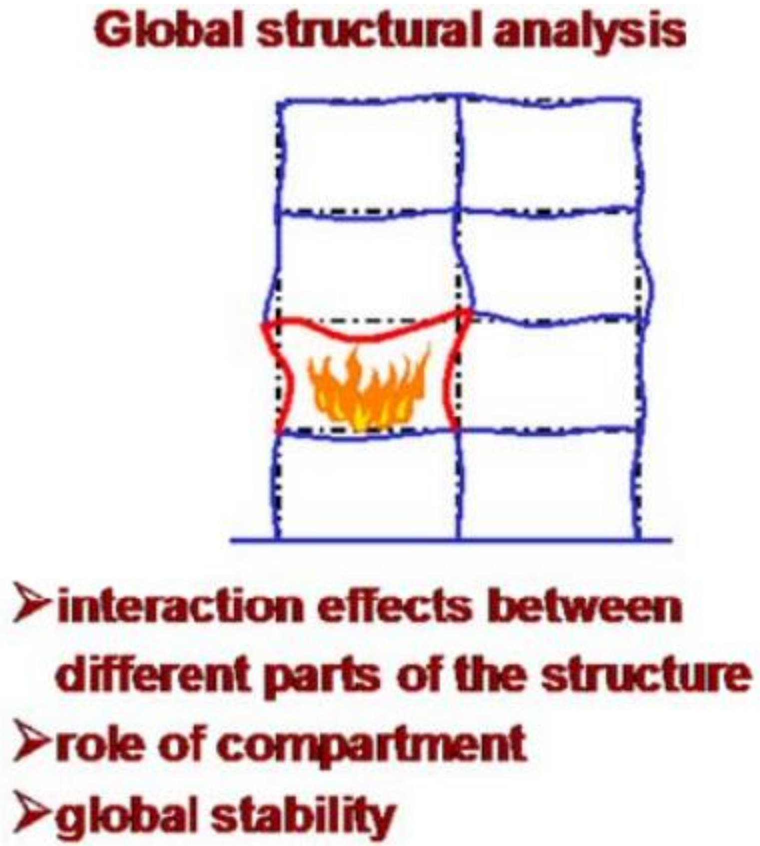
- Analysis of parts of the structures



2. Design approaches

Fire resistance design of steel structures:

- Global structures analysis



2. Design approaches

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

Critical temperature method

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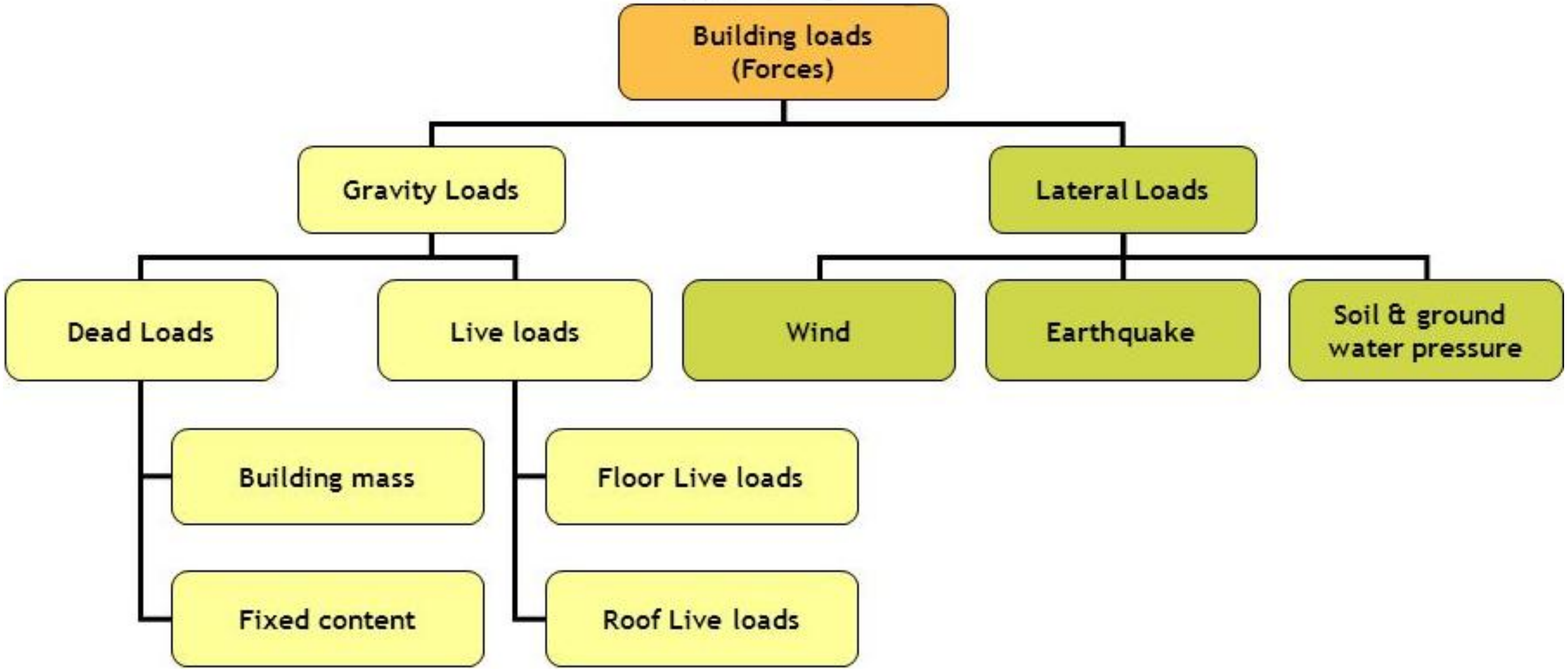
3. Critical temperature method

Step 1: Determination of applied design load to a steel member in the fire situation



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3. Critical temperature method

Classification of actions

- Variation in time
  - Permanent
  - Variable
  - Accidental
- Origin
  - Direct (e.g. forces)
  - Indirect (e.g. temperatures)
- Spatial variation
  - Fixed (e.g. self weight)
  - Free (e.g. predeformation)
- Nature
  - Static
  - Dynamic

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3. Design situation

Design situations shall be classified as follows:

- persistent design situations, which refer to the conditions of normal use;
- transient design situations, which refer to temporary conditions applicable to the structure, e.g. during execution or repair;
- accidental design situations, which refer to exceptional conditions applicable to the structure or to its exposure, e.g. to fire, explosion, impact or the consequences of localized failure;
- seismic design situations, which refer to conditions applicable to the structure when subjected to seismic events.

3. Critical temperature method

The combination of actions for fire situation can be expressed as:

$$\sum_{j\geq 1} G_{k,j} + P + A_d + \left(\psi_{1,1}\, or\, \psi_{2,1}\right) \cdot Q_{k,1} + \sum_{i\geq 1} \psi_{2,1} \cdot Q_{k,j}$$

$G_{k,j}$: are the characteristic values of the permanent actions
$Q_{k,1}$: is the characteristic leading variable action
$Q_{k,i}$ are the characteristic values of the accompanying variable actions
$\Psi_{1,1}$:is the factor for frequent value of a variable action
$\Psi_{2,1}$: is the factor for quasi-permanent values of the variable actions.

The choice between $\psi_{1,1}$ and $\psi_{2,1}$ should be related to the relevant accidental design situation (impact, fire or survival after an accidental event or situation).

