Fire resistance assessment of concrete structures

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Part I

BASIC DESIGN METHODS

Essential Requirements

The construction works must be designed and build in such a way, that in the event of an outbreak of fire :

- the load bearing resistance of the construction can be assumed for a specified period of time

- the generation and spread of fire and smoke within the works are limited

- the spread of fire to neighbouring construction works is limited

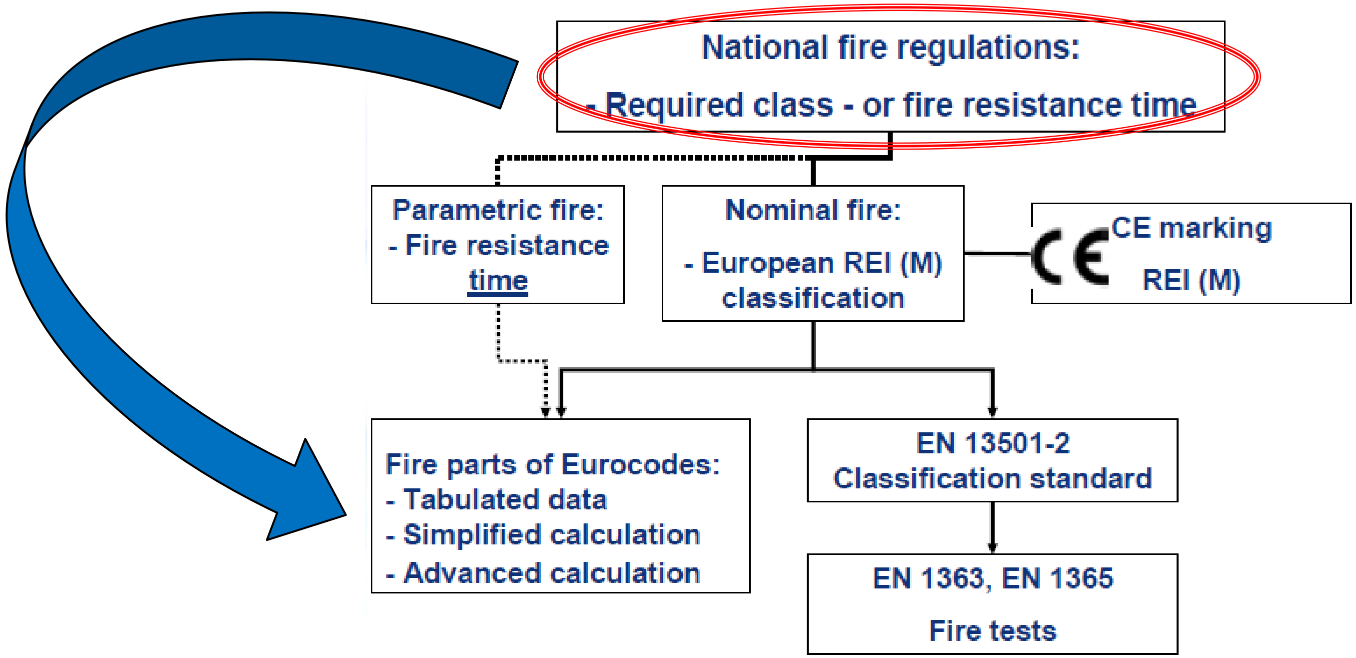
- the occupants can leave the works or can be rescued by other means

- the safety of rescue teams is taken into consideration

Essential Requirements

To prove compliance with Essential Requirements :

- Tests + extended applications of results
- calculation and/or design methods
- combination of tests and calculations

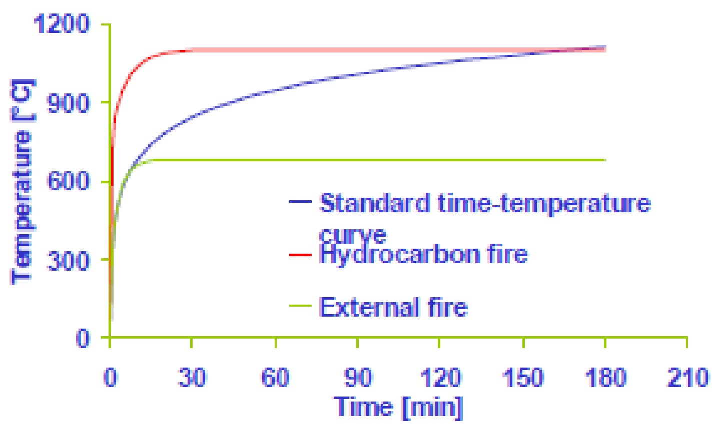


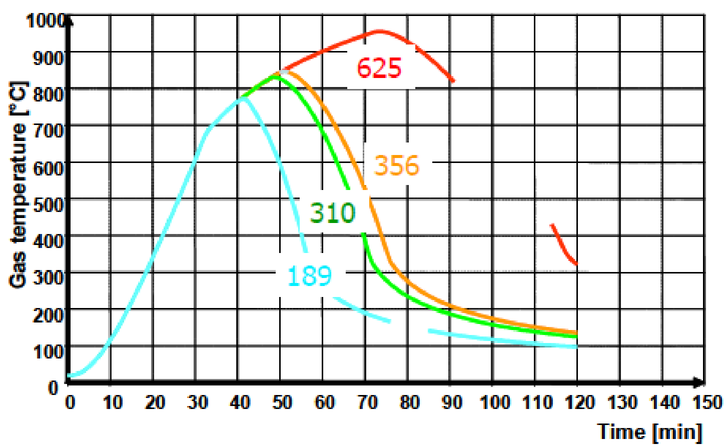
Alternative verification method

Project Design

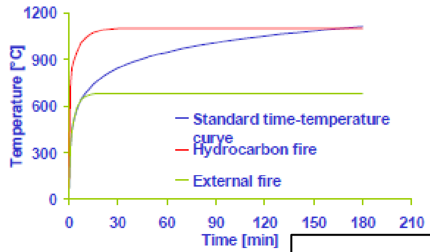
Prescriptive Regulation *(Thermal Actions given by a Nominal Fire)*

Performance-Based Code *(Physical Based Thermal Actions)*





Alternative verification method



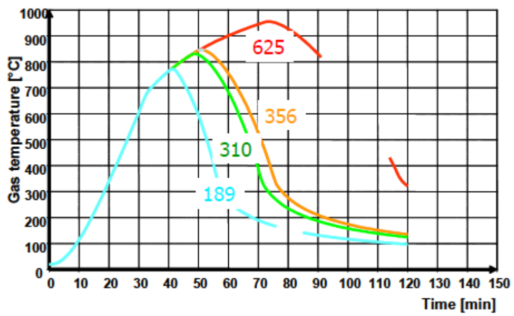
Prescriptive Rules
(Thermal Actions by Nominal Fire)

- Member Analysis
  - Calculation of Mechanical Actions at Boundaries
    - Tabulated Data
    - Simple Calculation Models
    - Advanced Calculation Models

- Analysis of Part of the Structure
  - Calculation of mechanical Actions at Boundaries
    - Simple Calculation Models
    - Advanced Calculation Models

- Analysis of Entire Structure
  - Selection of Mecahnical Actions
    - Advanced Calculation Models

Alternative verification method

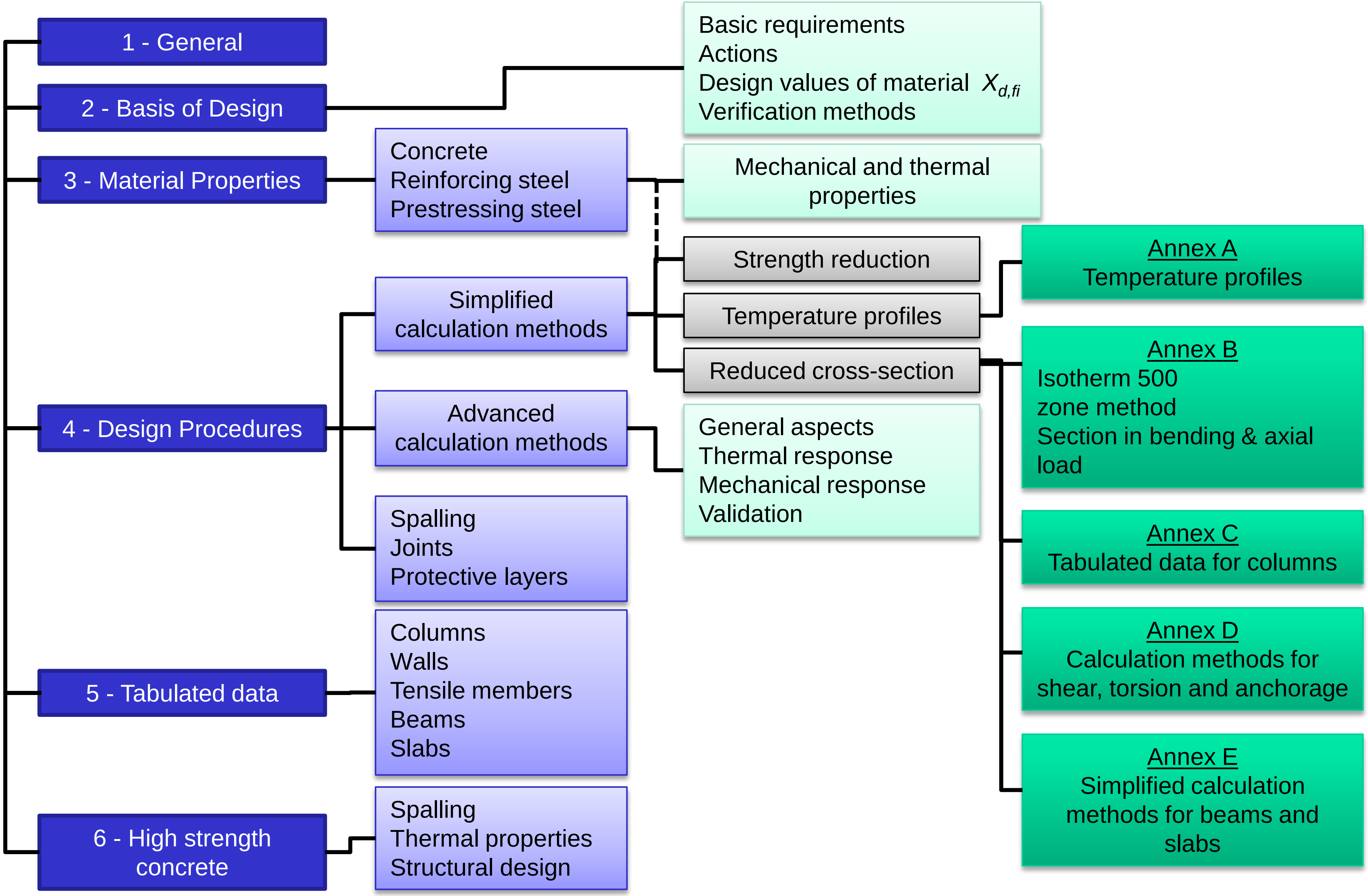


Performance-Based Code (Physically based Thermal Actions)

Selection of Simple or Advanced Fire Development Models

- **Member Analysis**
  - Calculation of Mechanical Actions at Boundaries
    - Simple Calculation Models (if available)
    - Advanced Calculation Models
- **Analysis of Part of the Structure**
  - Calculation of mechanical Actions et Boundaries
    - Advanced Calculation Models
- **Analysis of Entire Structure**
  - Selection of Mecahnical Actions
    - Advanced Calculation Models

Content of EN 1992-1-2



Scope

- Design of concrete structures for fire exposure in conjonction with EN 1992-1-1 and EN 1991-1-2
- Applicable to normal weight concrete up to C 90/105 and lightweight concrete up to LC 50/60

Requirements

✓ **Design to maintain the load-bearing function (R) and/or**

✓ **Design and construction to maintain the separating function (E, I)**

→ Nominal fire exposure during the required time period

→ Parametric fire exposure during the complete duration of fire (specific criterion for I in the decay phase)

Design values of material properties

- **Mechanical material properties**
  $X_{d,fi} = k_\theta \cdot X_k / \gamma_{M,fi}$
- **Thermal material properties**
  $X_{d,fi} = X_k / \gamma_{M,fi}$ (favourable)
  $X_{d,fi} = X_k \cdot \gamma_{M,fi}$ (unfavourable)

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

Verification method – member analysis

(1) The effect of actions should be determined for time $t = 0$ using combination factors $\psi_{1,1}$ or $\psi_{1,2}$ according to EN 1991-1-2 Section 4.

(2) As a simplification to (1) the effects of actions may be obtained from a structural analysis for normal temperature design as:

$$E_{d,fi} = \eta_{fi} E_d$$

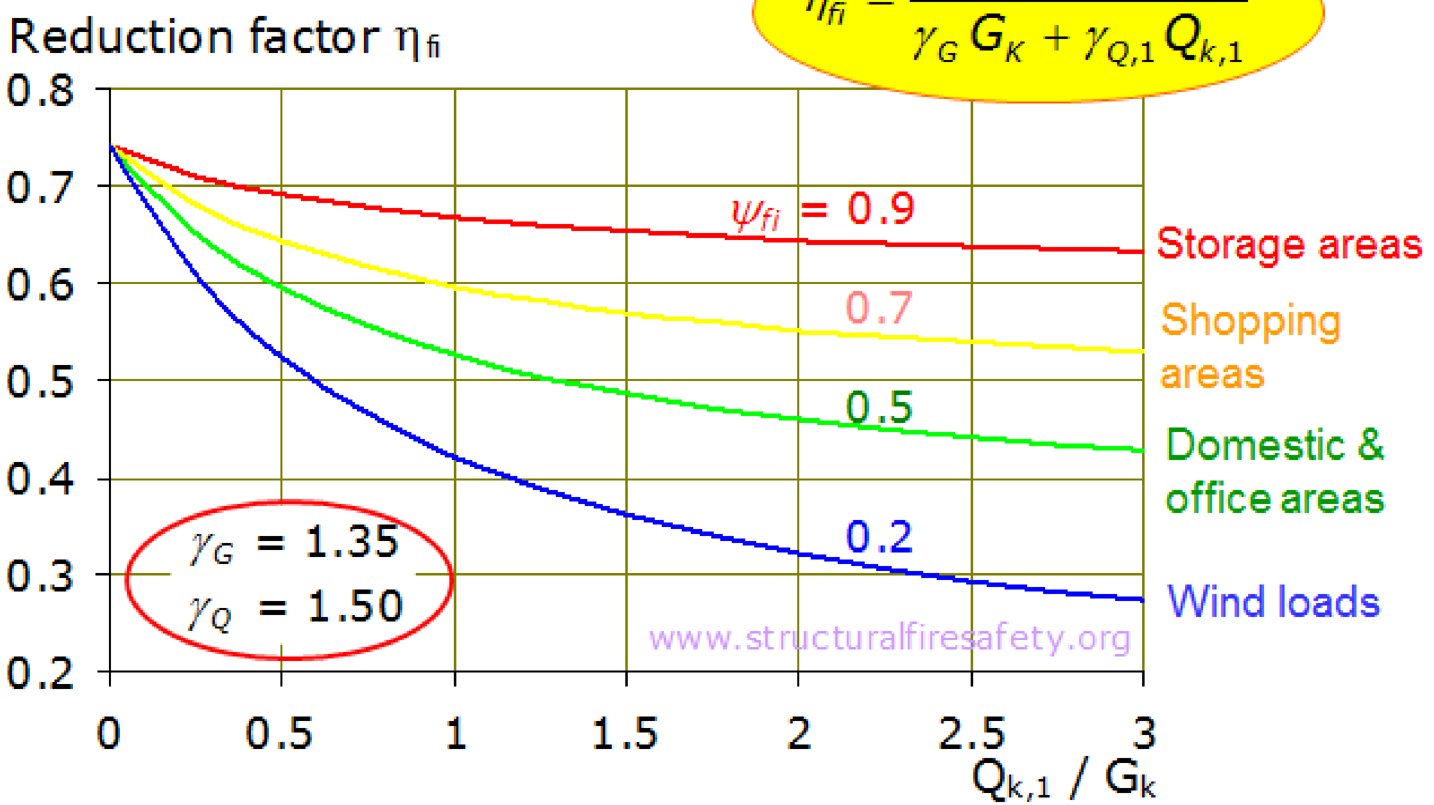
Where

E_d is the design value of the corresponding force or moment for normal temperature design, for a fundamental combination of actions (see EN 1990);

η_{fi} is the reduction factor for the design load level for the fire situation.

Example for η_{fi}

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



Note 2: As a simplification a recommended value of η_{fi} = 0,7 may be used.

