Training School for Young Researchers

Fire Engineering Research – Key Issues for the Future II

Codes of practice – prescriptive rules or performance-based approach?

Professor Paulo Vila Real

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Scope

- Introduction
- Thermal Actions
- Mechanical Actions
- Thermal Analysis
- Mechanical Analysis
- Design procedures
- Examples using different design procedures: prescriptive and performance-based approaches

Introduction
Question

- Prescriptive rules or performance-based approach?

Some background before to try to answer to this question.

Introduction
Two type of regulations or standards

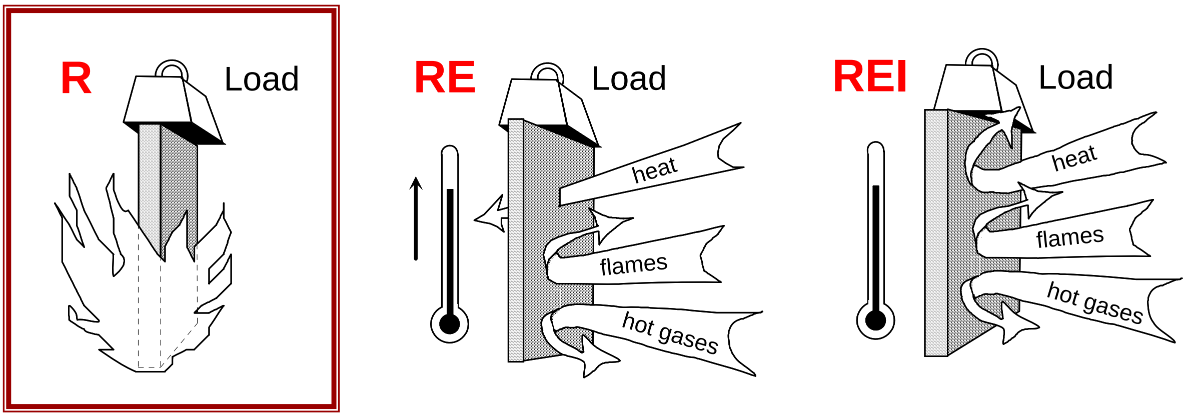
- Each country has its own regulations for fire safety of buildings where the requirements for fire resistance are given

- Standards for checking the structural fire resistance of the buildings - in Europe the structural EUROCODES

Introduction
Fire Resistance

- Classification criteria

R – Load bearing criterion; E – Integrity criterion; I – Insulation criterion



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

Introduction -Fire Resistance
Criteria R, E and I - UK Approved document B

Fire resistance *

B3.ii The fire resistance of an element of construction is a measure of its ability to withstand the effects of fire in one or more ways, as follows:

a. resistance to collapse, i.e. the ability to maintain loadbearing capacity (which applies to loadbearing elements only); **R**

b. resistance to fire penetration, i.e. an ability to maintain the integrity of the element; **E**

c. resistance to the transfer of excessive heat, i.e. an ability to provide insulation from high temperatures. **I**

*** In terms of time**

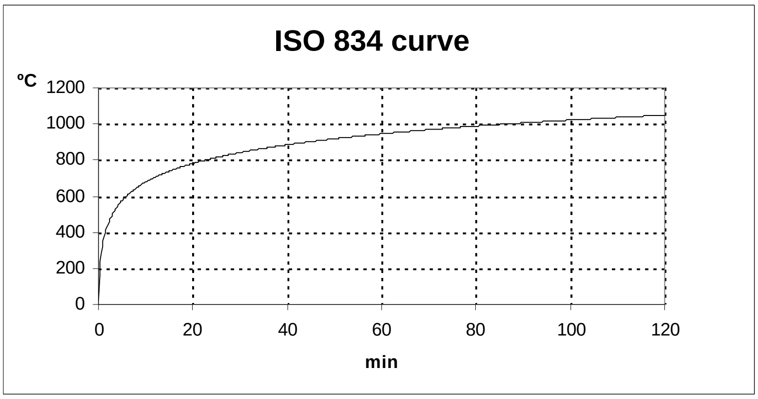
Examples: R90; REI120

Introduction
Fire Resistance – Criteria R, E and I

❑ **Standard fire curve**

Fire resistance is the time since the begining of the standard fire curve ISO 834 until the moment that the element doesn't fulfill the functions for that it has been designed (Load bearing and/or separating functions)

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



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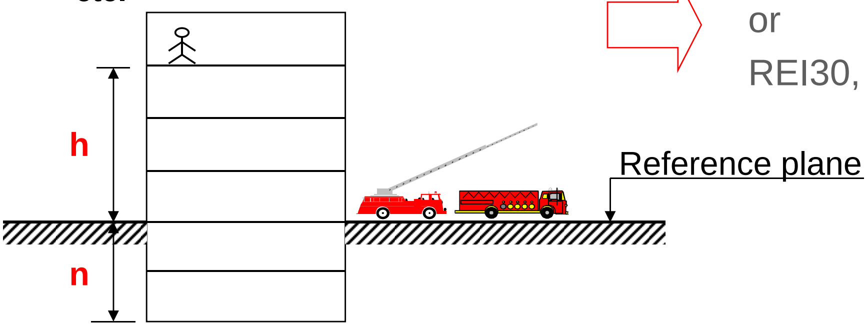
Introduction
Regulations for fire safety of buildings

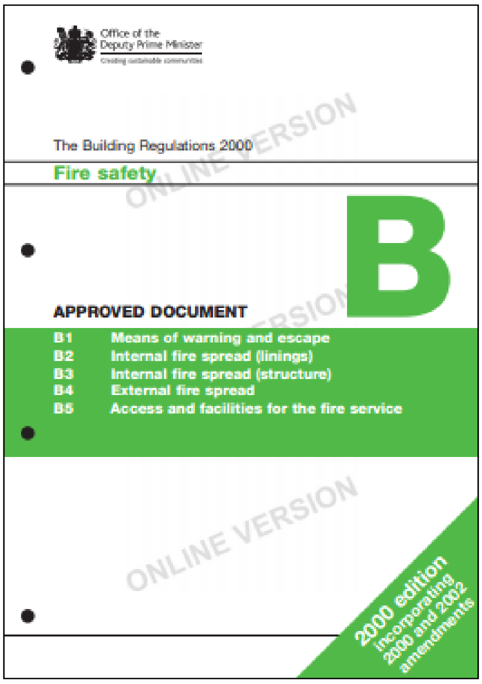
❑ **Normally the risk factors are:**

- **Height of the last occupied storey in the building (h) over the reference plane**
- **Number of storeys below the reference plane (n)**
- **Total gross floor area**
- **Number of occupants (effective)**
- **etc.**

R30, R60, R90, ...
or
REI30, REI60. REI90, ...



Introduction. Example
Regulations for fire safety – UK Approved document B



PERFORMANCE OF MATERIALS AND STRUCTURES

Table A2 Minimum periods of fire resistance

Purpose group of building	Minimum periods (minutes) for elements of structure in a:				
	Basement storey ($) including floor over		Ground or upper storey		
	Depth (m) of a lowest basement		Height (m) of top floor above ground, in a building or separated part of a building		
	More than 10	Not more than 10	Not more than 5	Not more than 18	Not more than 30
1. Residential (domestic):					
a. Flats and maisonettes	90	60	30*	60**†	90**
b. and c. Dwellinghouses	Not relevant	30*	30*	60@	Not relevant
2. Residential:					
a. Institutional œ	90	60	30*	60	90
b. Other residential	90	60	30*	60	90
3. Office:					
- Not sprinklered	90	60	30*	60	90
- Sprinklered (2)	60	60	30*	30*	60
4. Shop and commercial:					
- Not sprinklered	90	60	60	60	90
- Sprinklered (2)	60	60	30*	60	60
5. Assembly and recreation:					
- Not sprinklered	90	60	60	60	90

Introduction. Example
Regulations for fire safety – UK Approved document B

INTERNAL FIRE SPREAD (STRUCTURE) **B3**

The Requirement

This Approved Document deals with the following Requirement from Part B of Schedule 1 to the Building Regulations 2000.

Requirement	*Limits on application*
Internal fire spread (structure)	
B3. (1) The building shall be designed and constructed so that, in the event of fire, its stability will be maintained for a reasonable period.	
(2) A wall common to two or more buildings shall be designed and constructed so that it adequately resists the spread of fire between those buildings. For the purposes of this sub-paragraph a house in a terrace and a semi-detached house are each to be treated as a separate building.	
(3) To inhibit the spread of fire within the building, it shall be sub-divided with fire-resisting construction to an extent appropriate to the size and intended use of the building.	Requirement B3(3) does not apply to material alterations to any prison provided under Section 33 of the Prisons Act 1952.
(4) The building shall be designed and constructed so that the unseen spread of fire and smoke within concealed spaces in its structure and fabric is inhibited.	

Introduction. Example
Portuguese regulation for fire safety of buildings

❑ **Required fire resistance**

- The load-bearing or/and separating function should be maintained during the complete duration of the fire including the decay, or alternatively during the required time of standard fire exposure given in the table below:

Standard fire resistance of structural members in buildings

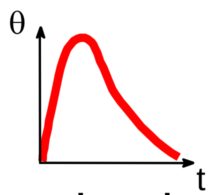
Classification according to the occupancy	Risk categories				Function of the structural member
	1.º	2.º	3.º	4.º	
I, III, IV, V, VI ,VII ,VIII ,IX ,X	R30 REI30	R60 REI60	R90 REI90	R120 REI120	Only load bearing Load bearing and separating
II, XI and XII	R60 REI60	R90 REI90	R120 REI120	R180 REI180	Only load bearing Load bearing and separating

Type I «Dwelling»: Type II «Car parks»; Type III «Administrative»; Type IV «Schools»; Type V «Hospitals»; Type VI «Theatres/cinemas and public meetings»; Type VII «Hotels and restaurants»; Type VIII «Shopping and transport centres»; Type IX «Sports and leisure»; Type X «Museums and art galleries»; Type XI «Libraries and archives»; Type XII «Industrial, workshops and storage»

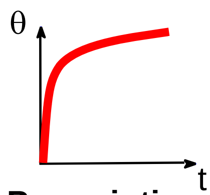
Introduction
Prescriptive or performance-based

- The load-bearing function is ensured when collapse is prevented during the complete duration of the fire including the decay phase or alternatively during the required period of time under standard fire exposure.

Natural fire



Sandard fire ISO 834



or

Performance-based approach

Prescriptive approach

Introduction
Codes for fire design in Europe: Structural Eurocodes

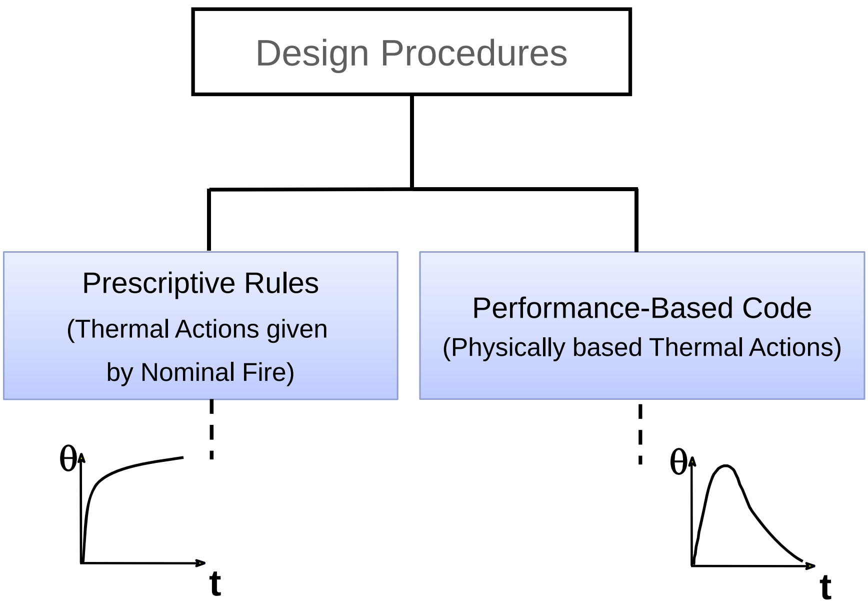
Eurocodes

EN 1990	**Eurocode:**	**Basis of Structural Design**
EN 1991	**Eurocode 1:**	**Actions on structures**
EN 1992	**Eurocode 2:**	**Design of concrete structures**
EN 1993	**Eurocode 3:**	**Design of steel structures**
EN 1994	**Eurocode 4:**	**Design of composite steel and concrete structures**
EN 1995	**Eurocode 5:**	**Design of timber structures**
EN 1996	**Eurocode 6:**	**Design of masonry structures**
EN 1997	**Eurocode 7:**	**Geotechnical design**
EN 1998	**Eurocode 8:**	**Design of structures for earthquake resistance**
EN 1999	**Eurocode 9:**	**Design of aluminium structures**

Fire design

Parts 1-2 **Except EN 1990, EN 1997 and EN 1998, all the Eurocodes have Part 1-2 for fire design**

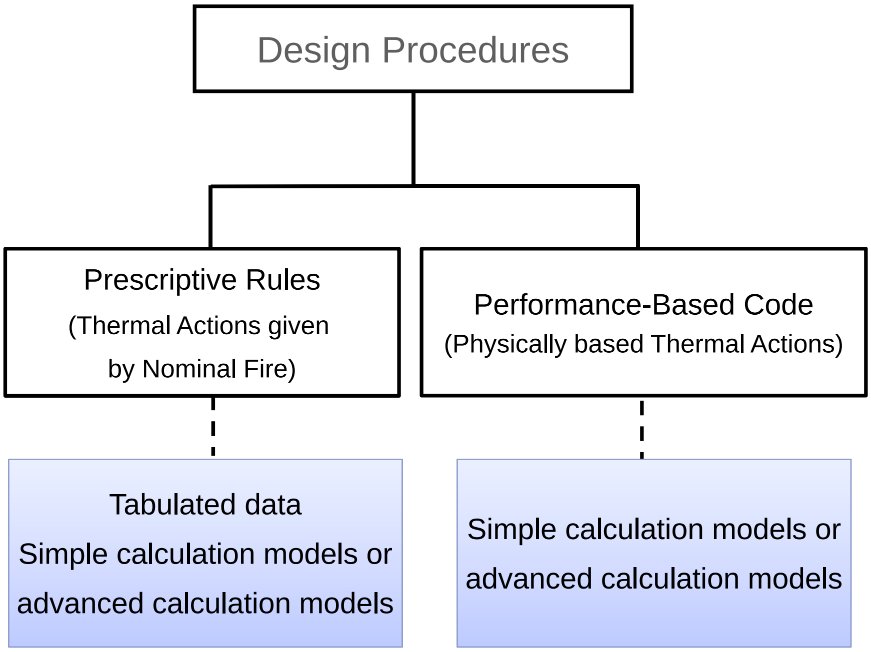
Introduction
Prescriptive or performance-based according the Eurocodes - 1



Nominal fire. Ex:
Standard fire ISO 834

Natural fire

Introduction
Prescriptive or performance-based according the Eurocodes - 2



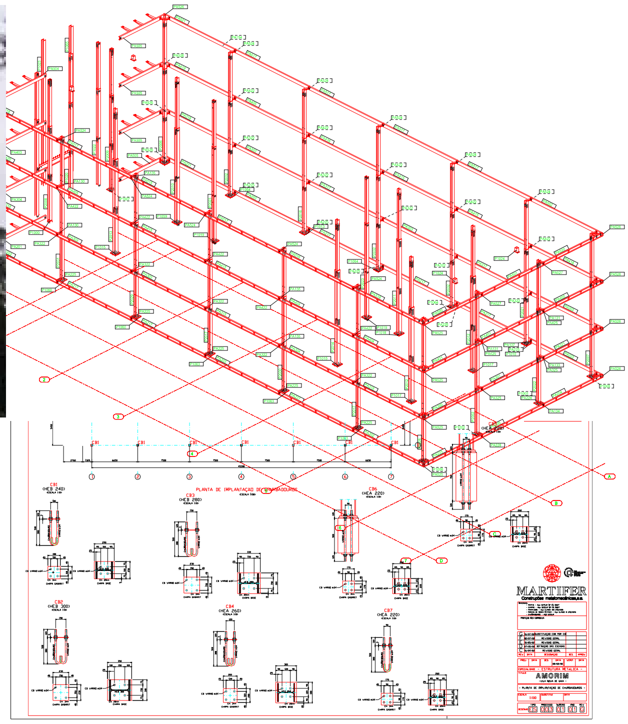
Introduction
Question

- **Prescriptive rules or performance-based approach?**

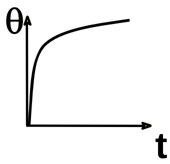
Depends on the type of structure, its importance for the society, its dimensions, etc.

Next it will be shown some examples where Prescriptive approach and performance-based approached has been used.

Introduction
Presciptive approach was used

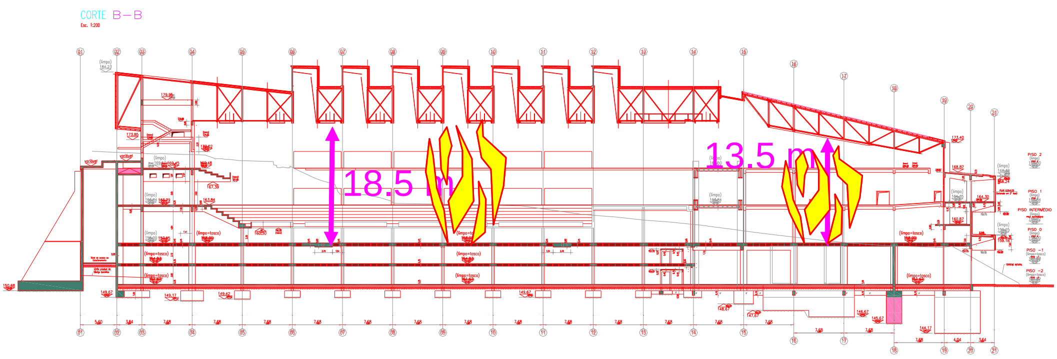


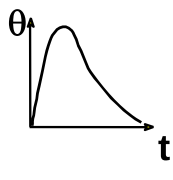
Steel Structure



Standard fire ISO 834 has been used

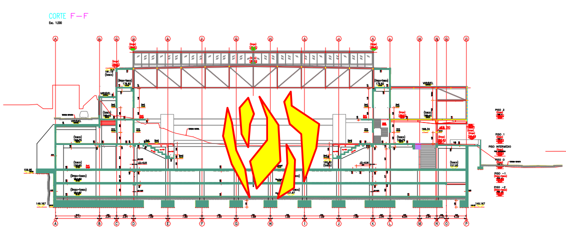
Introduction
Performance-based approach was used

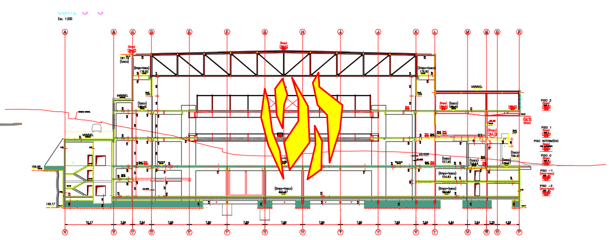




Natural fire

Steel Structure

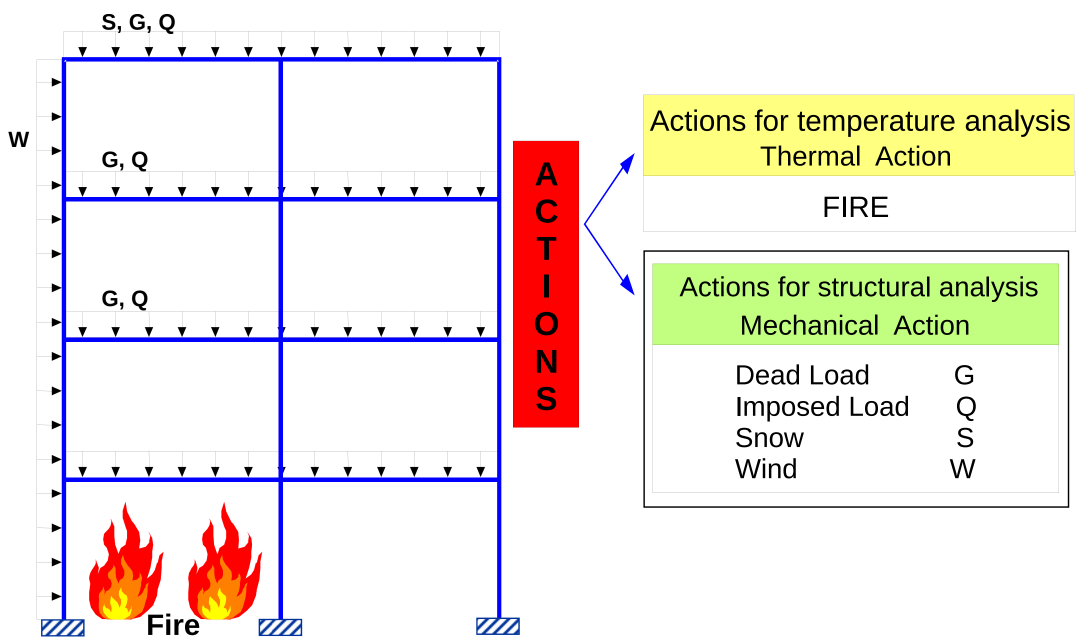




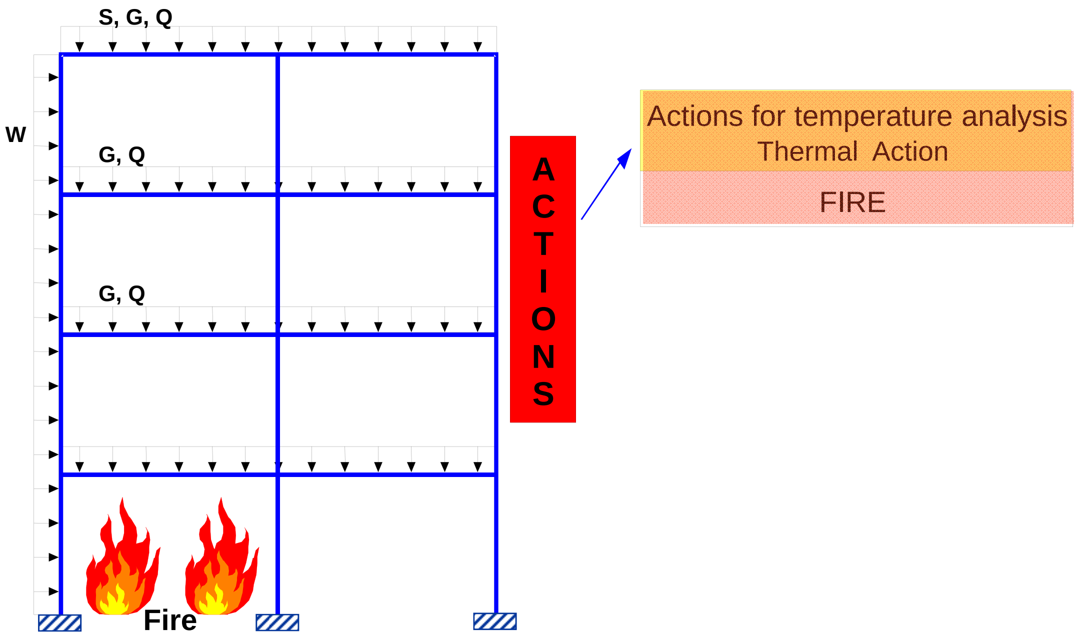
Fire Design of Structures
Four steps

1. Definition of the thermal loading - **EC1**
2. Definition of the mechanical loading - **EC0 +EC1**
3. Calculation of temperature evolution within the structural members – **All the Eurocodes**
4. Calculation of the mechanical behaviour of the structure exposed to fire – **All the Eurocodes**

Eurocode 1:
Actions on Structures



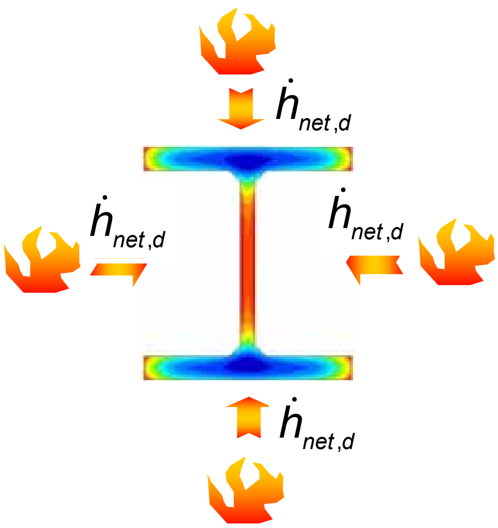
Eurocode 1:
Actions on Structures



Thermal actions
Heat transfer at surface of building elements

$$\dot{h}_{net,d} = \dot{h}_{net,c} + \dot{h}_{net,r}$$

Total net heat flux



Thermal actions
Heat transfer at surface of building elements

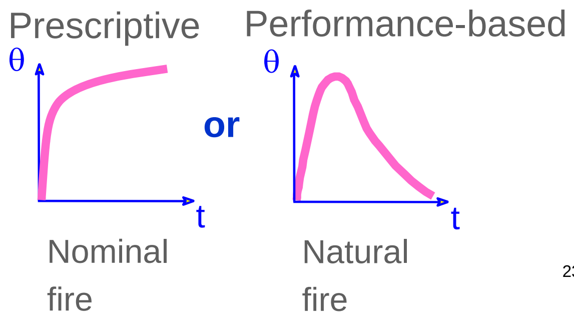
$$\dot{h}_{net,d} = \dot{h}_{net,c} + \dot{h}_{net,r}$$ **Total net heat flux**

$$\dot{h}_{net,c} = \alpha_c(\theta_g - \theta_m)$$ **Convective heat flux**

$$\dot{h}_{net,r} = \Phi \cdot \varepsilon_f \cdot \varepsilon_m \cdot \sigma \cdot [(\theta_r + 273)^4 - (\theta_m + 273)^4]$$ **Radiative heat flux**

$$\theta_g \approx \theta_r$$

Temperature of the fire compartment



Actions on Structures Exposed to Fire
EN 1991-1-2 - Actions on structures exposed to fire