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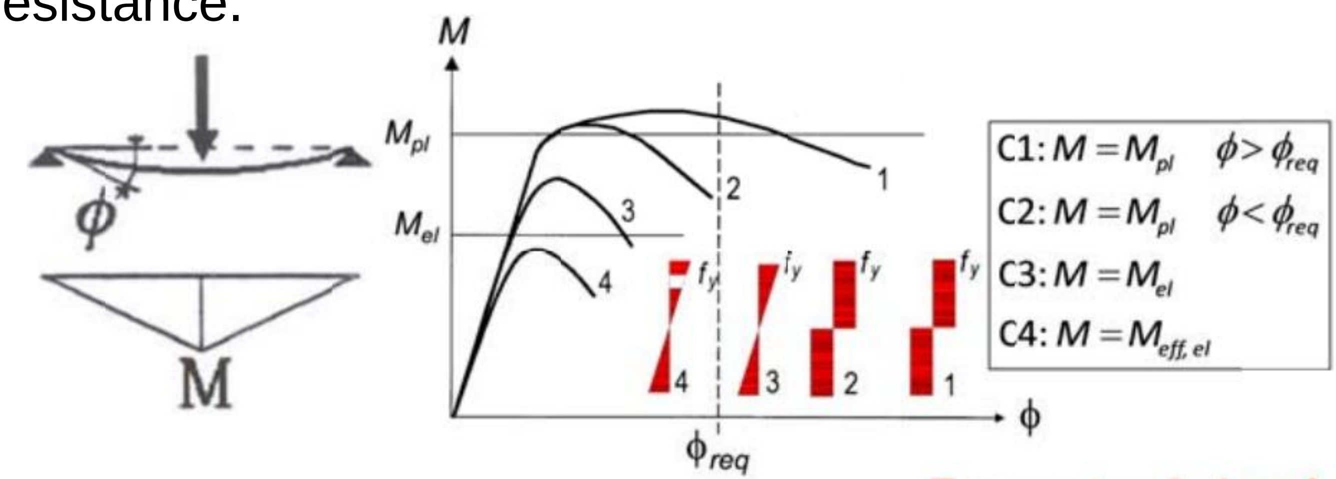
3. Critical temperature method

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 ≤ 30kN	0,7	0,7	0,6
Category G : traffic area, 30kN < vehicle weight ≤ 160kN	0,7	0,5	0,3
Category H : roofs	0	0	0
Snow loads on buildings (see EN 1991-1-3)*			
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 ≤ 1000 m a.s.l.	0,50	0,20	0
Wind loads on buildings (see EN 1991-1-4)	0,6	0,2	0
Temperature (non-fire) in buildings (see EN 1991-1-5)	0,6	0,5	0
NOTE The ψ values may be set by the National annex. * For countries not mentioned below, see relevant local conditions.			

3. Critical temperature method

Step 2: Classification of the steel member under the fire situation

The role of cross section classification is to identify the extent to which the resistance and rotation capacity of cross sections is limited by its local buckling resistance.



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

Temperature induced

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

3. Critical temperature method

-**Class 1** cross-sections are those which can form a plastic hinge with the rotation capacity required from plastic analysis without reduction of the resistance.

-**Class 2** cross-sections are those which can develop their plastic moment resistance, but have limited rotation capacity because of local buckling.

-**Class 3** cross-sections are those in which the stress in the extreme compression fibre of the steel member assuming an elastic distribution of stresses can reach the yield strength, but local buckling is liable to prevent development of the plastic moment resistance.

-**Class 4** cross-sections are those in which local buckling will occur before the attainment of yield stress in one or more parts of the cross-section.

3. Critical temperature method

Step 3: Calculation of design load-bearing capacity of the steel member at instant 0 of the fire

$$M_{c,Rd} = M_{pl,Rd} = \frac{W_{pl} \cdot f_y}{\gamma_{M0}}$$

for class 1 or 2 cross sections

$$M_{c,Rd} = M_{el,Rd} = \frac{W_{el} \cdot f_y}{\gamma_{M0}}$$

for class 3 cross sections

$$M_{c,Rd} = \frac{W_{eff,m}}{\gamma_{M0}} \qquad V_{pl,Rd} = \frac{A_v\left(f_y/\sqrt{3}\right)}{\gamma_{M0}}$$

for class 4 cross sections

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3. Critical temperature method

Step 4: Determination of degree of utilization of the steel member.

The "Degree of Utilisation"

… is the **design loading** of a me

as a proportion of its **design re**
ambient temperature (t = 0) but
material partial factors for fire de

Beams under bending with lateral buckling:

$$\mu_0 = \frac{M_{fi,d,t}}{M_{pl,fi,0}}$$ for beams in Class 1 or 2

$$\mu_0 = \frac{M_{fi,d,t}}{M_{el,fi,0}}$$ for beams in Class 3

A simple version of Degree of Utilisation:

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

buckling …

- **conservative if $\eta_{fi,t}$ calculated as proportion of design loading at ambient temperature.**

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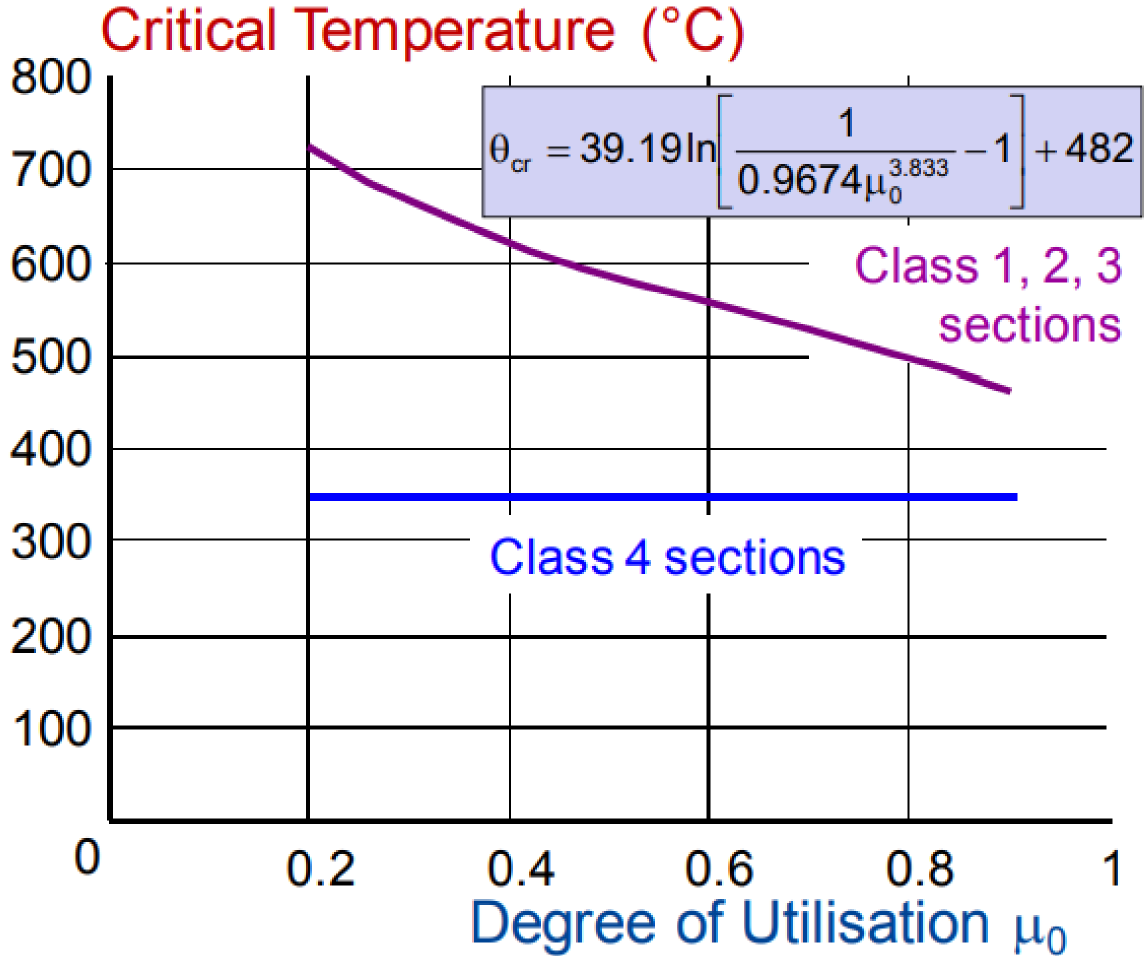
3. Critical temperature method