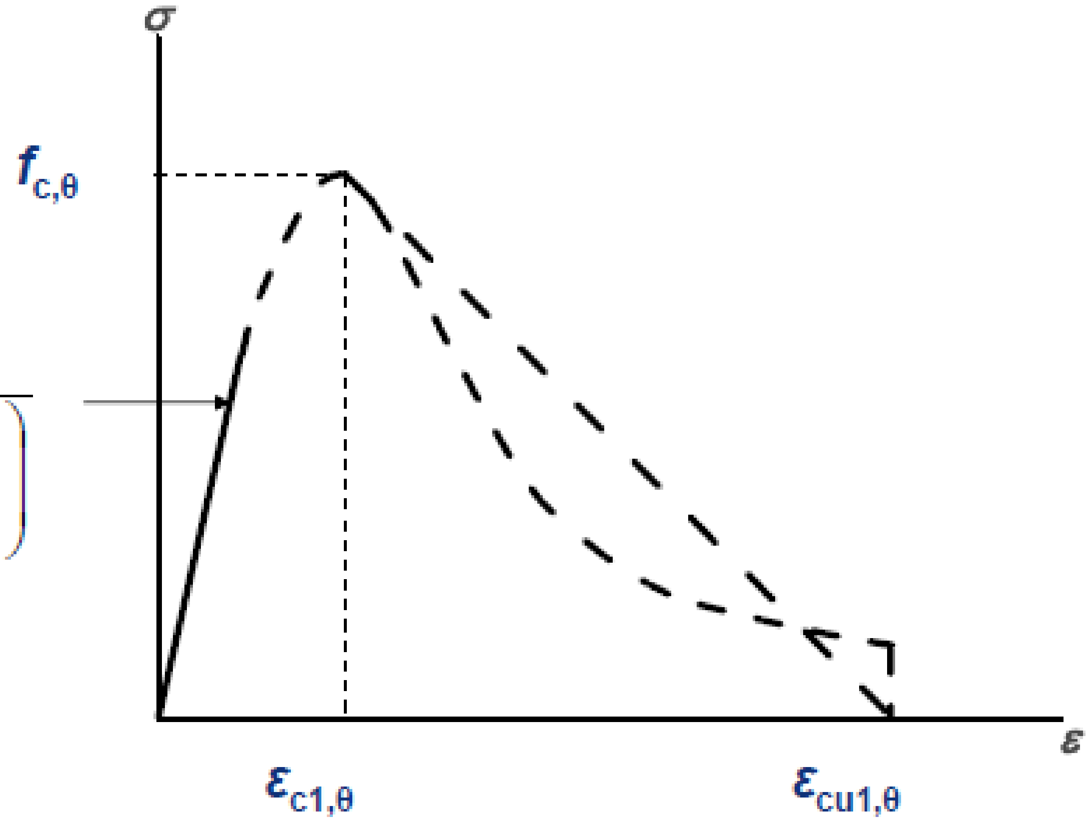
SECTION 3 - Material Properties

- Strength and deformation properties in Section 3 are given for simplified and advanced calculation methods
- Strength reduction curves for Tabulated data (in Section 5) and Simplified calculation methods (in Section 4) are derived from material properties in section 3
- Thermal properties are given in Section 3 for calculation of temperature distribution inside the structure
- Material properties for lightweight concrete are not given due to wide range of lightweight aggregates
  - **this does not exclude use of lightweight aggregate concrete, see e.g. Scope and Tabulated data**
- Strength and deformation properties are applicable to heating rates similar to standard fire curve (between 2 and 50 K/min)

Mathematical model and parameters $f_{c,\theta}$, $\varepsilon_{c1,\theta}$ and $\varepsilon_{cu1,\theta}$

α_{cc} = 1,0 in fire design

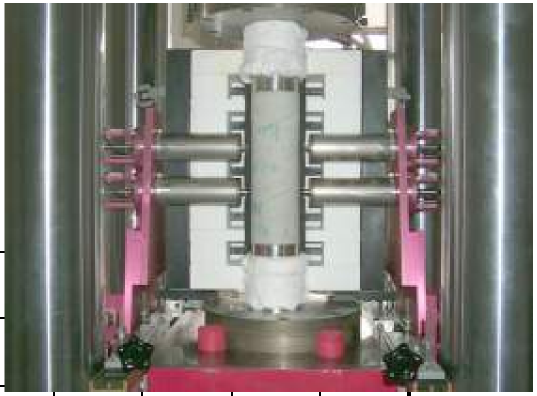
$$\frac{3\varepsilon f_{c,\theta}}{\varepsilon_{c1,\theta}\left(2+\left(\frac{\varepsilon}{\varepsilon_{c1,\theta}}\right)^3\right)}$$

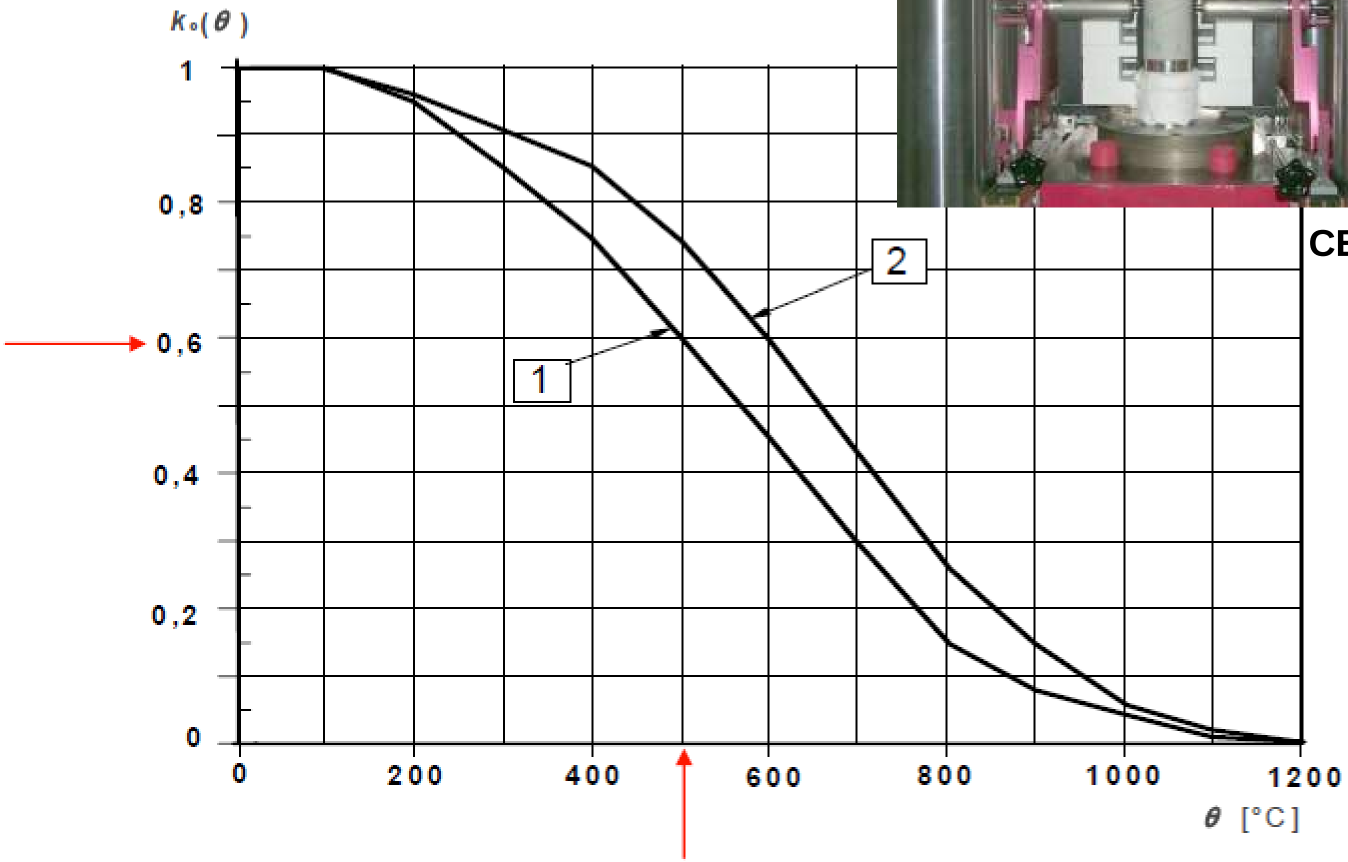


Strength reduction of concrete

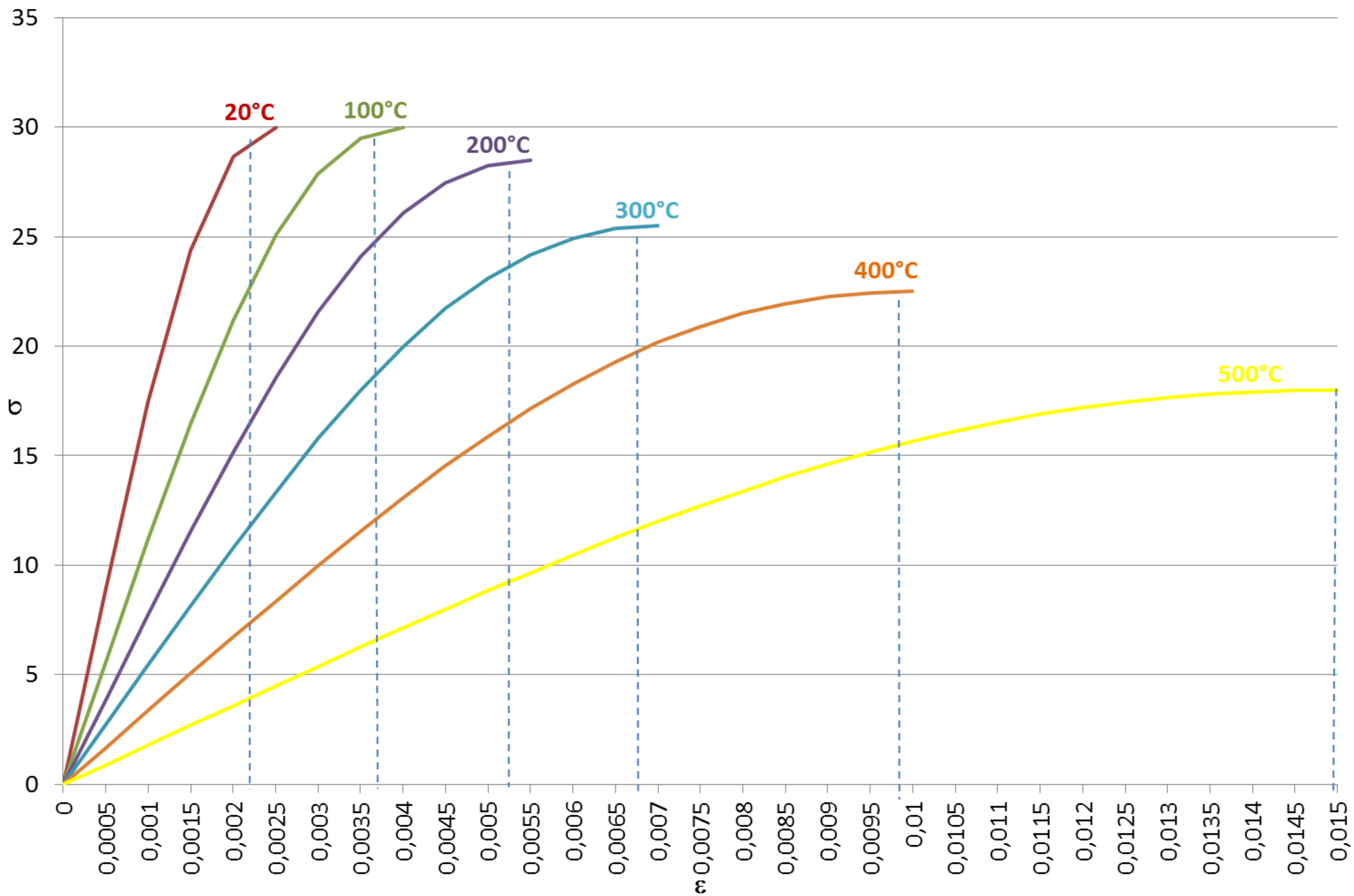
The same strength reduction values are given for simplified calculation methods in Section 4

1. Siliceous concrete
2. Calcareous concrete





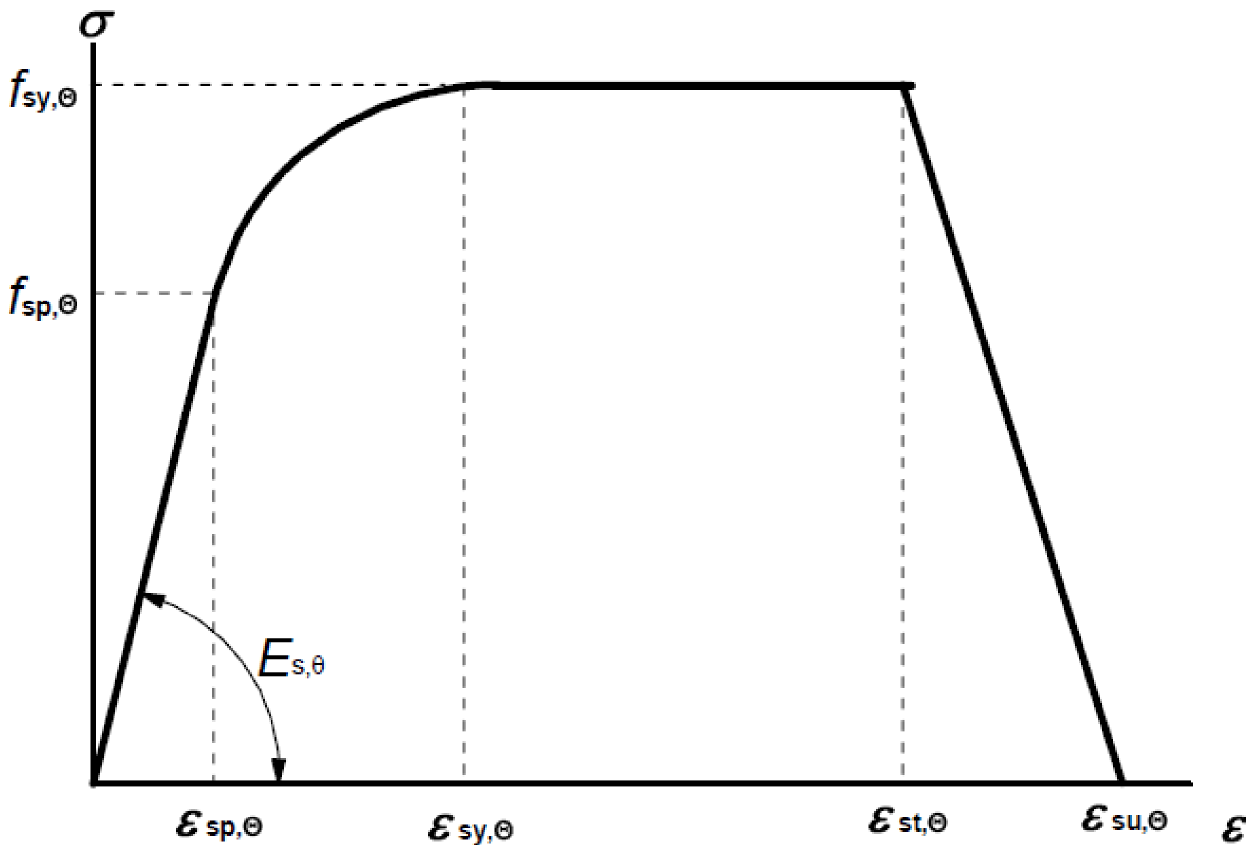
Concrete compressive strength



Reinforcing and prestressing steel : stress-strain relationship

$\varepsilon_{sp,\theta} = f_{sp,\theta} / E_{s,\theta}$ $\varepsilon_{sy,\theta} = 0{,}02$ $\varepsilon_{st,\theta} = 0{,}15$ $\varepsilon_{su,\theta} = 0{,}20$

Class A reinforcement: $\varepsilon_{st,\theta} = 0{,}05$ $\varepsilon_{su,\theta} = 0{,}10$



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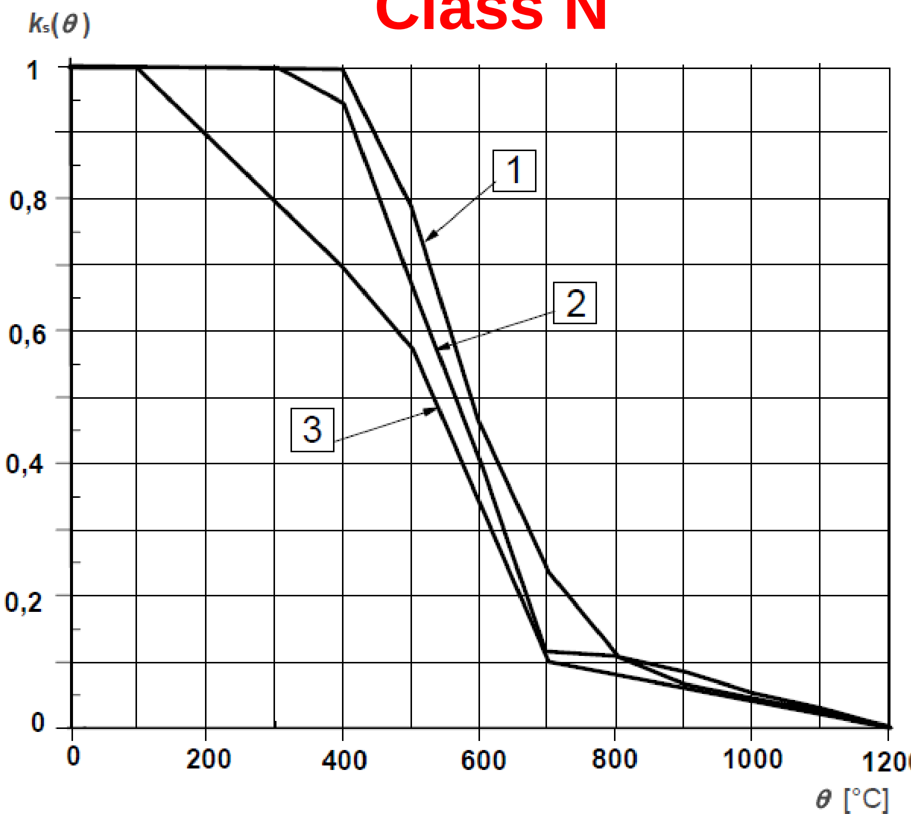
Strength reduction (f_{yk}) for reinforcing steel

Class N

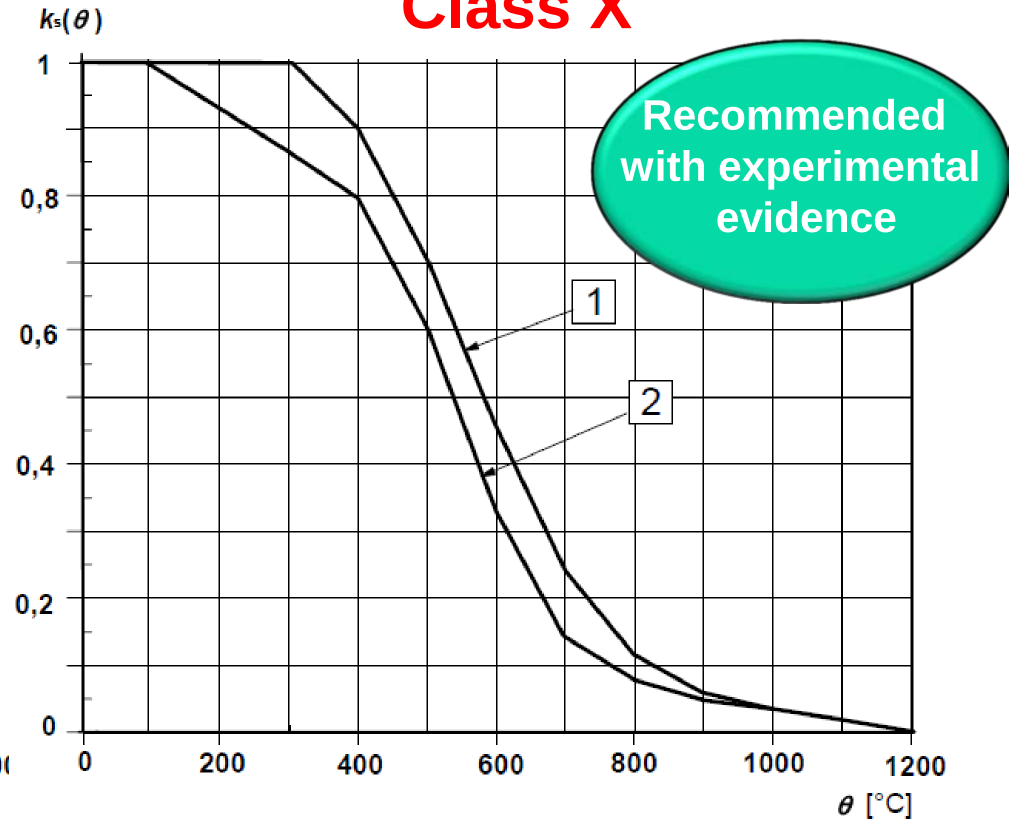


Curve 1 : Tension reinforcement (hot rolled) for strains $\varepsilon_{s,fi} \geq 2\%$