Nominal temperature-time curves
- **Standard temperature-time curve**
- **External fire curve**
- **Hydrocarbon curve**

Natural fire models
- **Simplified fire models**
  - Compartment fires - Parametric fire
  - Localised fires – Heskestad or Hasemi
- **Advanced fire models**
  - Two-Zones or One-Zone fire or a combination
  - CFD – Computational Fluid Dynamics

Actions on Structures Exposed to Fire
EN 1991-1-2 - Prescriptive rules or performance-based approach

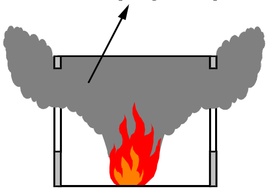
***) Nominal temperature-time curve**

Standard temperature-, External fire - & Hydrocarbon fire curve — **No data needed**

***) Simplified Fire Models**

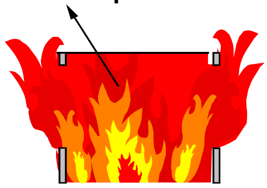
Localised Fire
- HESKESTADT
- HASEMI

θ (x, y, z, t)



Fully Engulfed Compartment
- Parametric Fire

θ (t) uniform in the compartment



Rate of heat release
Fire surface
Boundary properties
Opening area
Ceiling height

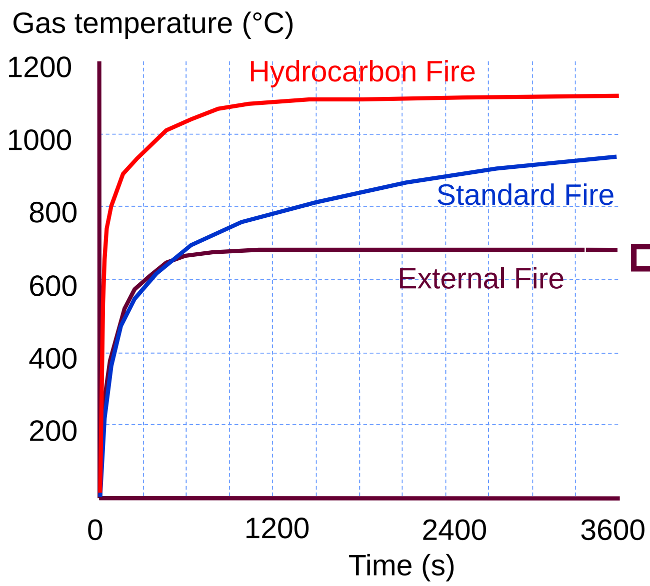
***) Advanced Fire Models**

- Two-Zone Model
- One-Zone Model
- Combined Two-Zones and One-Zone fire
- CFD

\+ Exact geometry

From DIFISEK+

Simplified fire models
Nominal Temperature-Time Curve



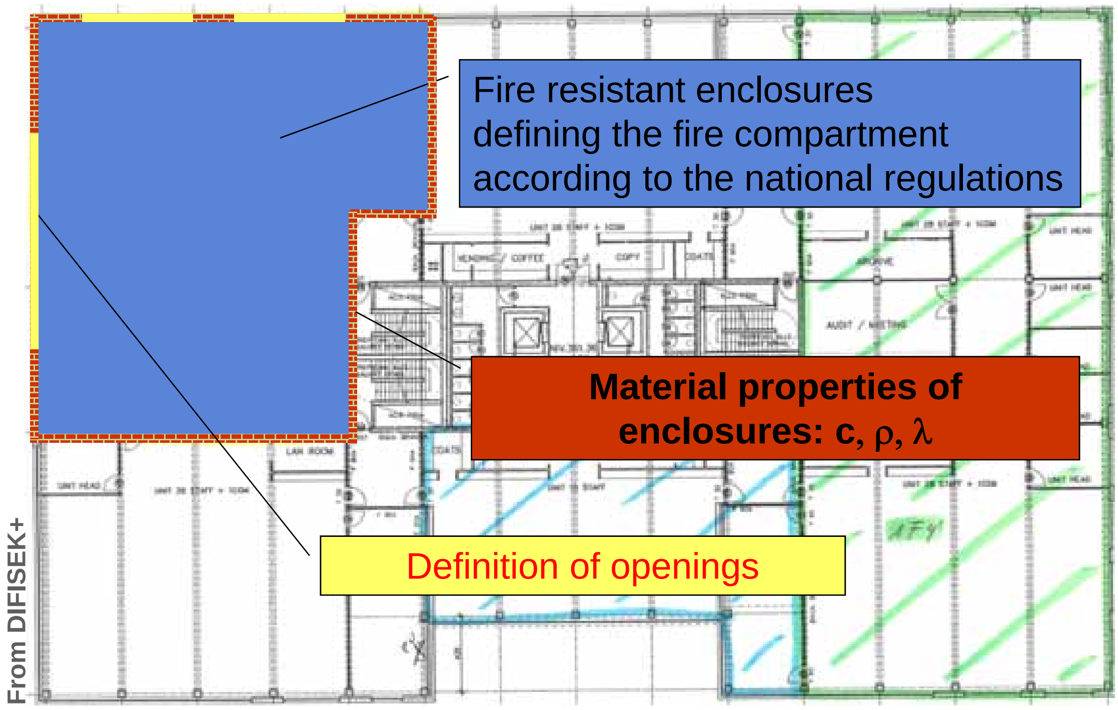
EC3 and EC9 do not use this external fire curve. A special Annex B on both Eurocodes gives a method for evaluating the heat transfer to external steelwork

List of Physical Parameters needed for Natural Fire Models

Geometry:
- Boundary properties
- Ceiling height
- Opening Area

Fire:
- Fire area
- Rate of heat release
- Fire load density

Characteristics of the Fire Compartment Natural Fire Model



Characteristics of the Fire Load from EN 1991-1-2
Natural Fire Model

Occupancy	Fire Growth Rate	RHR_f [kW/m²]	Fire Load $q_{f,k}$ 80% fractile [MJ/m²]
Dwelling	Medium	250	948
Hospital (room)	Medium	250	280
Hotel (room)	Medium	250	377
Library	Fast	500	1824
Office	Medium	250	511
School	Medium	250	347
Shopping Centre	Fast	250	730
Theatre (movie/cinema)	Fast	500	365
Transport (public space)	Slow	250	122

Design value of the fire load density
Natural Fire Model

$$q_{f,d} = q_{f,k} \cdot m \cdot \delta_{q1} \cdot \delta_{q2} \cdot \delta_n \qquad [\mathrm{MJ/m^2}]$$

m – Combustion factor. Its value is between 0 and 1. For mainly cellulosic materials a value of 0.8 may be taken. Conservatively a value of 1 can be used

δ_{q1} – factor taking into account the fire activation risk due to the size of the compartment

δ_{q2} – factor taking into account the fire activation risk due to the type of occupancy

δ_n – factor taking into account the different fire fighting measures

$$\delta_n = \prod_{i=1}^{10} \delta_{ni} = \delta_{n1} \cdot \delta_{n2} \cdots \delta_{n9} \cdot \delta_{n10}$$

Characteristics of the Fire Load from EN 1991-1-2
Natural Fire Model

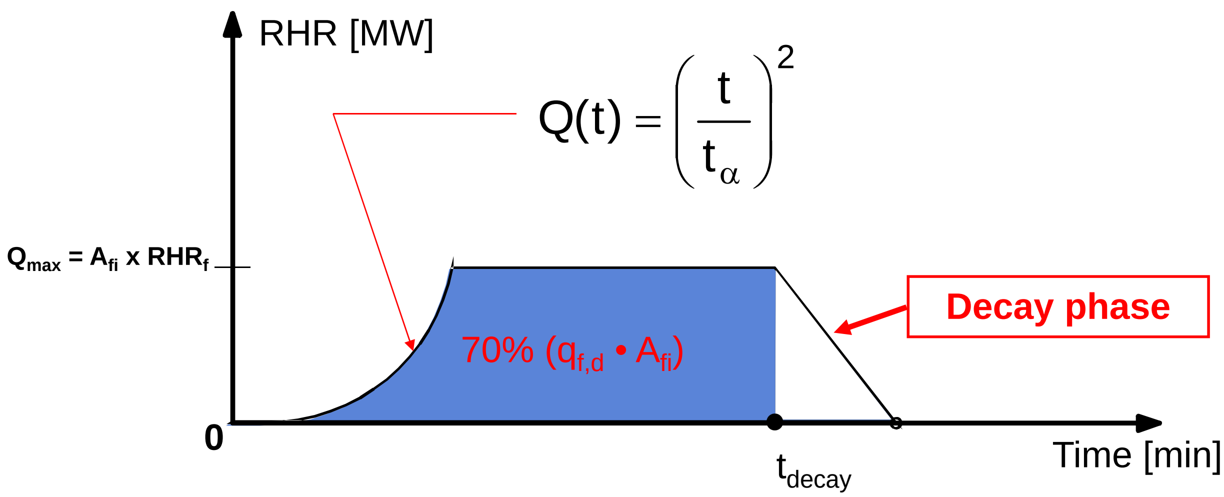
Compartment floor area A_f [m²]	Danger of Fire Activation δ_{q1}	Danger of Fire Activation δ_{q2}	Examples of Occupancies
25	1,10	0,78	Art gallery, museum, swimming pool
250	1,50	1,00	Residence, hotel, office
2500	1,90	1,22	Manufactory for machinery & engines
5000	2,00	1,44	Chemical laboratory, Painting workshop
			Manufactory of fireworks

$$q_{f,d} = \delta_{q1} \cdot \delta_{q2} \cdot \prod \delta_{ni} \cdot m \cdot q_{f,k}$$

Automatic Fire Suppression		Automatic Fire Detection			Manual Fire Suppression				
Automatic Water Extinguishing System	Independent Water Supplies (0 | 1 | 2)	Automatic fire Detection & Alarm by Heat	Automatic fire Detection & Alarm by Smoke	Automatic Alarm Transmission to Fire Brigade	Work Fire Brigade	Off Site Fire Brigade	Safe Access Routes	Fire Fighting Devices	Smoke Exhaust System
δ_{n1}	δ_{n2}	δ_{n3}	δ_{n4}	δ_{n5}	δ_{n6}	δ_{n7}	δ_{n8}	δ_{n9}	δ_{n10}
0,61	1,0 | 0,87 | 0,7	0,87 or 0,73		0,87	0,61 or 0,78		0,9 or 1 / 1,5	1,0 / 1,5	1,0 / 1,5

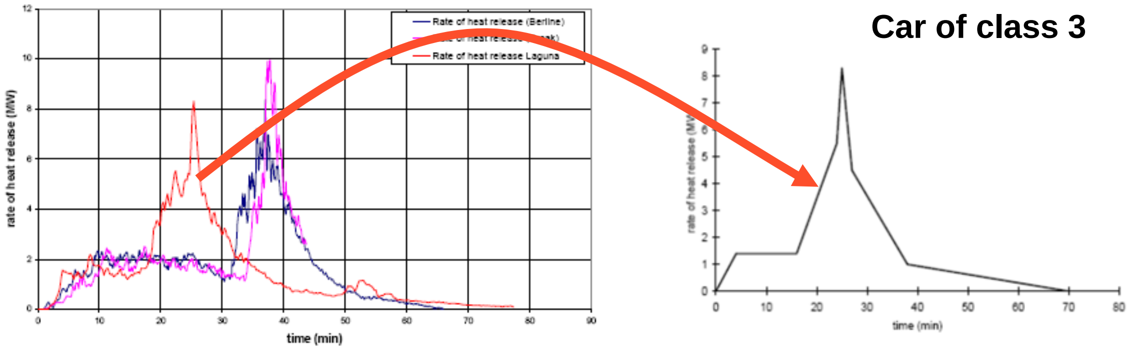
From DIFISEK+

Rate of Heat Release Curve from EN 1991-1-2
Natural Fire Model



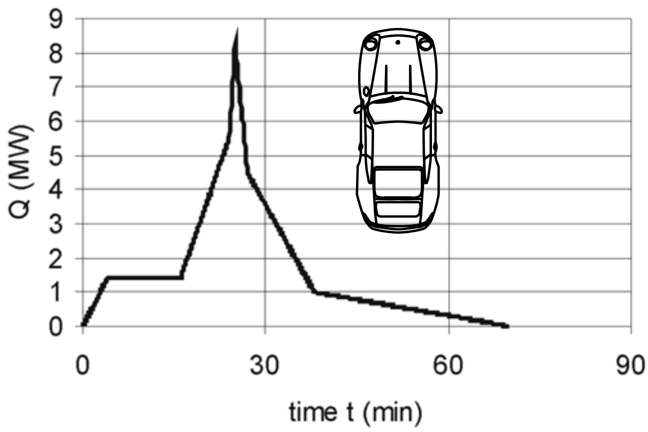
From DIFISEK+

Rate of Heat Release of a class 3 car. Experimental evaluation Natural Fire Model



Demonstration of real fire tests in car parks and high buildings – Contract no. 7215 PP 025, Projecto Europeu

An idealized Rate of Heat Release Curve for a car burning Natural Fire Model



Class 3	
Time (min)	Rate of heat release (MW)
0	0
4	1.4
16	1.4
24	5.5
25	8.3
27	4.5
38	1
70	0

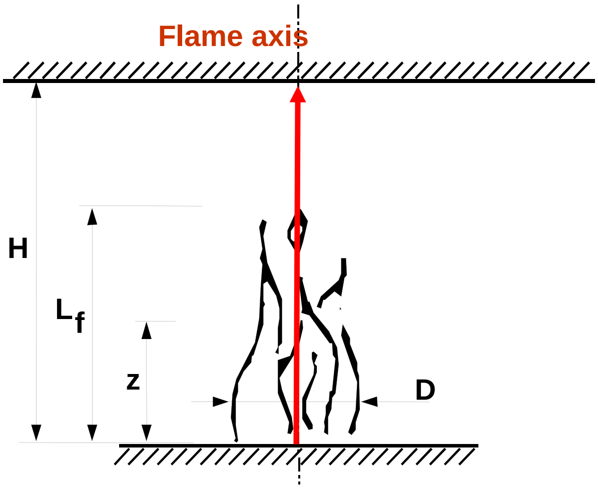
From ECSC Project: Demonstration of real fire tests in car parks and high buildings.

Localised Fire: HESKESTAD Method
Natural Fire Model

Annex C of EN 1991-1-2:

- Flame is not impacting the ceiling of a compartment ($L_f < H$)
- Fires in open air

$$\Theta_{(z)} = 20 + 0{,}25\ (0{,}8\ Q_c)^{2/3}\ (z-z_0)^{-5/3} \leq 900°C$$



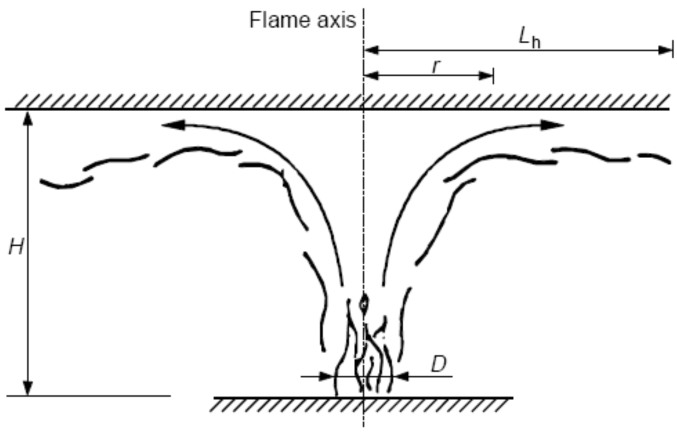
The flame length L_f of a localised fire is given by :

$$L_f = -1{,}02\ D + 0{,}0148\ Q^{2/5}$$

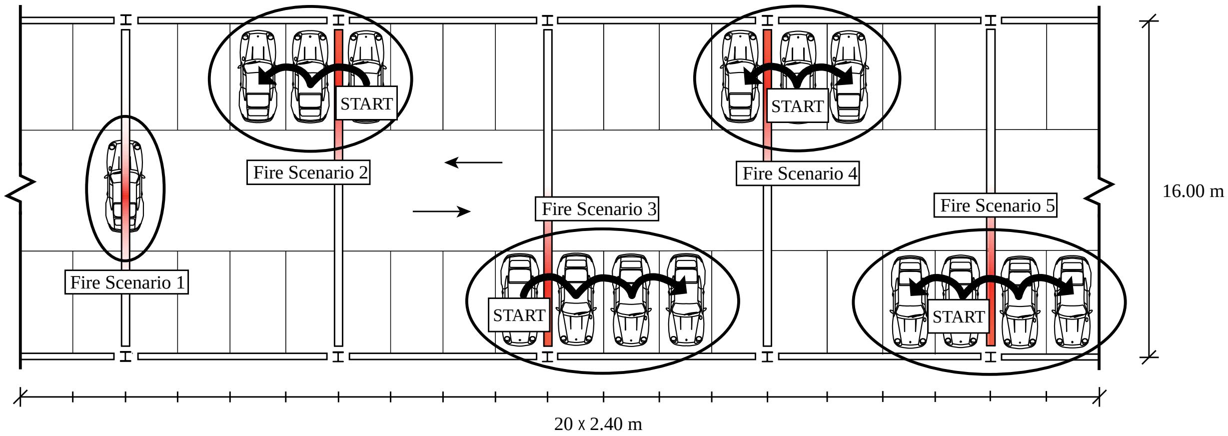
Localised Fire:HASEMI Method
Natural Fire Model

Annex C of EN 1991-1-2:

- Flame is impacting the ceiling ($L_f > H$)



Localised fires in a car park
Some fire scenarios

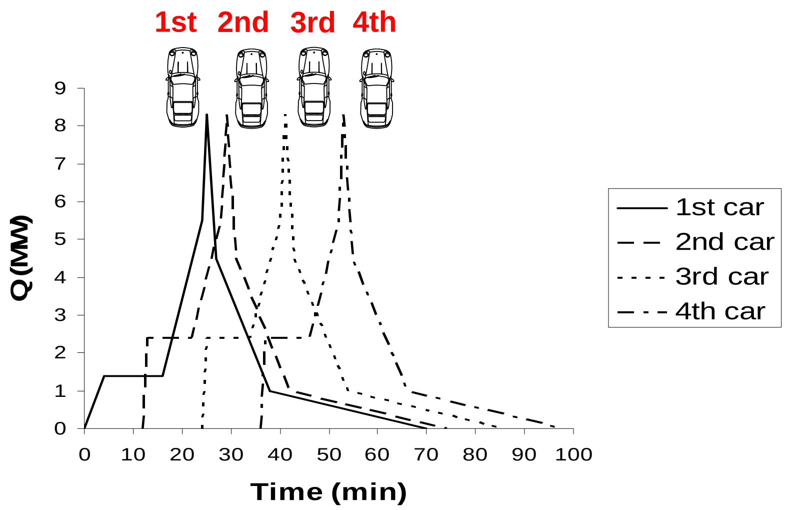


Height: H = 2.7 m
Diameter of flame: D = 3.9 m

Steel Beams: IPE 500

Localised fire
Rate of heat release of four burning cars

Curve of the rate of heat release of each car. A delay of 12 minutes between each burning car.

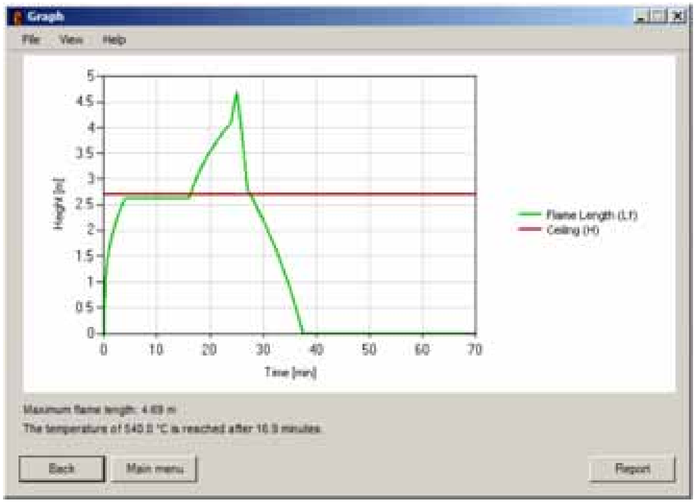


From ECSC Project: Demonstration of real fire tests in car parks and high buildings.

Two Localised fire models
Flame length

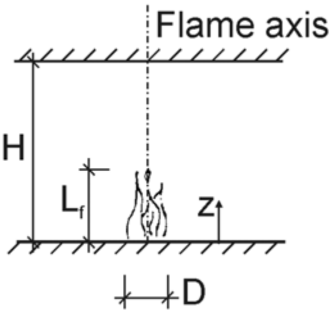
if $L_r \geq H$ ⇒ Hasemi method has to be used

if $L_r < H$ ⇒ Heskestad method has to be used

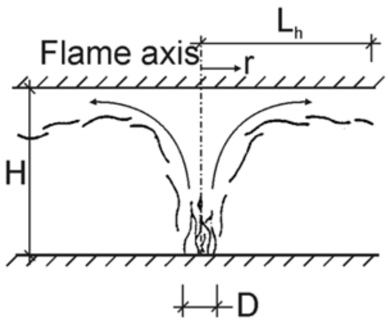


Program Elefir-EN

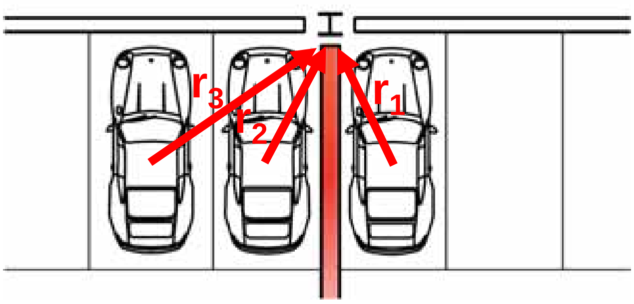
Heskestad Method

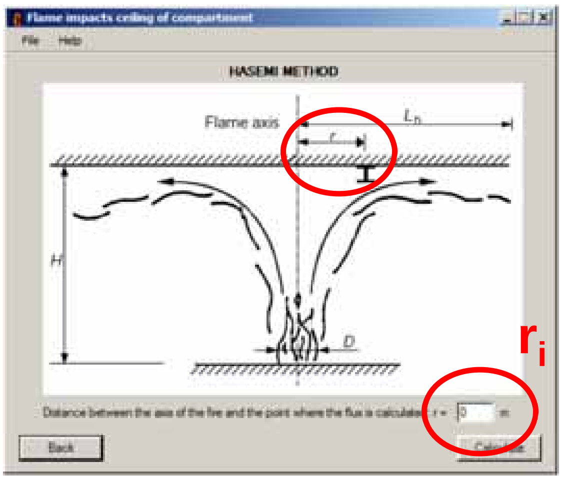


Hasemi Method

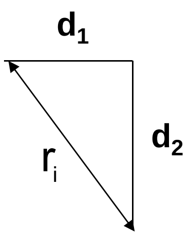


Hasemi method
Horizontal distances





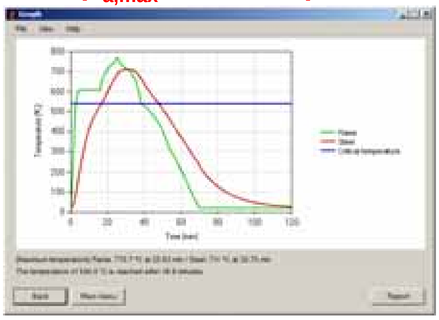
Program Elefir-EN



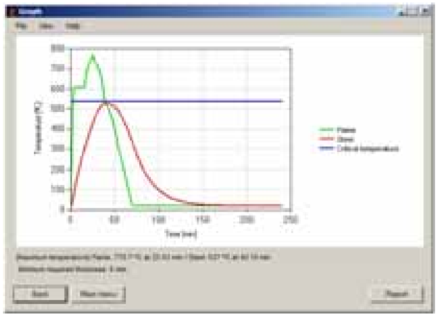
$$r_i = \sqrt{d_1^{\,2} + d_2^{\,2}}$$

Temperature development
Gas and steel temperture

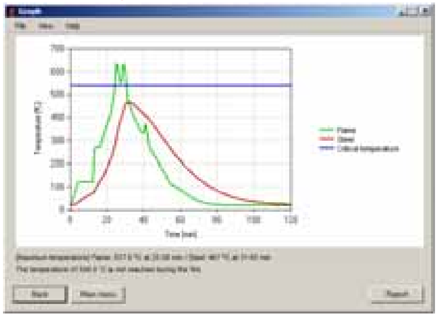
Scenario 1: unprotected steel ($\theta_{a,max}$ = 710.9 ºC)



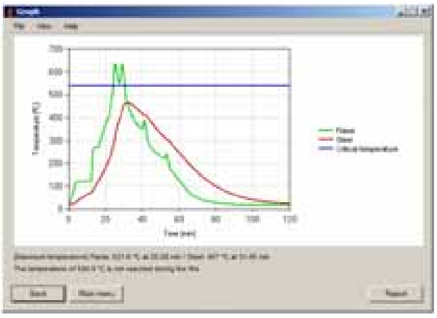
Scenario 1: protected steel ($\theta_{a,max}$ = 527 ºC)