Step 5: Calculation of critical temperature of the steel member.

- 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



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3. Critical temperature method

Summary

$$\theta_{cr} = f\left(\mu_0\right) = f\left(M_{fi,d,t}; M_{pl,fi,0}\right) = f\left(weight;\ span;\ combination\ coefficient\right)$$

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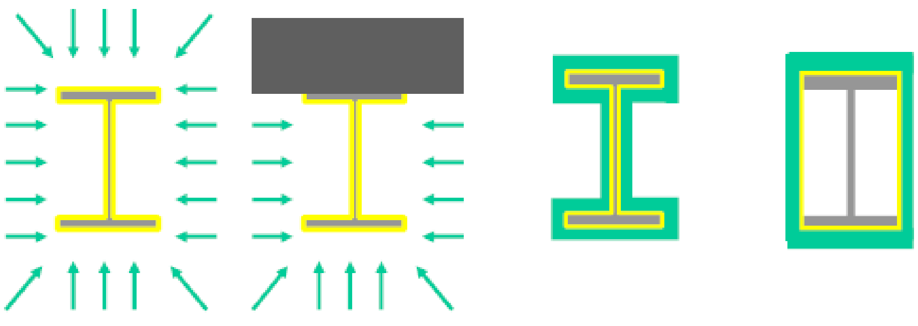
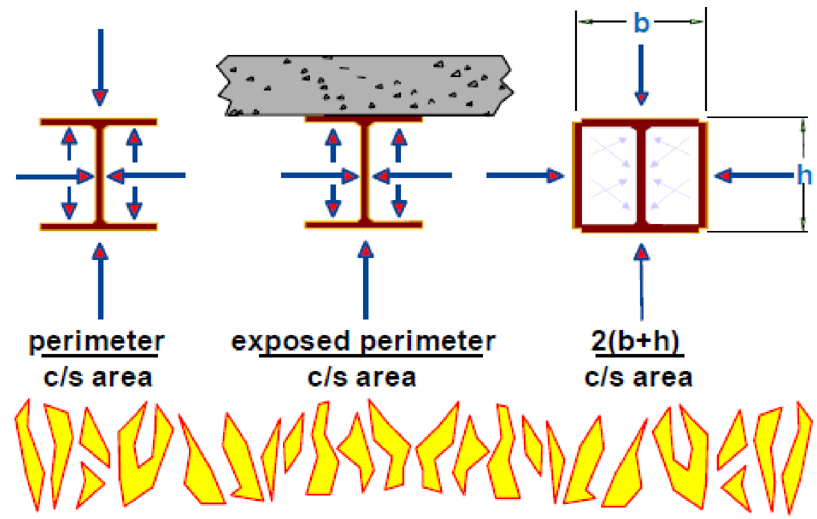
3. Critical temperature method

Step 6: Calculation of the section factor of unprotected steel members and correction factor for shadow effect



bare steel members

insulated steel members



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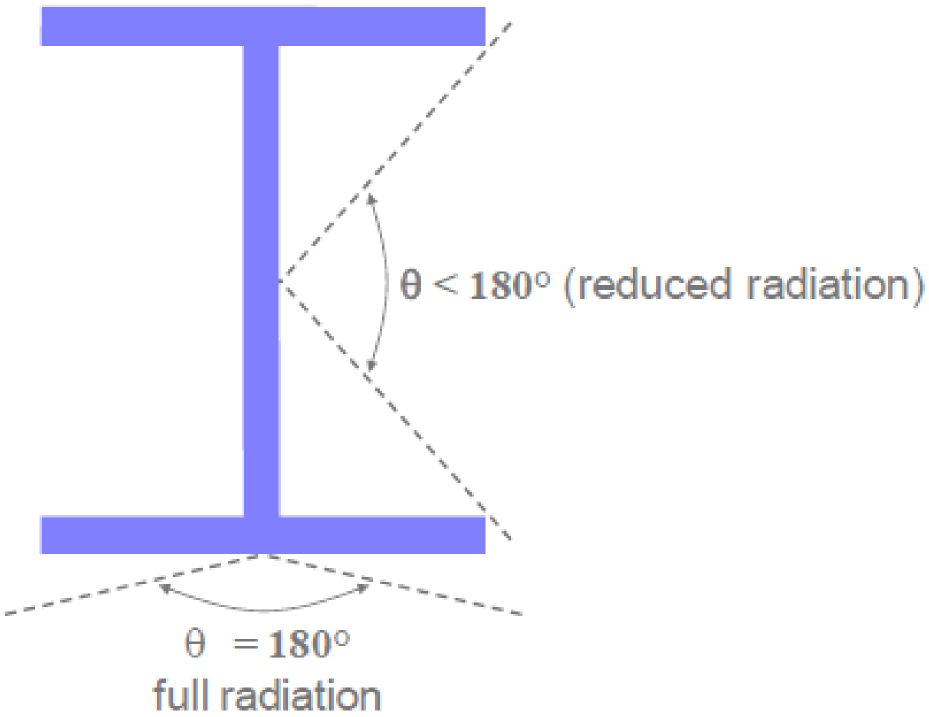
3. Critical temperature method

Correction factor for all cases:

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

Correction factor for I shape

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



A_m: is the perimeter of the element,
V : is the area of cross section
A_m /V: is the called the box value of the section factor

3. Critical temperature method

Step 7: Calculation of the heating of unprotected steel members

Increase of the temperature

$$\Delta\theta_{\alpha,t} = \frac{k_{sh}}{c_a \cdot \rho_a} \cdot \frac{A_m}{V} \cdot h_{net,d} \cdot \Delta t$$

Net heat flux per unit area

$$h_{net,d} = h_{net,r} + h_{net,c}$$

Radiation: $h_{net,r} = 5.67 \cdot 10^{-8} \phi \varepsilon_n \left(\left(\theta_{g+273} \right)^4 - \left(\theta_m + 2.73 \right)^4 \right)$

Convection: $h_{net,c} = \alpha_c \left(\theta_g - \theta_m \right)$

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3. Critical temperature method