Curve 2 : Tension reinforcement (cold worked) for strains $\varepsilon_{s,fi} \geq 2\%$

Curve 3 : Compression reinforcement and tension reinforcement for strains $\varepsilon_{s,fi} < 2\%$

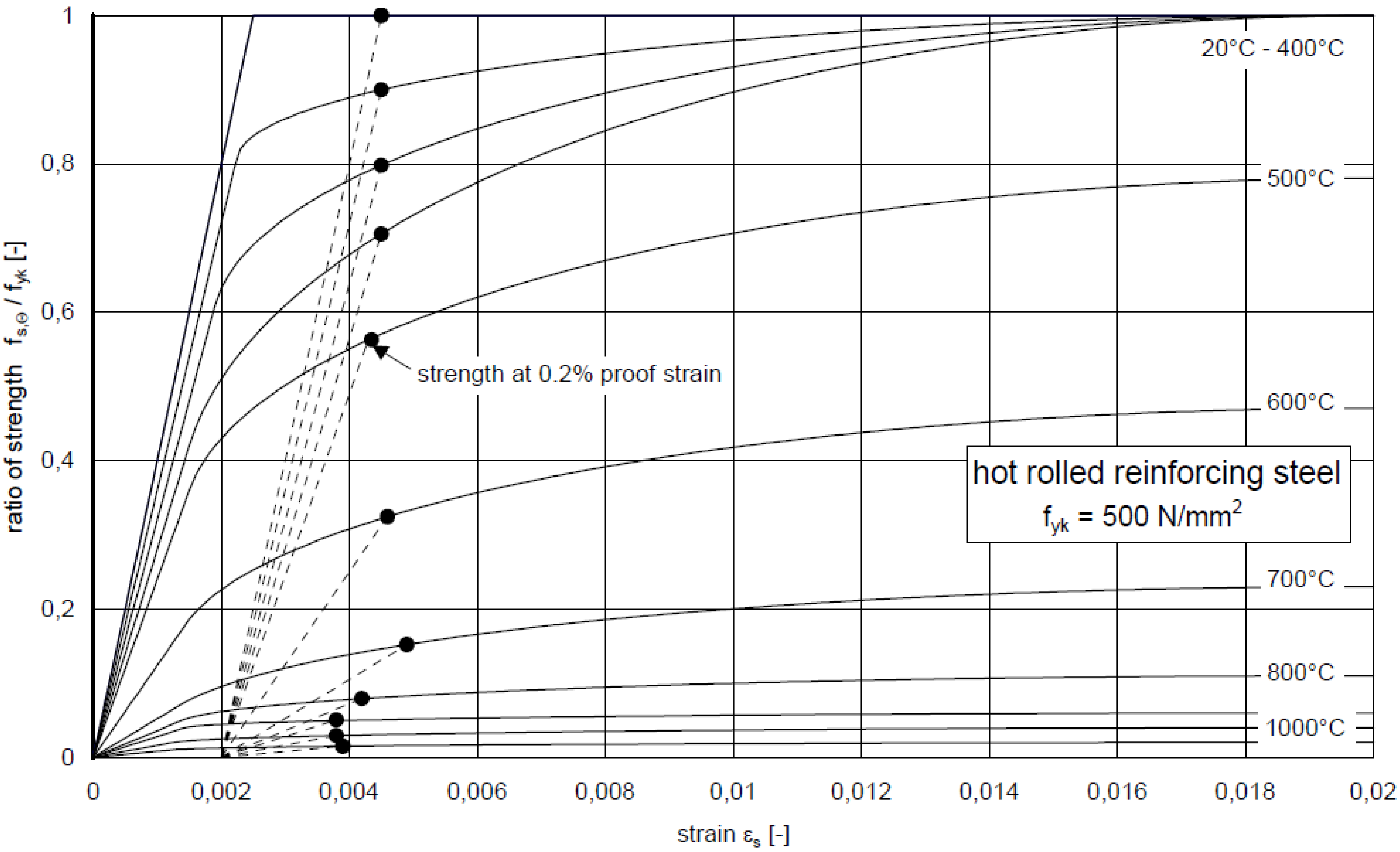
Class X



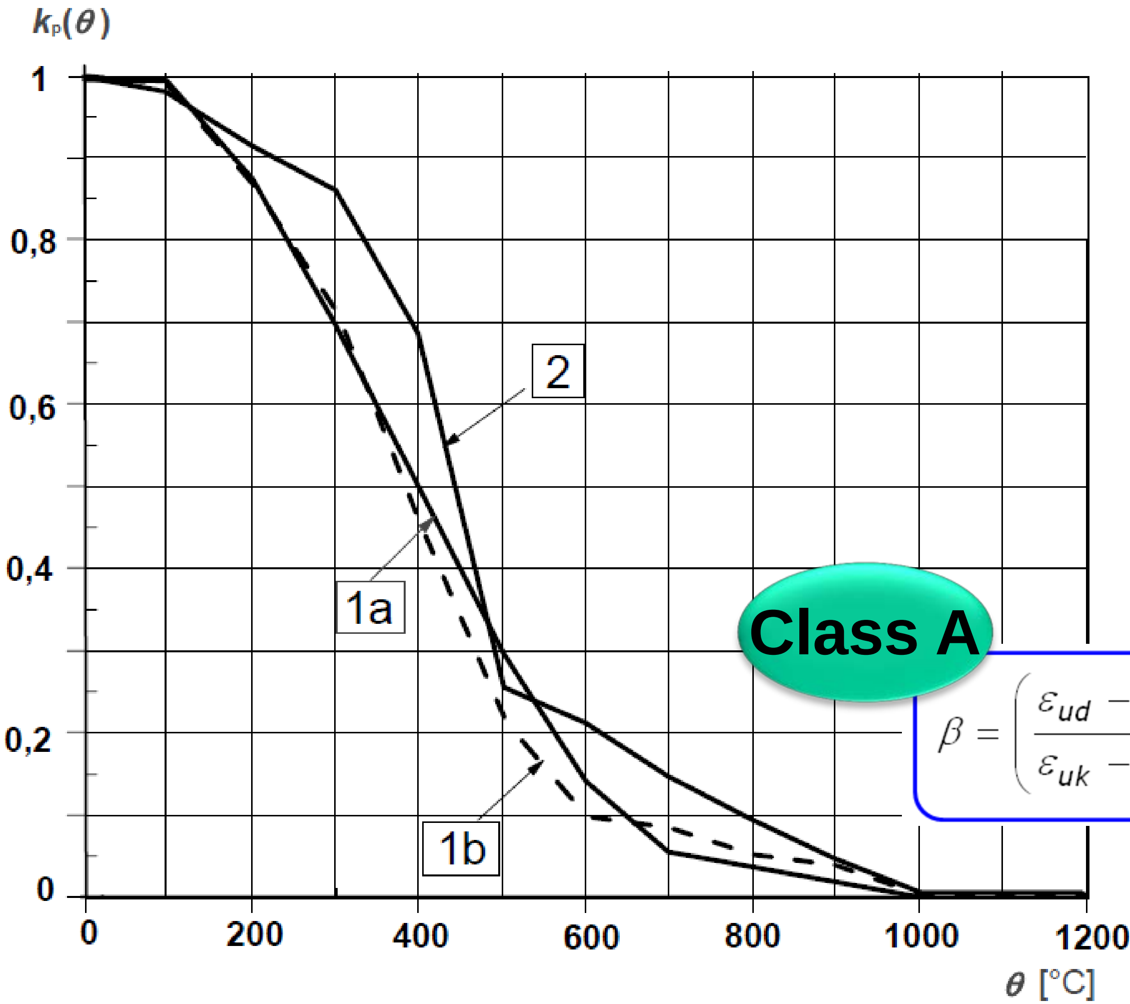
Curve 1 : Tension reinforcement (hot rolled and cold worked) for strains $\varepsilon_{s,fi} \geq 2\%$

Curve 2 : Compression reinforcement and tension reinforcement (hot rolled and cold worked) for strains $\varepsilon_{s,fi} < 2\%$

Strength reduction (f_{yk}) for reinforcing steel



Strength reduction (βf_{pk}) for prestressing steel



Curve 1a : Cold worked prestressing steel (wires and strands) Class A

Curve 1b : Cold worked prestressing steel (wires and strands) Class B

Curve 2 : Quenched and tempered prestressing steel (bars)

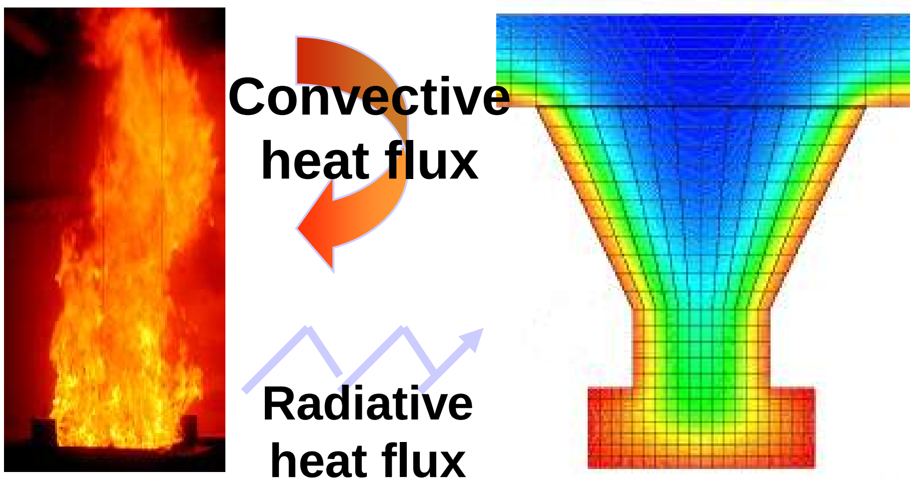
Class A

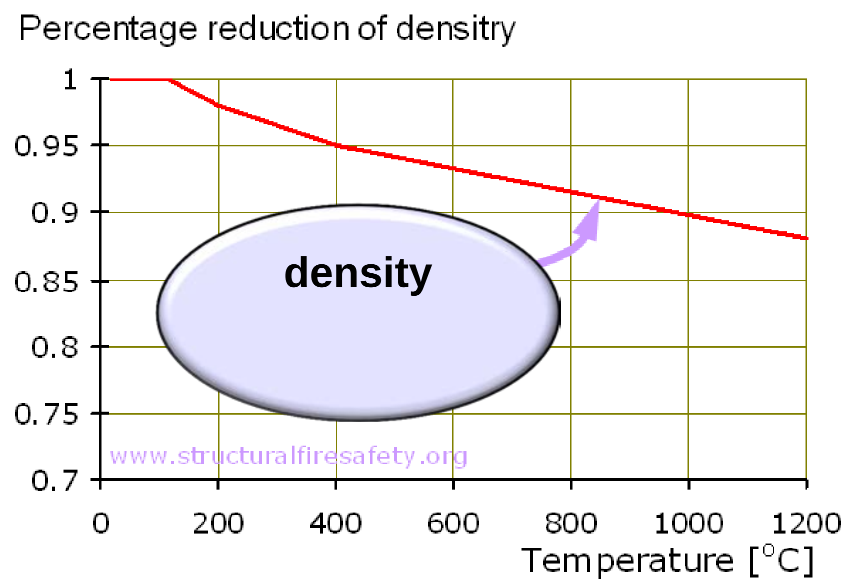
$$\beta = \left(\frac{\varepsilon_{ud} - f_{p0.1k} / E_p}{\varepsilon_{uk} - f_{p0.1k} / E_p} \right) \times \left(\frac{f_{pk} - f_{p0.1k}}{f_{pk}} \right) + \frac{f_{p0.1k}}{f_{pk}}$$