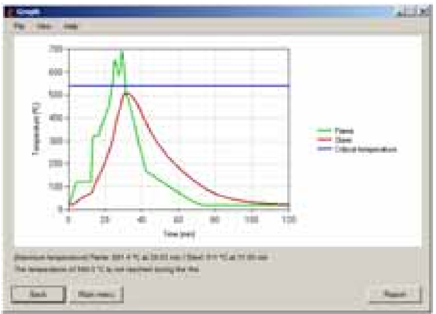
Scenario 2 ($\theta_{a,max}$ = 466.7 ºC)



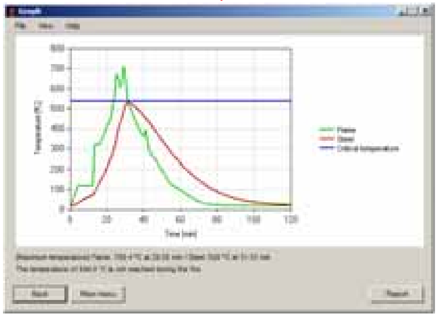
Scenario 3 ($\theta_{a,max}$ = 466.7 ºC)



Scenario 4 ($\theta_{a,max}$ = 510.9 ºC)



Scenario 3 ($\theta_{a,max}$ = 528.5 ºC)



Parametric fire. Needed parameters
Natural Fire Model

Fire load density - $q_{f,d}$

Opening factor - $O = A_v \sqrt{h} / A_t$

Wall factor - $b = \sqrt{\rho c \lambda}$

} Temperature θ = θ(t)

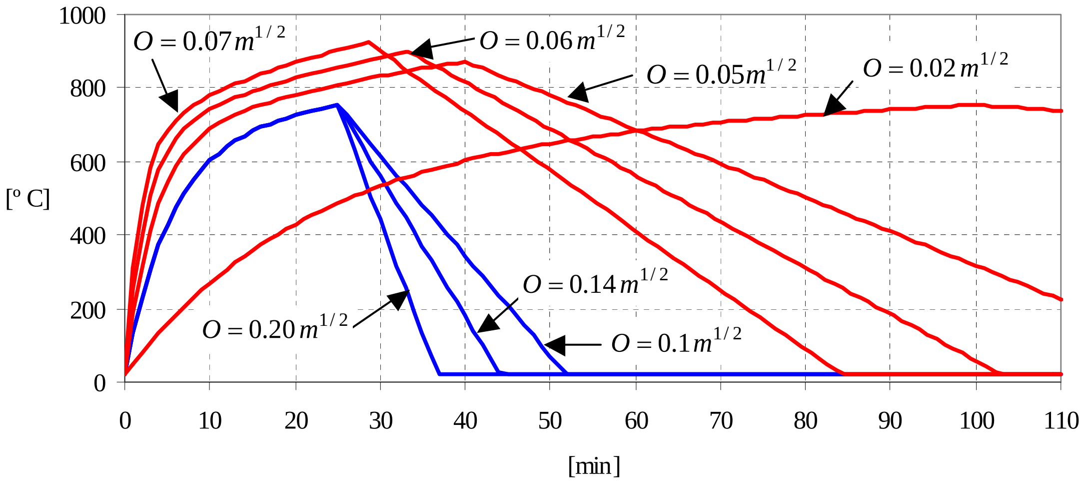
A_v - area of vertical openings; A_t - total area of enclosure

Limitations :

- $A_{floor} \leq 500$ m²
- No horizontal openings
- H ≤ 4 m
- Wall factor from 1000to 2200
- Fire load density, $q_{t,d}$ from 50 to 1000 MJ/m²

Parametric Fire
Natural Fire Model

Annex A of EN 1991-1-2



Ventilation controlled fires — Fuel controlled fires

Parametric fire curves function of - O

For a given $q_{f,d}$, b, A_t and A_f

Parametric Fire - Influence of the Actives Fire Safety Measures
Natural Fire Model

No Fire Active Measures	red			
Off Site Fire Brigade		orange	green	blue
Safe access routes		orange	green	blue
Automatic Fire Detection & Alarm by Smoke			green	blue
Fire fighting devices			green	blue
Automatic water extinguishing system - Sprinklers				blue
Automatic akarm transmission to fire brigade				blue

1567 = 511x0,8x1,14x1x 1x1x1x1x1x1x1x1,5x1,5x1,5

815 = 511x0,8x1,14x1x 1x1x1x1x1x1x0,78x1x1,5x1,5

397 = 511x0,8x1,14x1x 1x1x1x0,73x1x1x0,78x1x1x1,5

210 = 511x0,8x1,14x1x 0,61x1x1x0,73x0,87x1x0,78x1x1,5x1,5

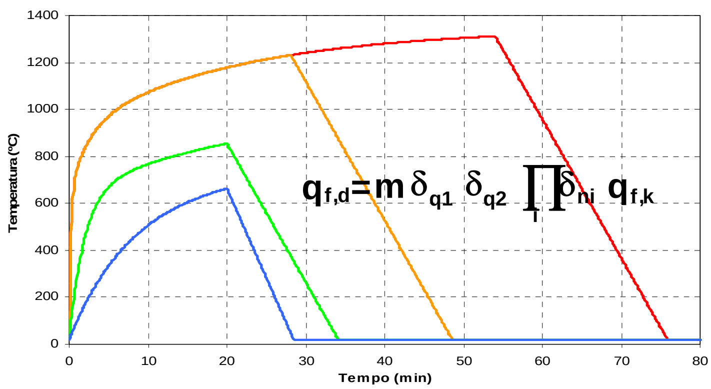
Office

A_f = 45,0 m²

***O* = 0,08 m$^{1/2}$**

$q_{f,k}$ = 511 MJ/m²

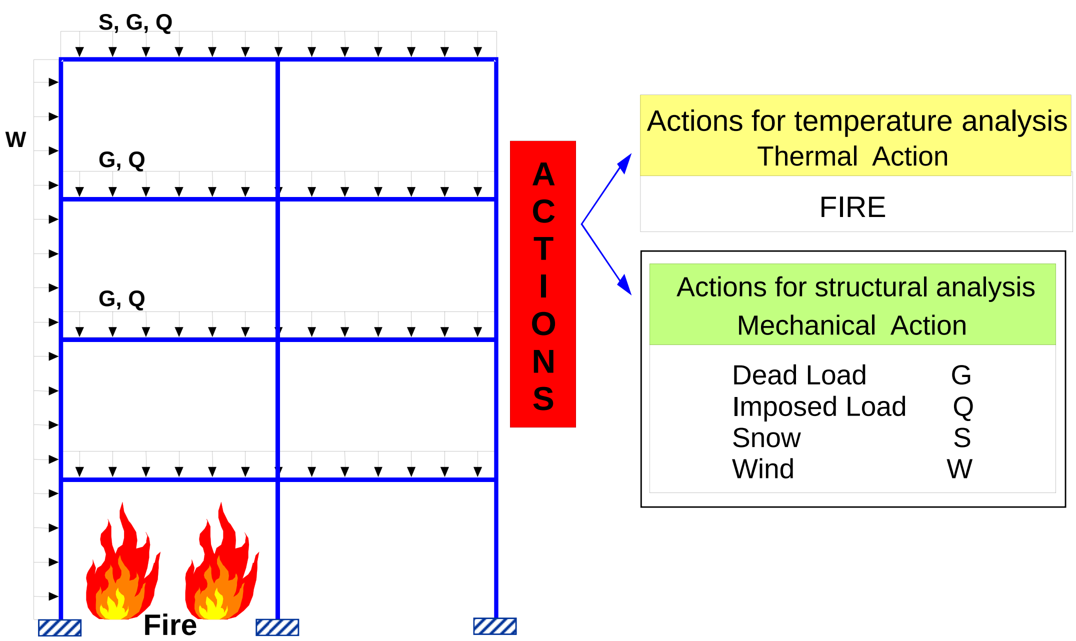
m = 0,8



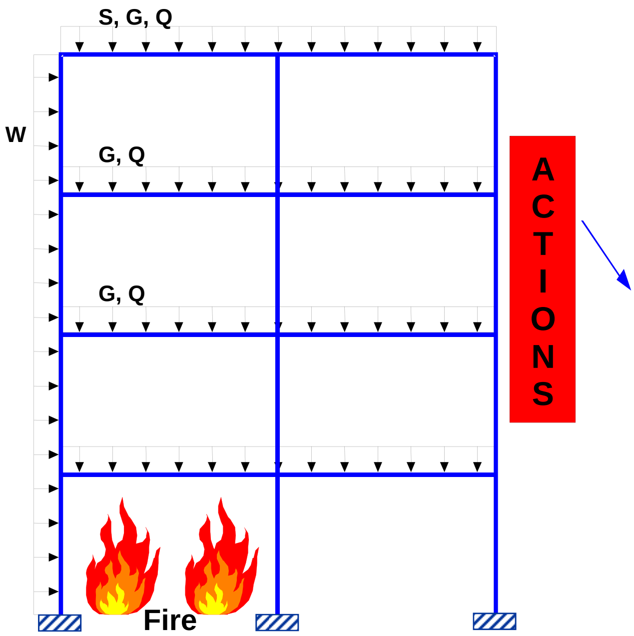
Fire Design of Steel Structures
Four steps

1. Definition of the thermal loading - **EC1**
2. Definition of the mechanical loading - **EC0 +EC1**
3. Calculation of temperature evolution within the structural members - **EC3**
4. Calculation of the mechanical behaviour of the structure exposed to fire - **EC3**

Actions on Structures



Actions on Structures



Actions for structural analysis	
Mechanical Action	
Dead Load	G
Imposed Load	Q
Snow	S
Wind	W

Combination Rules for Mechanical Actions
EN 1990: Basis of Structural Design

- At room temperature (**20 ºC**)

$$\sum_{j\geq 1} \gamma_{G,j} G_{k,j} + \gamma_{Q,1} \cdot Q_{k,1} + \sum_{i>1} \gamma_{Q,1} \psi_{0,i} \cdot Q_{k,i}$$

- In fire situation

1. Fire is an accidental action.
2. The simultaneous occurrence of other independent accidental actions need not be considered

$$\sum_{j\geq 1} G_{k,1} + (\psi_{1,1} \text{ ou } \psi_{2,1}) \cdot Q_{k,1} + \sum_{i>1} \psi_{2,i} \cdot Q_{k,i} + A_d$$

$\psi_{1,1} Q_{k,1}$ – Frequent value of the representative value of the variable action Q_1

$\psi_{2,1} Q_{k,1}$ – Quasi-permanent value of the representative value of the variable action Q_1

A_d – Indirect thermal action due to fire induced by the restrained thermal expansion may be neglected for member analysis

Combination Rules for Mechanical Actions
EN 1990: Basis of Structural Design

$$\sum_{j\geq 1} G_{k,1} + (\psi_{1,1} \text{ ou } \psi_{2,1}) \cdot Q_{k,1} + \sum_{i>1} \psi_{2,i} \cdot Q_{k,i} + A_d$$

Action	ψ_1	ψ_2
Imposed loads in buildings, category (see EN 1991-1-1)	0.5	0.3
Imposed loads in congregation areas and shopping areas	0.7	0.6
Imposed loads in storage areas	0.9	0.8
vehicle weight $\leq$ 30 kN	0.7	0.6
30 kN $\leq$ vehicle weight $\leq$ 160 kN	0.5	0.3
Imposed loads in roofs	0.0	0.0
Snow (Norway, Sweden …)	0.2	0.0
Wind loads on buildings	0.2	0.0

In some countries the National Annex recommends Ψ_1, Q_1, so that wind is always considered and so horizontal actions are always taken into account

Fire Design of Steel Structures
Four steps

1. Definition of the thermal loading - **EC1**
2. Definition of the mechanical loading - **EC0 +EC1**
3. Calculation of temperature evolution within the structural members - **EC3**
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Thermal response

Heat conduction equation

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial\theta}{\partial y}\right)+\dot{Q}=\rho c_p\frac{\partial\theta}{\partial t}$$

Boundary conditions

$$q_c = h_c(\theta-\theta_\infty)$$ **convection**

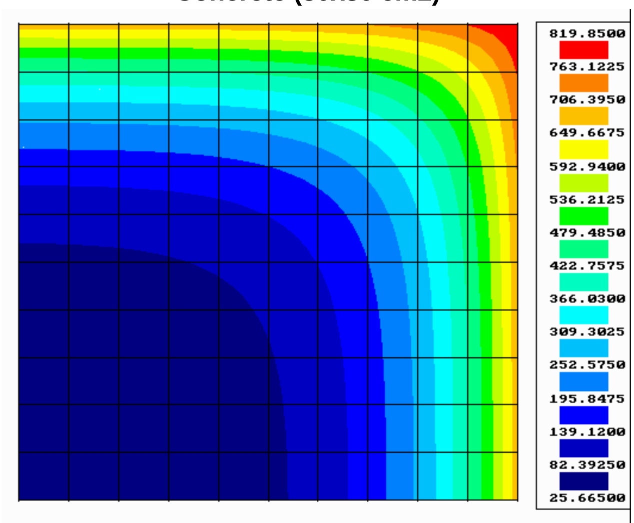
$$q_r = \beta\varepsilon(\theta^4-\theta_a^4)=\underbrace{\beta\varepsilon(\theta^2+\theta_a^2)(\theta+\theta_a)}_{h_r}(\theta-\theta_a)=h_r(\theta-\theta_a)$$ **radiation**

Thermal response
Temperature field by Finite Element Method – After 30 min. ISO

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial\theta}{\partial y}\right)+\dot{Q}=\rho c_p\frac{\partial\theta}{\partial t}$$

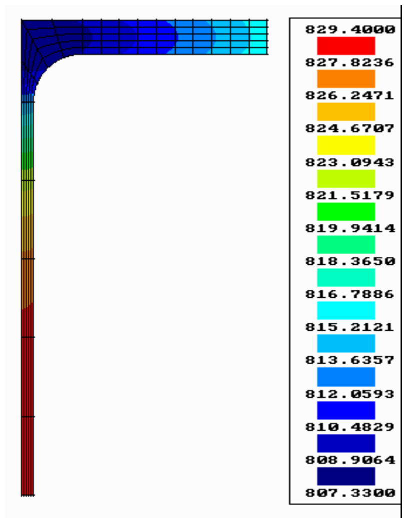
Note: this equation can be simplified for the case of current steel profiles

Concrete (30x30 cm2)



ΔT = 794 ºC

Steel (IPE300)

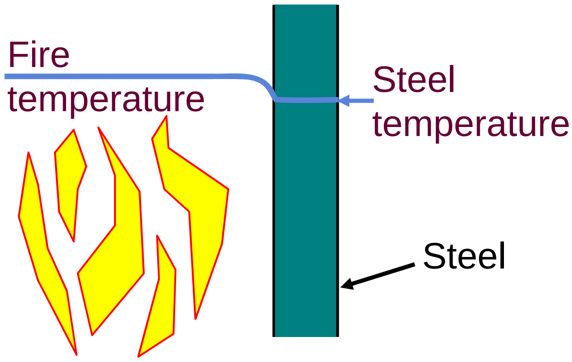


ΔT = 22 ºC

Temperature increase of unprotected steel
Simplified equation of EC3

Temperature increase in time step Δt:

$$\Delta\theta_{a.t} = k_{sh} \frac{A_m/V}{c_a \rho_a} \dot{h}_{net,d} \Delta t$$



Heat flux $\dot{h}_{net,d}$ has 2 parts:

Radiation:

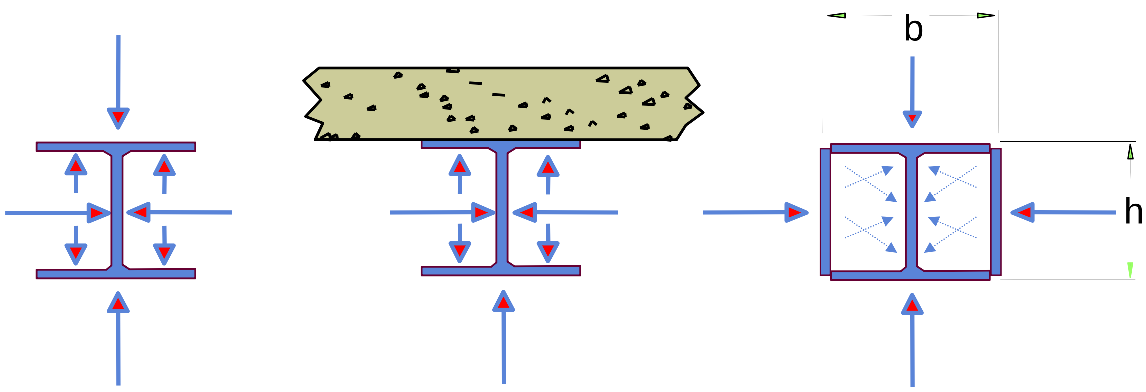
$$\dot{h}_{net,r} = 5{,}67 x 10^{-8} \Phi \varepsilon_f \varepsilon_m \left((\theta_r + 273)^4 - (\theta_m + 273)^4 \right)$$

Convection:

$$\dot{h}_{net,c} = \alpha_c \left(\theta_g - \theta_m \right)$$

Section factor A_m/V
Unprotected steel members

$$\Delta\theta_{a.t} = k_{sh} \frac{A_m/V}{c_a \rho_a} \dot{h}_{net,d} \Delta t$$



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

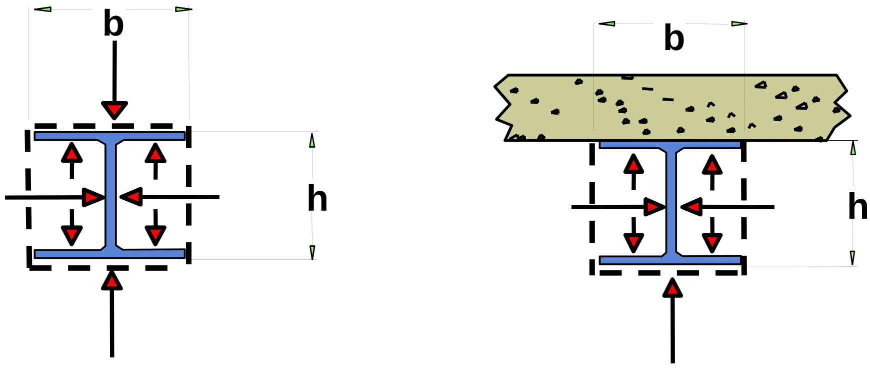
Correction factor for the Shadow effect k_{sh}

For I-sections under nominal fire: $\mathbf{k_{sh} = 0.9\ [A_m/V]_b/[A_m/V]}$

In all other cases: $\mathbf{k_{sh} = [A_m/V]_b/[A_m/V]}$

For cross-sections convex shape: $\mathbf{k_{sh} = 1}$

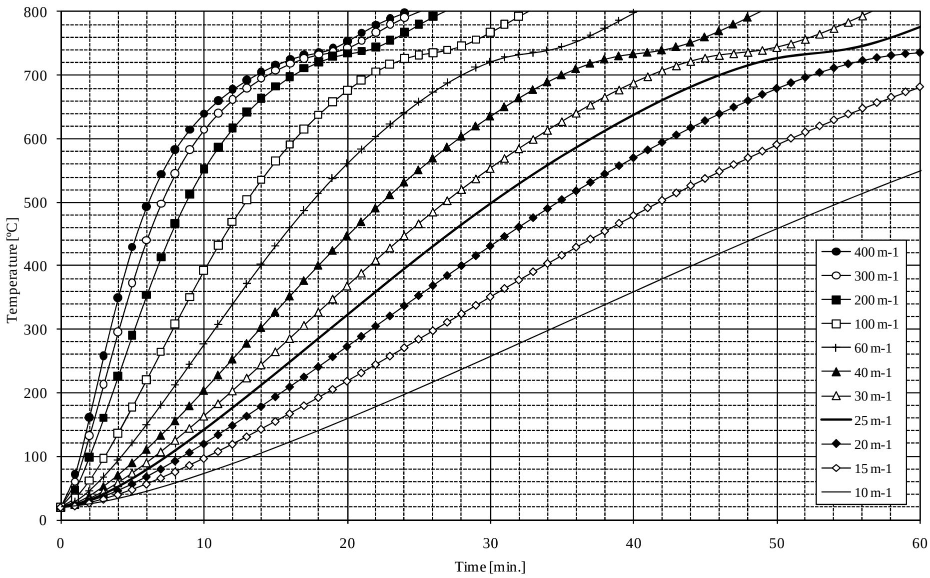
$[A_m/V]_b$ - Section factor as the profile has a hollow encasement fire protection



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

Nomogram for temperature Unprotected steel profiles

Nomogram for unprotected steel members subjected to the ISO 834 fire curve, for different values of $k_{sh} \cdot Am/V$ [m-1]



Structural fire protection

Passive Protection

Insulating Board

Gypsum, Mineral fibre, Vermiculite.
Easy to apply, aesthetically acceptable.
Difficulties with complex details.

Cementitious Sprays

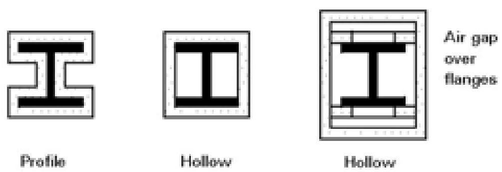
Mineral fibre or vermiculite in cement binder.
Cheap to apply, but messy; clean-up may be expensive.
Poor aesthetics; normally used behind suspended ceilings.

Intumescent Paints

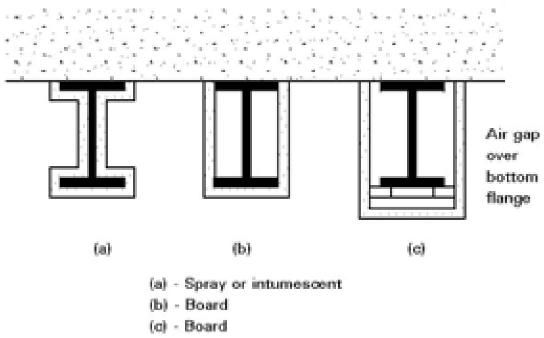
Decorative finish under normal conditions.
Expands on heating to produce insulating layer.
Can be done off-site.