Summary

$$\Delta\theta_{\alpha,t} = f\left(\left(\frac{A_m}{V}\right)_b\right)$$

3. Critical temperature method

Conclusion

Structural fire safety

$$\theta_{cr} = f\left(\mu_0\right) = f\left(M_{fi,d,t}; M_{pl,fi,0}\right) = f\left(weight; span; \text{sec}urity\ coefficient\right)$$

$$\Delta\theta_{\alpha,t} = f\left(\left(\frac{A_m}{V}\right)_b\right)$$

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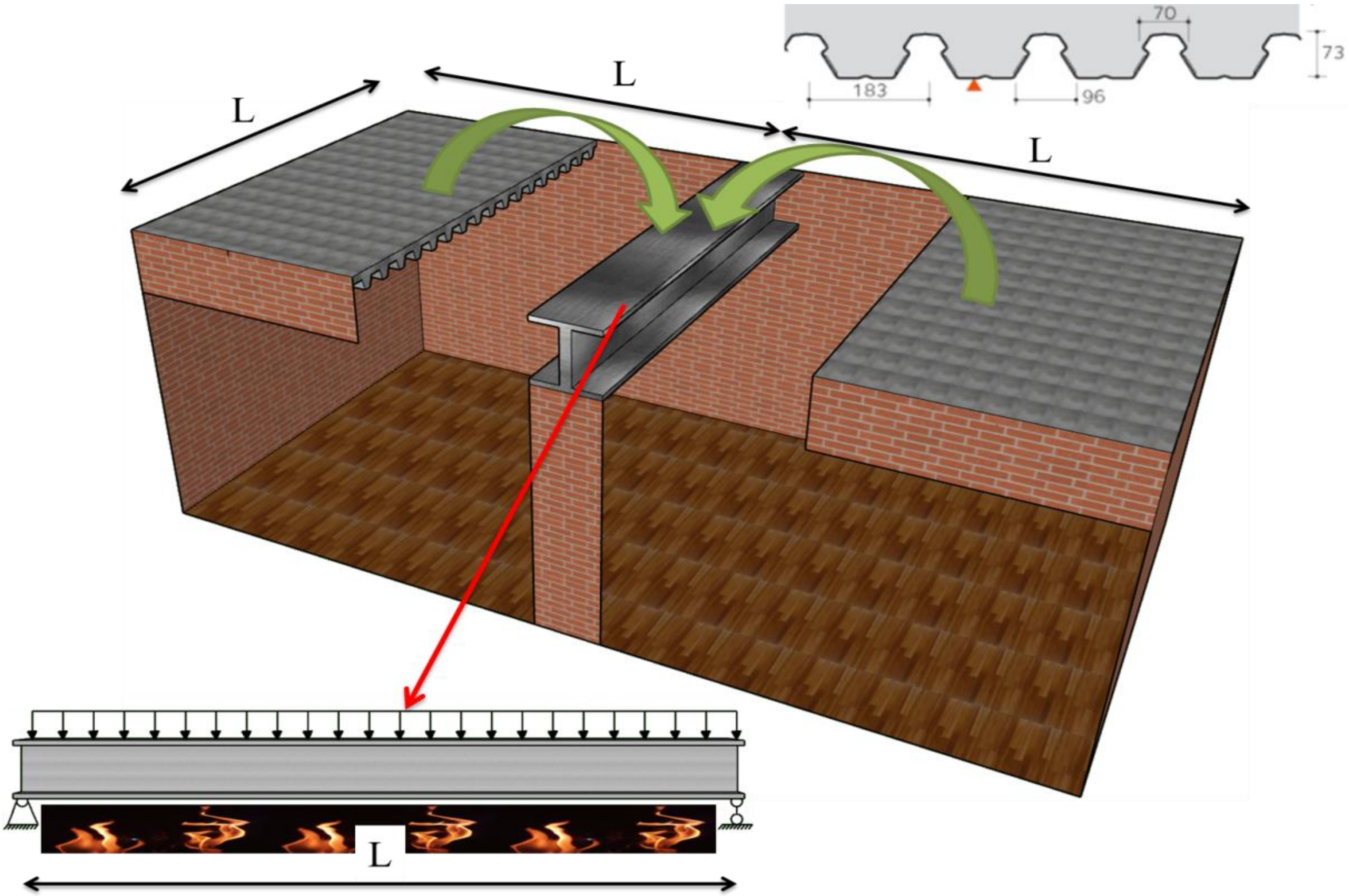
4. Case study



4. Case study

Loads applied to the structural elements

Typology	Material (layer)	Thickness (m)	Loads (kg/m2)
Permanent	*Cement layer*	*0.03*	*65*
	Vapor layer	*0.0002*	*0.2*
	Glass wool	*0.02*	*2*
	Polyethylene	*0.0002*	*0.2*
	Concrete slab	*0.13*	*250*
	Steel sheet	*0.00075*	*10*
	Total		**327.5**
Variable	*Partitions weight*		80
	Permanent load for offices		250

$$q_{fi,S} = \left(\sum_{j \geq 1} \gamma_{G,j} \cdot G_{k,j} + \sum_{i \geq 1} \gamma_{Q,i} \cdot Q_{k,i} \right) \cdot L = \left(1.35 \cdot 3.3 + 1.5 \cdot (0.8 + 2.5)\right) \cdot 3 \approx 28 kN / ml$$

$$q_{acc} = \left(\sum_{j \geq 1} G_{k,j} + \sum_{i \geq 1} \psi_{2,1} \cdot Q_{k,i} \right) \cdot L = \left(1 \cdot 3.3 + 0.3 \cdot (0.8 + 2.5)\right) \cdot 3 \approx 12.9 kN / ml$$

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4. Case study

Internal loads

$$\overbrace{M_{fi,S} = \frac{q_{fi,S} \cdot L^2}{8} = \frac{28 \cdot 3^2}{8} = 31.5kNm}^{ULS\ combination}$$

$$V_{fi,S} = \frac{q_{fi,S} \cdot L}{2} = \frac{28 \cdot 3}{2} = 42kN$$

$$\overbrace{M_{acc} = \frac{q_{acc} \cdot L^2}{8} = \frac{12.9 \cdot 3^2}{8} = 14.5kNm}^{Accidental\ combination}$$

$$V_{acc} = \frac{q_{acc} \cdot L}{2} = \frac{12.9 \cdot 3}{2} = 19.3kN$$

Minimal plastic moment

$$W_{pl} \geq \frac{M_{pl,Rd} \cdot \gamma_{M0}}{f_y} = \frac{31.5 \cdot 10^3}{275} \approx 115cm^3$$

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4. Case study

Degree of utilization

$$\mu_0 = \max\begin{cases} \dfrac{M_{fi,d,t}}{M_{Rd}} \cdot \dfrac{\gamma_{M0}}{\gamma_{M,fi}} = \dfrac{14.5}{37.1} = 0.39 \\ \dfrac{V_{fi,d,t}}{V_{Rd}} \cdot \dfrac{\gamma_{V0}}{\gamma_{V,fi}} = \dfrac{19.3}{99.7} = 0.19 \end{cases} = 0.39$$

Critical temperature

$$\theta_{cr} = 39.19 \ln\left(\frac{1}{0.9674 \cdot \mu_0^{3.833}} - 1\right) + 482 = 39.19 \cdot \ln\left(\frac{1}{0.9674 \cdot 0.39^{3.833}} - 1\right) + 482 \approx 624^{\circ}C$$