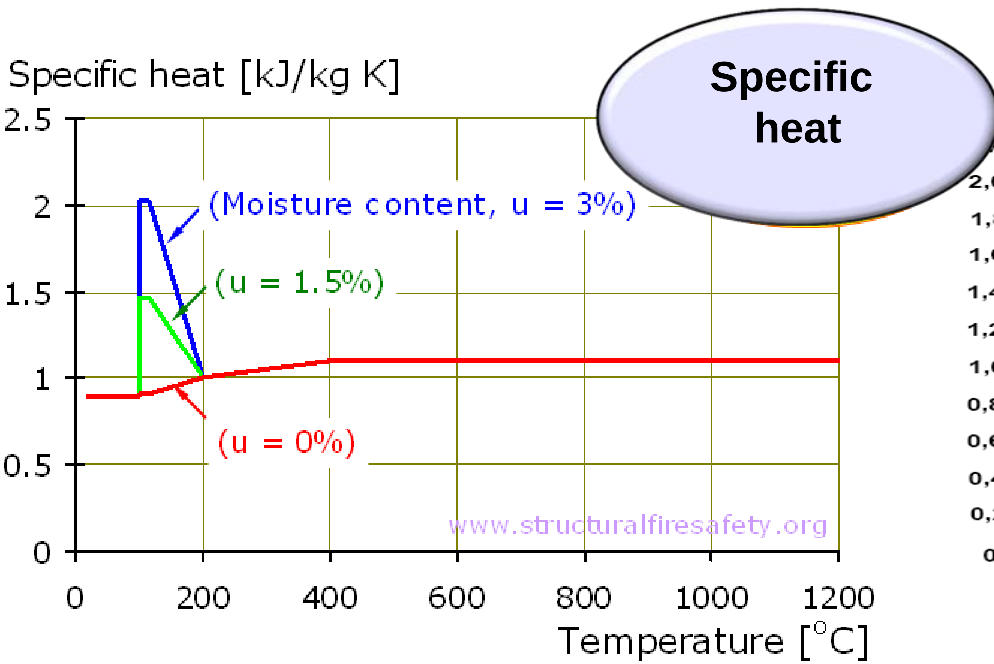
Class B

$$\beta = 0.9$$

Thermal properties







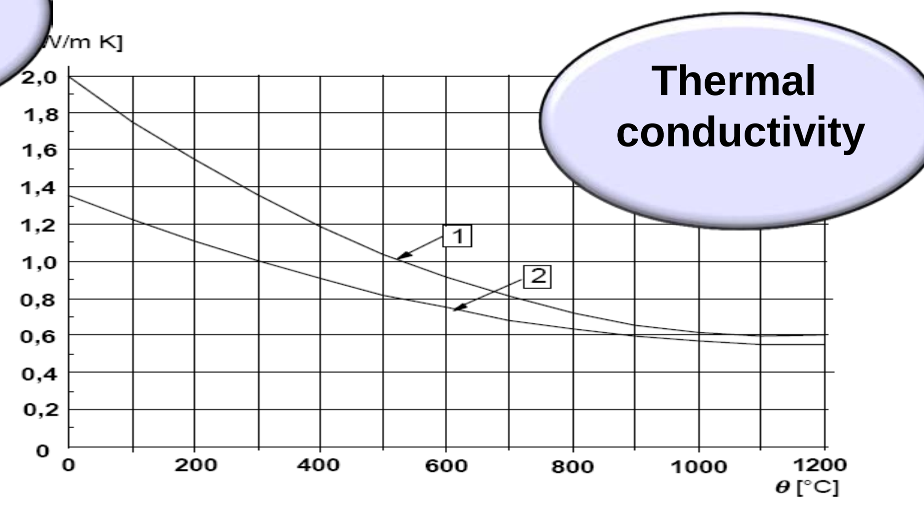
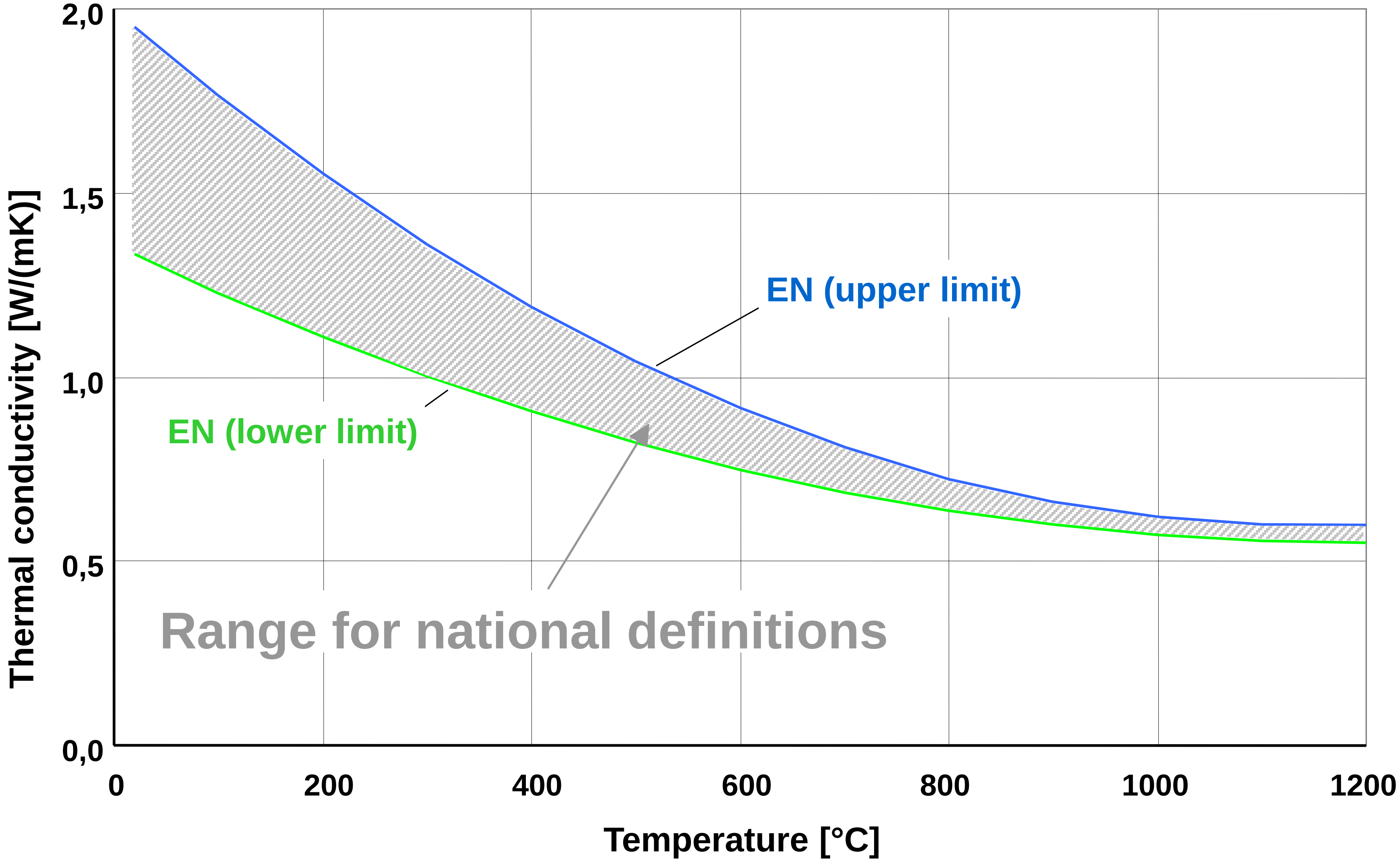
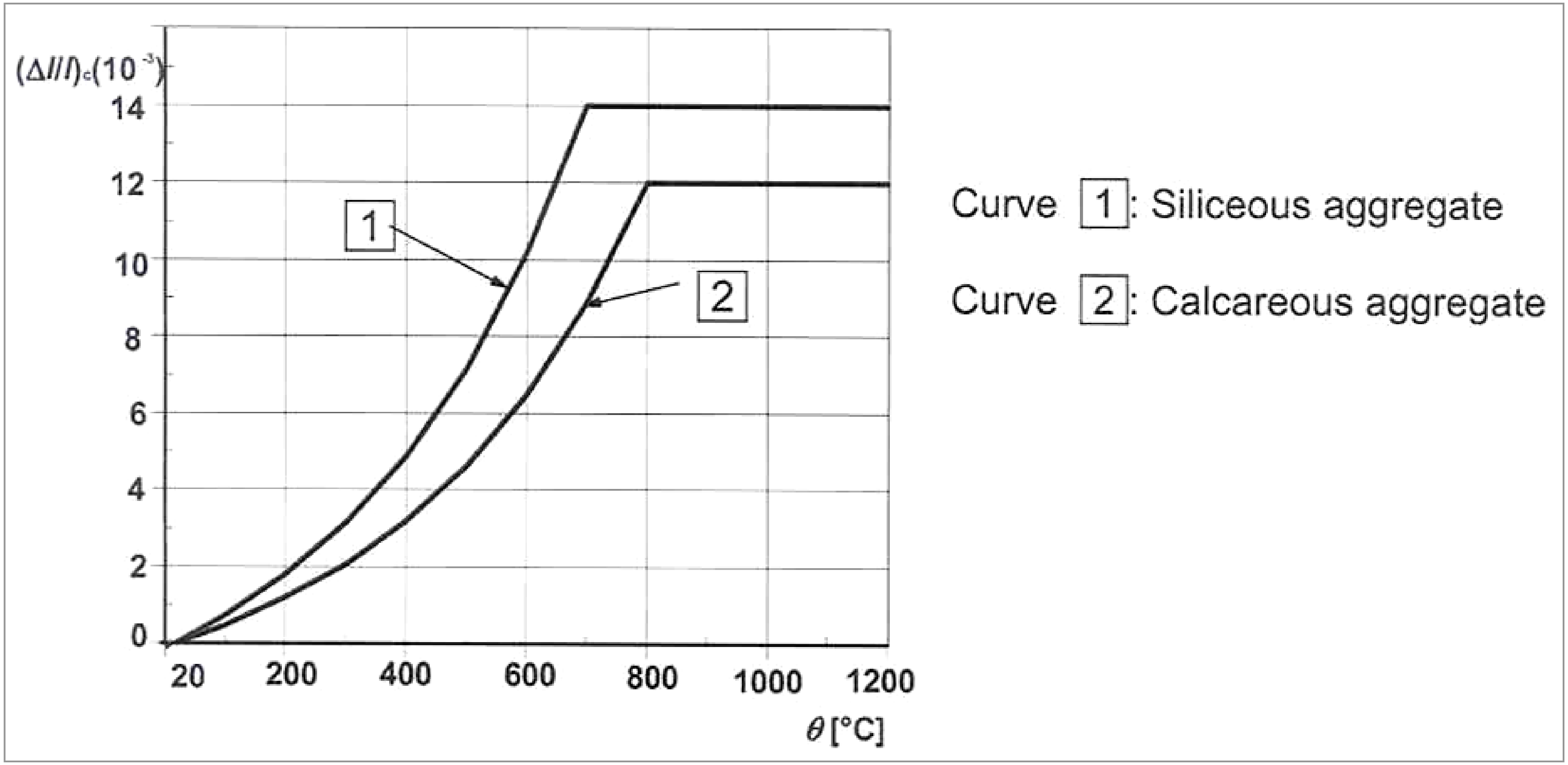


Figure 3.7 – Conductivité thermique du béton

Thermal Conductivity



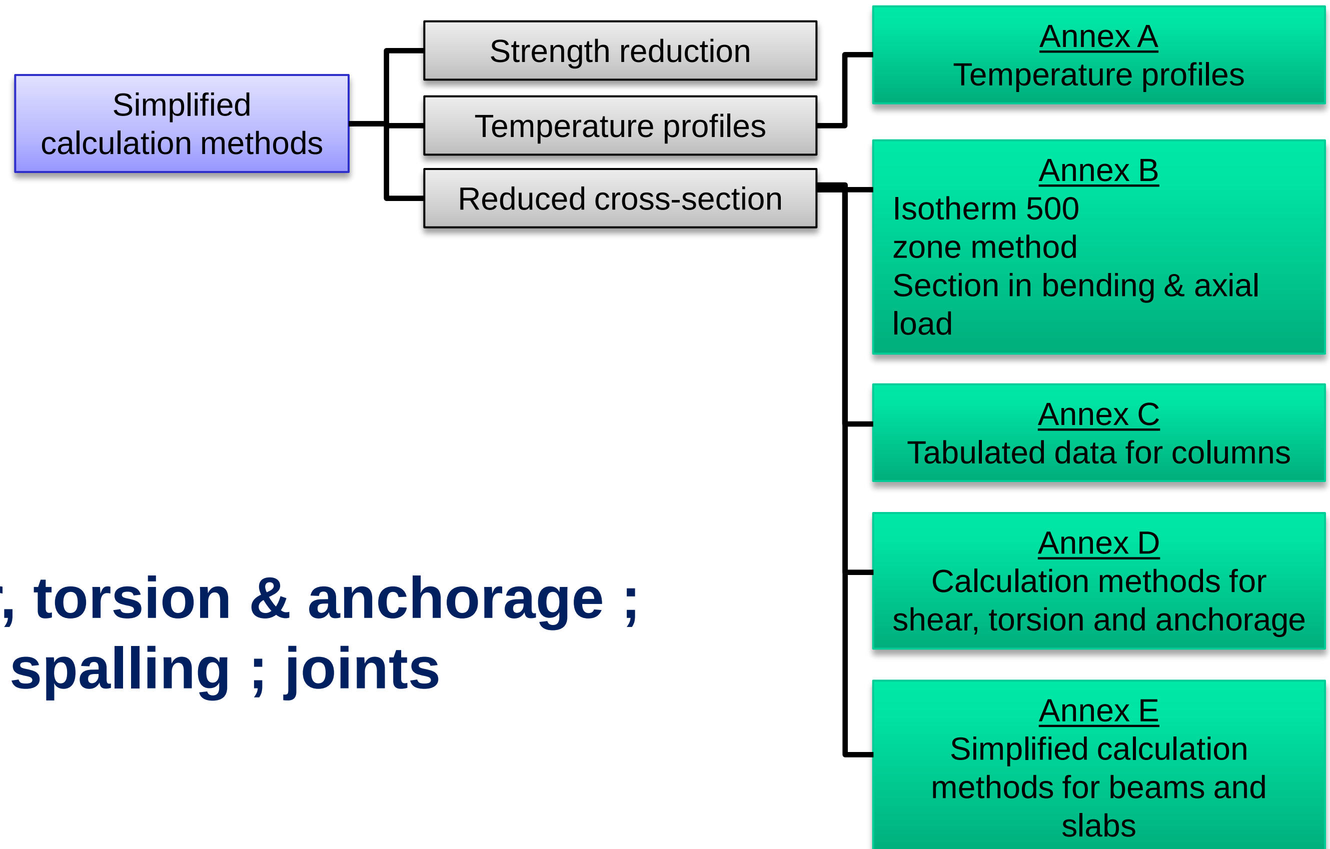
Thermal Elongation



Total thermal elongation of concrete

SECTION 4 - Design procedure

- **advanced calculation methods** for simulating the behaviour of structural members, parts of the structure or the entire structure, see 4.3
  - only principles are given, no detailed design rules
- **simplified calculation methods** for specific types of members, see 4.2

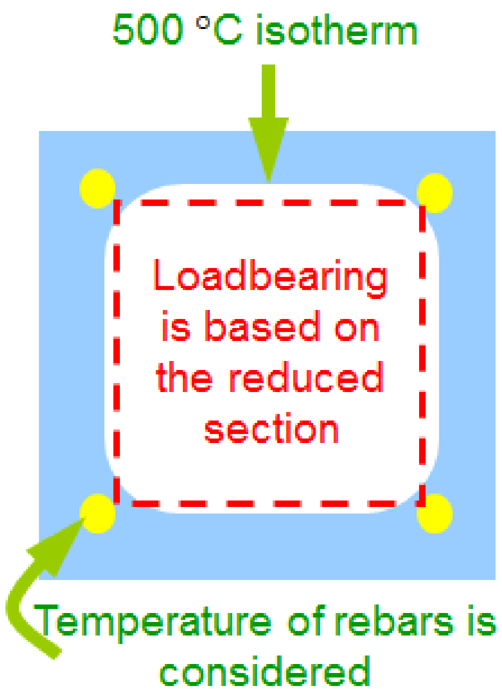


- **shear, torsion & anchorage ; spalling ; joints**

Simplified calculation methods

- **500°C isotherm method**

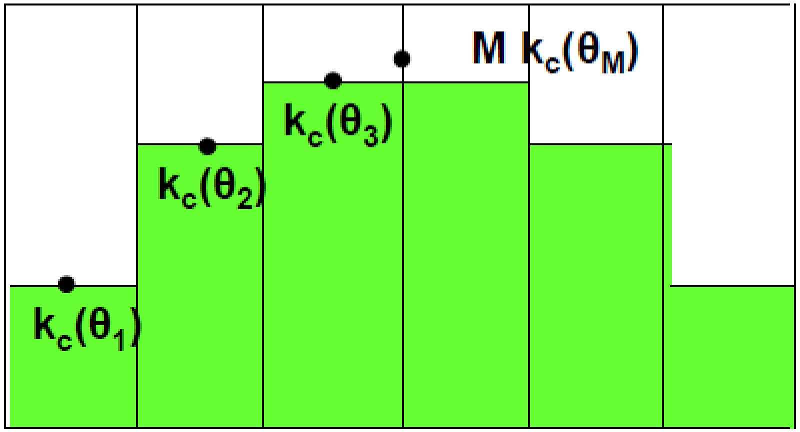
  Concrete with temperature below 500°C retains full strength and the rest is disregarded



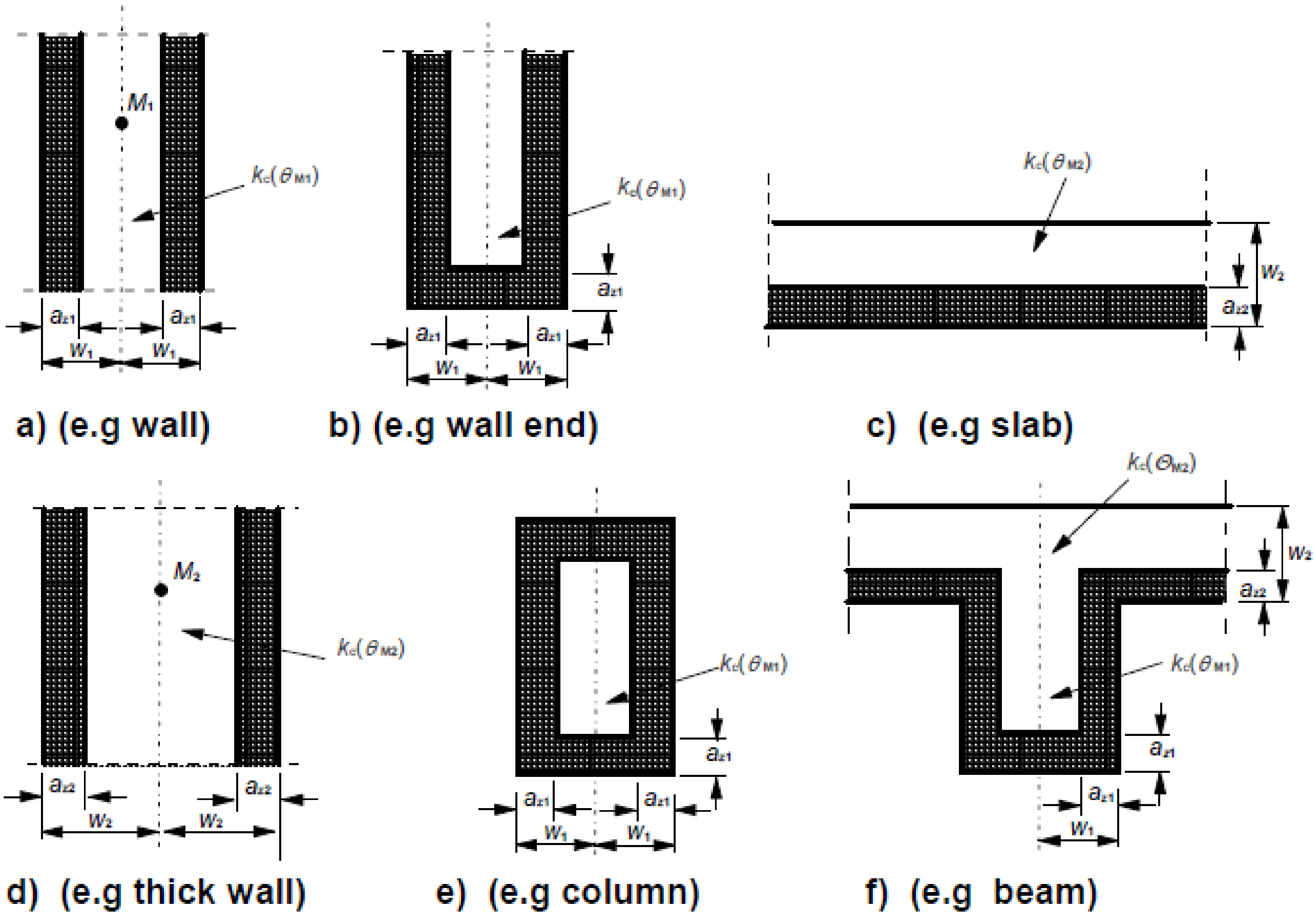
- **Zone method**

  Cross section is divided in zones. Mean temperature and corresponding strength of each zone is used