Structural fire protection

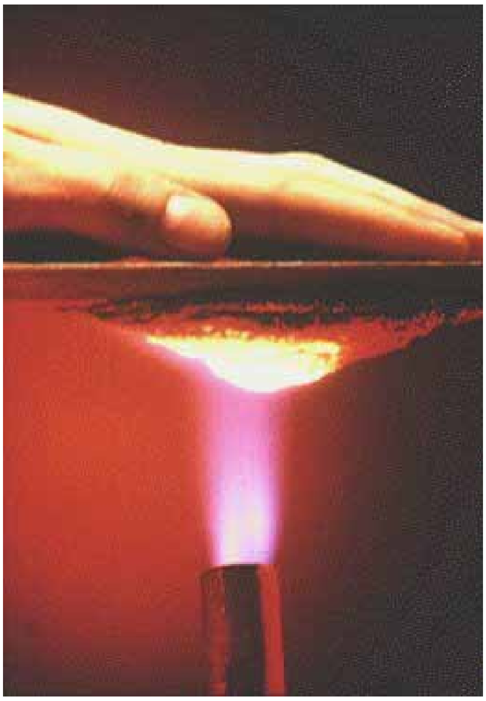
Columns:



Beams:



Structural fire protection
Intumescent paint



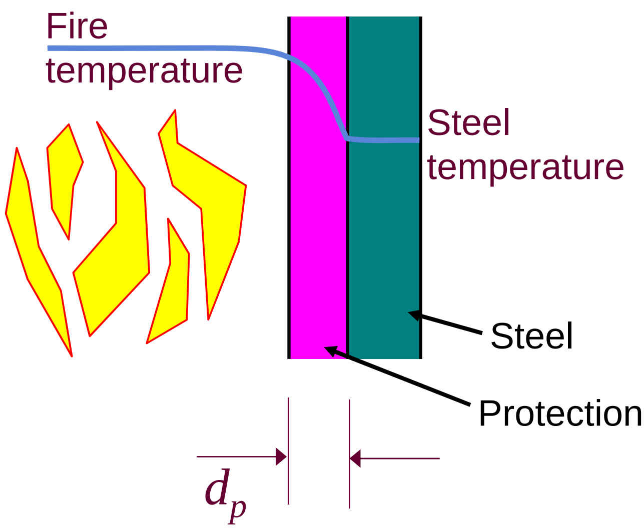
Structural fire protection
Cementitious Sprays

Structural fire protection
Insulating Board

Temperature increase of protected steel
Simplified equation of EC3

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

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

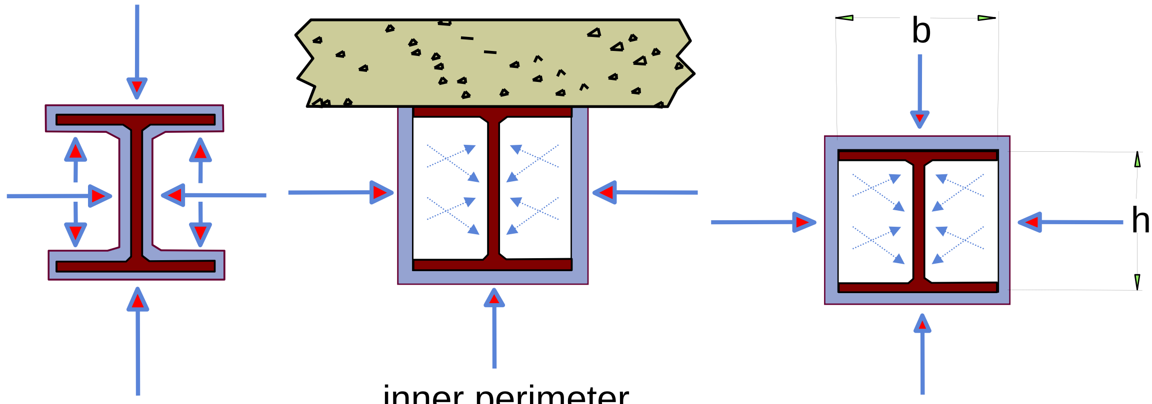


- **Temperature rise of steel in time increment Δt**

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

Section factor A_p/V
Protected steel members

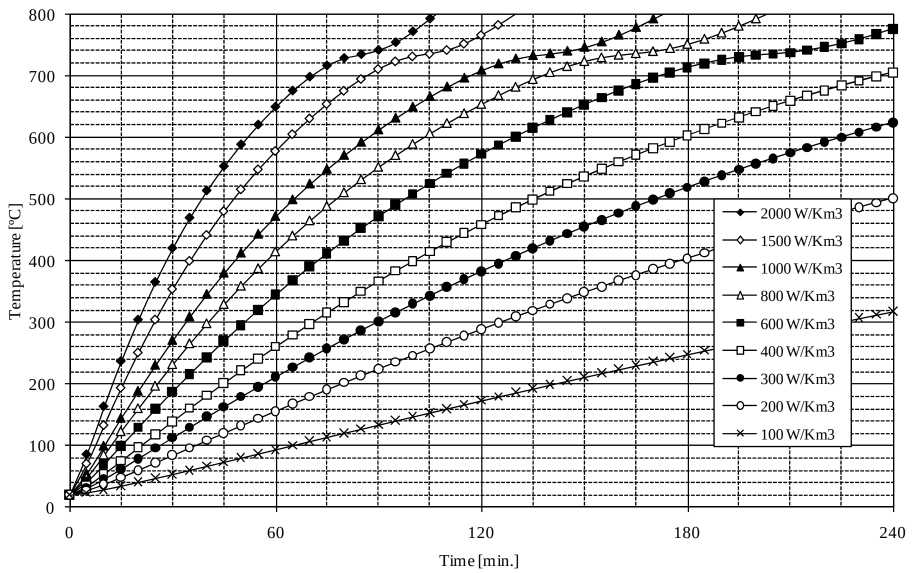
$$\Delta\theta_{a.t} = \frac{\lambda_p/d_p}{c_a\rho_a}\frac{A_p}{V}\left(\frac{1}{1+\phi/3}\right)(\theta_{g.t}-\theta_{a.t})\Delta t - (e^{\phi/10}-1)\Delta\theta_{g.t}$$



$\frac{\text{Steel perimeter}}{\text{steel c/s area}}$ $\frac{\text{inner perimeter of board}}{\text{steel c/s area}}$ $\frac{2(b+h)}{\text{c/s area}}$

Nomogram for temperature
Protected steel profiles

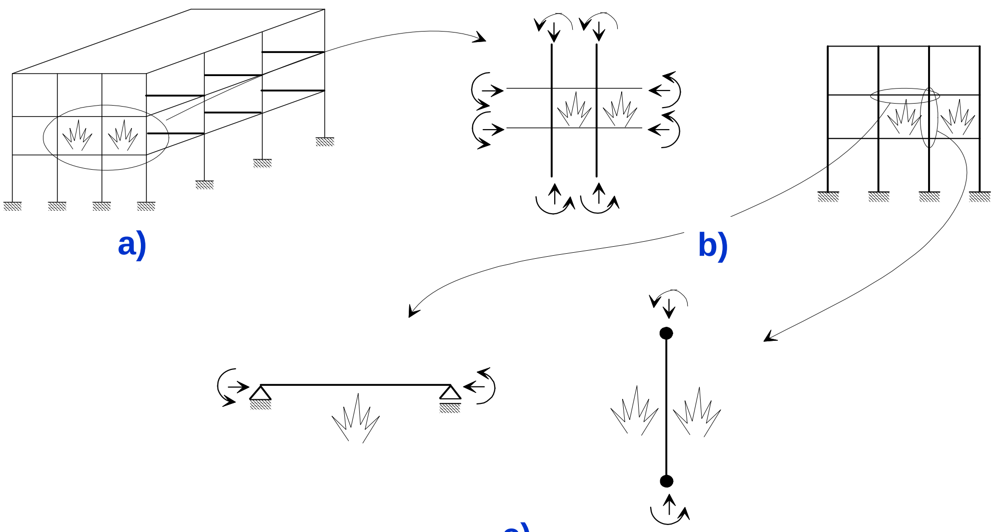
Nomogram for unprotected steel members subjected to the ISO 834 fire curve, for different values of $[A_p/V][\lambda_p/d_p]$ [W/Km3]



Fire Design of Steel Structures
Four Steps

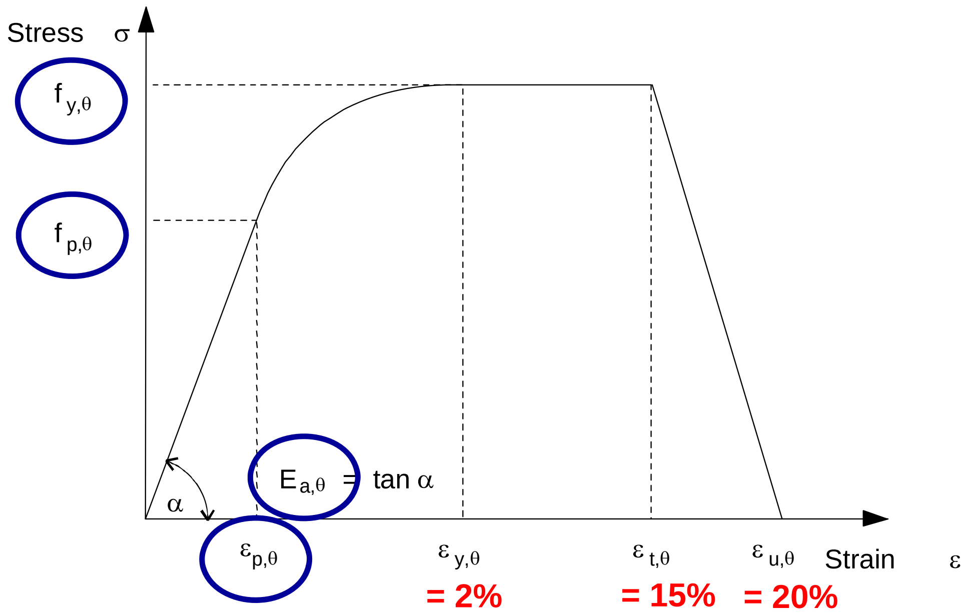
1. Definition of the thermal loading - **EC1**
2. Definition of the mechanical loading - **EC0 +EC1**
3. Calculation of temperature evolution within the structural members - **EC3**
4. Calculation of the mechanical behaviour of the structure exposed to fire - **EC3**

Degree of simplification of the structure



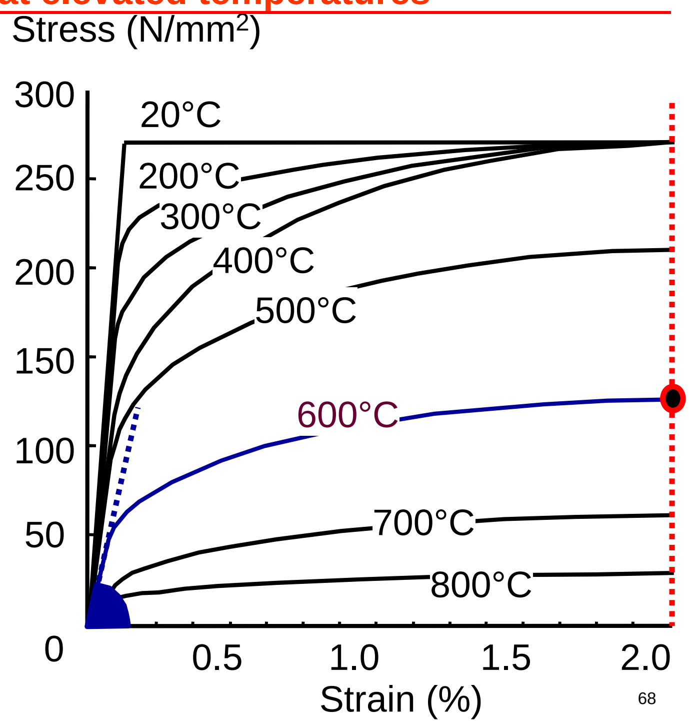
Analysis of: a) Global structure; b) Parts of the structure; c) Members

Mechanical properties of carbon steel
Stress-strain relationship at elevated temperatures



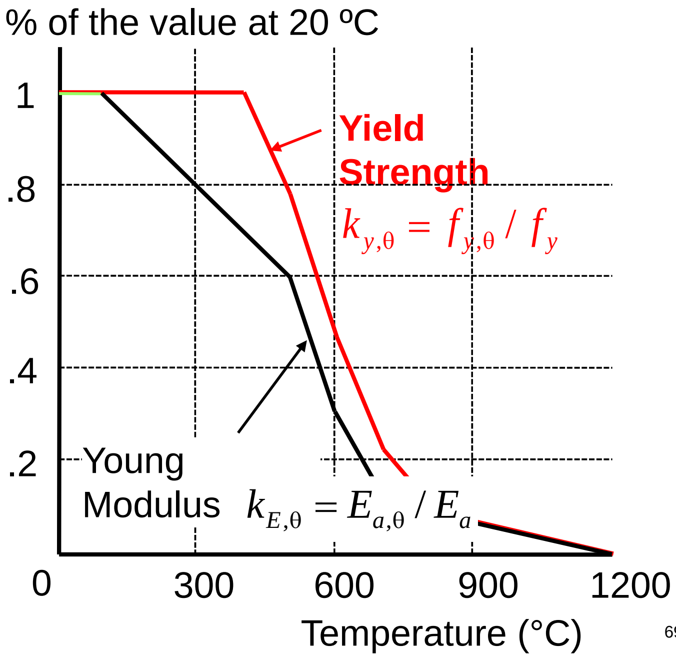
Mechanical properties of carbon steel
Stress-strain relationship at elevated temperatures

- Strength/stiffness reduction factors for elastic modulus and yield strength (2% total strain).
- Elastic modulus at 600°C reduced by about 70%.
- Yield strength at 600°C reduced by over 50%.

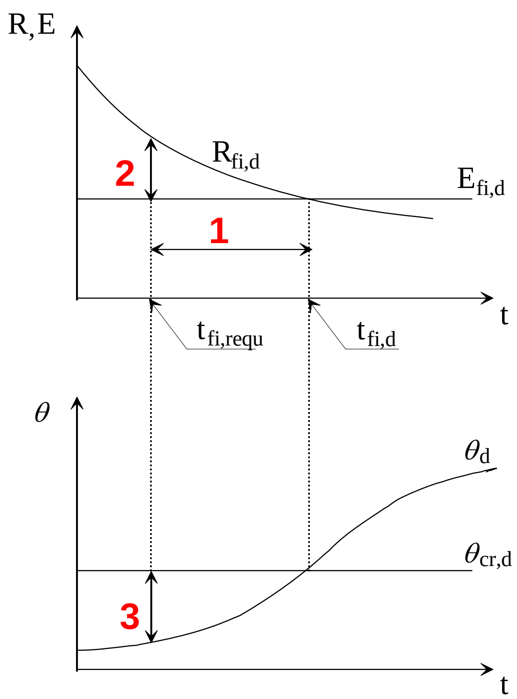


Reduction factors for stress-strain relationship of carbon steel at elevated temperatures

	Reduction factors at temperature θ_a relative to the value of f_y or E_a at 20°C		
Steel Temperature θ_a	Reduction factor (relative to f_y) for effective yield strength $k_{y,\theta} = f_{y,\theta}/f_y$	Reduction factor (relative to f_y) for proportional limit $k_{p,\theta} = f_{p,\theta}/f_y$	Reduction factor (relative to E_a) for the slope of the linear elastic range $k_{E,\theta} = E_{a,\theta}/E_a$
20°C	1,000	1,000	1,000
100°C	1,000	1,000	1,000
200°C	1,000	0,807	0,900
300°C	1,000	0,613	0,800
400°C	1,000	0,420	0,700
500°C	0,780	0,360	0,600
600°C	0,470	0,180	0,310
700°C	0,230	0,075	0,130
800°C	0,110	0,050	0,090
900°C	0,060	0,0375	0,0675
1000°C	0,040	0,0250	0,0450
1100°C	0,020	0,0125	0,0225
1200°C	0,000	0,0000	0,0000

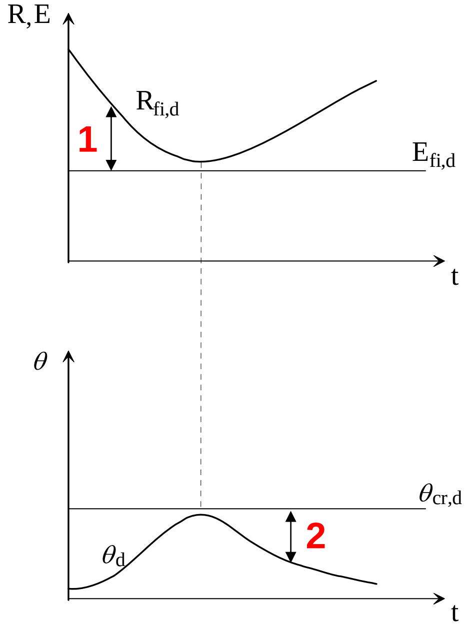


Checking Fire Resistance: Strategies with nominal fires



1. Time:
   $t_{fi,d} > t_{fi,requ}$
2. Load resistance:
   $R_{fi,d,t} > E_{fi,d}$
3. Temperature:
   $\theta_d < \theta_{cr,d}$

Checking Fire Resistance: Strategies with natural fires



1. Load resistance:

$R_{fi,d,t} > E_{fi,d}$

collapse is prevented during the complete duration of the fire including the decay phase or during a required period of time.

2. Temperature:

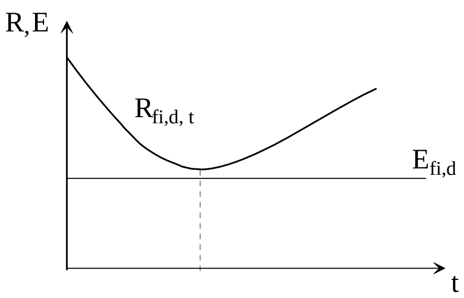
$\theta_d < \theta_{cr,d}$

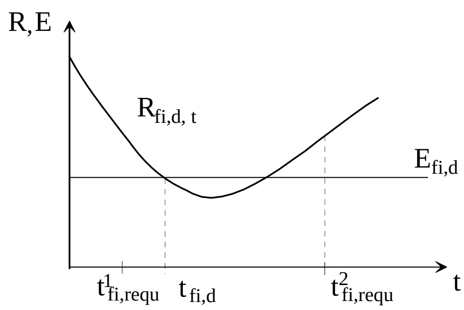
collapse is prevented during the complete duration of the fire including the decay phase or during a required period of time.

Note: With the agreement of authorities, verification in the time domain can be also performed. The required periodo of time defining the fire resistance must be accepted by the authorities.

Checking Fire Resistance: Strategies with natural fires

The Load-bearing function is ensured if collapse is prevented during the complete duration of the fire including the decay phase, or during a required period of time.





Collapse is prevented during the complete duration of the fire including the decay phase.

Collapse is prevented during a required period of time, $t^1_{fi,req}$.

Design methods

- ❑ **Tabulated data (EC2, EC4, EC6)**
- ❑ **Simple calculation models (All the Eurocodes)**
- ❑ **Advanced calculation models (All the Eurocodes)**

Eurocode 2: Tabulated data
Fire resistance of a RC beam

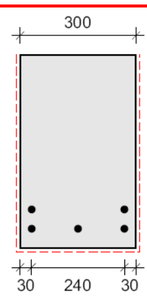
Table 5.5: Minimum dimensions and axis distances for simply supported beams made with reinforced and prestressed concrete

Standard fire resistance	Minimum dimensions (mm)						
	Possible combinations of a and b_{min} where a is the average axis distance and b_{min} is the width of beam				Web thickness b_w		
					Class WA	Class WB	Class WC
1	2	3	4	5	6	7	8
a) R 30	b_{min}= 80 a = 25	120 20	160 15*	200 15*	80	80	80
R 60	b_{min}= 120 a = 40	160 35	200 30	300 25	100	80	100
R 90	b_{min}= 150 a = 55	200 45	300 40	400 35	110	100	100
b) R 120	b_{min}= 200 a = 65	240 60	300 55	500 50	130	120	120
R 180	b_{min}= 240 a = 80	300 70	400 65	600 60	150	150	140
R 240	b_{min}= 280 a = 90	350 80	500 75	700 70	170	170	160
$a_{sd} = a + 10$mm (see note below)							

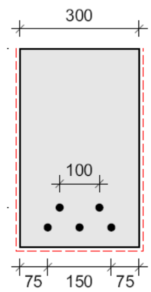
For prestressed beams the increase of axis distance according to 5.2(5) should be noted.

a_{sd} is the axis distance to the side of beam for the corner bars (or tendon or wire) of beams with only one layer of reinforcement. For values of b_{min} greater than that given in Column 4 no increase of a_{sd} is required.

* Normally the cover required by EN 1992-1-1 will control.



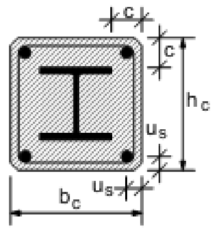
a) R 60



b) R 180

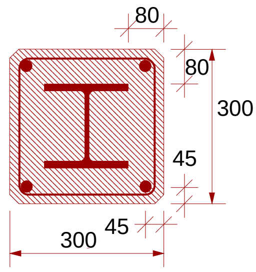
Eurocode 4: Tabulated data
Fire resistance of a RC column

Table 4.4: Minimum cross-sectional dimensions, minimum concrete cover of the steel section and minimum axis distance of the reinforcing bars, of composite columns made of totally encased steel sections.



		Standard Fire Resistance					
		R30	R60	R90	R120	R180	R240
1.1	Minimum dimensions h_c and b_c [mm]	150	180	220	300	350	400
1.2	minimum concrete cover of steel section c [mm]	40	50	50	75	75	75
1.3	minimum axis distance of reinforcing bars u_s [mm]	20*	30	30	40	50	50
	or						
2.1	Minimum dimensions h_c and b_c [mm]	-	200	250	350	400	-
2.2	minimum concrete cover of steel section c [mm]	-	40	40	50	60	-
2.3	minimum axis distance of reinforcing bars u_s [mm]	-	20*	20*	30	40	-

NOTE: *) These values have to be checked according to 4.4.1.2 of EN 1992-1-1

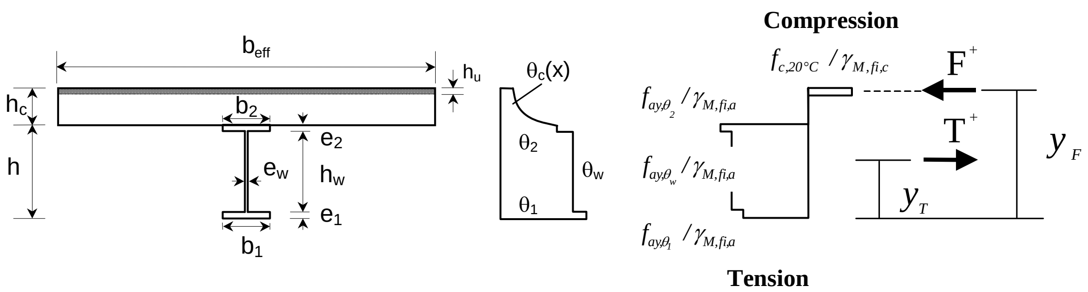


R 120

Design procedures

- ❑ **Tabulated data (EC2, EC4, EC6)**
- ❑ **Simple calculation models (All the Eurocodes)**
- ❑ **Advanced calculation models (All the Eurocodes)**

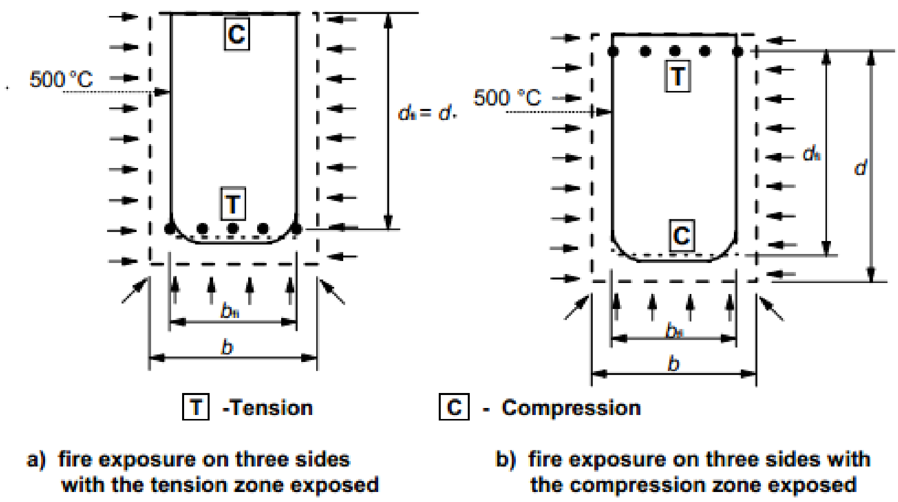
Eurocode 4: Simple calculation model
Sagging moment resistance of a composite beam



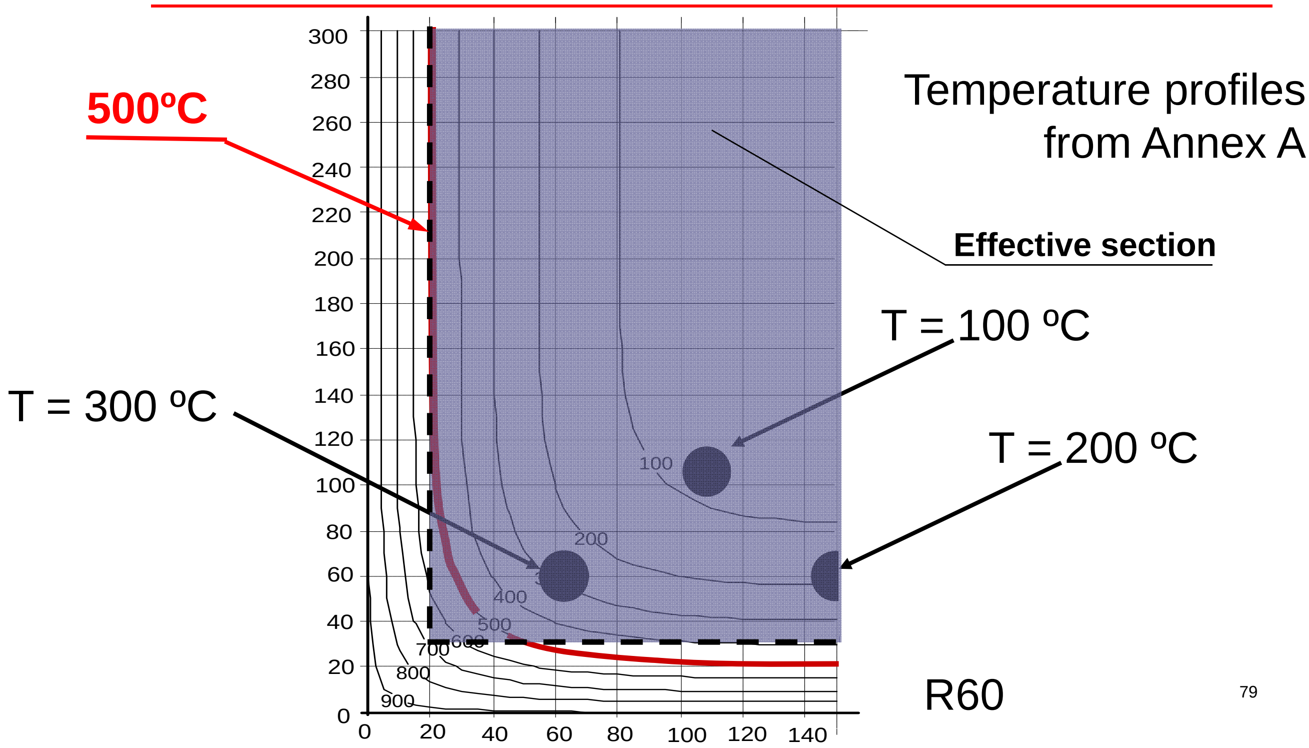
$$M_{fi,Rd}^{+} = T\,(y_F - y_T)$$

Eurocode 2: Simplified calculation model
500°C isotherm method

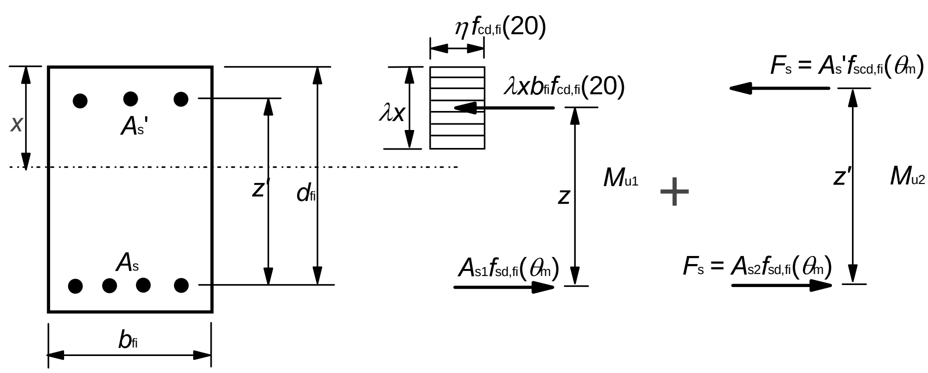
Damaged concrete, i.e. concrete with temperatures in excess of 500°C, is assumed not to contribute to the load bearing capacity of the member, whilst the residual concrete cross-section retains its initial values of strength and modulus of elasticity.