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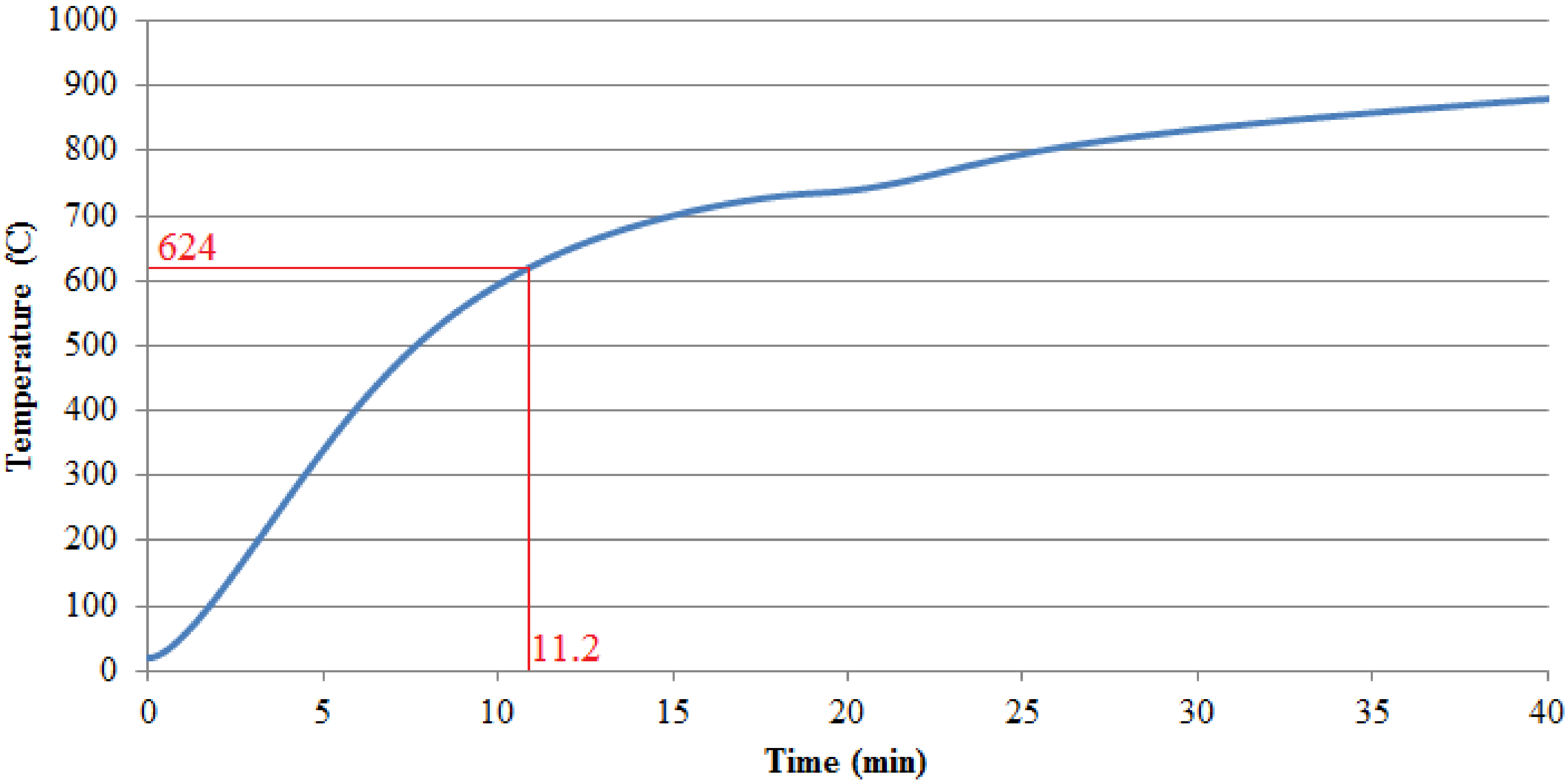
4. Case study

Time-temperature curve for the steel beam



5. Influence of design parameter

35 case studies

Span variation (3 – 9 m)

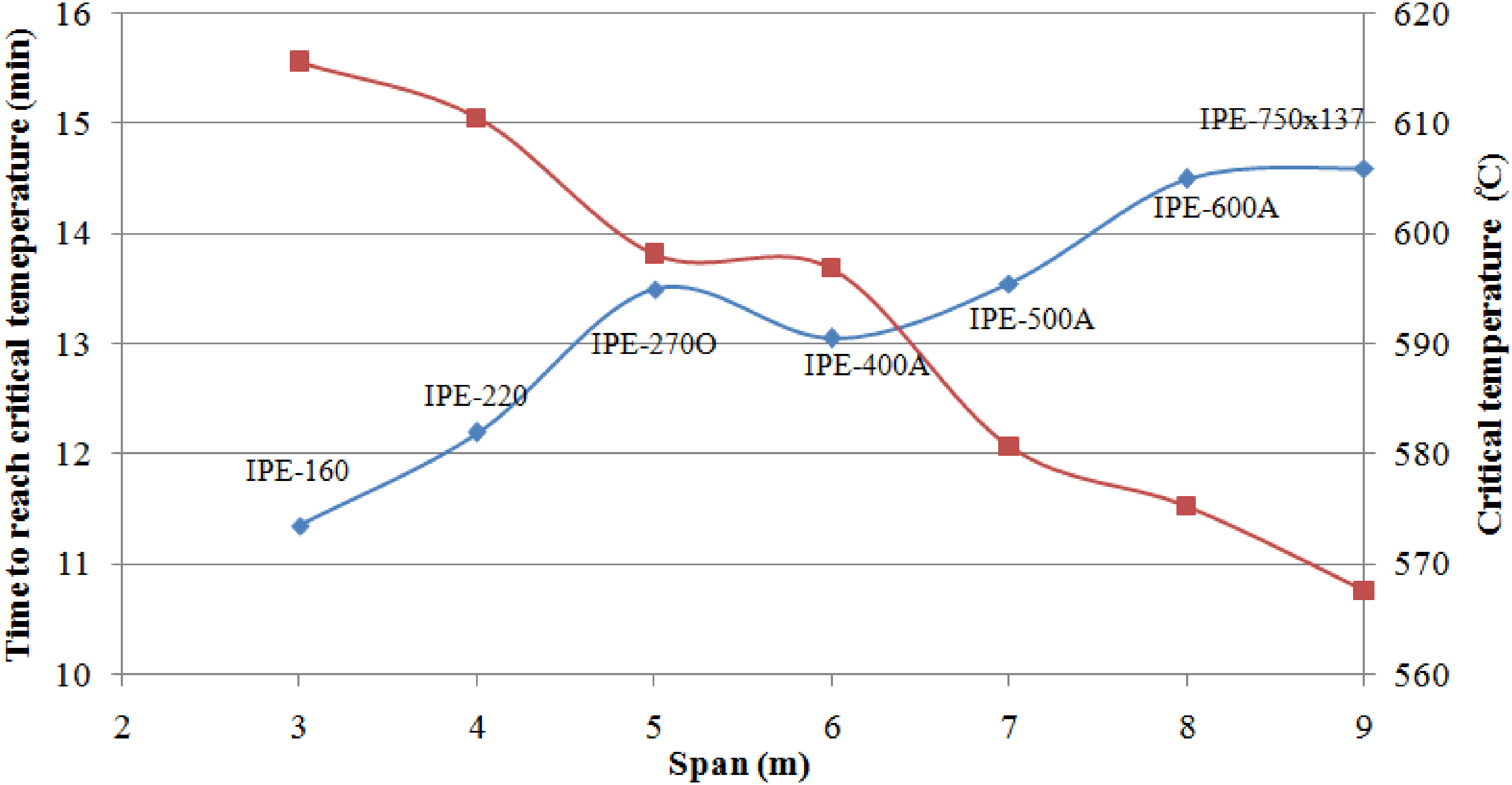
Combination coefficient (0.3 – 0.5)