  This method is more accurate for small cross sections than 500°C isotherm method

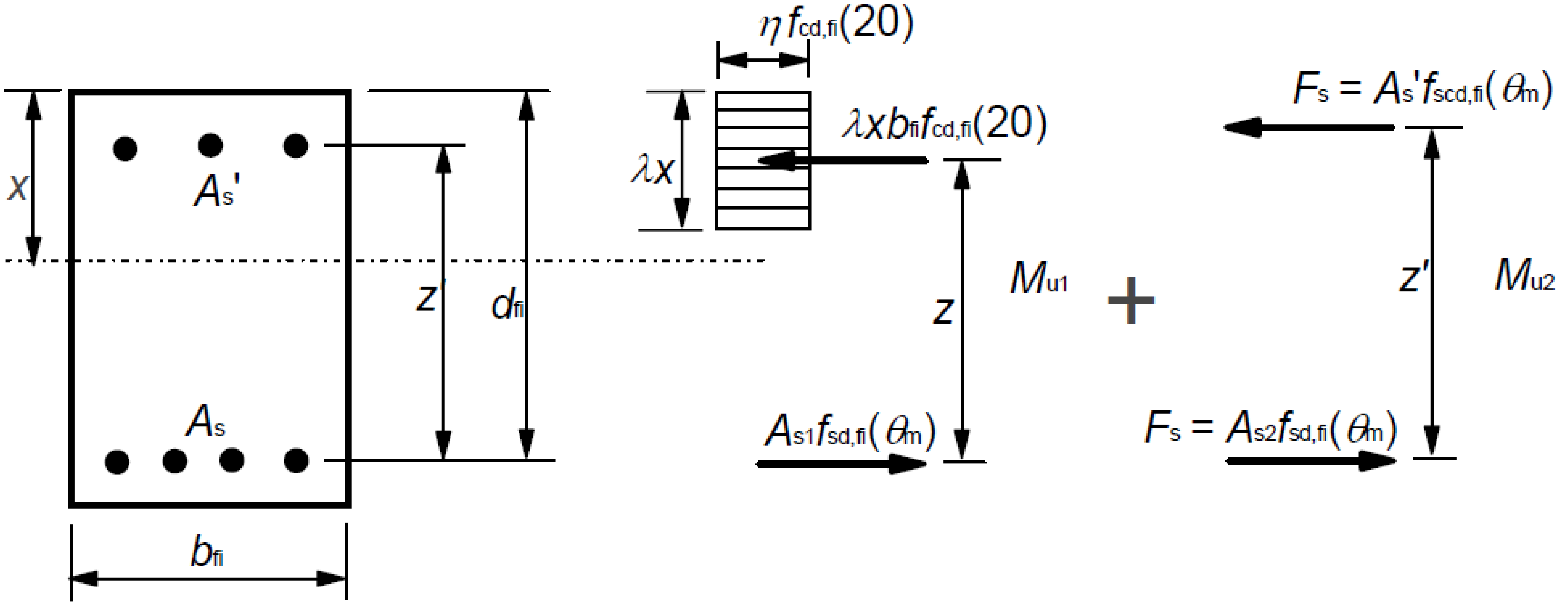


Simplified calculation methods



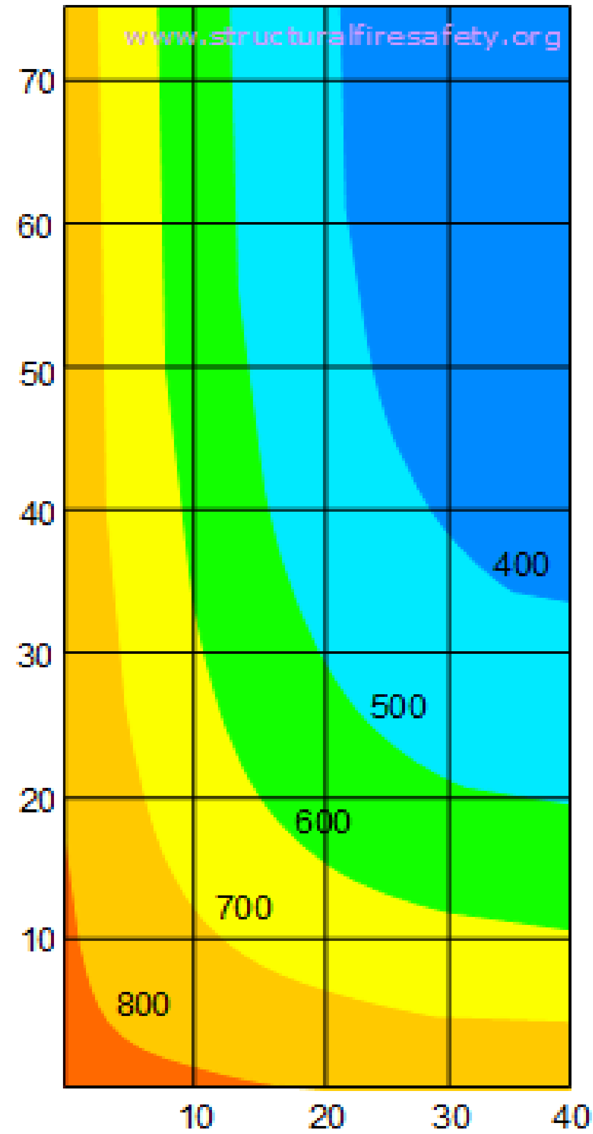
Simplified calculation methods

- **Determine the 500°C isotherm and the reduced width b_{fi} and effective depth d_{fi}**
- **Determine the temperature of reinforcing bars and the reduced strength**
- **Use conventional calculation methods**



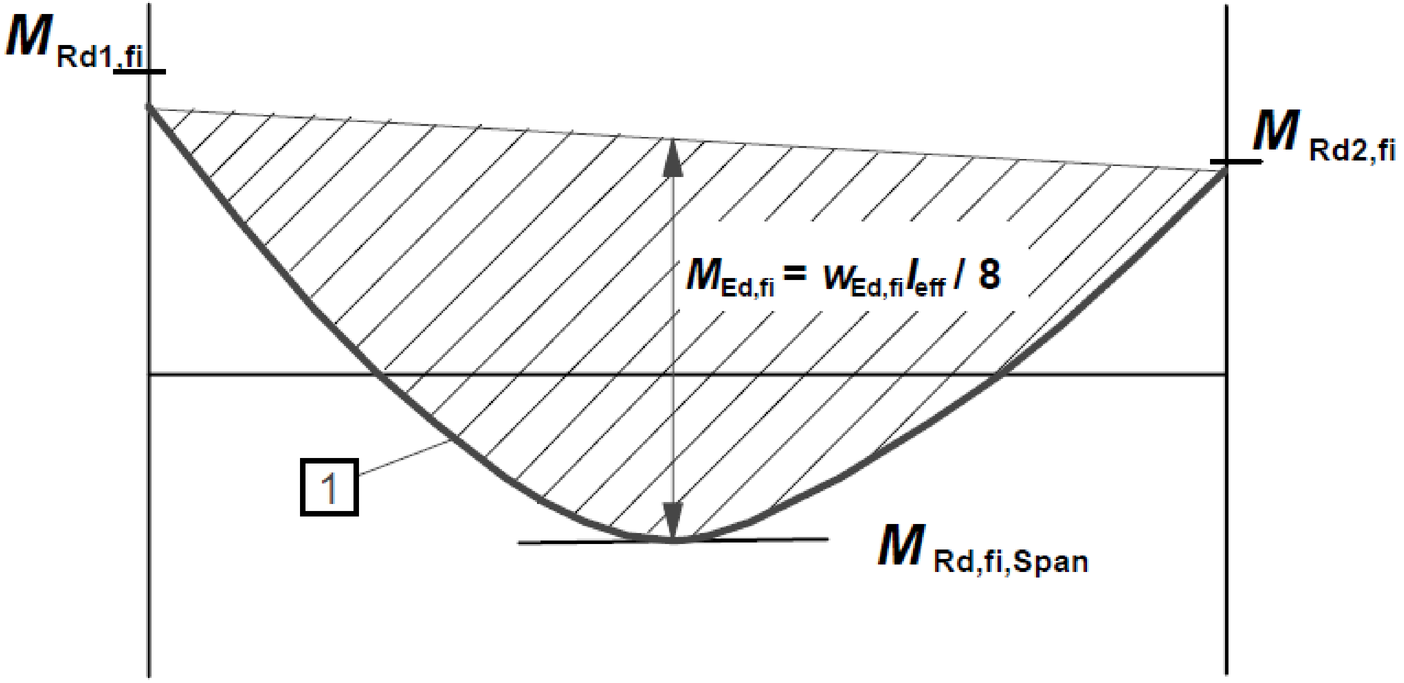
Temperature profiles

- **Temperature distribution in the cross section can be calculated from the thermal properties**
- **Annex A of EN 1992-1-2 gives temperature profiles for slabs, beams and columns**



Simplified calculation method for beam and slabs

- Annex E
- Simplified method to calculate bending capacity for predominantly uniformly distributed loads
- This is some kind of extension of Tabulated data

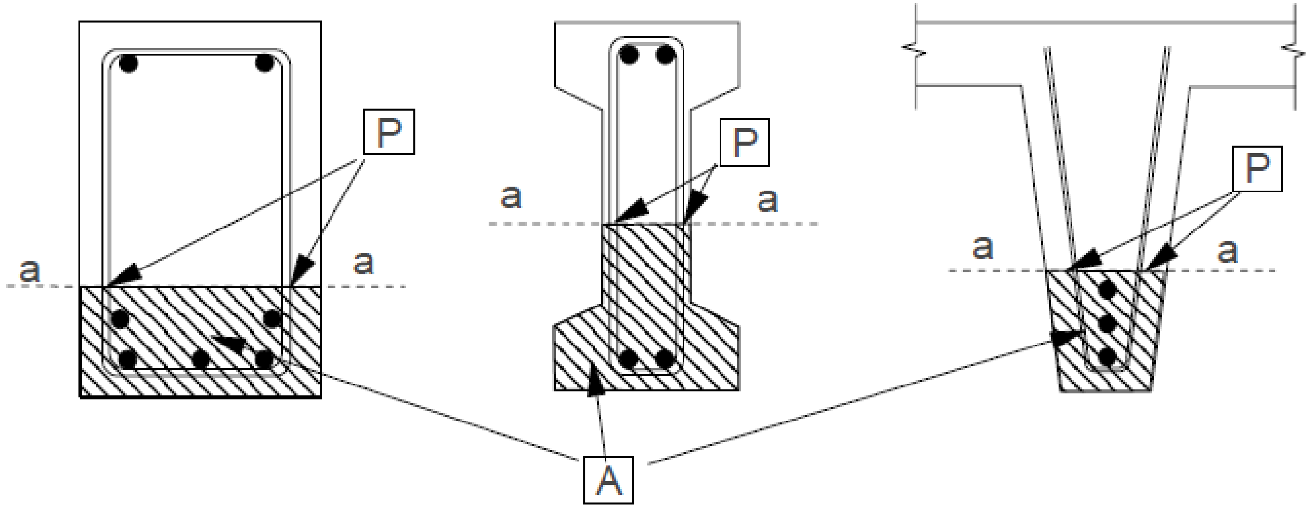


1 Free moment diagram for uniformly distributed load under fire conditions

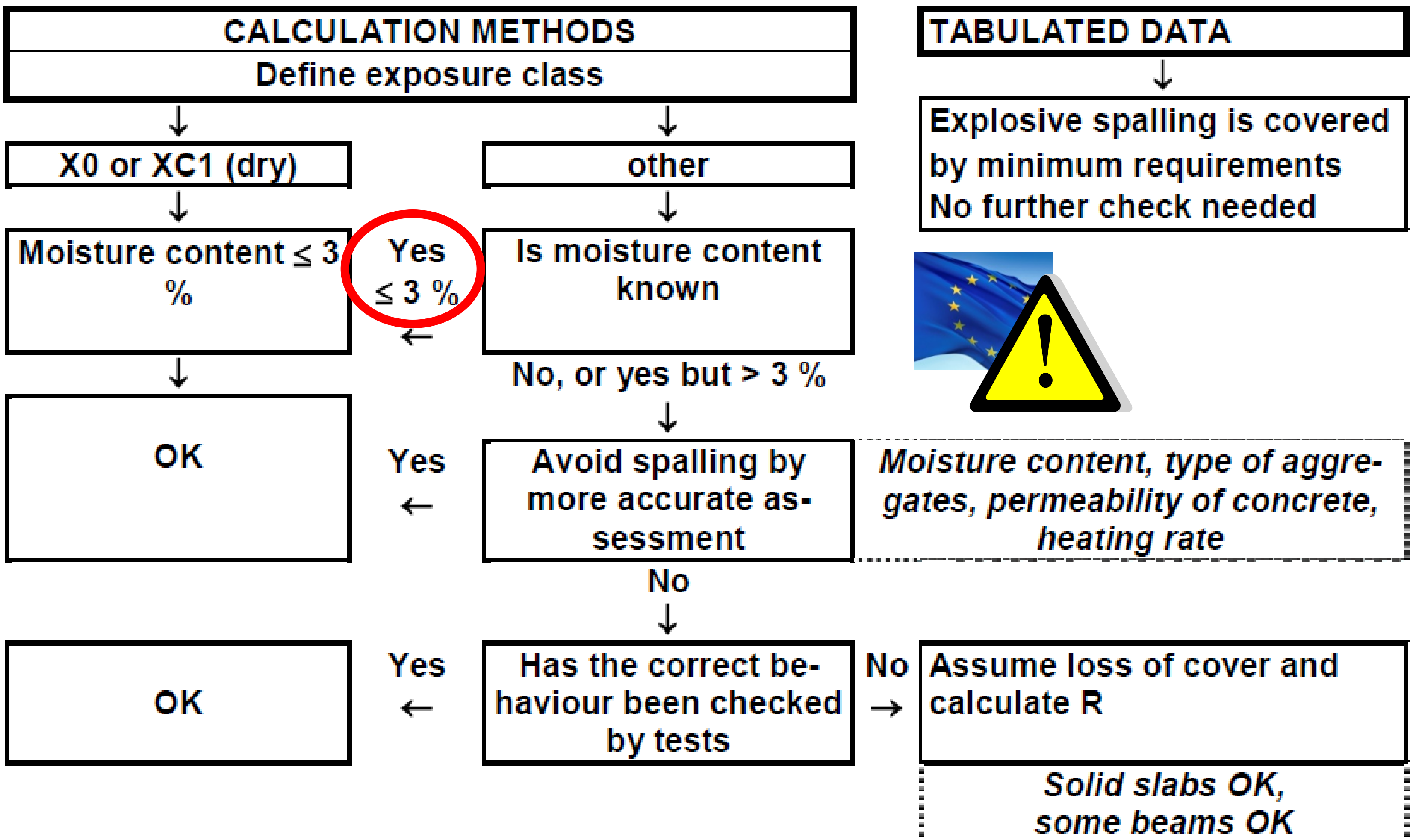
Annex D (informative)

- Shear failures due to fire are very uncommon. However, the calculation methods given in this Annex are not fully verified.

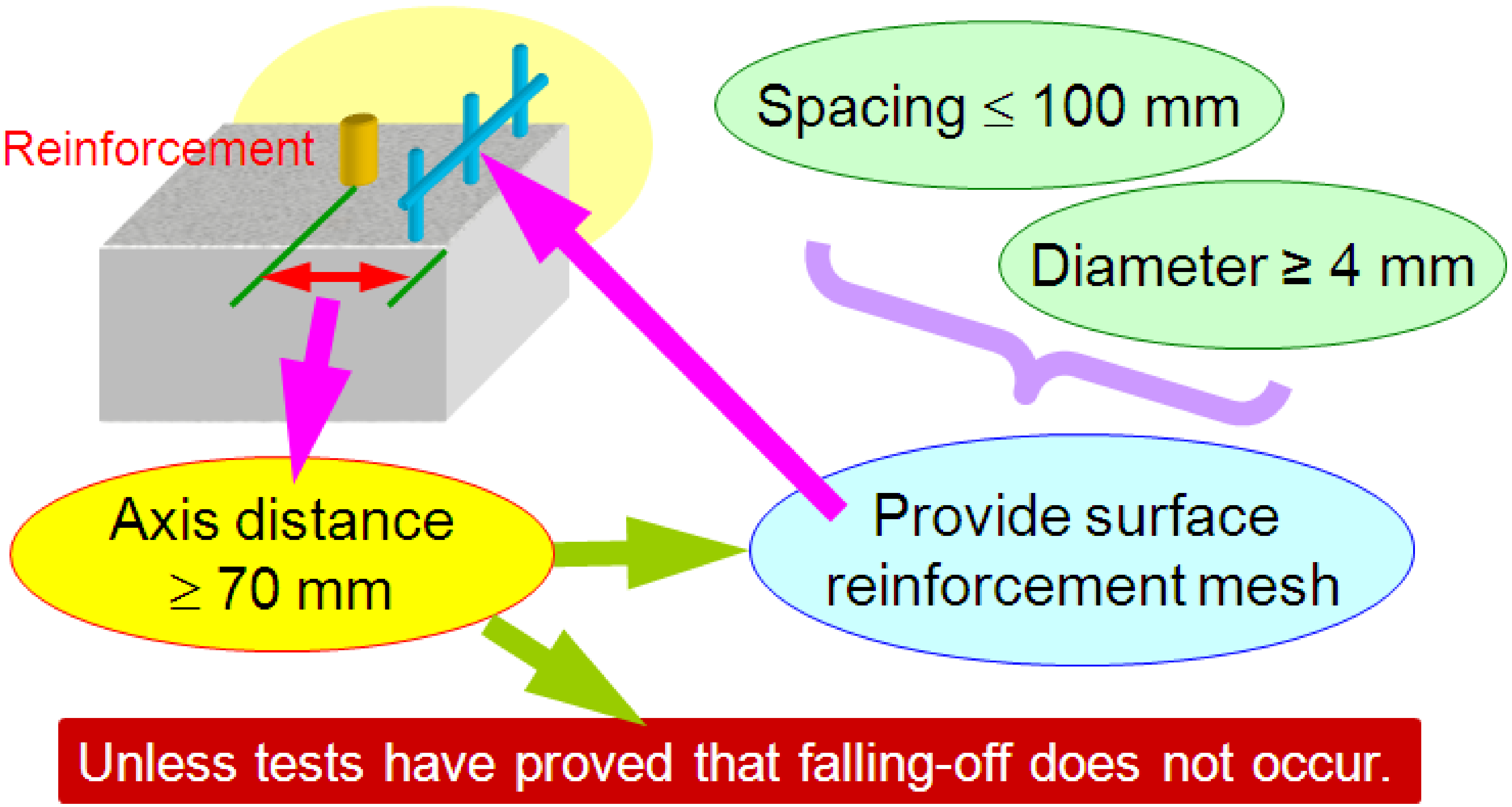
The reference temperature θ_p should be evaluated at points P along the line 'a -a' for the calculation of the shear resistance. The effective tension area A may be obtained from EN 1992-1 (SLS of cracking).



Spalling


CALCULATION METHODS
Define exposure class
X0 or XC1 (dry)
other
Moisture content ≤ 3 %
Yes ≤ 3 %
Is moisture content known
No, or yes but > 3 %
OK
Yes
Avoid spalling by more accurate assessment
No
Yes
OK
Has the correct behaviour been checked by tests
No
Assume loss of cover and calculate R
Solid slabs OK, some beams OK
TABULATED DATA
Explosive spalling is covered by minimum requirements
No further check needed
Moisture content, type of aggregates, permeability of concrete, heating rate

Falling off of concrete



SECTION 5 – Tabulated data

(1) This section gives recognised design solutions for the standard fire exposure up to 240 minutes. The rules refer to member analysis.

Note: The tables have been developed on an empirical basis confirmed by experience and theoretical evaluation of tests. The data is derived from approximate conservative assumptions for the more common structural elements and is valid for the whole range of thermal conductivity in 3.3. More specific tabulated data can be found in the product standards for some particular types of concrete products or developed, on the basis of the calculation method in accordance with 4.2, 4.3 and 4.4.

(2) The values given in the tables apply to normal weight concrete (2000 to 2600 kg/m3, made with siliceous aggregates.
If calcareous aggregates or lightweight aggregates are used in beams or slabs the minimum dimension of the cross-section may be reduced by 10%.

(3) When using tabulated data no further checks are required concerning shear and torsion capacity and anchorage details.

(4) When using tabulated data no further checks are required concerning spalling, except for surface reinforcement.

SECTION 5 – Tabulated data

Tabulated data are based on a reference load level $\eta_{fi} = 0,7$, unless otherwise stated in the relevant clauses.

Note: Where the partial safety factors specified in the National Annexes of EN 1990 deviate from those indicated in 2.4.2, the above value $\eta_{fi} = 0,7$ may not be valid. In such circumstances the value of η_{fi} for use in a Country may be found in its National Annex.