Eurocode 2: Simplified calculation model
500°C isotherm method – RC beam



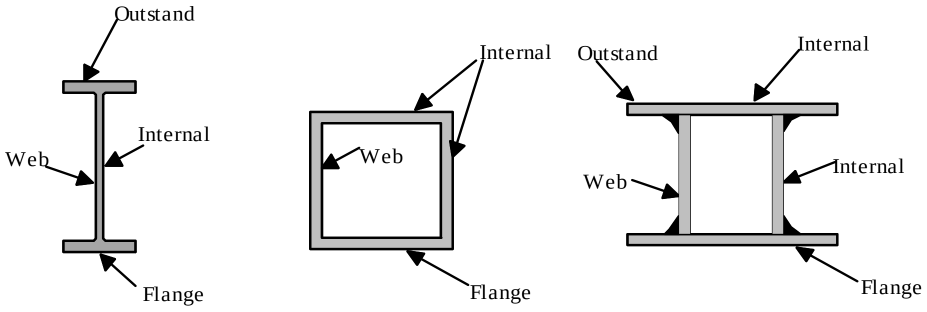
Eurocode 2: Simplified calculation model
Sagging moment resistance of a RC beam



Eurocode 3

Classification of the cross-sections - 1

Steel profiles can be considered as na assembly of individual plates



a) b) c)

Internal and outstand elements

a) Rolled section; b) Hollow section; c) Welded section

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Eurocode 3

Classification of the cross-sections - 2

The slenderness of the compression plates is a key parameter when studying the local buckling of plates

$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \sqrt{\frac{f_y}{k_\sigma \dfrac{\pi^2 E t^2}{12(1-\nu^2)b^2}}} = \frac{b/t}{\sqrt{k_\sigma}\sqrt{\dfrac{\pi^2}{12(1-\nu^2)}}} \frac{1}{\sqrt{\dfrac{E}{f_y}}} =$$

$$= \frac{b/t}{28.4\sqrt{k_\sigma}} \frac{1}{\sqrt{\dfrac{235}{f_y}}\sqrt{\dfrac{E}{210000}}} = \frac{b/t}{28.4\sqrt{k_\sigma}} \frac{1}{\varepsilon} = \frac{b/t}{28.4\varepsilon\sqrt{k_\sigma}}$$

$$\varepsilon = \sqrt{\frac{235}{f_y}}\sqrt{\frac{E}{210000}} \quad \text{with } f_y \text{ and } E \text{ in MPa}$$

This parameter is widly used in EC3

Classification of the cross-sections - 3

Cross-sections are classified based on the parameter

$$\varepsilon = \sqrt{\frac{235}{f_y}}\sqrt{\frac{E}{210000}}$$ **with f_y and E in MPa**

For the case of carbon steel at normal temperature the, Young modulus takes the value 210 GPa:

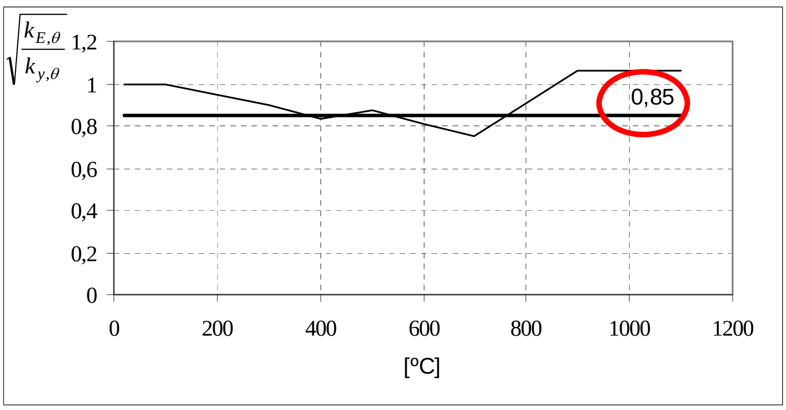
- At normal temperature ⇨ $$\varepsilon = \sqrt{\frac{235}{f_y}}\sqrt{\frac{210000}{210000}} = \sqrt{\frac{235}{f_y}}$$

- At elevated temperature ⇨ See next slide ⇨

Classification of the cross-sections - 4

$$\varepsilon_\theta = \sqrt{\frac{235}{f_{y,\theta}}}\sqrt{\frac{E_\theta}{210000}} = \sqrt{\frac{235}{k_{y,\theta} f_y}}\sqrt{\frac{k_{E,\theta}E}{210000}} = \sqrt{\frac{k_{E,\theta}}{k_{y,\theta}}}\sqrt{\frac{235}{f_y}}\sqrt{\frac{E}{210000}} =$$

$$= \sqrt{\frac{k_{E,\theta}}{k_{y,\theta}}}\sqrt{\frac{235}{f_y}} \approx 0.85\sqrt{\frac{235}{f_y}} = 0.85\varepsilon$$

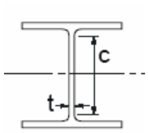
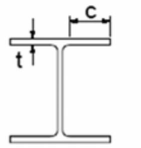


$$\varepsilon_\theta = 0.85\sqrt{\frac{235}{f_y}} = 0.85\varepsilon$$

Classification of the cross-sections - 5

For carbon steel:

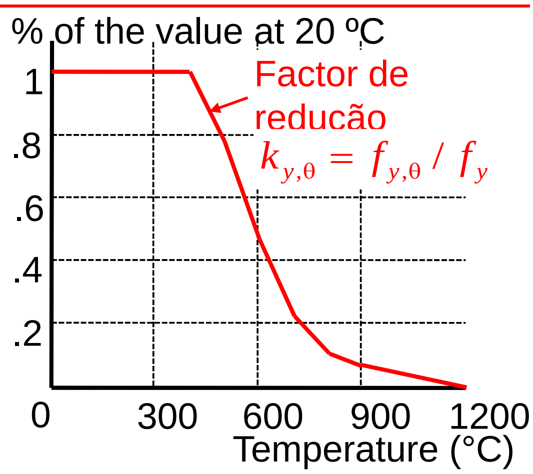
$$\varepsilon = 0.85\sqrt{\frac{235}{f_y}}$$ and tables from EN 1993-1-1

			
Element	**Class 1**	**Class 2**	**Class 3**
Flange	c / t = 9 ε	c / t = 10 ε	c / t = 14 ε
Web subjected to compression	c / t = 33 ε	c / t = 38 ε	c / t = 42 ε
Web subected tobending	c / t = 72 ε	c / t = 83 ε	c / t = 124 ε

For stainless steel:

$$\varepsilon_\theta = 0.85\sqrt{\frac{235}{f_y}\frac{E}{210000}}$$ and tables from EN 1993-1-4

Eurocode 3: Fire Resistance: Tension members - 1



- The design resistance of a tension member with uniform temperature θ_a is:

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

or

$$N_{fi,\theta,Rd} = k_{y,\theta} N_{Rd} [\gamma_{M0} / \gamma_{M,fi}]$$

N_{Rd} = design resistance of the cross-section $N_{pl,Rd}$ for normal temperature design

Eurocode 3: Fire Resistance: Compression members with Class 1, 2 or 3 cross-sections - 1

- Design buckling resistance of a compression member with uniform temperature θ_a is →

$$N_{b,fi,\theta,Rd} = \chi_{fi} A k_{y,\theta} f_y \frac{1}{\gamma_{M,fi}}$$

With

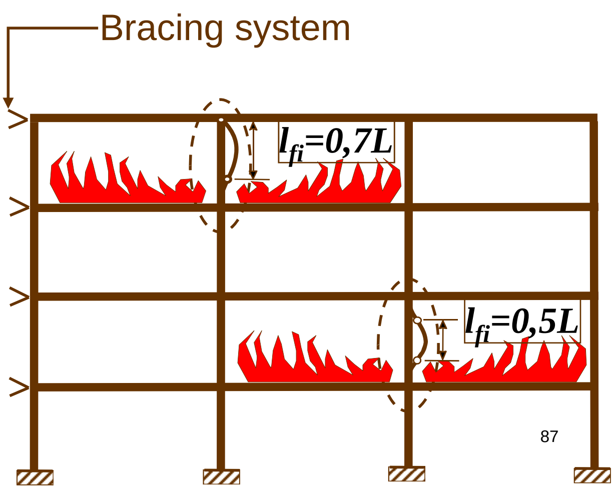
$$\chi_{fi} = \frac{1}{\phi_\theta + \sqrt{\phi_\theta^2 - \bar{\lambda}_\theta^2}}$$

$$\phi_\theta = \frac{1}{2}\left[1 + \alpha \bar{\lambda}_\theta + \bar{\lambda}_\theta^2\right]$$

$$\alpha = 0.65\sqrt{235/f_y}$$ ~~(Curves a, b, c, d, a_0)~~

- Non.dimensional slenderness:

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



Eurocode 3: Fire Resistance: Laterally restrained beams with Class 1, 2 or3 cross-sections with uniform temperature - 1

- The design moment resistance of a Class 1, 2 or Class 3 cross-section with a uniform temperature θ_a is: →

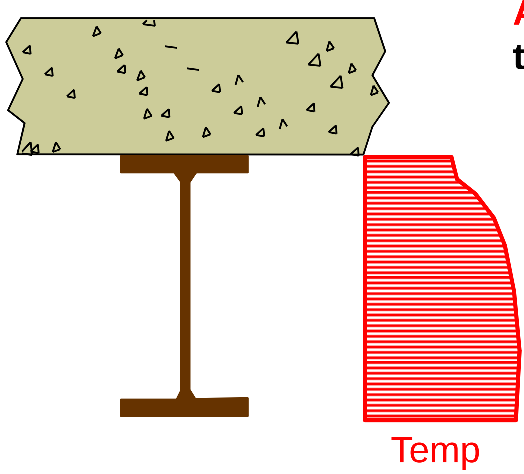
$$M_{fi,\theta,Rd} = M_{Rd} k_{y,\theta}\left(\frac{\gamma_{M0}}{\gamma_{M,fi}}\right)$$

$M_{Rd} = M_{pl,Rd}$ – Class 1 or 2 cross-sections

$M_{Rd} = M_{el,Rd}$ – Class 3 cross-sections

Eurocode 3: Fire Resistance: Laterally restrained beams with Class 1, 2 or 3 cross-sections with non-uniform temperature - 2

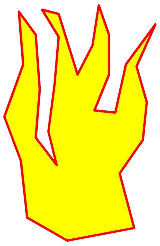
Adaptation factors to take into account the non-uniform temperature distribution



Moment Resistance:

$$M_{fi,\theta,Rd} = M_{Rd} k_{y,\theta} \left(\frac{\gamma_{M0}}{\gamma_{M,fi}} \right) \frac{1}{\kappa_1 \kappa_2}$$

κ_1 is an adaptation factor for non-uniform temperature across the cross-section



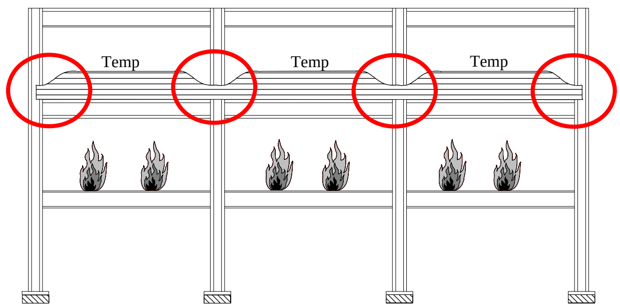
κ_1=1,0 for a beam exposed on all four sides

κ_1=0,7 for an unprotected beam exposed on three sides

κ_1=0,85 for a protected beam exposed on three sides

Eurocode 3: Fire Resistance: Laterally restrained beams with Class 1, 2 or 3 cross-sections with non-uniform temperature - 3

Adaptation factors to take into account the non-uniform temperature distribution



Moment Resistance:

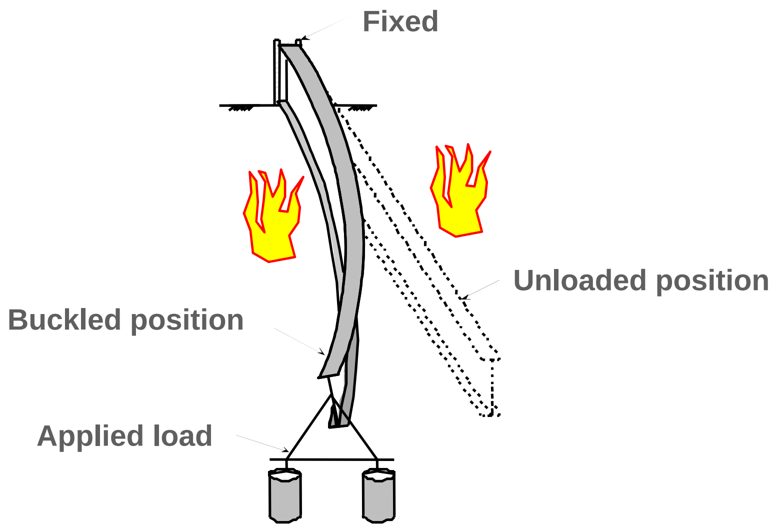
$$M_{fi,\theta,Rd} = M_{Rd} k_{y,\theta} \left(\frac{\gamma_{M0}}{\gamma_{M,fi}} \right) \frac{1}{\kappa_1 \kappa_2}$$

κ_2 is an adaptation factor for non-uniform temperature along the beam.

κ_2=0,85 at the supports of a statically indeterminate beam

κ_2=1.0 in all other cases

Eurocode 3: Fire Resistance: Laterally unrestrained beams - 1



Lateral-torsional buckling

Eurocode 3: Fire Resistance: Laterally unrestrained beams - 2

- Design lateral torsional buckling resistance moment of a laterally unrestrained beam at the max. temp. in the comp. flange $\theta_{a.com}$ is ➜

$$M_{b.fi.\theta.Rd} = \chi_{LT.fi} W_y k_{y.\theta.com} f_y \frac{1}{\gamma_{M.fi}}$$

- $\chi_{LT.fi}$ the reduction factor for lateral-torsional buckling in the fire design situation.

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

$$\bar{\lambda}_{LT.\theta.com} = \bar{\lambda}_{LT} \sqrt{k_{y.\theta.com} / k_{E.\theta.com}}$$

$$\phi_{LT,\theta,com} = \frac{1}{2}\left[1 + \alpha \bar{\lambda}_{LT,\theta,com} + (\bar{\lambda}_{LT,\theta,com})^2\right]$$

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y f_y}{M_{cr}}}$$

$$\alpha = 0.65\sqrt{235 / f_y}$$

(Curves a, b, c, d)

Eurocode 3: Fire Resistance
Shear Resistance

Design shear resistance

$$V_{fi,t,Rd} = k_{y,\theta,web} V_{Rd} \left(\frac{\gamma_{M,0}}{\gamma_{M,fi}} \right)$$

V_{Rd} is the shear resistance of the gross cross-section for normal temperature design, according to EN 1993-1-1.

θ_{web} is the average temperature in the web of the section.

$k_{y,\theta,web}$ is the reduction factor for the yield strength of steel at the steel temperature θ_{web}.

Eurocode 3: Members with Class 1, 2 or 3 cross-sections, subject to combined bending and axial compression - 1

Without lateral-torsional buckling

Class 1 and 2

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

Class 3

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

Eurocode 3: Members with Class 1, 2 or 3 cross-sections, subject to combined bending and axial compression - 2

With lateral-torsional buckling

Class 1 and 2

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

Class 3

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

Fire Resistance: verifications of the fire resistance not covered by EN 1993-1-2

Clause 1.1.2 (Scope of Part 1.2 of Eurocode 3) of EN 1993-1-2 states "*This Part 1-2 of EN 1993 deals with the design of steel structures for the accidental situation of fire exposure and is intended to be used in conjunction with EN 1993-1-1 and EN 1991-1-2. This part 1.2 only identifies differences from or supplements to normal temperature design*"

This means that for the cases not covered by EN 1993-1-2, the formulae from the part 1.1 of EC3 should be used but modified for use at elevated temperature.

Fire Resistance: Cross-sectional verification of a member subjected to bending and axial force (compression or tension) - 1

For class 1 and class 2

$$\left[\frac{M_{y,fi,Ed}}{M_{N,y,fi,Rd}}\right]^{\alpha} + \left[\frac{M_{z,fi,Ed}}{M_{N,z,fi,Rd}}\right]^{\beta} \leq 1.0$$

where $M_{N,y,fi,Rd}$ and $M_{N,z,fi,Rd}$ are the the design plastic moment resistance reduced due to the axial force.

For class 3

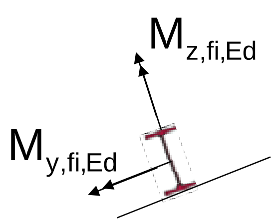
$$\frac{N_{fi,Ed}}{N_{fi,Rd}} + \frac{M_{y,fi,Ed}}{M_{y,fi,Rd}} + \frac{M_{z,fi,Ed}}{M_{z,fi,Rd}} \leq 1.0$$

Fire Resistance: Cross-sectional verification of a member subjected to bi-axial bending - 1

For class 1 and class 2

$$\left[\frac{M_{y,fi,Ed}}{M_{y,fi,Rd}}\right]^{\alpha} + \left[\frac{M_{z,fi,Ed}}{M_{z,fi,Rd}}\right]^{\beta} \leq 1.0$$

Example: a purlin



For class 3

$$\frac{M_{y,fi,Ed}}{M_{y,fi,Rd}} + \frac{M_{z,fi,Ed}}{M_{z,fi,Rd}} \leq 1.0$$

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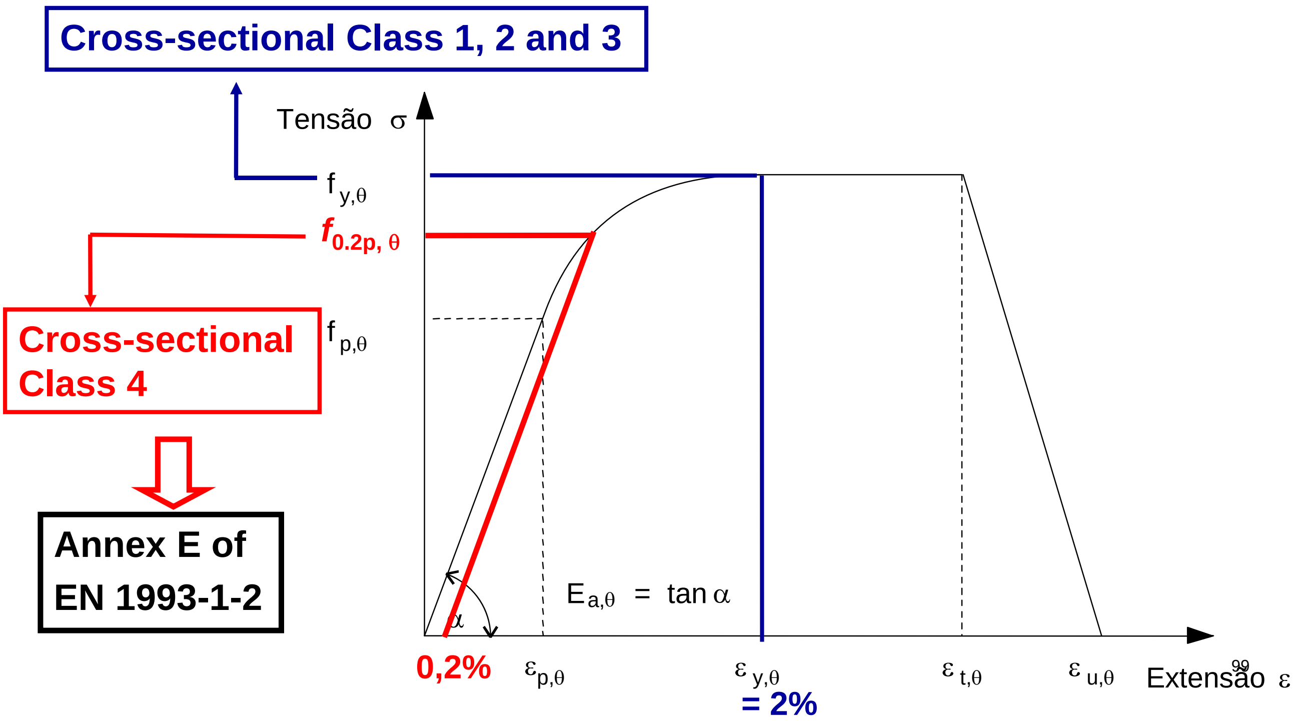
Eurocode 3: Fire Resistance

Design yield strength to be used with simple calculation models



Eurocode 3: Fire Resistance

Members with Class 4 cross-sections

Two procedures:

1. In the absence of calculation, a **critical temperature of 350 ºC** should be considered (conservative results).

2. Alternatively use Annex E, considering the **effective area** and the **effective section modulus** determined in accordance with EN 1993-1-3 and EN 1993-1-5, i.e. based on the material properties at 20°C.

$$\overline{\lambda}_{p,\theta} \approx \overline{\lambda}_{20°C}$$ (Slenderness of the plates)

(See next slide) ⇨

Eurocode 3: Fire Resistance

Non-dimensional slenderness of plates

- At normal temperature

$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \sqrt{\frac{f_y}{k_\sigma \frac{\pi^2 E t^2}{12(1-\nu^2)b^2}}}$$

- At elevated temperature

$$\bar{\lambda}_{p,\theta} = \sqrt{\frac{f_{y,\theta}}{\sigma_{cr,\theta}}} = \sqrt{\frac{f_{y,\theta}}{k_\sigma \frac{\pi^2 E_\theta t^2}{12(1-\nu^2)b^2}}} =$$

$$\sqrt{\frac{k_{y,\theta} f_y}{k_\sigma \frac{\pi^2 k_{E,\theta} E t^2}{12(1-\nu^2)b^2}}} = \bar{\lambda}_p \sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}}$$

Eurocode 3: Fire Resistance

Non-dimensional slenderness of plates at elevated temperature

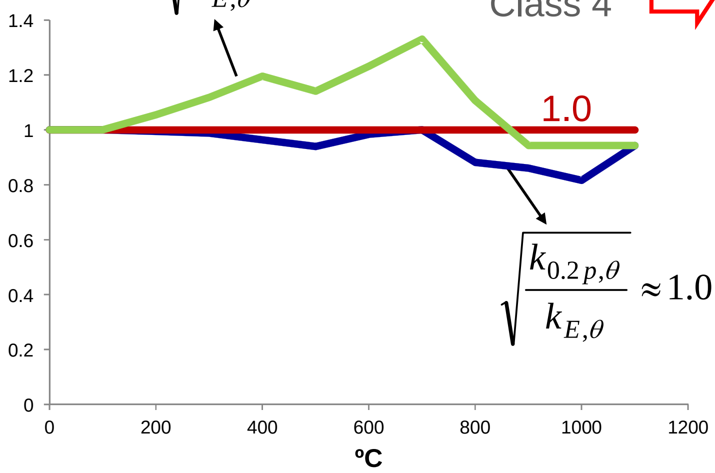
Class 1, 2, 3

$$\bar{\lambda}_{p,\theta} = \sqrt{\frac{f_{y,\theta}}{\sigma_{cr,\theta}}} = \bar{\lambda}_p \sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}}$$

$$\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}}$$

Class 4

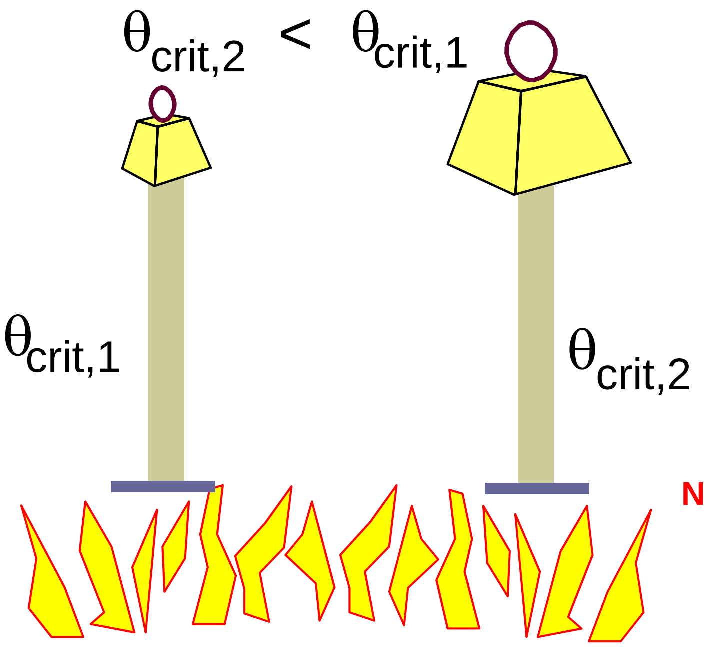
$$\bar{\lambda}_{p,\theta} = \sqrt{\frac{f_{0.2p,\theta}}{\sigma_{cr,\theta}}} = \bar{\lambda}_p \underbrace{\sqrt{\frac{k_{0.2p,\theta}}{k_{E,\theta}}}}_{\approx 1.0}$$



$$\sqrt{\frac{k_{0.2p,\theta}}{k_{E,\theta}}} \approx 1.0$$

$$\bar{\lambda}_{p,\theta} = \bar{\lambda}_{p,20°C}$$

Concept of critical temperature - 1



The designer should provide the owner with value of the critical temperature, so that the thickness of the fire protection material can be defined in a more economical way.

Note: the concept of critical temperature should only be used if uniform temperature in the cross-section is adopted.