Self weight (250 – 700 kg/m^2)

Section factor (50 – 200 m^{-1})

5. Influence of design parameter

Influence of variation of span critical temperature and time to reach it



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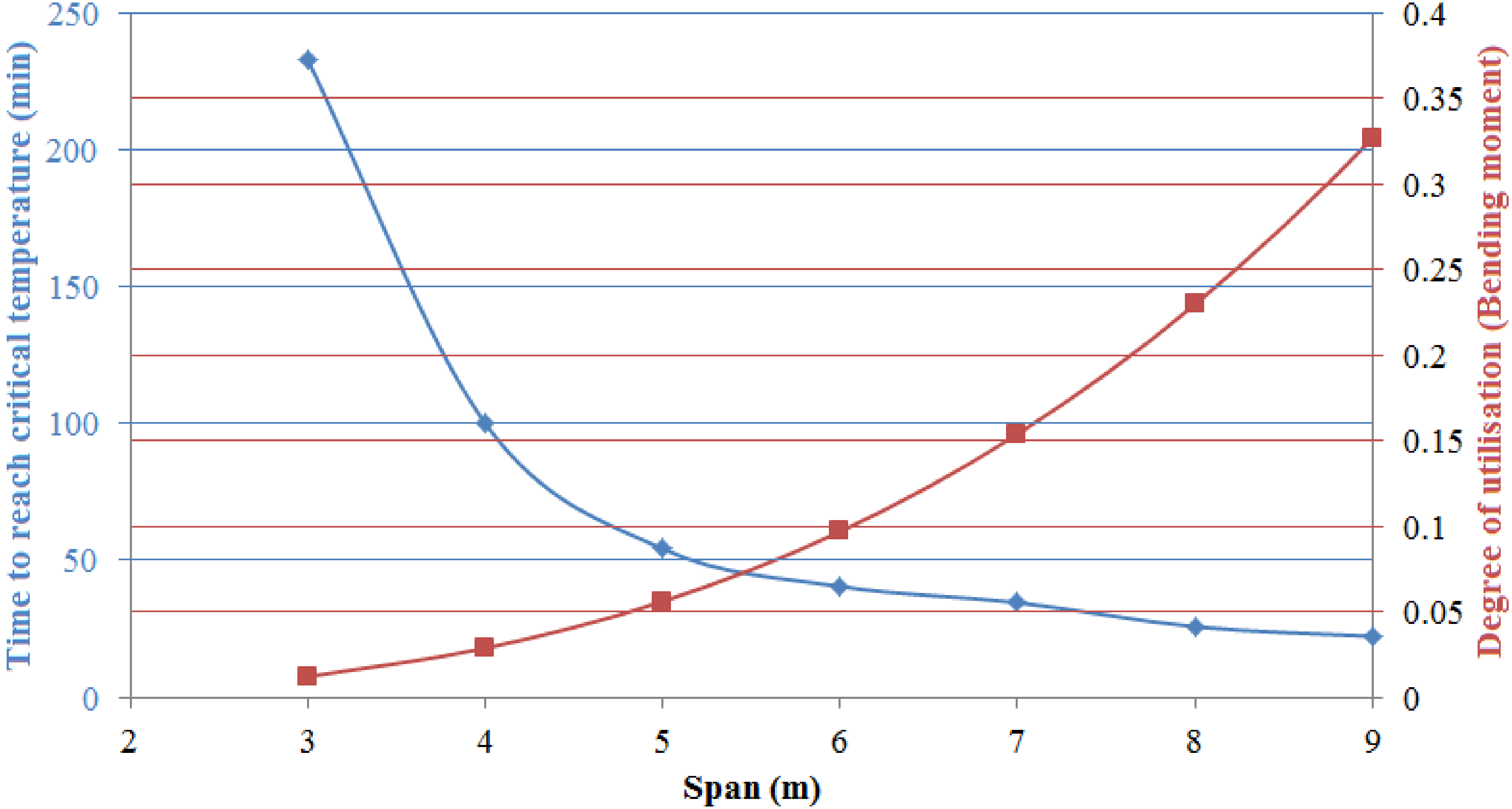
5. Influence of design parameter

Influence of variation of span in time to reach critical temperature and degree of utilization



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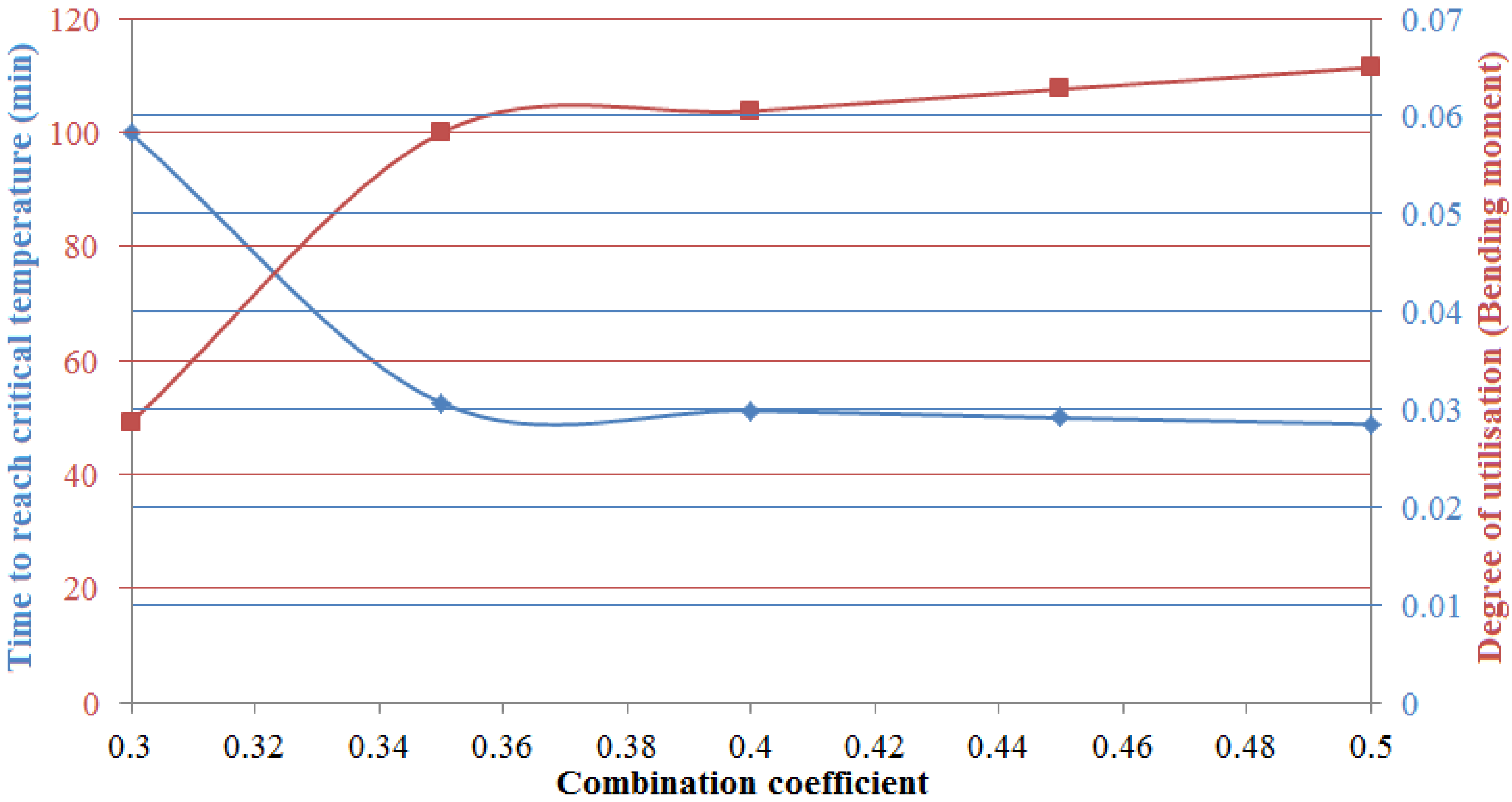
5. Influence of design parameter