For walls and columns load level η_{fi} or degree of utilisation μ_{fi} is included in the tables

TABULATED DATA FOR COLUMNS

- Two optional methods are given
  - **Method A** is derived from test results, but field of application is limited to buckling length ≤ 3 m and first order eccentricity ≤ 0,15h to 0,4h (depending on the National Annex)
  - **Method B** is based on calculations, it is more conservative and many interpolations are needed. Limitations for normative table: eccentricity ≤ 0,25h and $\lambda_{fi} \leq 30$
    9 pages of tables in Annex C

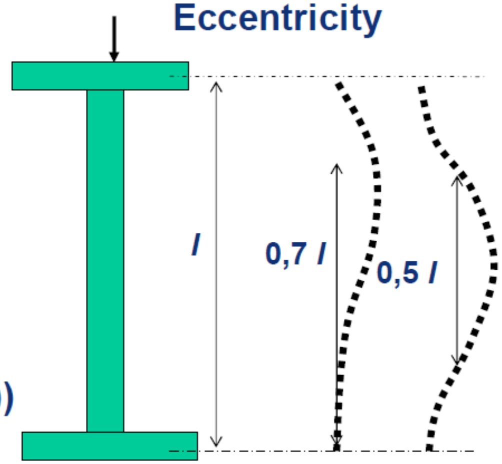
In Method A degree of utilisation:

$\mu_{fi} = N_{Ed.fi} / N_{Rd}$

In Method B load level is defined as:

$n = N_{0Ed,fi} / (0,7(A_c f_{cd} + A_s f_{yd}))$

Eccentricity



Slenderness, $l_{o,fi}$
- upper floor 0,7 l
- intermediate floor 0,5 l

TABULATED DATA FOR COLUMNS : tables for Method B

Standard fire resistance	Mechanical reinforcement ratio ω	Minimum dimensions (mm). Column width b_{min}/axis distance a			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
1	2	3	4	5	6
R 30	0,100	150/25*	150/25*	200/30:250/25*	300/30:350/25*
	0,500	150/25*	150/25*	150/25*	200/30:250/25*
	1,000	150/25*	150/25*	150/25*	200/30:300/25*
R 60	0,100	150/30:200/25*	200/40:300/25*	300/40:500/25*	500/25*
	0,500	150/25*	150/35:200/25*	250/35:350/25*	350/40:550/25*
	1,000	150/25*	150/30:200/25*	200/40:400/25*	300/50:600/30
R 90	0,100	200/40:250/25*	300/40:400/25*	500/50:550/25*	550/40:600/25*
	0,500	150/35:200/25*	200/45:300/25*	300/45:550/25*	500/50:600/40
	1,000	200/25*	200/40:300/25*	250/40:550/25*	500/50:600/45
R 120	0,100	250/50:350/25*	400/50:550/25*	550/25*	550/60:600/45
	0,500	200/45:300/25*	300/45:550/25*	450/50:600/25*	500/60:600/50
	1,000	200/40:250/25*	250/50:400/25*	450/45:600/30	600/60
R 180	0,100	400/50:500/25*	500/60:550/25*	550/60:600/30	(1)
	0,500	300/45:450/25*	450/50:600/25*	500/60:600/50	600/75
	1,000	300/35:400/25*	450/50:550/25*	500/60:600/45	(1)
R 240	0,100	500/60:550/25*	550/40:600/25*	600/75	(1)
	0,500	450/45:500/25*	550/55:600/25*	600/70	(1)
	1,000	400/45:500/25*	500/40:600/30	600/60	(1)

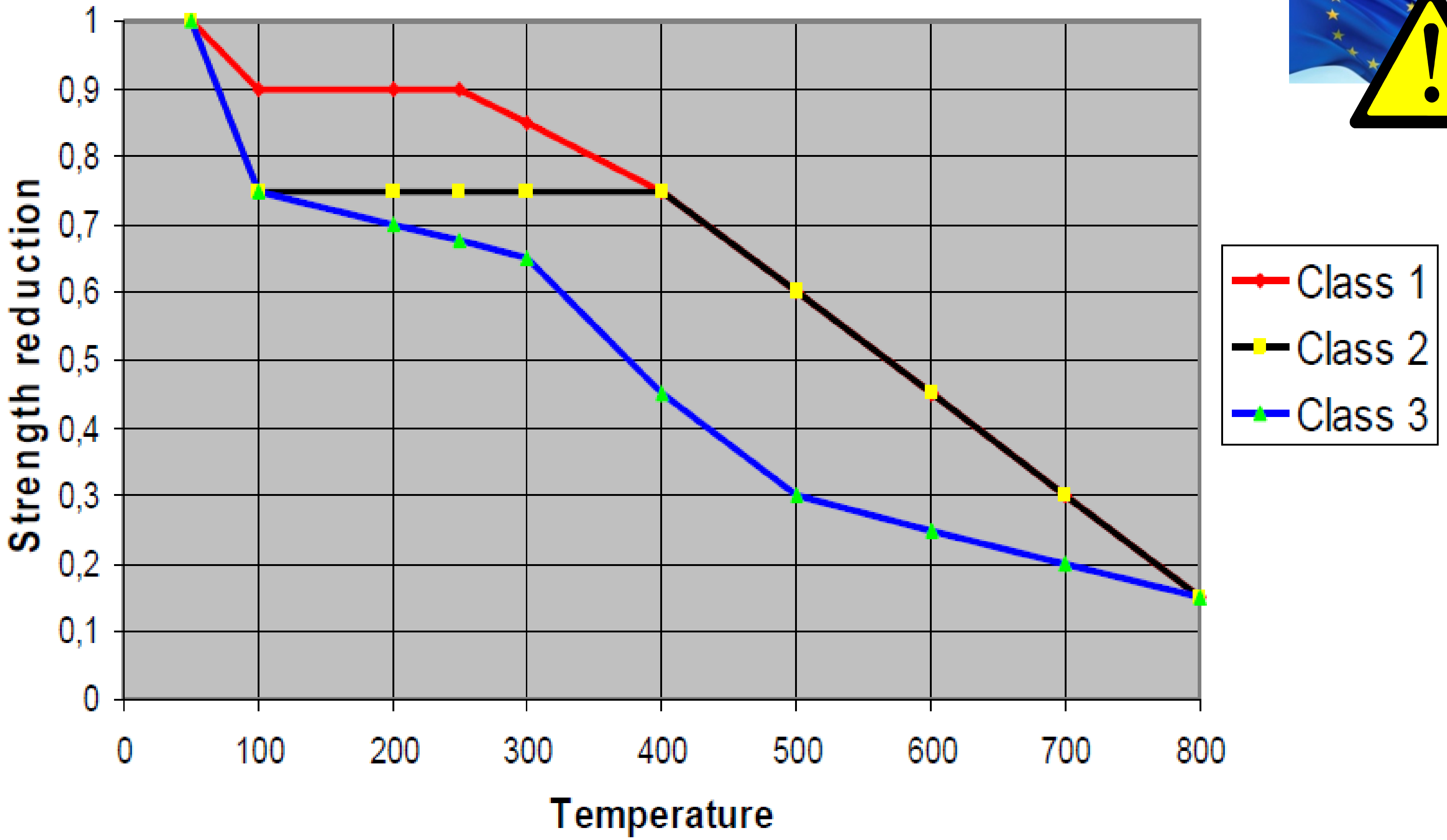
* Normally the cover required by EN 1992-1-1 will control.

(1) Requires width greater than 600 mm. Particular assessment for buckling is required.

SECTION 5 – Tabulated data

- **Tables for loadbearing and non loadbearing wall**
- **Fire walls have been added**
  - Classification M, to be used only if there are national requirements
- **Tables for simply supported and continuous beams**
- **Tables for simply supported and continuous slabs, flat slabs, ribbed slabs**

Reduction of strength at elevated temperature



Concrete C 55/67 and C 60/75 is Class 1, concrete C 70/85 and C80/95 is Class 2 and concrete C90/105 is Class 3.

Spalling

Methods for concrete grades C 55/67 to C 80/95 with higher content of silica fume than 6% by weight of cement and for concrete grades 80/95 < C ≤

Method A

Use reinforcement mesh with a nominal cover of 15 mm:

- Wire diameter ≥ 2 mm
- Pitch ≤ 50 x 50 mm
- Nominal cover to main reinforcement ≥ 40 mm

Method B

Use a type of concrete that will not spall under fire exposure – demonstrated by local experience or testing.

Method C

Use a protective layers which has been demonstrated that no spalling of concrete occurs under fire exposure.

Method D

Include in the concrete mix more than **2 kg/m³** of monofilament propylene fibres.

SECTION 6 - High strength concrete

(a1) (a2) (a3) (b1) (b2)

Tests done on samples (R90 - ISO curve) with the following concretes :

- Concrete M100 Bathonien : (a1) 1,2 kg/m^3, (a2) 1,5 kg/m^3, (a3) 2 kg/m^3 of monofilament polypropylen fibres Mf – L18Ø18

- Concrete M100 Garonne : (b1) 0,9 kg/m^3, (b2) 1,2 kg/m^3 of monofilament polypropylen fibres Mf – L18Ø18

SECTION 6 - High strength concrete

- **Thermal properties (thermal conductivity)**
- **specific structural design**

Increase of minimum cross section by factor	Class 1	Class 2
- Walls and slabs exposed on one side	1,1	1,3
- Other structural members	1,2	1,6
Increase of axis distance by factor	1,1	1,3
Note: Factors are recommended values, and may be modified in National Annex		
Factor for axis distance in Class 2 seems to be too high, and it should not depend on the strength reduction		

Moment capacity reduction factors for beams and slabs	k_m Class 1	k_m Class 2
Beams Slabs exposed to fire in the compression zone	0,98 0,98	0,95 0,95
Slabs exposed to fire in the tension side, $h_s \geq 120$ mm Slabs exposed to fire in the tension side, $h_s = 50$ mm	0,98 0,95	0,95 0,85

References of the presentation

- **Dissemination of information for training workshop, 18-20 February 2008, Brussels**

- **EN 1992-1-2 : 2004, The university of Manchester, www.structuralfiresafety.org**

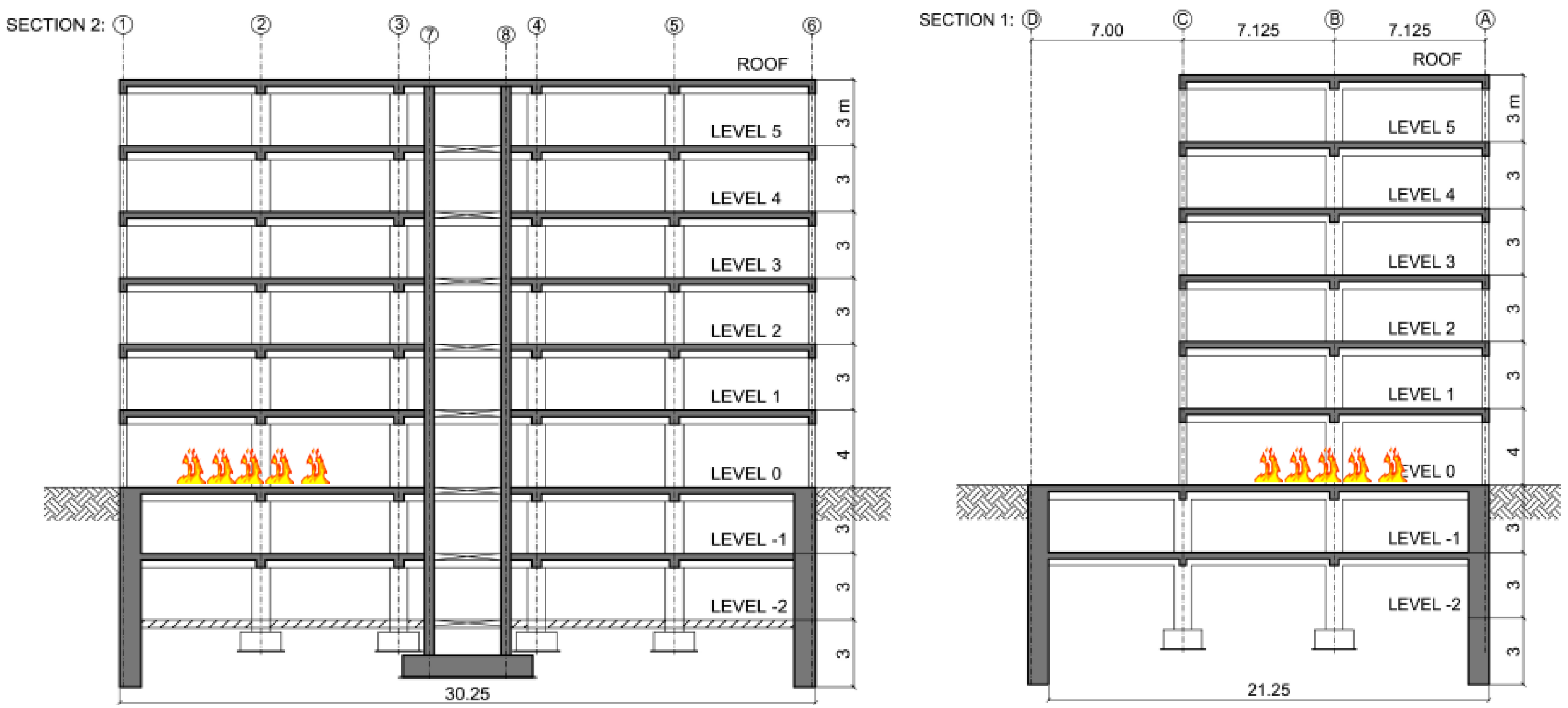
- **EN 1992-1-2 : 2004**

Part II

WORKED EXAMPLES

Worked example – building description

The studied building has been originally designed for « Design of concrete buildings » workshop held on 20-21 October 2011, Brussels and organised by JRC

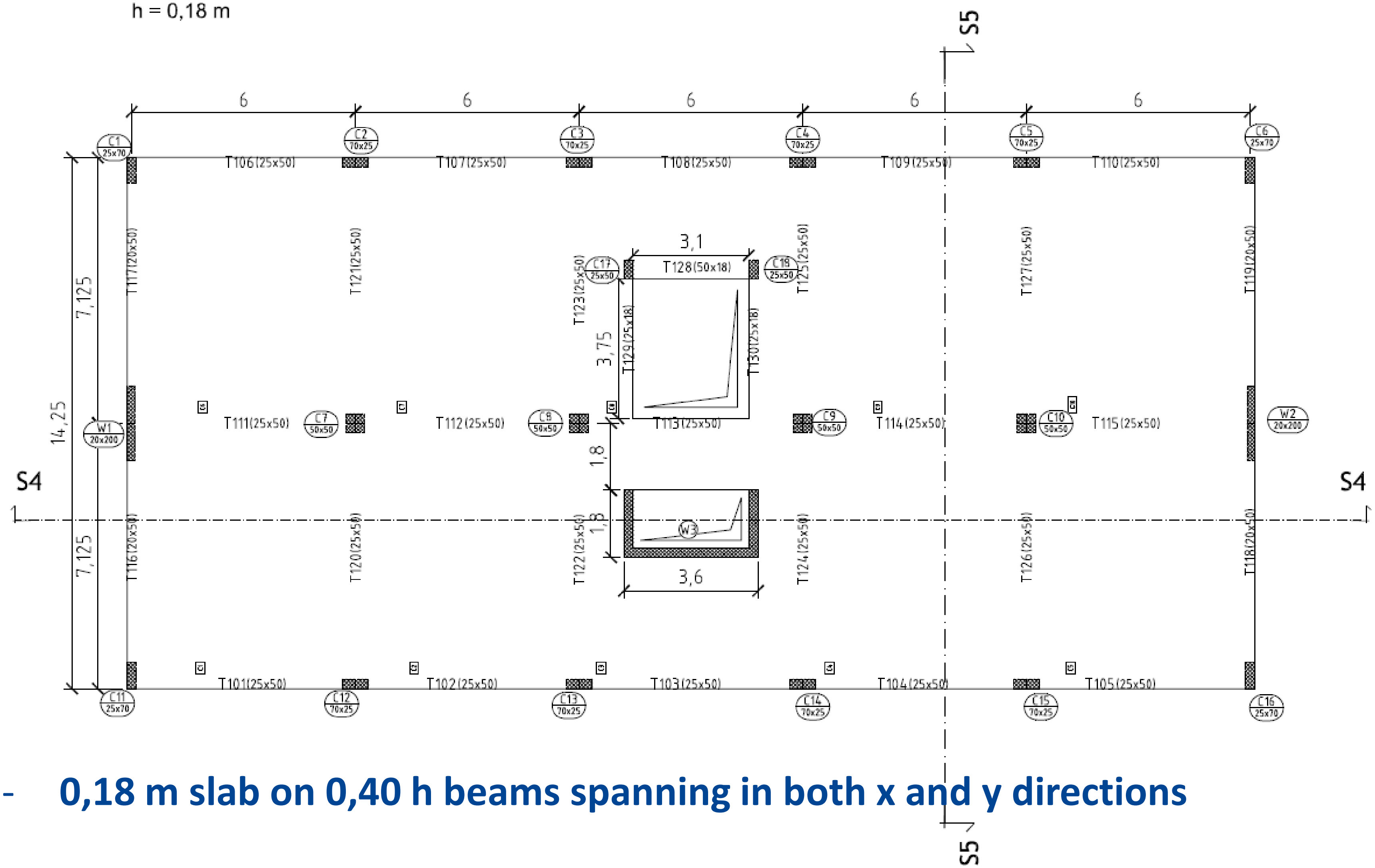


- **2-level underground parking**
- **ground floor and 1st to 5th floor : offices open to public, meeting rooms**
- **roof**