Concept of critical temperature - 2

EN 1993-1-2:

4.2.4 Critical temperature

(1) As an alternative to 4.2.3, verification may be carried out in the temperature domain.

(2) Except when considering deformation criteria or when stability phenomena have to be taken into account, the critical temperature $\theta_{a,cr}$ of carbon steel according to 1.1.2 (6) at time t for a uniform temperature distribution in a member may be determined for any degree of utilization μ_0 at time $t = 0$ using:

$$\theta_{a,cr} = 39,19 \ln\left[\frac{1}{0,9674\,\mu_0^{3,833}} - 1\right] + 482 \qquad (4.22)$$

where μ_0 must not be taken less than 0.013.

What is the meaning of this equation?

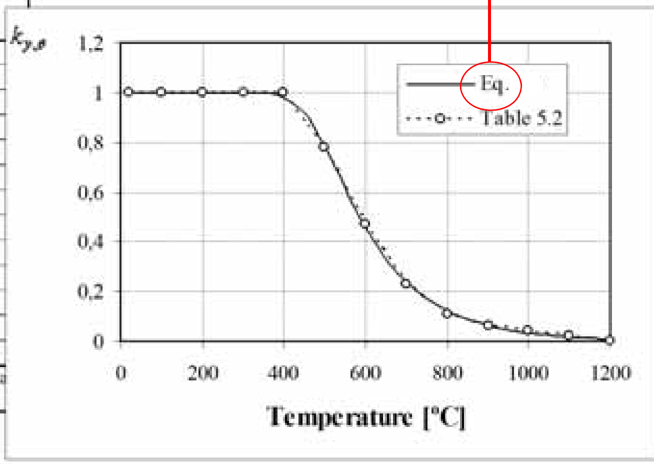
Eurocode 3: Fire Resistance
Concept of critical temperature - 3

The best fit curve to the points of this table can be obtained as:

Steel Temperature θ_a	Reduction factors at temperature θ_a relative to the value of f_y or E_a at 20°C			
	Reduction factor (relative to f_y) for effective yield strength	Reduction factor (relative to f_y) for proportional limit	Reduction factor (relative to E_a) for the slope of the linear elastic range	Reduction factor (relative to f_y) for the design strength of hot rolled and welded thin walled sections (Class 4)
	$k_{y,\theta}=f_{y,\theta}/f_y$	$k_{p,\theta}=f_{p,\theta}/f_y$	$k_{E,\theta}=E_{a,\theta}/E_a$	$k_{0.2p,\theta}=f_{0.2p,\theta}/f_y$
20 °C	1.000	1.000	1.000	1.000
100 °C	1.000	1.000	1.000	1.000
200 °C	1.000	0.807	0.900	0.890
300 °C	1.000	0.613	0.800	0.780
400 °C	1.000	0.420	0.700	0.650
500 °C	0.780	0.360	0.600	0.530
600 °C	0.470	0.180	0.310	0.300
700 °C	0.230	0.075	0.130	0.130
800 °C	0.110	0.050	0.090	0.070
900 °C	0.060	0.0375	0.0675	0.050
1000 °C	0.040	0.0250	0.0450	0.030
1100 °C	0.020	0.0125	0.0225	0.020
1200 °C	0.000	0.0000	0.0000	0.000

NOTE: For intermediate values of the steel temperature, linear interpolation ma[y] be used.

$$k_{y,\theta} = \left\{ 0.9674 \left(e^{\frac{\theta_a - 482}{39.19}} + 1 \right) \right\}^{-1/3.833} \leq 1$$



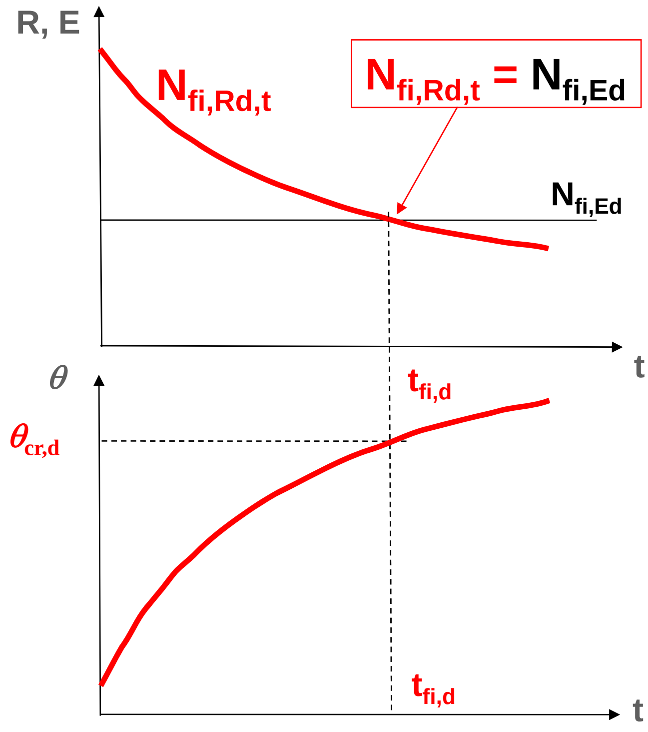
Eurocode 3: Fire Resistance
Concept of critical temperature - 4

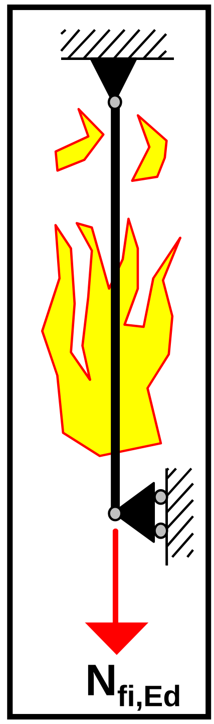
$$k_{y,\theta} = \left\{ 0.9674 \left(e^{\frac{\theta_a - 482}{39.19}} + 1 \right) \right\}^{-1/3.833} \leq 1$$

$$\theta_{a,cr} = \left(k_{y,\theta}\right)^{-1}$$

$$\theta_{a,cr} = 39.19 \ln\left[\frac{1}{0,9674 k_{y,\theta}^{\;3,833}} - 1 \right] + 482$$

Fire Resistance:
Concept of critical temperature for a member in tension -1





Eurocode 3: Fire Resistance
Concept of critical temperature for a member in tension - 2

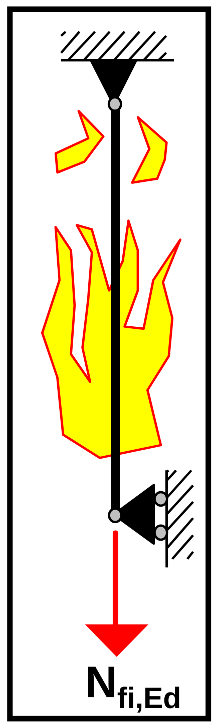
- Resistance at normal temperature:

$$N_{Rd} = Af_y/\gamma_{M0}$$

- Resistance in fire situation:

$$N_{fi,Rd} = Ak_{y,\theta}f_y/\gamma_{M,fi}$$

$k_{y,\theta} \leq 1$



Eurocode 3: Fire Resistance
Concept of critical temperature for a member in tension - 3

Collapse occurs when:

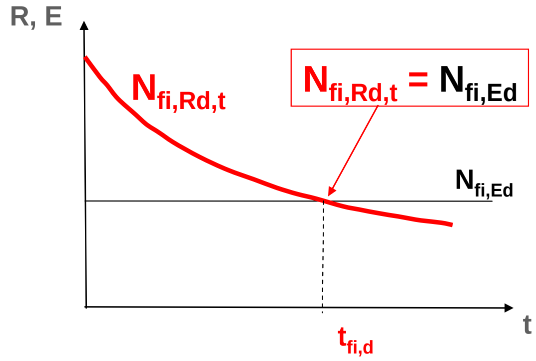
$$N_{fi,Rd,t} = N_{fi,Ed}$$

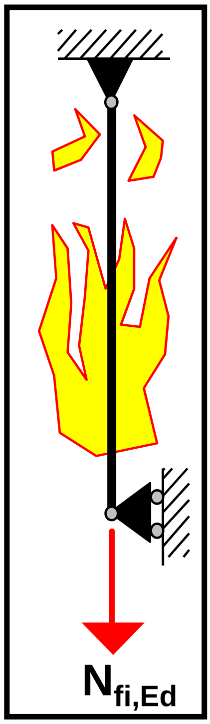
⇓

$$A k_{y,\theta} f_y / \gamma_{M,fi} = N_{fi,Ed} \;\Rightarrow\; k_{y,\theta} = N_{fi,Ed} / (A f_y / \gamma_{M,fi})$$

⇓

$$\theta_{a,cr}$$





Eurocode 3: Fire Resistance
Concept of critical temperature for a member in tension - 4

$$k_{y,\theta} = N_{fi,Ed} / (A f_y / \gamma_{M,fi})$$

By interpolation

Steel Temperature θ_a	Reduction factors at temperature θ_a relative to the value of f_y or E_a at 20°C			
	Reduction factor (relative to f_y) for effective yield strength $k_{y,\theta}=f_{y,\theta}/f_y$	Reduction factor (relative to f_y) for proportional limit $k_{p,\theta}=f_{p,\theta}/f_y$	Reduction factor (relative to E_a) for the slope of the linear elastic range $k_{E,\theta}=E_{a,\theta}/E_a$	Reduction factor (relative to f_y) for the design strength of hot rolled and welded thin walled sections (Class 4) $k_{0.2p,\theta}=f_{0.2p,\theta}/f_y$
20 °C	1.000	1.000	1.000	1.000
100 °C	1.000	1.000	1.000	1.000
200 °C	1.000	0.807	0.900	0.890
[illegible]	[illegible]	0.613	0.800	0.780
[illegible]	[illegible]	0.420	0.700	0.650
[illegible]	[illegible]	0.360	0.600	0.530
600 °C	0.470	0.180	0.310	0.300
700 °C	0.230	0.075	0.130	0.130
800 °C	0.110	0.050	0.090	0.070
900 °C	0.060	0.0375	0.0675	0.050
1000 °C	0.040	0.0250	0.0450	0.030
1100 °C	0.020	0.0125	0.0225	0.020
1200 °C	0.000	0.0000	0.0000	0.000

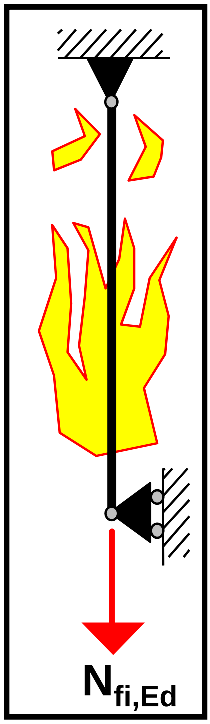
NOTE: For intermediate values of the steel temperature, linear interpolation may be used.

$\theta_{a,cr} \leftarrow k_{y,\theta}$

$$\theta_{a,cr}$$

or

$$\theta_{a,cr} = 39.19 \ln\left[\frac{1}{0,9674\, k_{y,\theta}^{3,833}} - 1\right] + 482$$



Eurocode 3: Fire Resistance
Concept of critical temperature for a member in tension - 5

$$\theta_{a,cr} = 39.19 \ln\left[\frac{1}{0,9674 k_{y,\theta}^{3,833}} - 1\right] + 482$$

$$k_{y,\theta} = N_{fi,Ed} / (Af_y/\gamma_{M,fi})$$

Eurocode 3

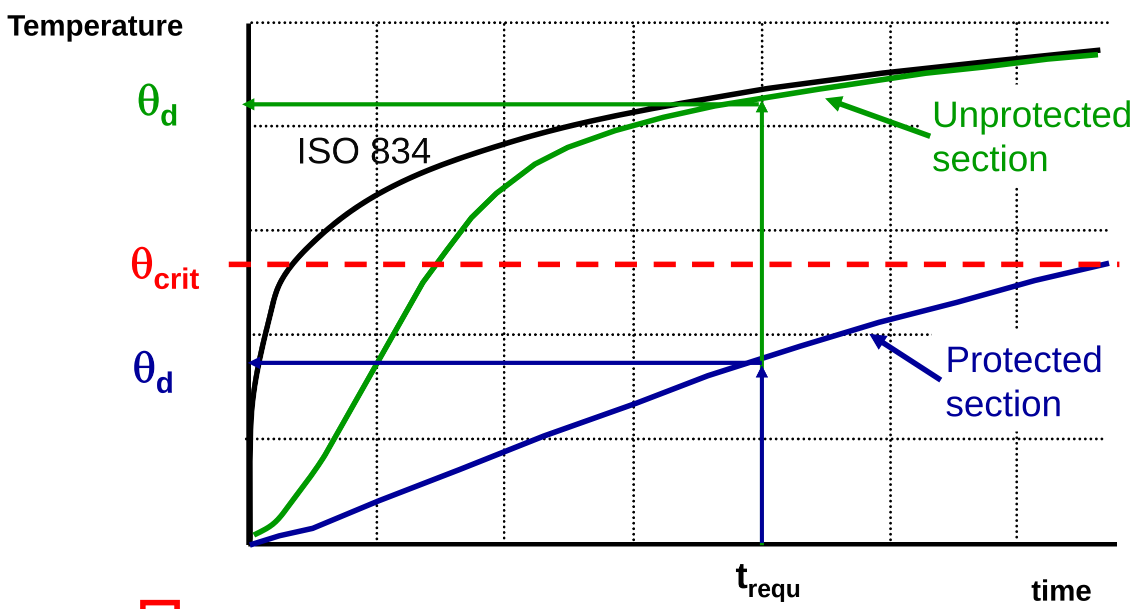
$$\theta_{a,cr} = 39.19 \ln\left[\frac{1}{0,9674 \mu_0^{3,833}} - 1\right] + 482$$

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

For the case of tension

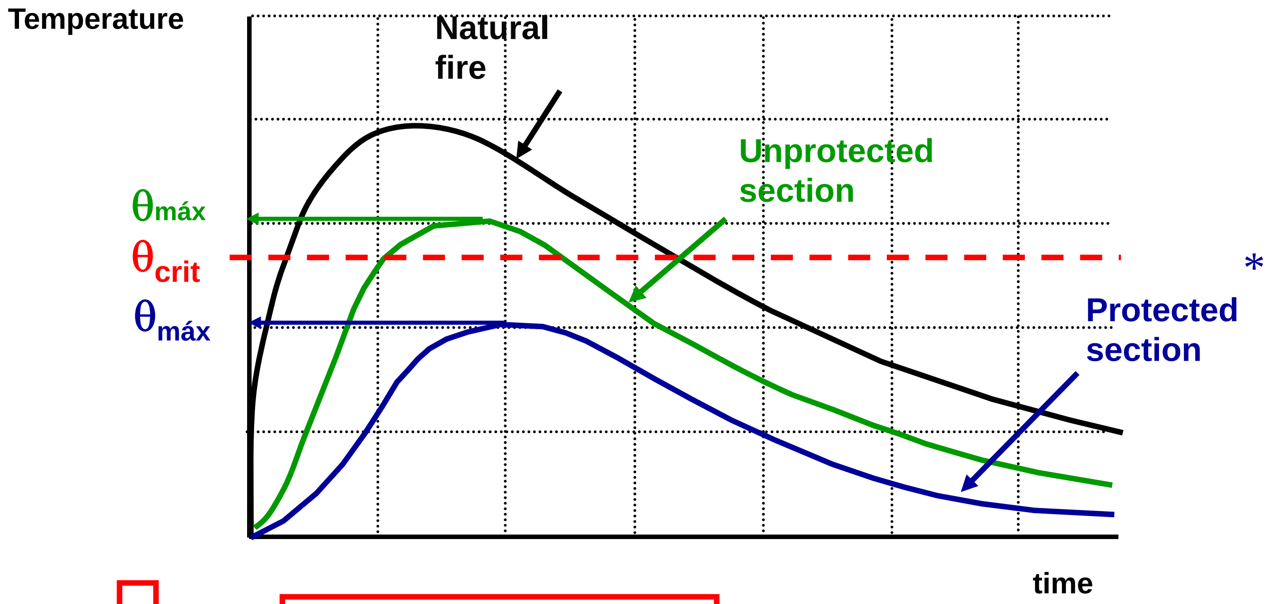
$$\mu_0 = \frac{E_{fi,d}}{R_{fi,d,0}} = \frac{N_{fi,Ed}}{Af_y / \gamma_{M,fi}}$$

Checking Fire Resistance in the temperature domain:
Strategy for nominal fires



$$\theta_d \leq \theta_{crit} \quad !$$

Checking Fire Resistance in the temperature domain: Strategy for natural fires

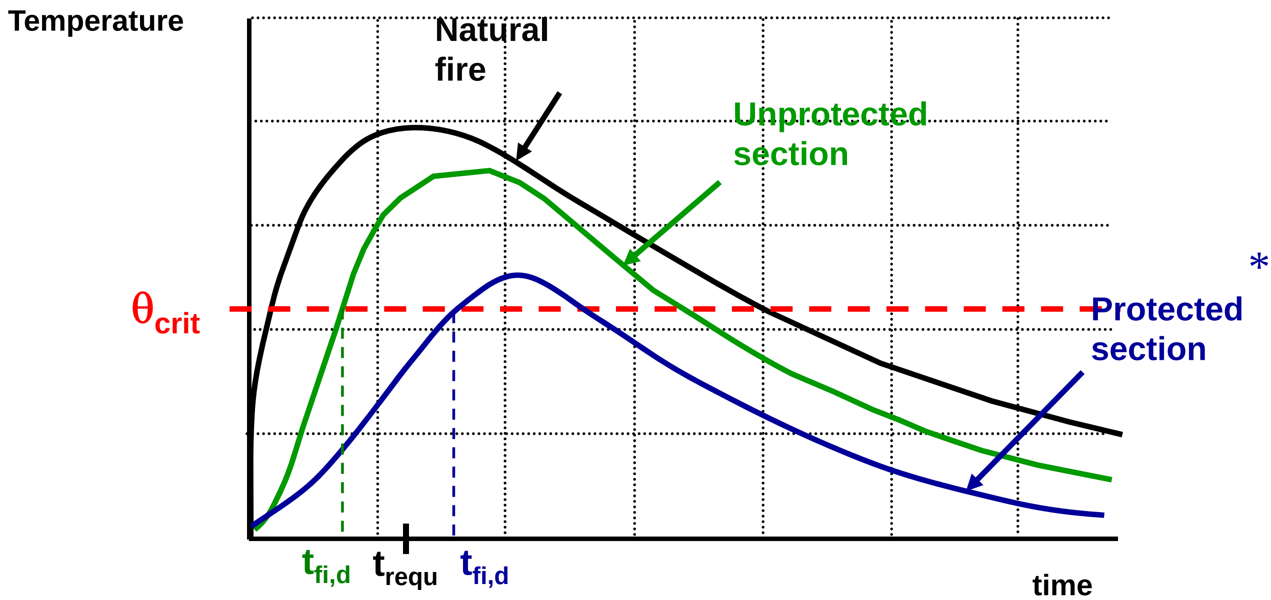


$$\theta_{máx} \leq \theta_{crit} \; !$$

* - or using active fire fighting measures

cost universidade de aveiro

Checking Fire Resistance in the time domain: Strategy for natural fires – if accepted by the authorities



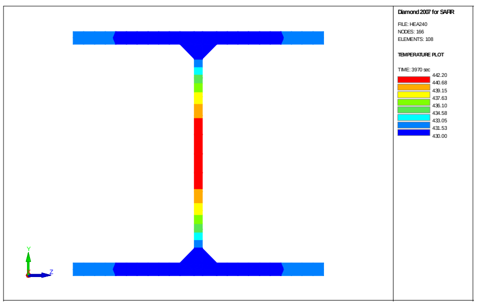
$$t_{requ} \leq t_{fi,d} \; !$$

* - or using active fire fighting measures

Design procedures

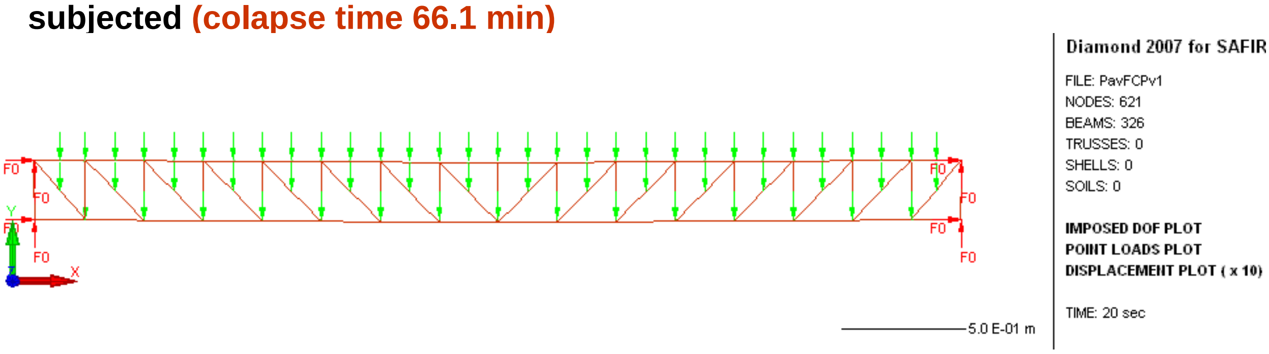
- ❑ **Tabulated data (EC2, EC4, EC6)**
- ❑ **Simple calculation models (All the Eurocodes)**
- ❑ **Advanced calculation models (All the Eurocodes)**

Advanced calculation models



Temperature field in a profile

Truss without the possibility of expanding longitudinally subjected (colapse time 66.1 min)

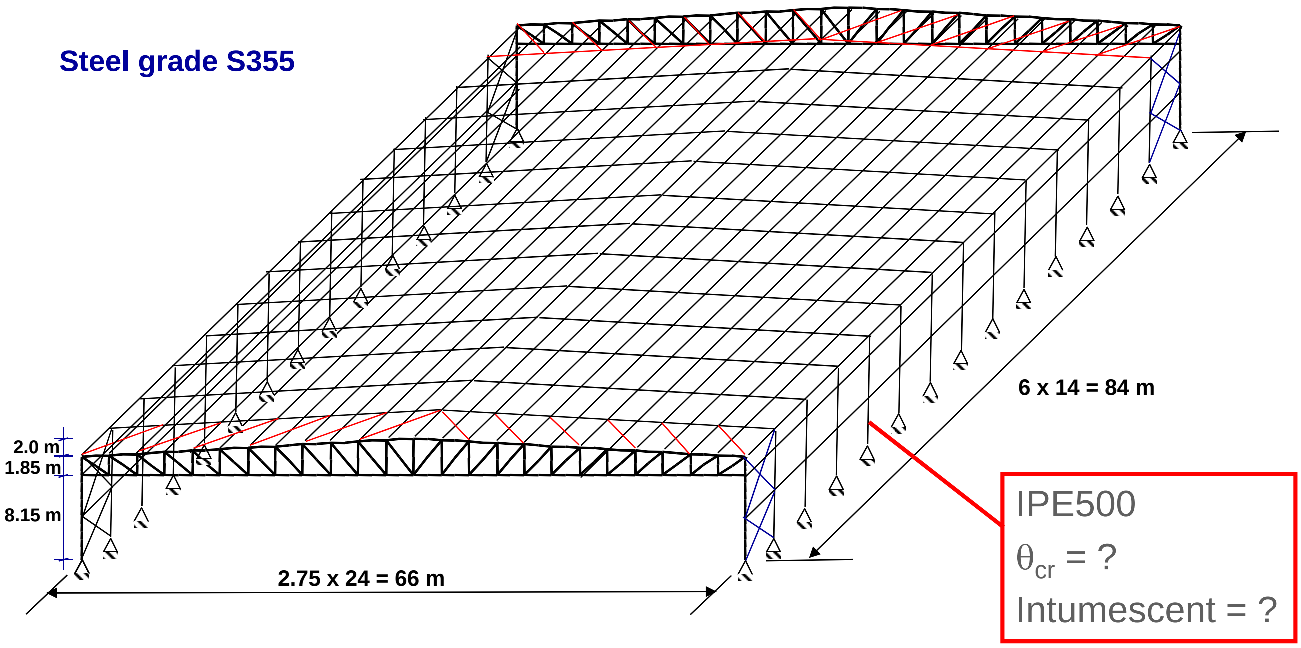


Examples using different methodologies.
Fire resistance of steel structures

- ❑ **Using tables from the suppliers of the fire protection material**
  Prescriptive approach
- ❑ **Comparison between simplified calculation methods and advanced calculation models – Prescriptive / Performance-based approach**
- ❑ **Cases where it is not possible to use simplified calculation method**
  Performance-based approach