Influence of variation of combination coefficient in time to reach critical temperature and degree of utilization



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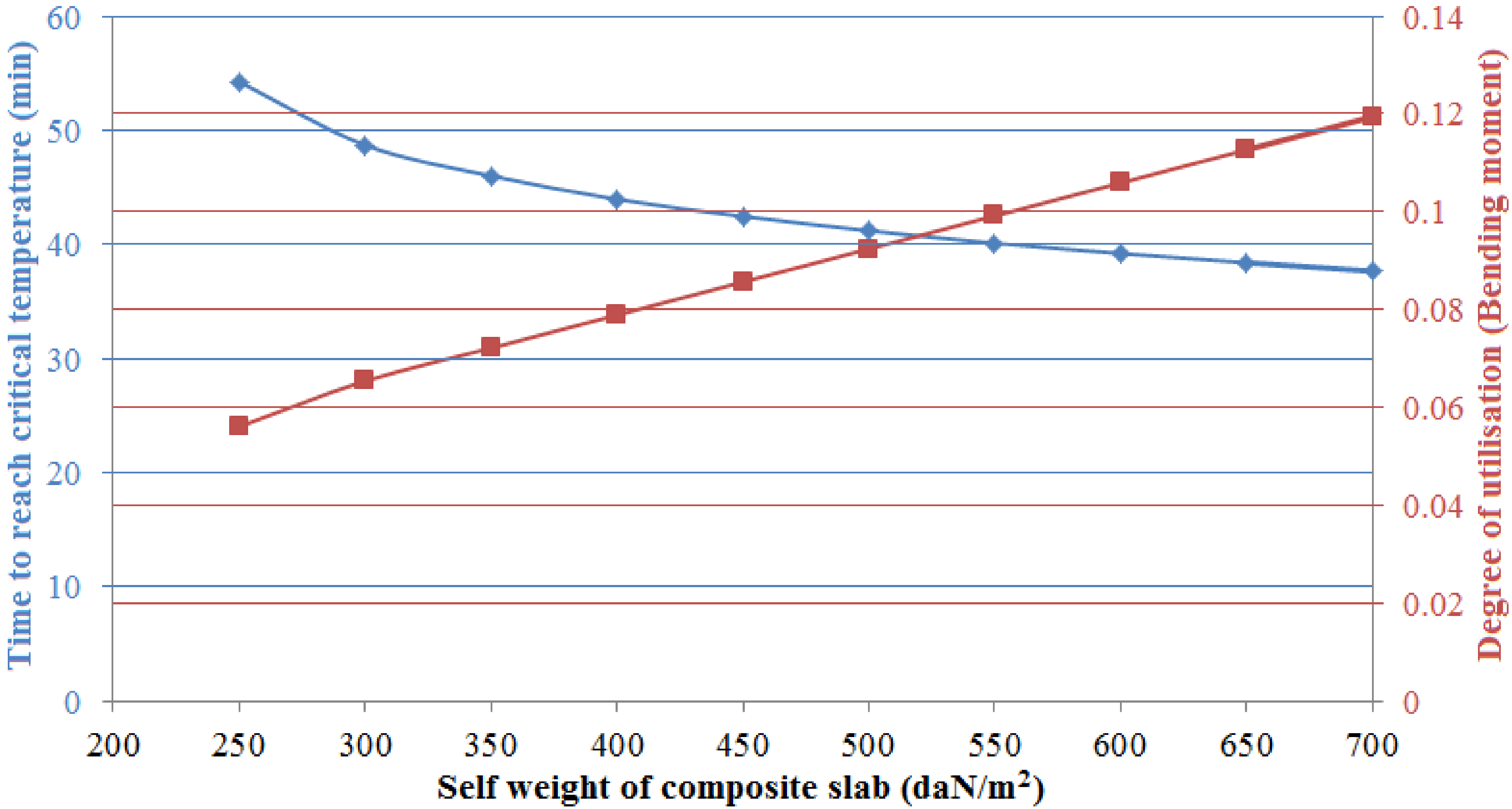
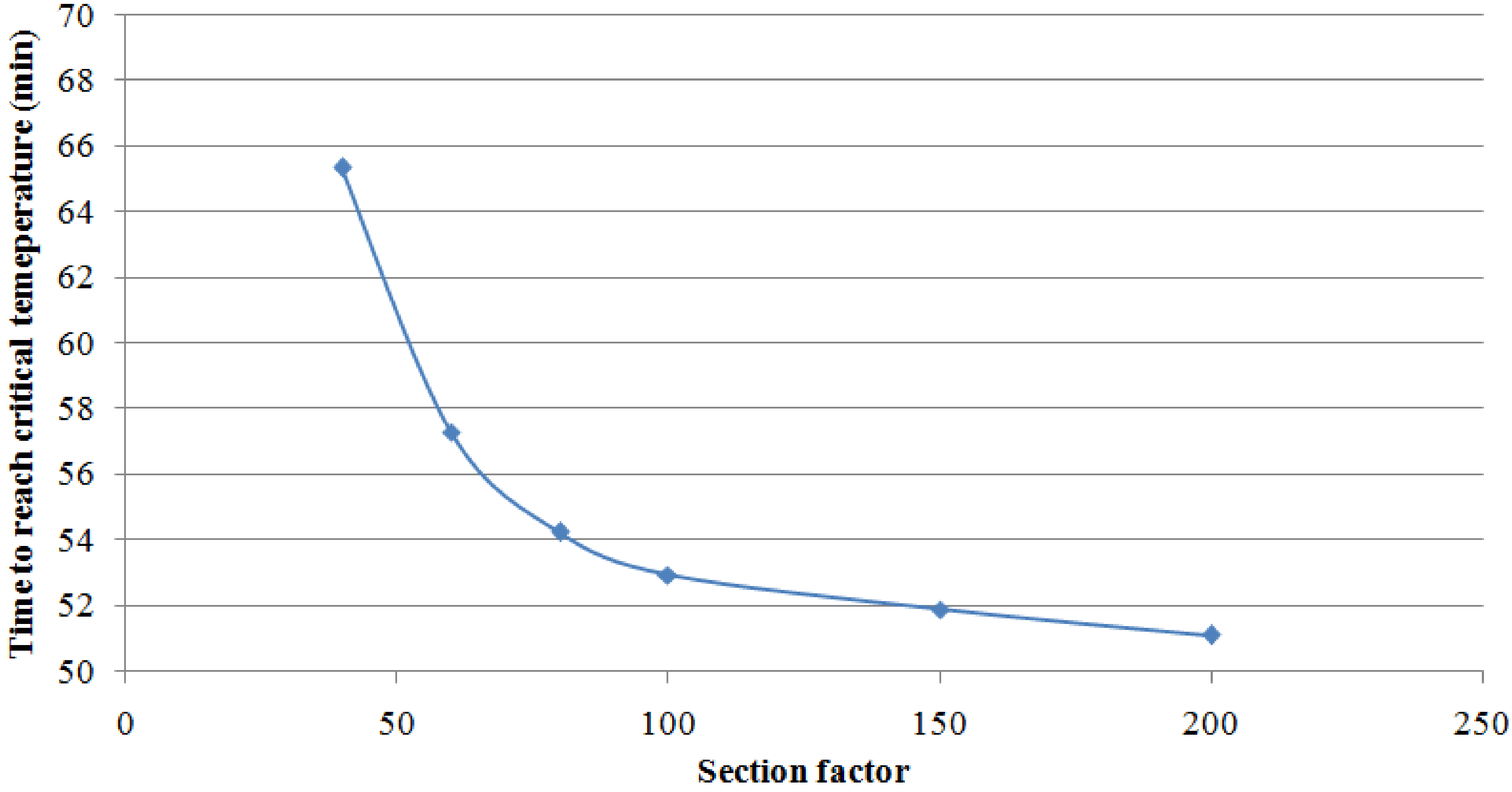
5. Influence of design parameter