Worked example – building description

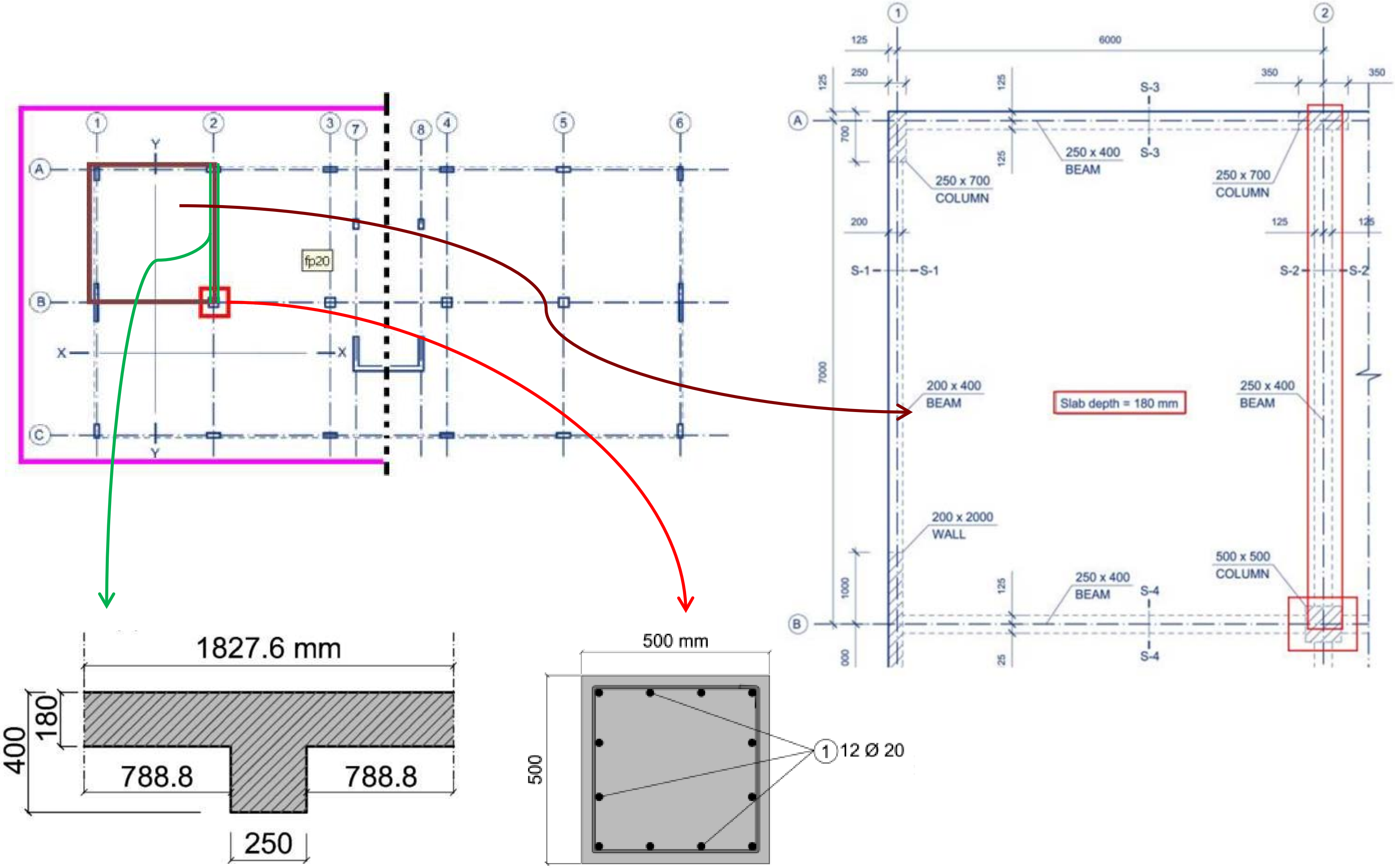
A-A SLAB ON BEAMS

h = 0,18 m



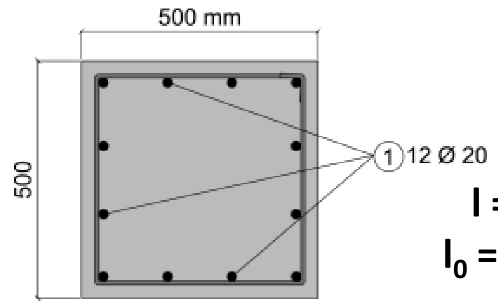
- **0,18 m slab on 0,40 h beams spanning in both x and y directions**

Worked example – studied elements



Worked example – studied elements

COLUMN

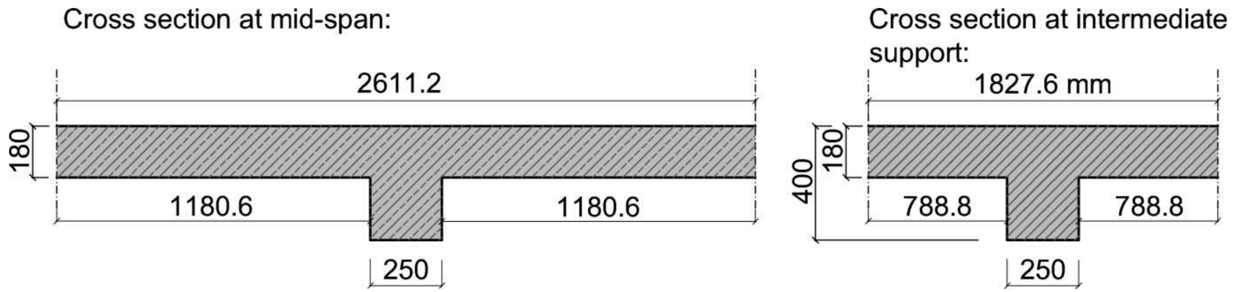


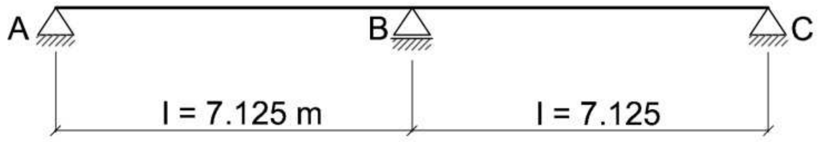
$l = 4m$

$l_0 = 3{,}1\ m$

COLUMN	Ø	Axis distance
Longitudinal reinforcement	12Ø20	52 mm
Stirrups	Ø12/200mm	36 mm

BEAM

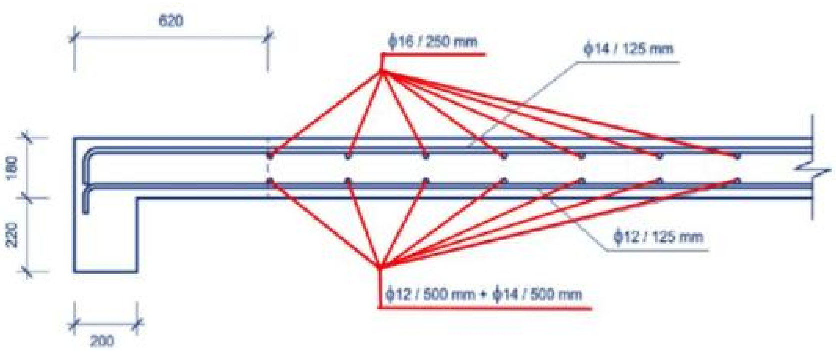


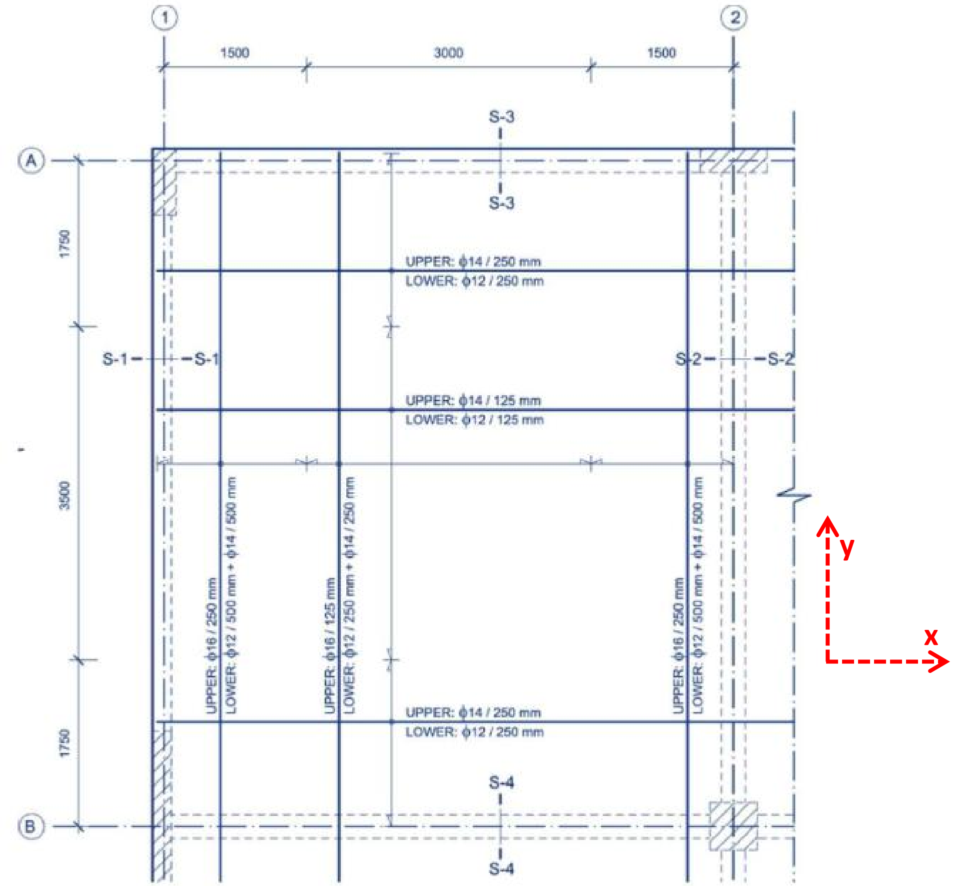


BEAM	Perimeter support	Mid-span	Intermediate support	Axis distance
upper	7Ø12	2Ø10	9Ø12	42 mm
lower	3Ø16	3Ø16	3Ø16	44 mm
Stirrups	Ø6/175	Ø6/175	Ø6/175	33 mm

Worked example – studied elements

SLAB





Due to the low lateral rigidity of the peripheral beams of the building, no bending moment will be considered at the end support of the slab

X direction SLAB	Middle strip (3m)	Axis distance
upper	Ø14/125mm	37 mm
lower	Ø12/125mm	36 mm

Y direction SLAB	Middle strip (3,5m)	Axis distance
upper	Ø16/125mm	52 mm
lower	Ø12/250mm Ø14/250mm	49 mm

Worked example : assumptions

LOADS :

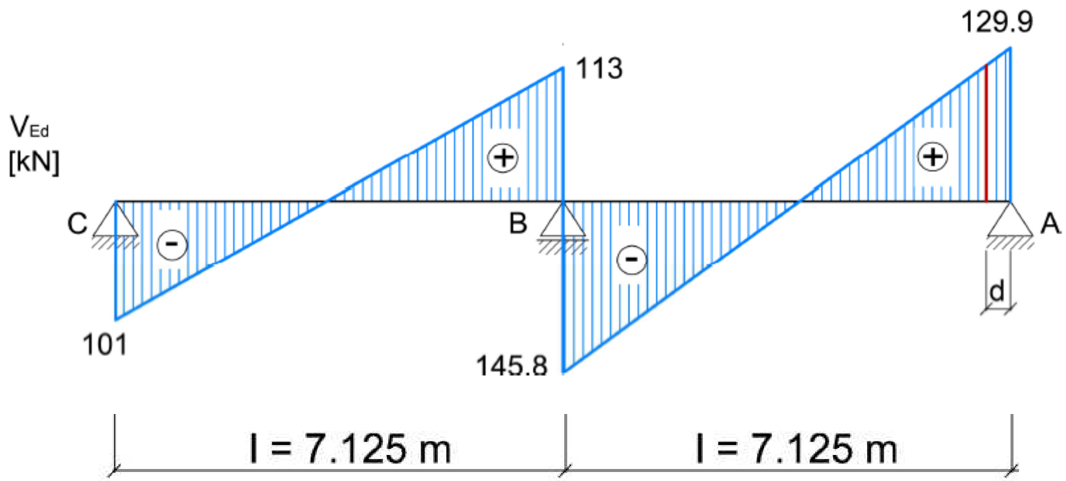
1. Self weight G1 : based on reinforced concrete unit weight (25 kN/m^3) and the geometry of structural elements.
2. Permanent loads G2 : Finishing, pavement, embedded services, partitions: 1,5 kN/m^2
3. Variable loads (office open to public, meeting rooms) : q_k = 4 kN/m^2 and ψ_2 = 0,6

$$\eta_{fi} = \frac{G_k + \psi_{fi} Q_{k,1}}{\gamma_G G_k + \gamma_{Q,1} Q_{k,1}} = 0{,}6$$

-Column B2 : N_{0Ed} = 4 384 kN ⇨ $N_{0Ed,\,fi}$ = 2 630 kN, e_{tot} = 3 cm

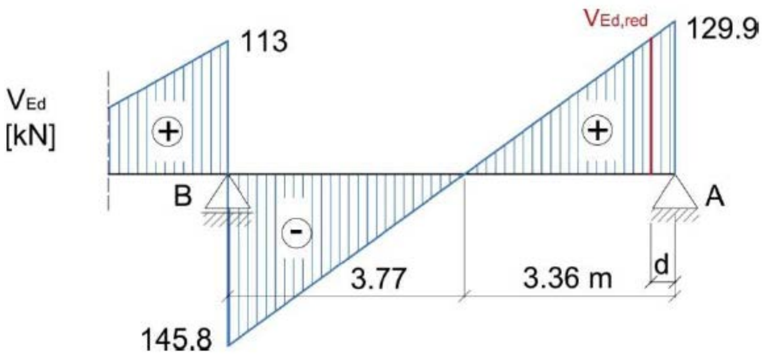
-Beam (AB) : p_{AB} = 21 kN/m ⇨ $p_{AB,fi}$ = 12,6 kN/m ➔ $M_{0Ed,fi}$ = 80 kN.m

- Beam (AB) :



The shear force may be determined at distance d from the support. So $V_{Ed,red}$ is calculated as:

$$\frac{129.9}{3.36} = \frac{V_{Ed,red}}{(3.36-0.372)} \Rightarrow V_{Ed,red} = 115.52\,kN$$



$V_{Ed,\,red,fi}$ = 69,3 **kN**

Worked example : assumptions

- Slab : $q_{slab,fi} = 25 \times 0{,}18 + 1{,}5 + 0{,}6 \times 4 = 8{,}4\ kN/m^2$

$\rho = \frac{\ell_x}{\ell_y}$	μ_x	μ_y
0,50	0,0965	0,2584
0,55	0,0892	0,2889
0,60	0,0820	0,3289
0,65	0,0750	0,3781
0,70	0,0683	0,4388
0,75	0,0620	0,5124
0,80	0,0561	0,5964
0,85	0,0506	0,6871
0,90	0,0456	0,7845
0,95	0,0410	0,8887
1,00	0,0368	1,0000

$$M_x^0 = \mu_x p \ell_x^2 \qquad M_y^0 = \mu_y M_x^0$$

ρ = 6/7,125 = 0,84
μ_x = 0,052
μ_x = 0,667

$M_{0Edx,\,fi}$ = 15,7 kN.m/m
$M_{0Edy,\,fi}$ = 10,5 kN.m/m

We have to check that :

$$M_{spanx,\,fi} + (M_{end\ supportx,\,fi} + M_{intermediate\ supportx,\,fi})/2 \geq M_{0Edx,\,fi}$$

$$M_{spany,\,fi} + (M_{end\ supporty,\,fi} + M_{intermediate\ supporty,\,fi})/2 \geq M_{0Edy,\,fi}$$

Worked example : assumptions

- Due to non uniformity of EU National choices, to avoid country specific conditions, for the example no exposure classes were selected and nominal cover to reinforcement c_{nom} was fixed:
  $c_{nom} = 30$ mm

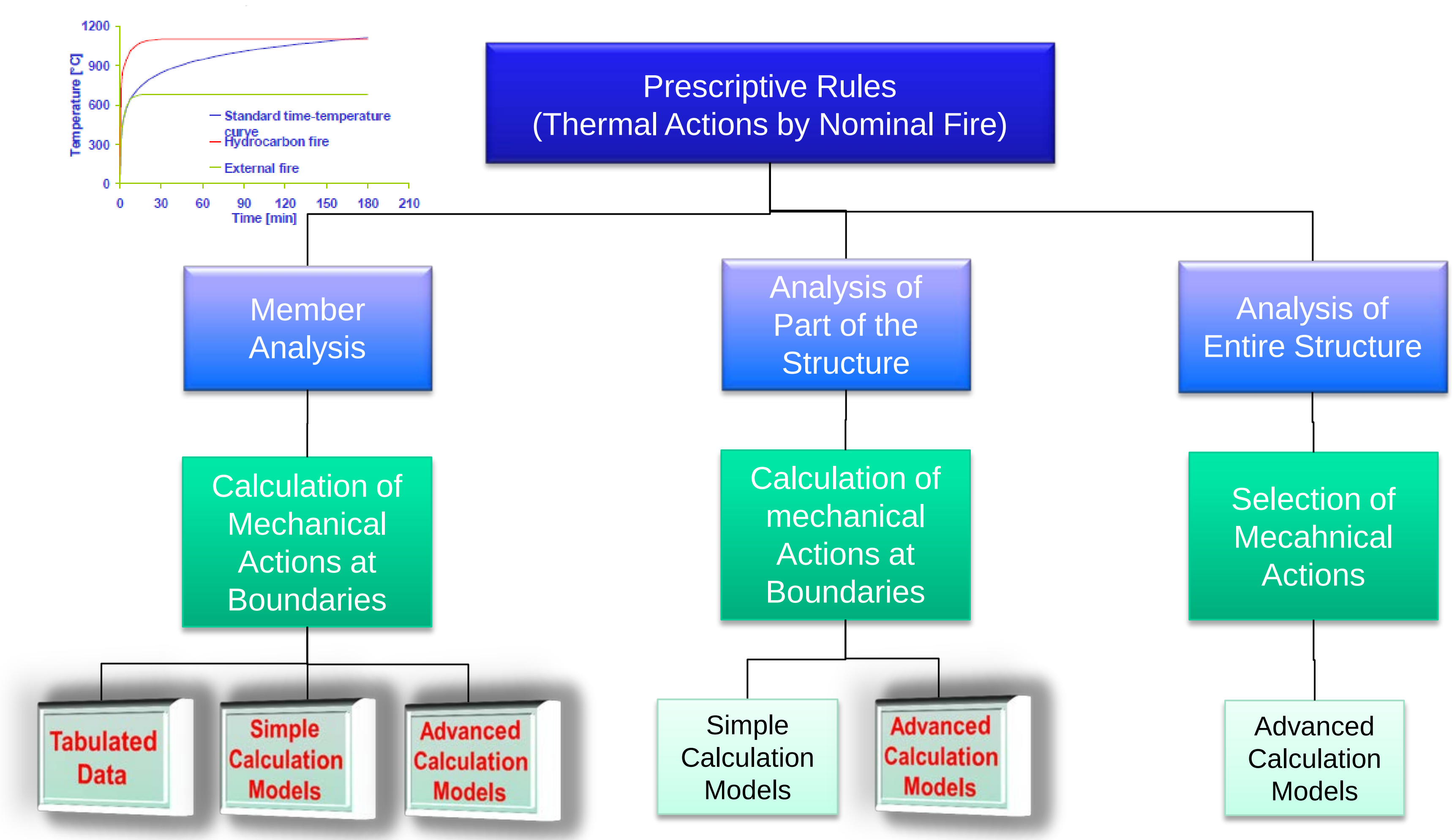
- Steel : Grade 500 class B, hot rolled, Strength $f_{yk} \geq 500$ MPa