Single storey hall – R60

Steel grade S355



Load combinations

G – Dead load
Q – Live load in the roof
W - Wind

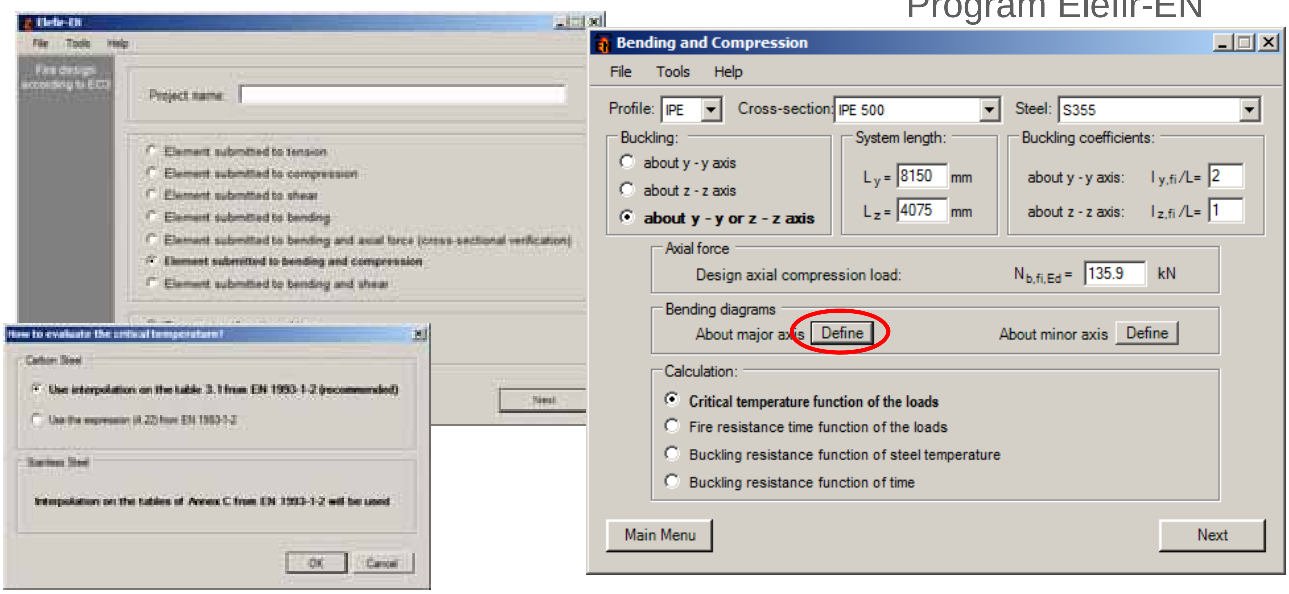
Load combination 1: $G + \psi_{1,Q} Q + \psi_{2,W} W = G + 0.0Q + 0.0W = G$

Load combination 2: $G + \psi_{1,W} W + \psi_{2,Q} Q = G + 0.2W + 0.0Q = G + 0.2W$

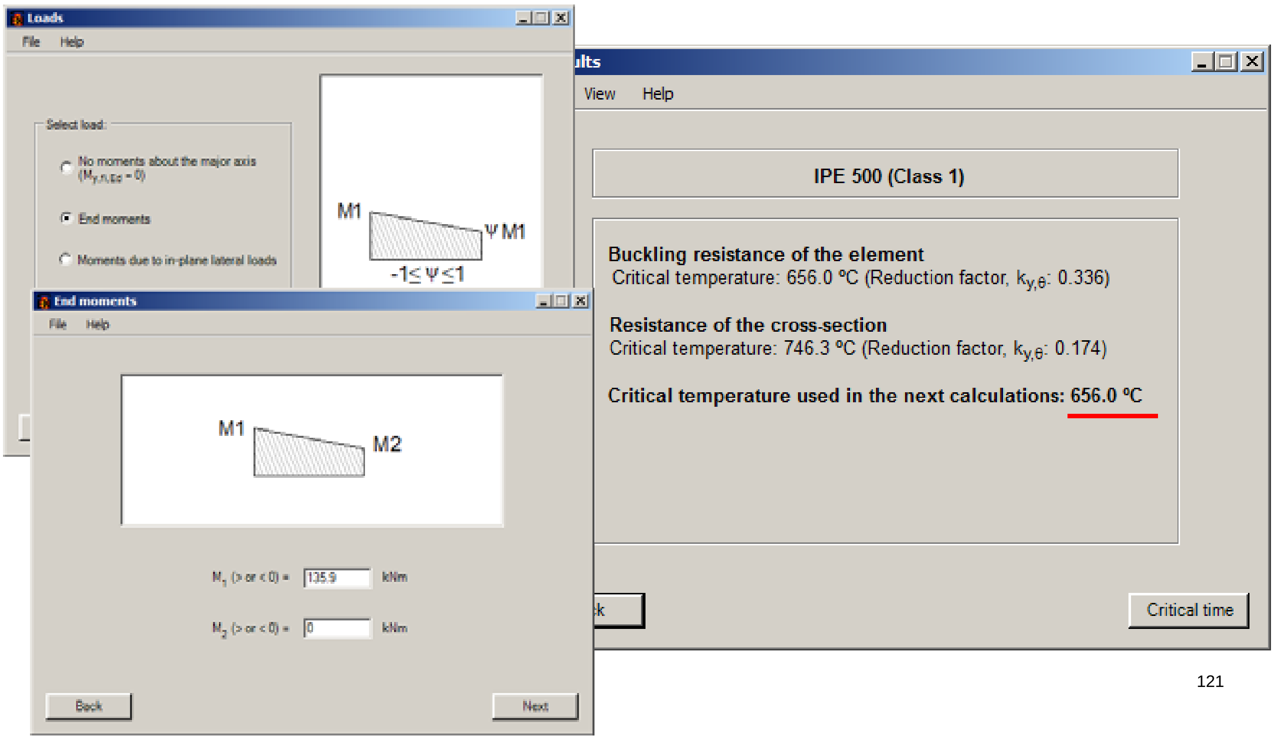
Critical temperature for load combination 1

Section	N	M_1	M_2	q	$l_{fi,y}$	$l_{fi,z}$
-	[kN]	[kNm]	[kNm]	[kN/m]	[m]	[m]
IPE 500	-139.4	0	135.9	0	16.300	-
	-139.4	0	0	0	-	4.075

Program Elefir-EN

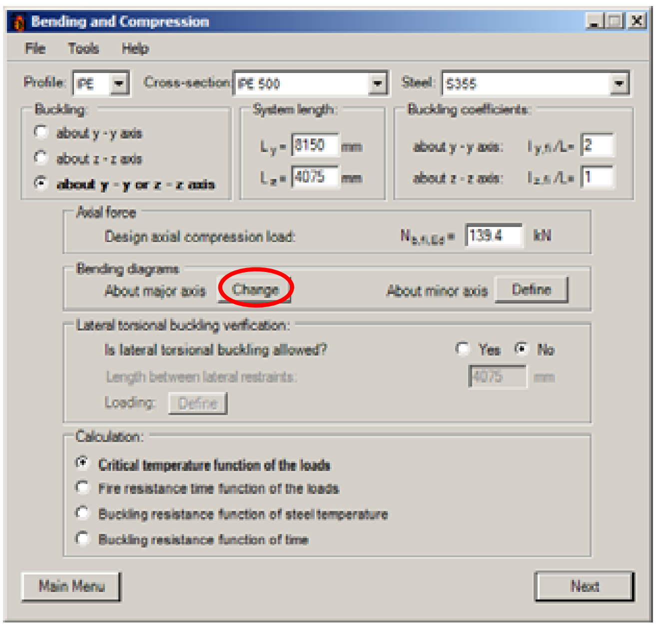


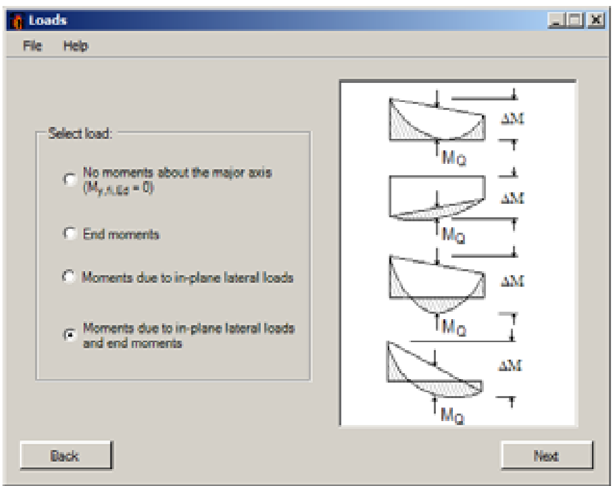
Critical temperature for load combination 1



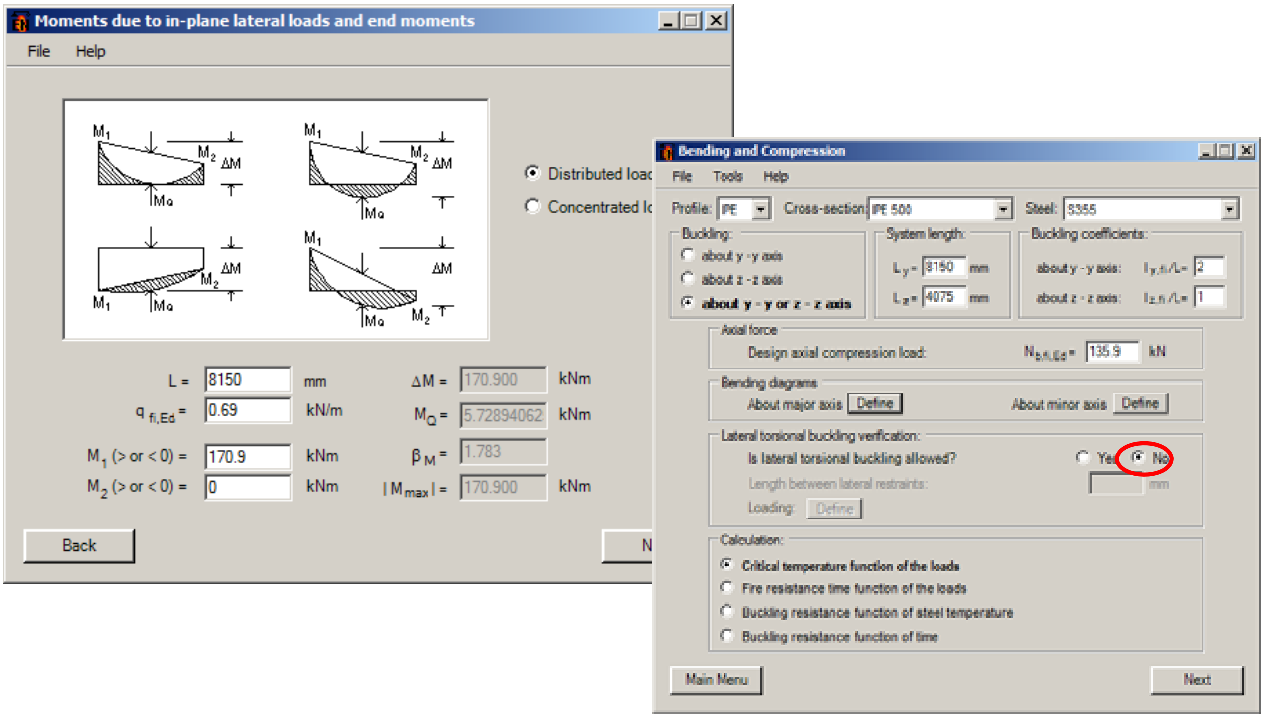
Critical temperature for load combination 2

Section	N	M_1	M_2	q	$l_{fi,y}$	$l_{fi,z}$
-	[kN]	[kNm]	[kNm]	[kN/m]	[m]	[m]
IPE 500	-135.9	0	170.9	0.69	16.300	-
	-135.9	0	0	0	-	4.075

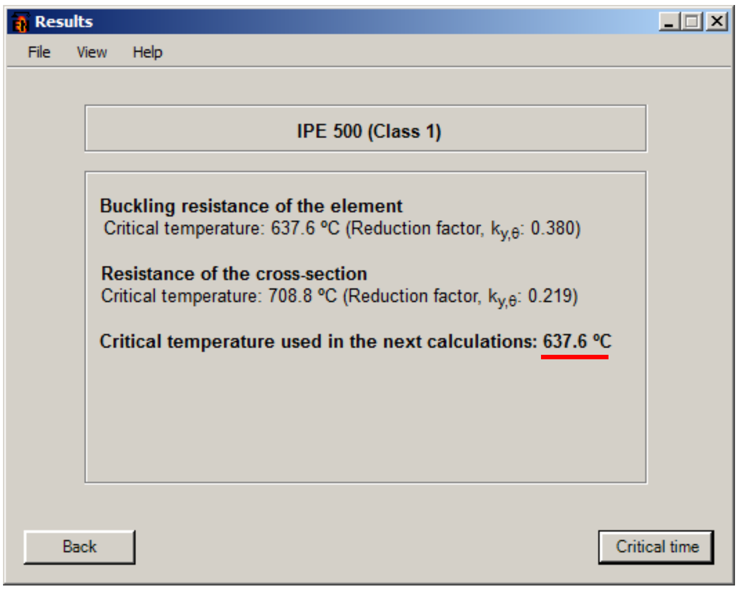




Critical temperature for load combination 2



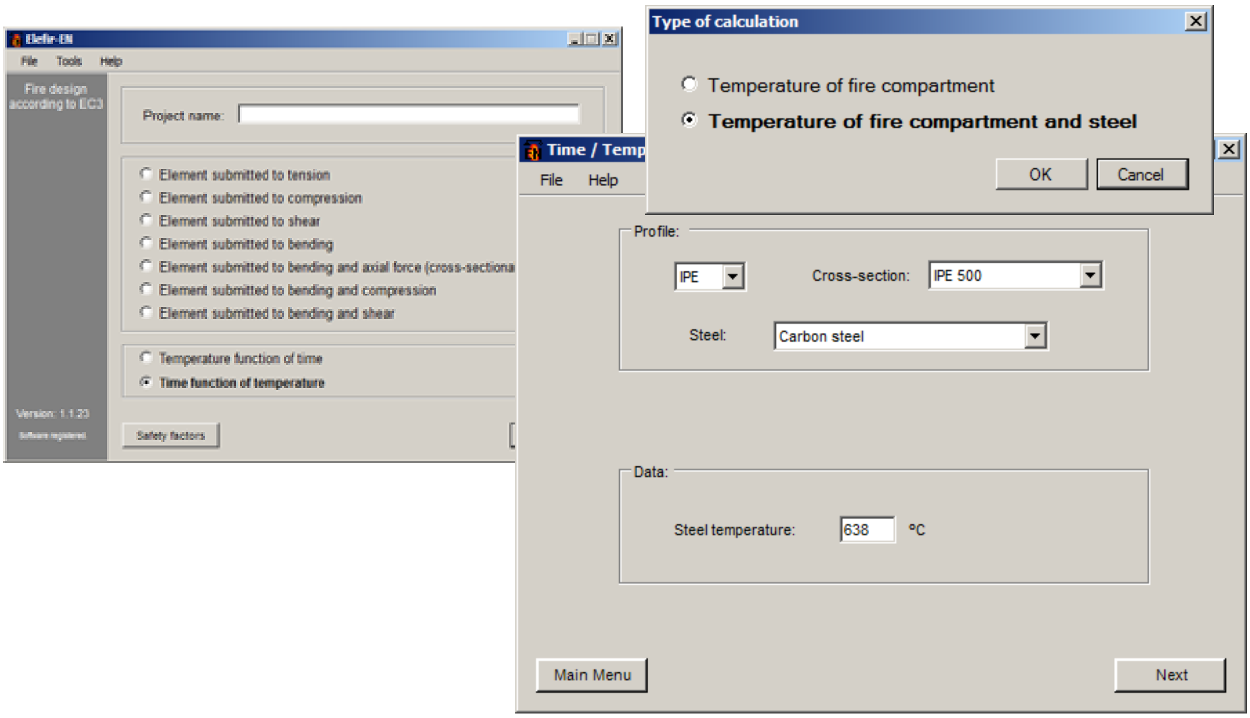
Critical temperature for load combination 2



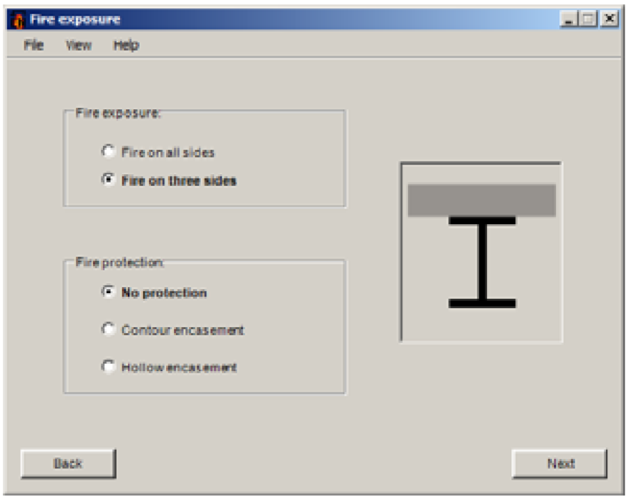
Critical temperature of the column IPE 500

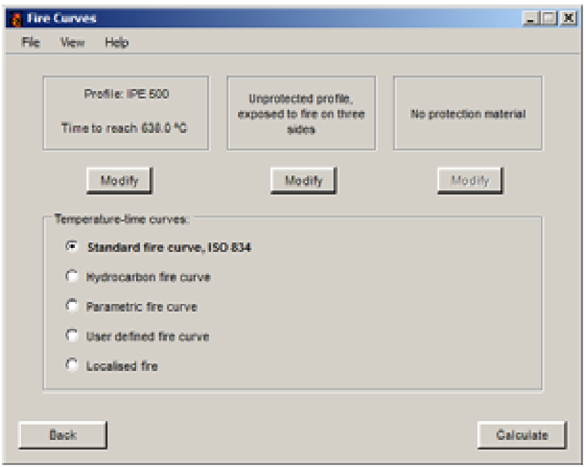
$$\theta_{a,cr} = \min(656\ ºC;\ 638\ ºC) = 638\ ºC$$

Critical time with ISO 834
Using Elefir-EN

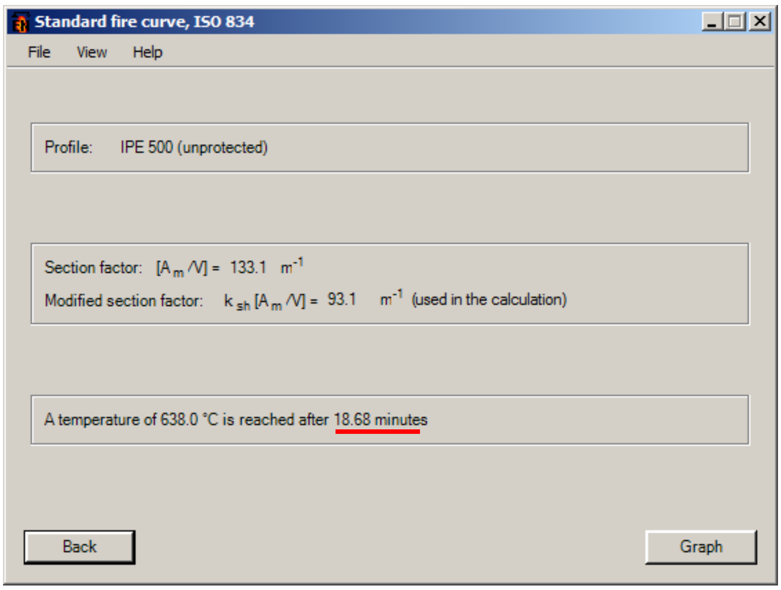


Critical time with ISO 834
Using Elefir-EN



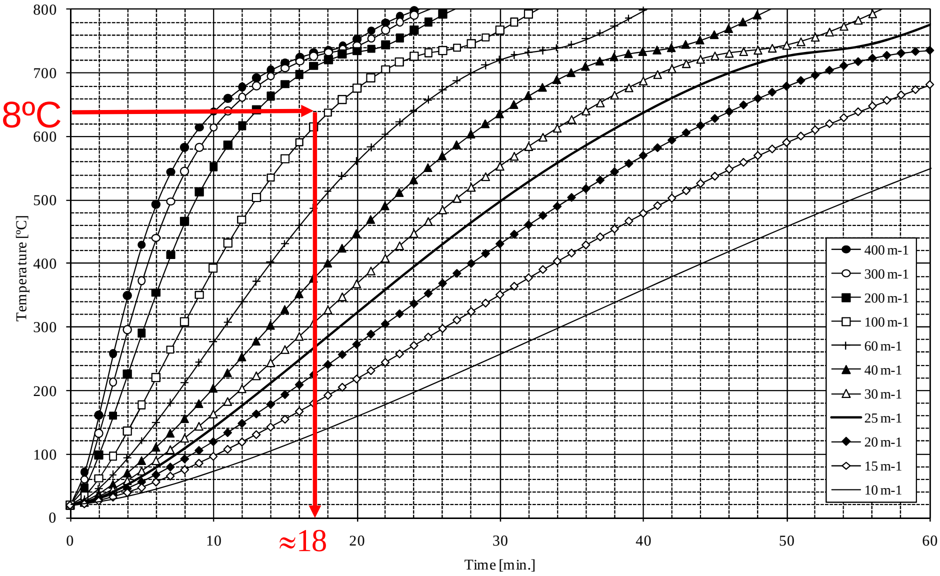


Critical time with ISO 834
Using Elefir-EN



$t_{fi,d} < t_{requ} = 60$ min ⇨ Fire protection is needed for a critical temperature of $\theta_{a,cr} = 638$ ºC

Critical time with ISO 834
Using Nomogram



$t_{fi,d} < t_{requ} = 60$ min ⇨ Fire protection is needed for a critical temperature of $\theta_{a,cr} = 638$ ºC

Table 3 continued: Three Sided I-Section Beams: 450°C

60 minutes				Secti
Section factor up to m^{-1}	Thickness mm	Section factor up to m^{-1}	Thickness mm	
25	0.250	175	0.888	
30	0.268	180	0.910	
35	0.287	185	0.933	
40	0.305	190	0.955	
45	0.324	195	0.978	
50	0.342	200	1.000	
55	0.361	205	1.116	
60	0.379	210	1.231	
65	0.398	215	1.347	
70	0.416	220	1.462	
75	0.438	225	1.578	
80	0.460	230	1.693	
85	0.483	235	1.809	
90	0.505	240	1.924	
95	0.528	245	2.040	
100	0.550	250	2.156	
105	0.573	255	2.271	
110	0.595	260	2.386	
115	0.618	265	2.502	
120	0.640	270	2.617	
125	0.663	275	2.733	
130	0.685	280	2.849	
135	0.708	285	2.964	
140	0.730	290	3.080	
145	0.753	295	3.195	
150	0.775	300	3.311	
155	0.798	305	3.426	
160	0.820	310	3.542	
165	0.843	315	3.657	
170	0.865			

Thickness is intumescent only. Beams with a concrete slab

Table 4 continued: Three Sided I-Section Beams: 500°C

60 minutes			
Section factor up to m^{-1}	Thickness mm	Section factor up to m^{-1}	Thick mm
30	0.228	180	0.7
35	0.234	185	0.8
40	0.250	190	0.8
45	0.266	195	0.8
50	0.283	200	0.8
55	0.299	205	0.9
60	0.315	210	0.9
65	0.332	215	0.9
70	0.348	220	0.9
75	0.364	225	0.9
80	0.381	230	1.0
85	0.397	235	1.1
90	0.413	240	1.2
95	0.433	245	1.3
100	0.454	250	1.4
105	0.476	255	1.5
110	0.497	260	1.6
115	0.519	265	1.7
120	0.540	270	1.8
125	0.562	275	1.9
130	0.583	280	2.0
135	0.605	285	2.1
140	0.626	290	2.2
145	0.648	295	2.3
150	0.669	300	2.4
155	0.691	305	2.5
160	0.712	310	2.6
165	0.734	315	2.7
170	0.755	320	2.8
175	0.777		

Thickness is intumescent only. Beams with

Table 5 continued: Three Sided I-Section Beams: 550°C ■ ■ ■

60 minutes				90 minutes		120 minutes	
Section factor up to m^{-1}	Thickness mm	Section factor up to m^{-1}	Thickness mm	Section factor up to m^{-1}	Thickness mm	Section factor up to m^{-1}	Thickness mm
30	0.228	180	0.721	155	1.000	160	3.144
35	0.233	185	0.743	160	1.134	165	3.242
40	0.245	190	0.765	165	1.267	170	3.341
45	0.257	195	0.786	170	1.401	175	3.439
50	0.270	200	0.808	175	1.535	180	3.537
55	0.282	205	0.830	180	1.668	185	3.635
60	0.294	210	0.852	185	1.802		
65	0.307	215	0.874	190	1.936		
70	0.319	220	0.896	195	2.070		
75	0.331	225	0.917	200	2.203		
80	0.344	230	0.939	205	2.337		
85	0.356	235	0.961	210	2.471		
90	0.368	240	0.983	215	2.604		
95	0.381	245	1.015	220	2.738		
100	0.393	250	1.092	225	2.872		
105	0.405	255	1.168	230	3.006		
110	0.418	260	1.244	235	3.139		
115	0.437	265	1.320	240	3.273		
120	0.459	270	1.397	245	3.407		
125	0.481	275	1.473	250	3.540		
130	0.503	280	1.549	255	3.674		
135	0.525	285	1.626				
140	0.546	290	1.702				
145	0.568	295	1.778				
150	0.590	300	1.854				
155	0.612	305	1.931				
160	0.634	310	2.007				
165	0.655	315	2.083				
170	0.677	320	2.159				
175	0.699						

Thickness is intumescent only. Beams with a concrete slab.

This Company has sheets for the temperatures: 350, 400, 450, 500, 550, 600, 620, 650 and 700ºC

Thickness of intumescent painting

... 600ºC , 620ºC, 650ºC, ...