Influence of variation of self-weight in time to reach critical temperature and degree of utilization



5. Influence of design parameter

Influence of section factor n in time to reach critical temperature



5. Influence of design parameter

Contribution of design parameters

$$R_C = \frac{R_{time\ resistance}}{R_{design\ parameter}} = \frac{\dfrac{T_{\max} - T_{\min}}{T_{\max}}}{\dfrac{D_{\max} - D_{\min}}{D_{\max}}}$$

$D_{\max}$ - maximal value of design parameter,

$D_{\min}$ - minimal value of design parameter,

$T_{\max}$ - maximal time resistance corresponding to the maximal value of design parameter

$T_{\min}$ - minimal time resistance corresponding to minimal value of design parameter.

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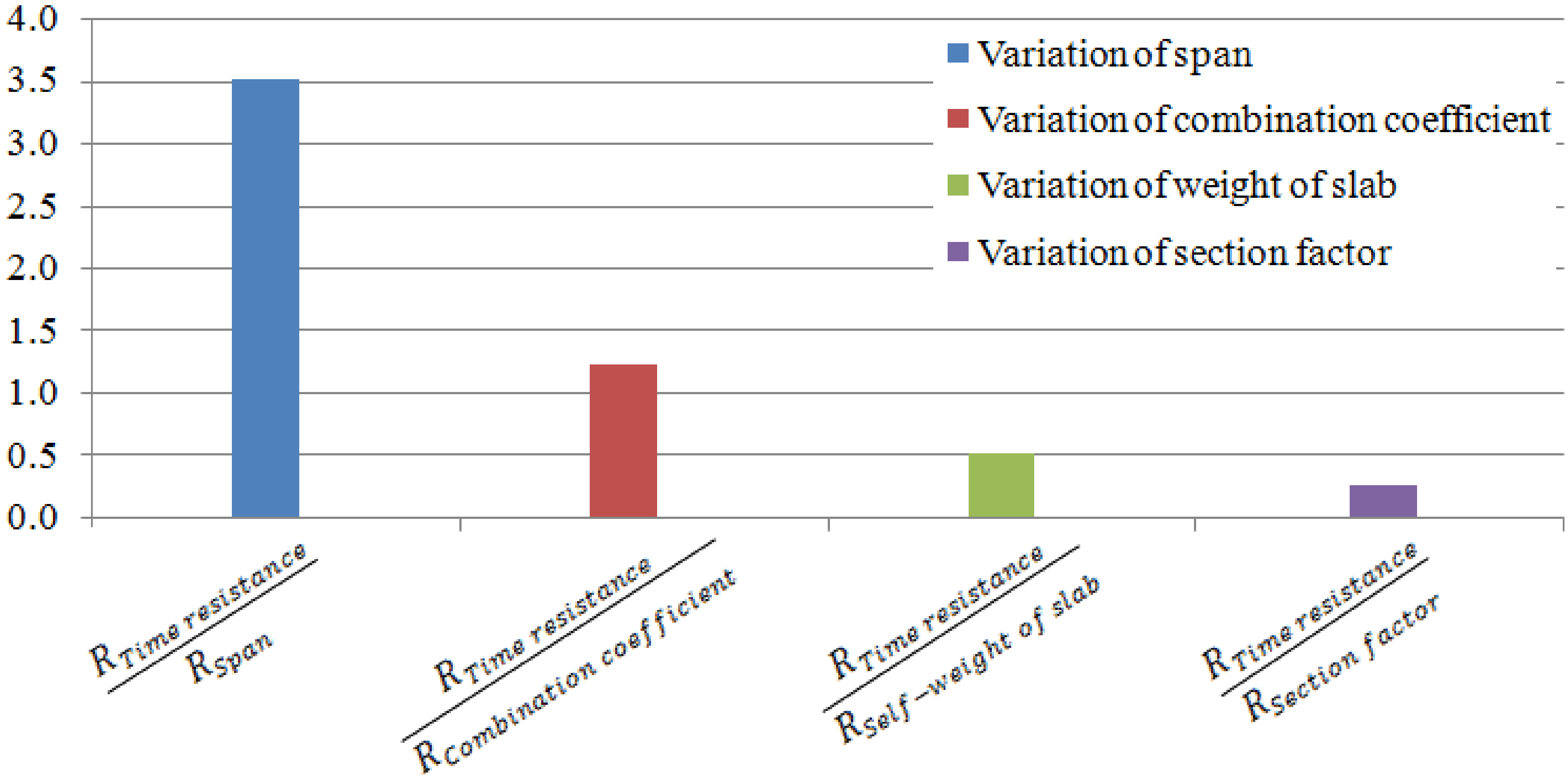
5. Influence of design parameter

Influence of parameter in time resistance of steel beam



6. Conclusions

- Identification of parameters influencing structural fire safety:
  - Span,
  - weight of slab,
  - combination coefficient
  - section factor
- Optimal span should be considered 5 m
- Light slab structures are most adequate
- Better to insulate then to increase the dimension of structural elements

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References

For all references of this presentation please referee to the lecture paper

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Knowledge **FO**r **R**esilient so**C**i**E**ty