$\theta_{a,cr}$ = 638 ºC

$$\frac{A_m}{V} = 133.1 \approx 135\, m^{-1}$$

Table 7 continued: Three Sided I-Section Beams: 620°C

60 minutes				90 minutes				120 minutes	
Section factor up to m^{-1}	Thickness mm	Section factor up to m^{-1}	Thickness mm	Section factor up to m^{-1}	Thickness mm	Section factor up to m^{-1}	Thickness mm	Section factor up to m^{-1}	Thickness mm
45	0.235	185	0.518	50	0.420	185	1.000	40	0.945
50	0.244	190	0.530	55	0.441	190	1.101	45	1.023
55	0.254	195	0.543	60	0.463	195	1.202	50	1.101
60	0.263	200	0.555	65	0.484	200	1.303	55	1.179
65	0.272	205	0.587	70	0.506	205	1.403	60	1.257
70	0.281	210	0.619	75	0.527	210	1.504	65	1.335
75	0.291	215	0.650	80	0.549	215	1.605	70	1.413
80	0.300	220	0.682	85	0.570	220	1.706	75	1.491
85	0.309	225	0.714	90	0.592	225	1.807	80	1.569
90	0.318	230	0.746	95	0.613	230	1.908	85	1.647
95	0.328	235	0.778	100	0.635	235	2.008	90	1.725
100	0.337	240	0.809	105	0.656	240	2.109	95	1.803
105	0.346	245	0.841	110	0.678	245	2.210	100	1.881
110	0.355	250	0.873	115	0.699	250	2.311	105	1.96
115	0.365	255	0.905	120	0.721	255	2.412	110	2.038
120	0.374	260	0.936	125	0.742	260	2.513	115	2.116
125	0.383	265	0.968	130	0.764	265	2.614	120	2.194
130	0.392	270	1.000	135	0.785	270	2.714	125	2.272
135	0.402	275	1.063	140	0.807	275	2.815	130	2.35
140	0.411	280	1.126	145	0.828	280	2.916	135	2.428
145	0.420	285	1.190	150	0.850	285	3.017	140	2.506
150	0.432	290	1.253	155	0.871	290	3.118	145	2.584

Thickness of intumescent painting

In some Countries default temperatures are suggested if no calculation is made. Normally for columns or other members susceptible of instability phenomena a critical temperature of 500ºC is suggested.

If, instead of a critical temperature of 638ºC, a critical temperature of 500ºC was used, a thickness of 0,605 mm would be obtained.

θ_{cr} = 638ºC => e = 0,402 mm

θ_{cr} = 500ºC => e = 0.605 mm

=> More than 50%

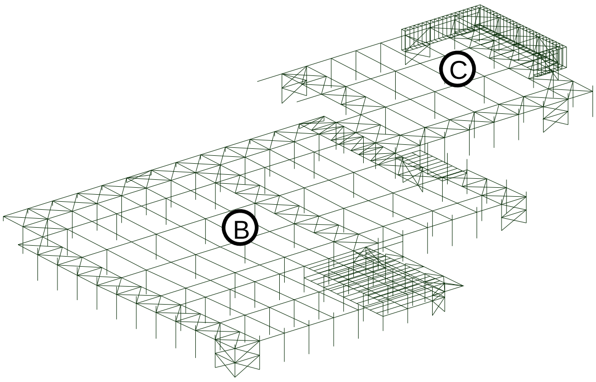
Examples using different methodologies.
Fire resistance of steel structures

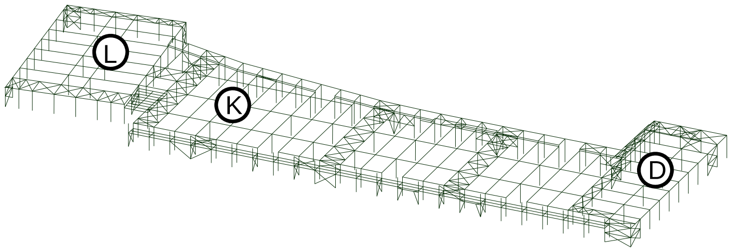
- Using tables from the suppliers of the fire protection material
  Prescriptive approach
- Comparison between simplified calculation methods and advanced calculation models – Prescriptive / Performance-based approach
- Cases where it is not possible to use simplified calculation method
  Performance-based approach

BARREIRO RETAIL PARK

Required fire resistance 90 minutes (R90)

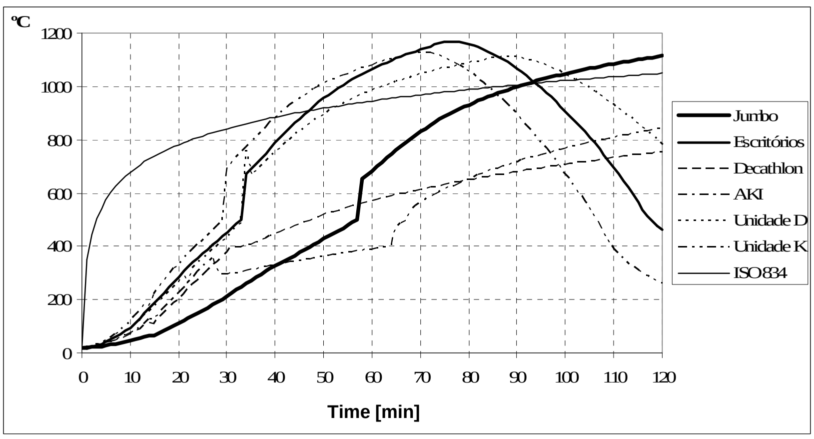
Different zones for fire scenarios





S275

Temperature development for different fire scenarios



Temperatures obtained using the program Ozone

Unit B - Jumbo

Combination of actions: $1.0G_k + \psi_{1,1}Q_{k,1} = 1.0G_k + 0.0Q_{k,1} = G_k$

	N_{Ed} (kN)	M_1 (kN.m)	M_2 (kN.m)	l_{fi}/L	L (m)	θ_{cr} (ºC)	$t_{fi,d}$ (min)
HEA 260	80	0.00	23	1.0	7.3	672.9	19.25
HEA 240	34	0.00	45	1.0	7.3	593.5	15.23
IPE 360	0.00	76.0	0.0	-	-	682.8	17.92

Without fire protection

Unit B - Jumbo

Prescriptive approach

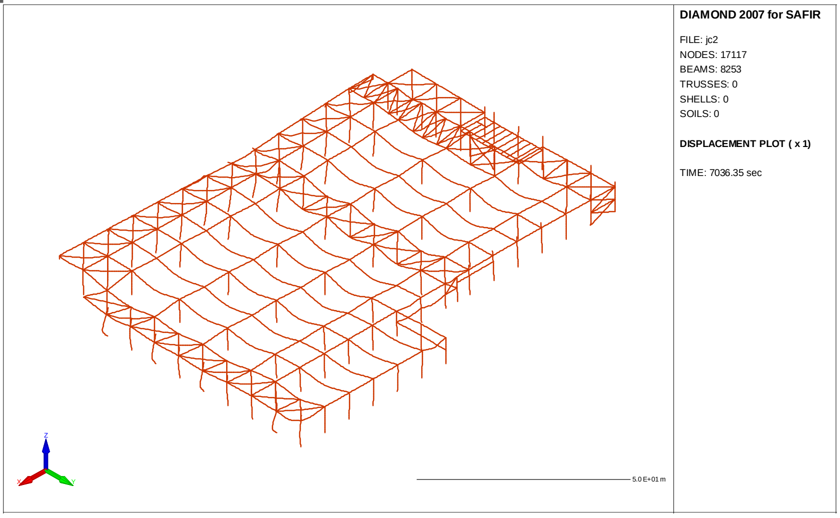
Performance-based approach

	θ_{cr} (ºC)	ISO (min)	Natural Fire + Simplified Method (min)	Natural Fire + Advanced Method (min)
HEA 260	672.9	> 90	> 90	
HEA 240	593.5	80.8	> 90	> 90
IPE 360	682.8	> 90	> 90	

With fire protection for R60 and a critical temperature of 500ºC

Deformed shape
Obtained with Advanced Calculation Methods

Deformed shape of Unit B (Jumbo supermarket) after 117 minutes of exposure to a natural fire



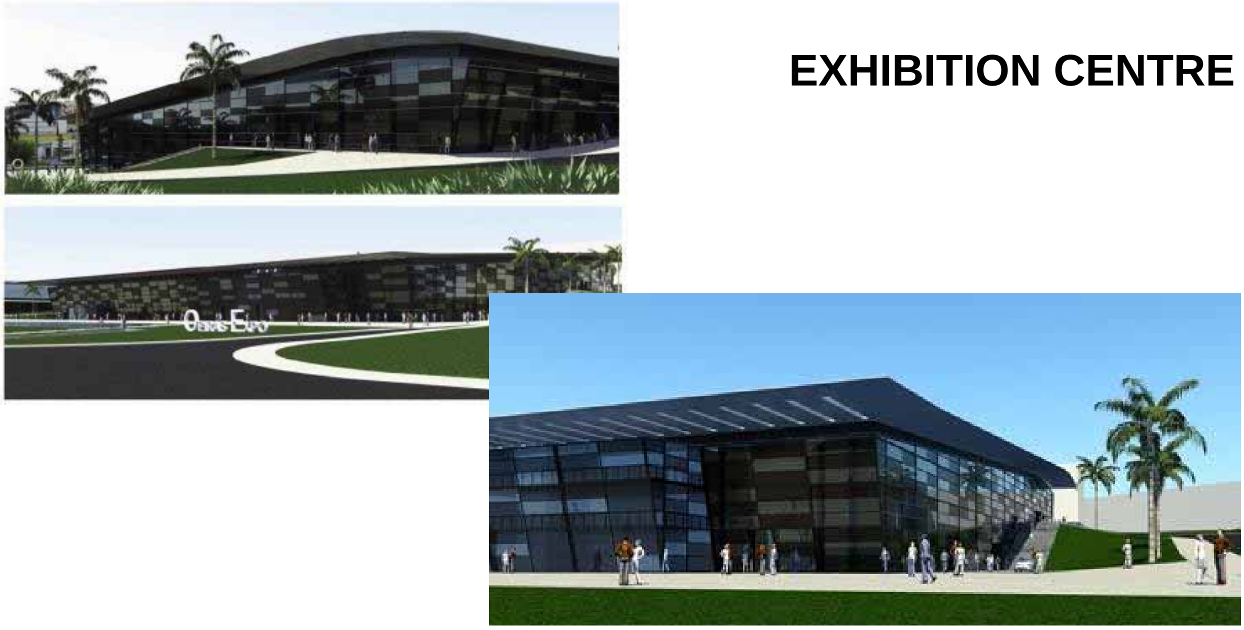
Software: GiD (for the numerical model mesh);

SAFIR (for the analysis)

Examples using different methodologies.
Fire resistance of steel structures

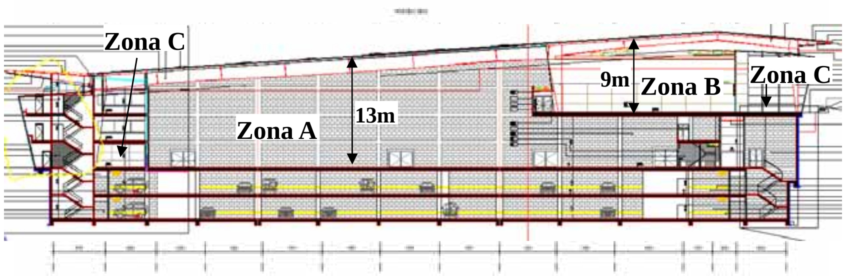
- ❑ **Using tables from the suppliers of the fire protection material**
  Prescriptive approach
- ❑ **Comparison between simplified calculation methods and advanced calculation models – Prescriptive / Performance-based approach**
- ❑ **Cases where it is not possible to use simplified calculation method**
  Prescriptive / Performance-based approach

EXHIBITION CENTRE



Required fire resistance 120 minutes (R120)

Main Structure



56.0 m
30.0 m

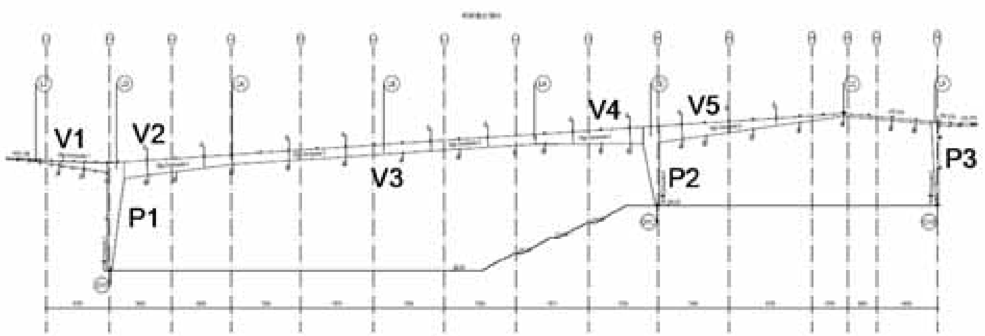
Main Portal Frame

Choice of the structural analysis

The main structure is made of non-uniform class 4 elements. There are no simplified methods, for the time being, for such type of elements. Two options were possible:

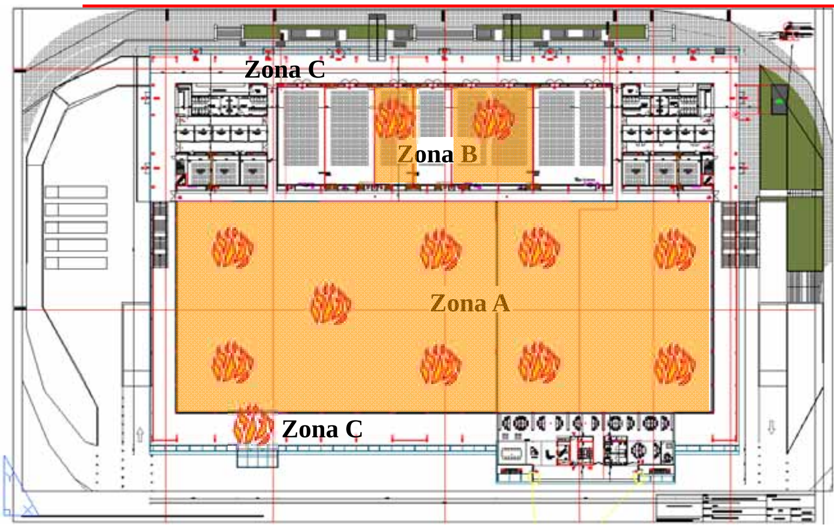
- Using a prescriptive approach, protect the structure for a citical temperature of 350ºC;

- Using performance-based approach with advanced claculation methods.



Required fire resistance 120 minutes (R120)

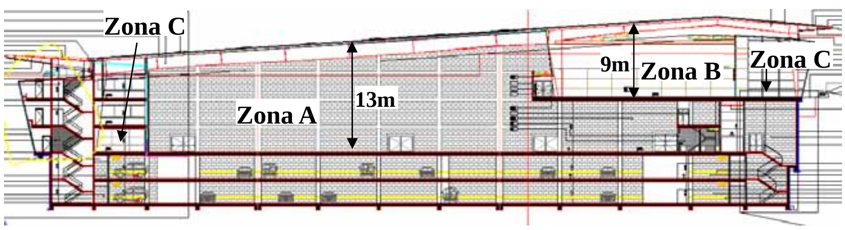
Fire scenarios



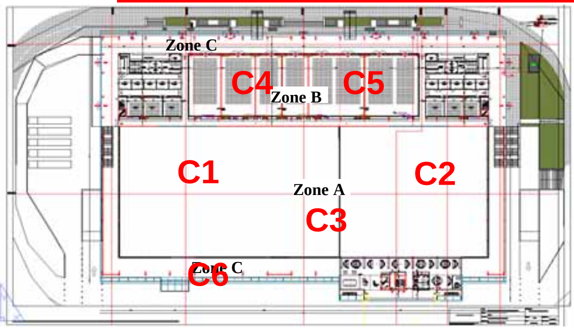
6 fire scenarios

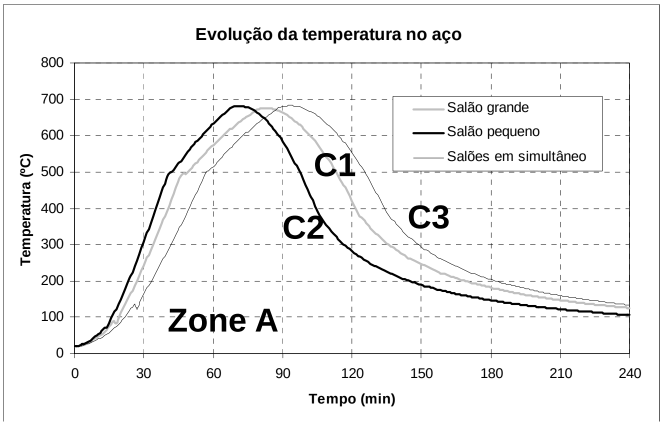
Fire load density reduced by 39% due to the sprinklers

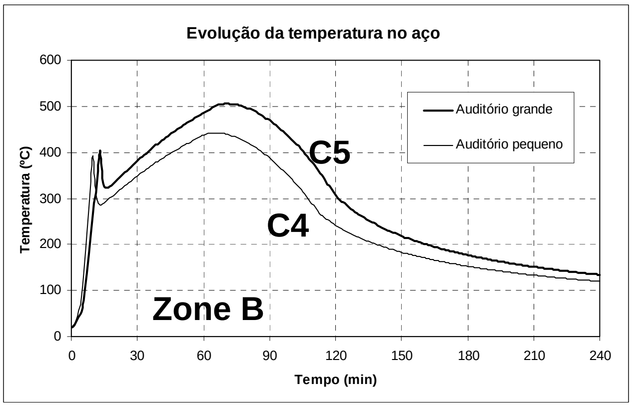
Fire resistance (R120)



Fire scenarios





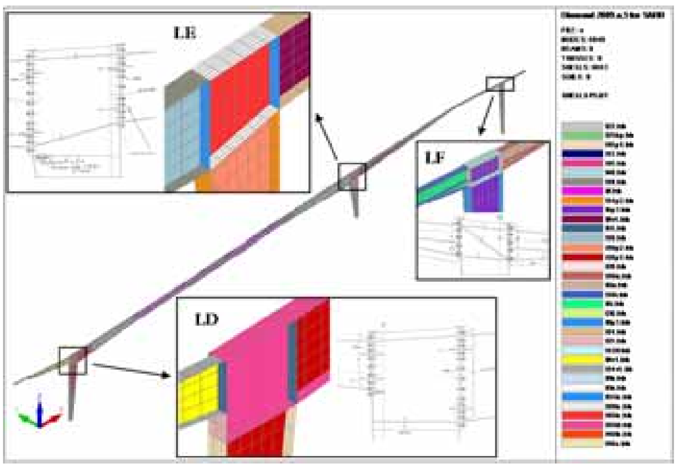


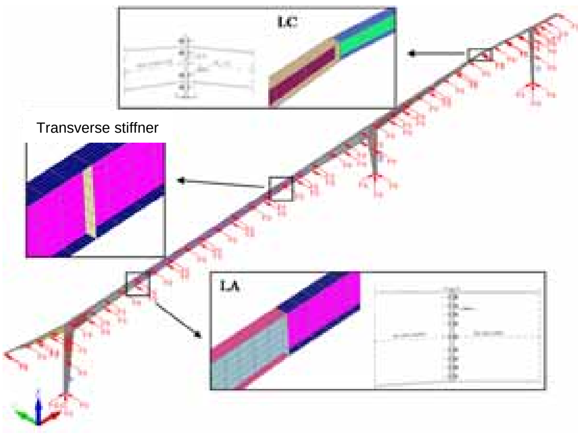
C1-5* - *Software OZone

C6 is a localized fire in Zone C - Elefir-EN

Structural Analysis

Main structure – portal frame with built-up non-uniform class 4 steel elements

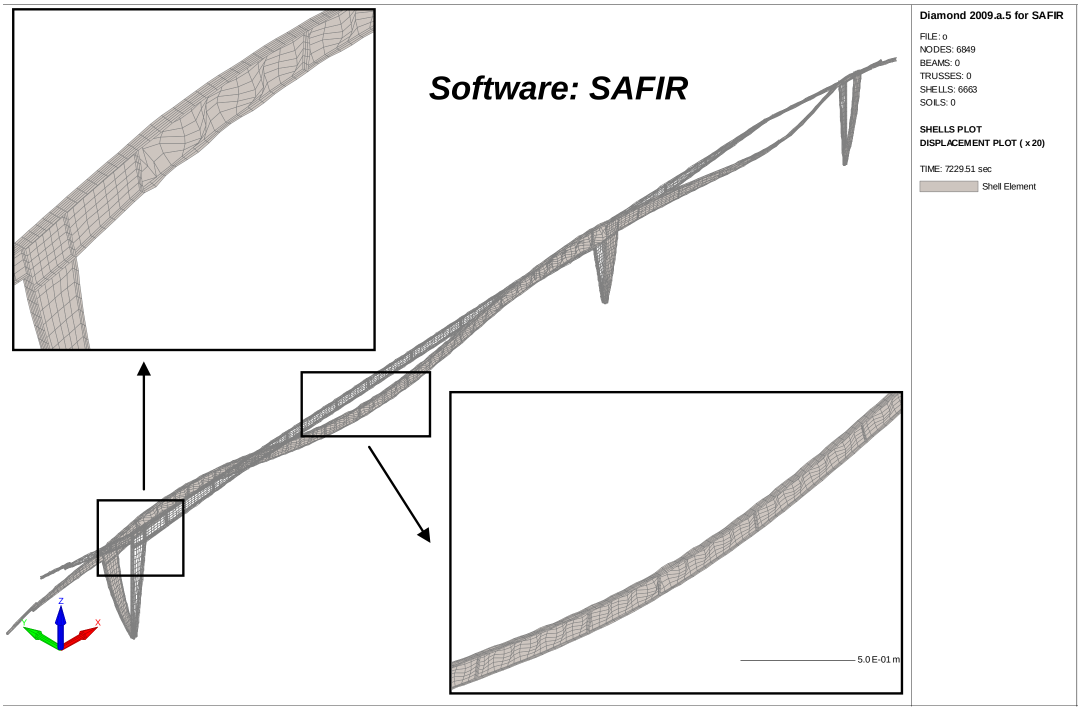




Software: GiD (for the numerical model mesh);

SAFIR (for the analysis)

Structural Analysis



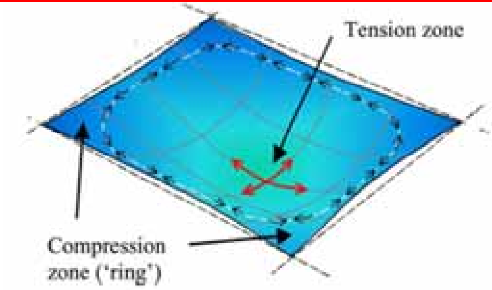
Deformed shape at Zone A, for the combination of actions 1, after 120 minutes (x20)

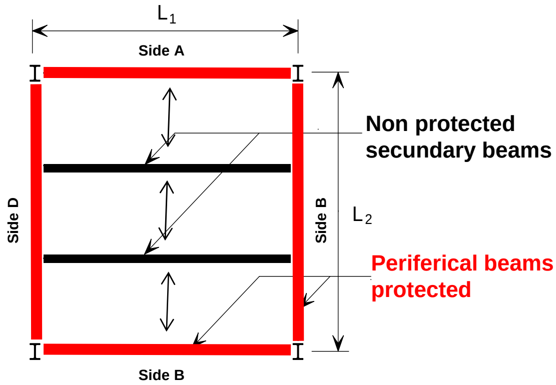
Conclusions

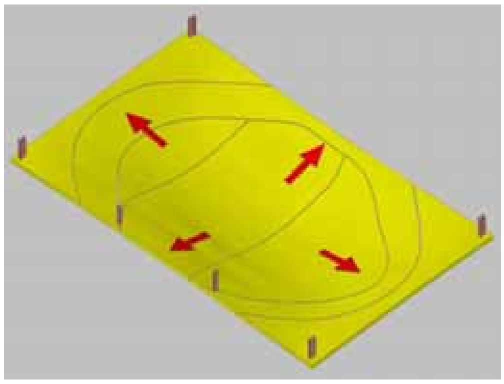
➢A performance-based analysis, demonstrated in this study that, protecting the structure for a standard fire resistance of 60 minutes (R60), considering a critical temperature of 500ºC, the load-bearing function is ensured during the complete duration of the fire, including the cooling phase.

➢The steel structure of the Center for Exhibitions and Fairs in Oeiras consists of class 4 cross section profiles. In a prescriptive approach and without making any calculation, this structure should have been protected for a critical temperature of 350ºC and for R120.

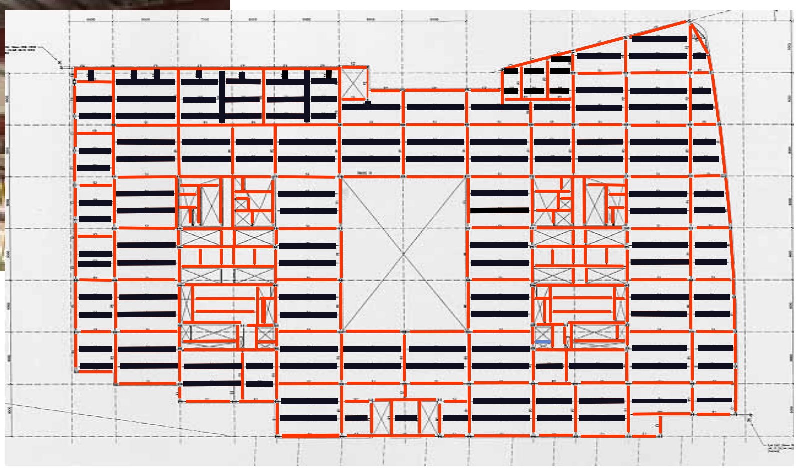
One example of a new finding that may be included in the next generation of EN 1994-1-2 – So-called MEMBRANE ACTION







One example of a new finding that may be included in the next generation of EN 1994-1-2 – So-called MEMBRANE ACTION



One example of a new finding that may be included in the next generation of EN 1994-1-2 – So-called MEMBRANE ACTION

40 to 55% of beams can be left unprotected by placing protection where it is needed.

One example of a new finding that may be included in the next generation of EN 1994-1-2 – So-called MEMBRANE ACTION

The shard in London

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Thank you for your attention

pvreal@ua.pt