- Concrete :
  → Beams and slabs: C25/30
  → Columns: C30/37

Thermal and physical properties for thermal transfert :

- Water content : 1,5 %
- Thermal conductivity : lower limit given in § 3.3.3
- Siliceous aggregates
- Emissivity related to the concrete surface : 0,7 as given in § 2.2

Worked example



European Commission

Tabulated data - column

Method B

Applicable if $\lambda_{fi} \leq 30$ and $e_{max} = 100$ mm

- $$n_{column} = \frac{N_{0Ed,fi}}{0{,}7 \times (A_c f_{cd} + A_s f_{yd})}$$

$$n_{column} = \frac{2630.10^3}{0{,}7 \times (500^2 \times 30/1{,}5 + 12 \times \pi \times 10^2 \times 500/1{,}15)}$$

$$n_{column} = 0{,}57$$

- l_0 = 3,1 m
- λ = 22,5
- $e_{tot} = e_0 + e_i$ = 30 mm
- $$w = \frac{A_s f_{yd}}{A_c f_{cd}} = 0{,}33$$
- Axis distance = 52 mm

Standard fire resistance	Mechanical reinforcement ratio ω	Minimum dimensions (mm). Column width b_{min}/axis distance a			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
1	2	3	4	5	6
R 30	0,100 0,500 1,000	150/25* 150/25* 150/25*	150/25* 150/25* 150/25*	200/30:250/25* 150/25* 150/25*	300/30:350/25* 200/30:250/25* 200/30:300/25*
R 60	0,100 0,500 1,000	150/30:200/25* 150/25* 150/25*	200/40:300/25* 150/35:200/25* 150/30:200/25*	300/40:500/25* 250/35:350/25* 200/40:400/25*	500/25* 350/40:550/25* 300/50:600/30
R 90	0,100 0,500 1,000	200/40:250/25* 150/35:200/25* 200/25*	300/40:400/25* 200/45:300/25* 200/40:300/25*	500/50:550/25* 300/45:550/25* 250/40:550/25*	550/40:600/25* 500/50:600/40 500/50:600/45
R 120	0,100 0,500 1,000	250/50:350/25* 200/45:300/25* 200/40:250/25*	400/50:550/25* 300/45:550/25* 250/50:400/25*	550/25* 450/50:600/25* 450/45:600/30	550/60:600/45 500/60:600/50 600/60
R 180	0,100 0,500 1,000	400/50:500/25* 300/45:450/25* 300/35:400/25*	500/60:550/25* 450/50:600/25* 450/50:550/25*	550/60:600/30 500/60:600/50 500/60:600/45	(1) 600/75 (1)
R 240	0,100 0,500 1,000	500/60:550/25* 450/45:500/25* 400/45:500/25*	550/40:600/25* 550/55:600/25* 500/40:600/30	600/75 600/70 600/60	(1) (1) (1)

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

(1) Requires width greater than 600 mm. Particular assessment for buckling is required.

Tabulated data - column

Method B

Standard fire resistance	Mechanical reinforcement ratio ω	Minimum dimensions (mm). Column width b_{min}/axis distance a			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
1	2	3	4	5	6
R 30	0,100	150/25*	150/25*	200/30:250/25*	300/30:350/25*
	0,500	150/25*	150/25*	150/25*	200/30:250/25*
	1,000	150/25*	150/25*	150/25*	200/30:300/25*
R 60	0,100	150/30:200/25*	200/40:300/25*	300/40:500/25*	500/25*
	0,500	150/25*	150/35:200/25*	250/35:350/25*	350/40:550/25*
	1,000	150/25*	150/30:200/25*	200/40:400/25*	300/50:600/30
R 90	0,100	200/40:250/25*	300/40:400/25*	500/50:550/25*	550/40:600/25*
	0,500	150/35:200/25*	200/45:300/25*	300/45:550/25*	500/50:600/40
	1,000	200/25*	200/40:300/25*	250/40:550/25*	500/50:600/45
R 120	0,100	250/50:350/25*	400/50:550/25*	550/25*	550/60:600/45
	0,500	200/45:300/25*	300/45:550/25*	450/50:600/25*	500/60:600/50
	1,000	200/40:250/25*	250/50:400/25*	450/45:600/30	600/60
R 180	0,100	400/50:500/25*	500/60:550/25*	550/60:600/30	(1)
	0,500	300/45:450/25*	450/50:600/25*	500/60:600/50	600/75
	1,000	300/35:400/25*	450/50:550/25*	500/60:600/45	(1)
R 240	0,100	500/60:550/25*	550/40:600/25*	600/75	(1)
	0,500	450/45:500/25*	550/55:600/25*	600/70	(1)
	1,000	400/45:500/25*	500/40:600/30	600/60	(1)

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

(1) Requires width greater than 600 mm. Particular assessment for buckling is required.

Linear interpolation between the values given in the tables may be carried out.

Minimal dimensions required for ω=0,33 and n=0,57 : 500/43

➔ **Column R90**

Tabulated data - beam

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
R 30	b_{min}= 80 a = 15*	160 12*			80	80	80
R 60	b_{min}= 120 a = 25	200 12*			100	80	100
R 90	b_{min}= 150 a = 35	250 25			110	100	100
R 120	b_{min}= 200 a = 45	300 35	450 35	500 30	130	120	120
R 180	b_{min}= 240 a = 60	400 50	550 50	600 40	150	150	140
R 240	b_{min}= 280 a = 75	500 60	650 60	700 50	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 3 no increase of a_{sd} is required.

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

R 120 : Interpolation between columns 2 and 3 gives for a width of 250 mm an axis distance of 40 mm.

The beam has only one layer of reinforcement :

a_{sd} = a+10 mm = 50 mm > 44 mm

➔ **Beam R 90**

European Commission

Tabulated data - slab

Standard fire resistance	Minimum dimensions (mm)			
	slab thickness h_s (mm)	axis-distance *a*		
		one way	two way: $l_y/l_x \leq 1,5$	two way: $1,5 < l_y/l_x \leq 2$
1	2	3	4	5
REI 30	60	10*	10*	10*
REI 60	80	20	10*	15*
REI 90	100	30	15*	20
REI 120	120	40	20	25
REI 180	150	55	30	40
REI 240	175	65	40	50

l_x and l_y are the spans of a two-way slab (two directions at right angles) where l_y is the longer span.

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

The axis distance *a* in Column 4 and 5 for two way slabs relate to slabs supported at all four edges. Otherwise, they should be treated as one-way spanning slab.

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

$l_y/l_x = 1,19 < 1,5$ → column 4 applies

Axis distance < 40 mm in X direction → **Slab R 180**

Additional rules on rotation capacity on supports may be given in National Annex

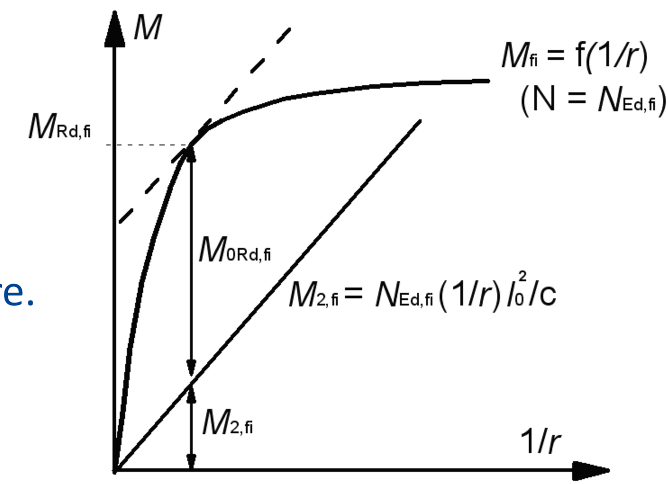
Annex B.3 : Assessment of a reinforced concrete cross-section exposed to bending moment and axial load by the method based on estimation of curvature

(A) Determine the moment-curvature diagram for $N_{Ed,fi}$ using, for each reinforcing bar and for each concrete zone, the relevant stress-strain diagram according to section 3 "Material properties"

(B) Use conventional calculation methods to determine the ultimate moment capacity, $M_{Rd,fi}$ for $N_{Ed,fi}$ and the nominal second order moment, $M_{2,fi}$, for the corresponding curvature.

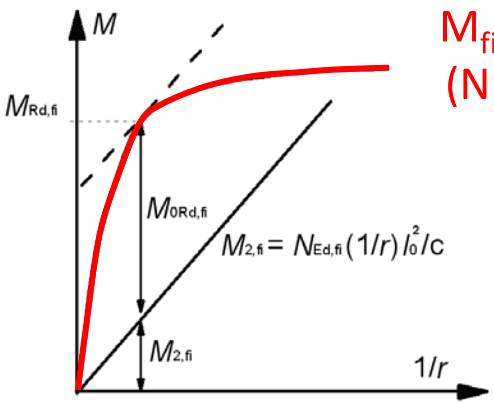
(C) Determine the remaining ultimate first order moment capacity, $M_{0Rd,fi}$, for the specified fire exposure and $N_{Ed,fi}$ as the difference between ultimate moment capacity, $M_{Rd,fi}$, and nominal second order moment, $M_{2,fi}$, so calculated.

(D) Compare the ultimate first order moment capacity, $M_{0Rd,fi}$, with the design first order bending moment for fire conditions $M_{0Ed,fi}$.

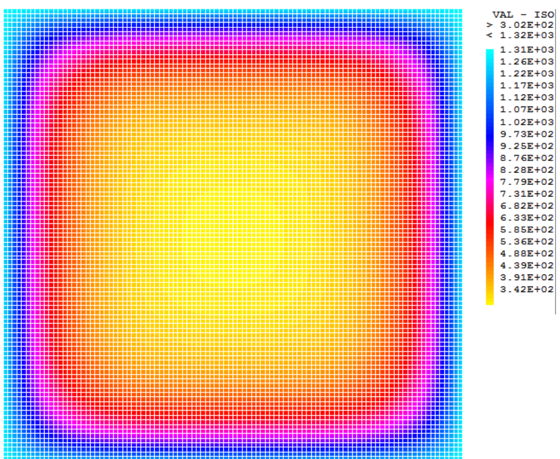


European Commission

Verification method for column



$M_{fi} = f(1/r)$
$(N = N_{Ed,fi})$



Thermal analysis led on ANSYS

INITIALIZATION :

$\kappa = \kappa_i$: **initialization of the curvature at the 1st calculation point i**

$N_{0Ed,fi}$: **axial load**

$\varepsilon_0 = 0$: **initialization of the strain at the column neutral axis**

$N_{temp} = N_c(\varepsilon_0, \kappa_i) + N_s(\varepsilon_0, \kappa_i)$ **total axial strength in the section (concrete + steel)**

$M_{temp} = M_c(\varepsilon_0, \kappa_i) + M_s(\varepsilon_0, \kappa_i)$ **total moment in the section (concrete + steel)**

$$dN_{temp} = \frac{\partial N_{temp}}{\partial \varepsilon_0}$$

$\Delta\varepsilon_0 = (N_{0Ed,fi} - N_{temp}) / dN_{temp}$ **strain increment calculation at the column neutral axis**

$\varepsilon_0 = \varepsilon_0 + \Delta\varepsilon_0$

$|N_{0Ed,fi} - N_{temp}| < \delta$

no

yes

result for $\kappa = \kappa_i$

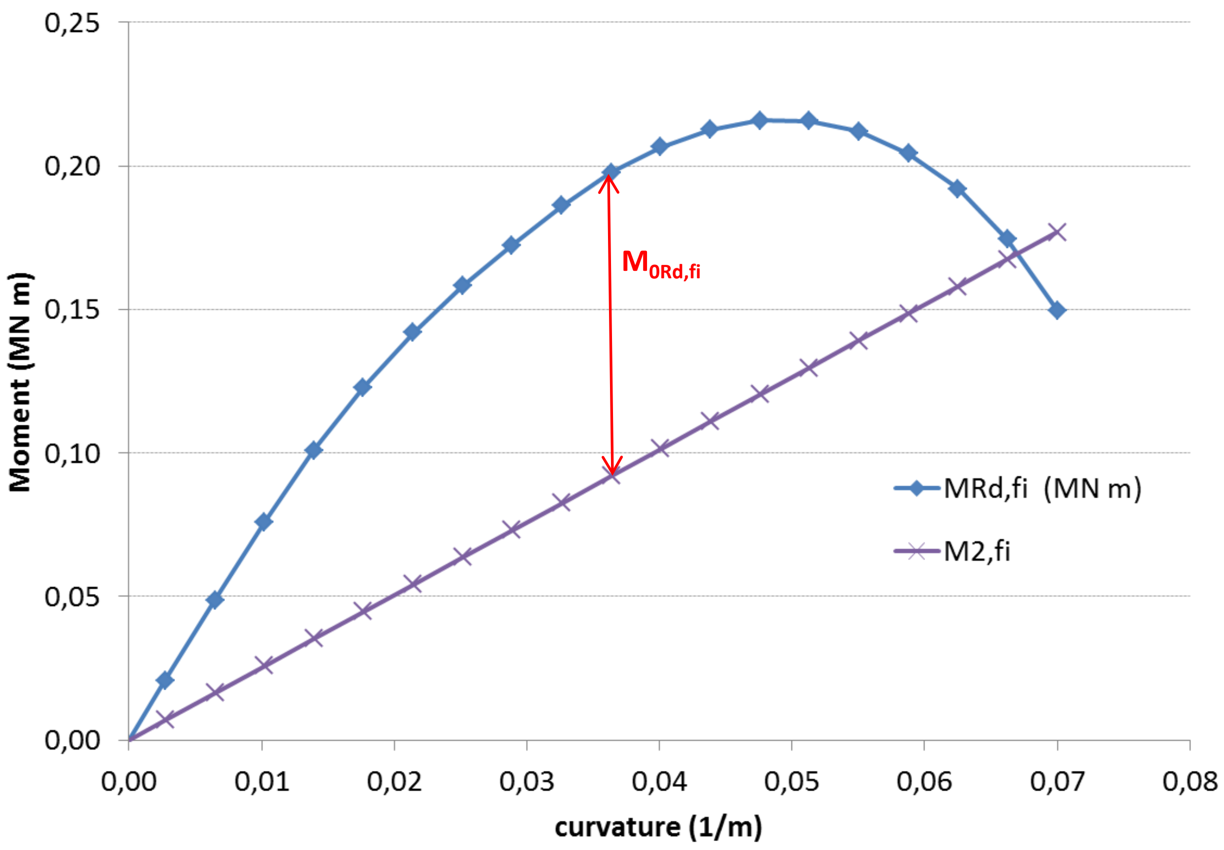
$M_i = M_{temp}$

Increment of κ

$\kappa = \kappa_{i+1}$

Verification method for column

Moment-curvature diagram at 240 minutes



l_0 = 3,1 m
e_{tot} = 3 cm
c = 10

$N_{0,Ed,fi}$ = 2,6300 MN
$M_{0Ed,fi}$ = 0,0789 MN m

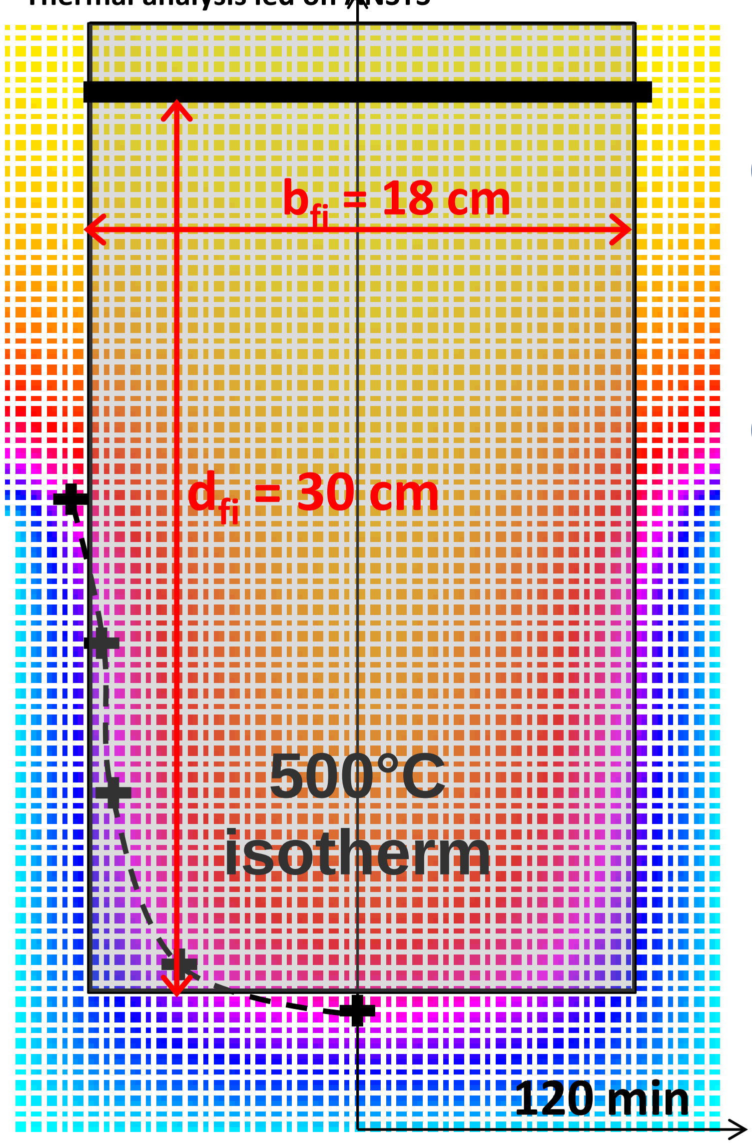
1/r = 0,0364
$M_{2,fi}$ = 0,0919 MN m
$M_{Rd,fi}$ = 0,1977 MN m
$M_{0,Rd,fi}$ = 0,1058 MN m

$M_{0,Rd,fi} > M_{0Ed,fi}$

➔ column R240

Verification method for beam

Thermal analysis led on ANSYS



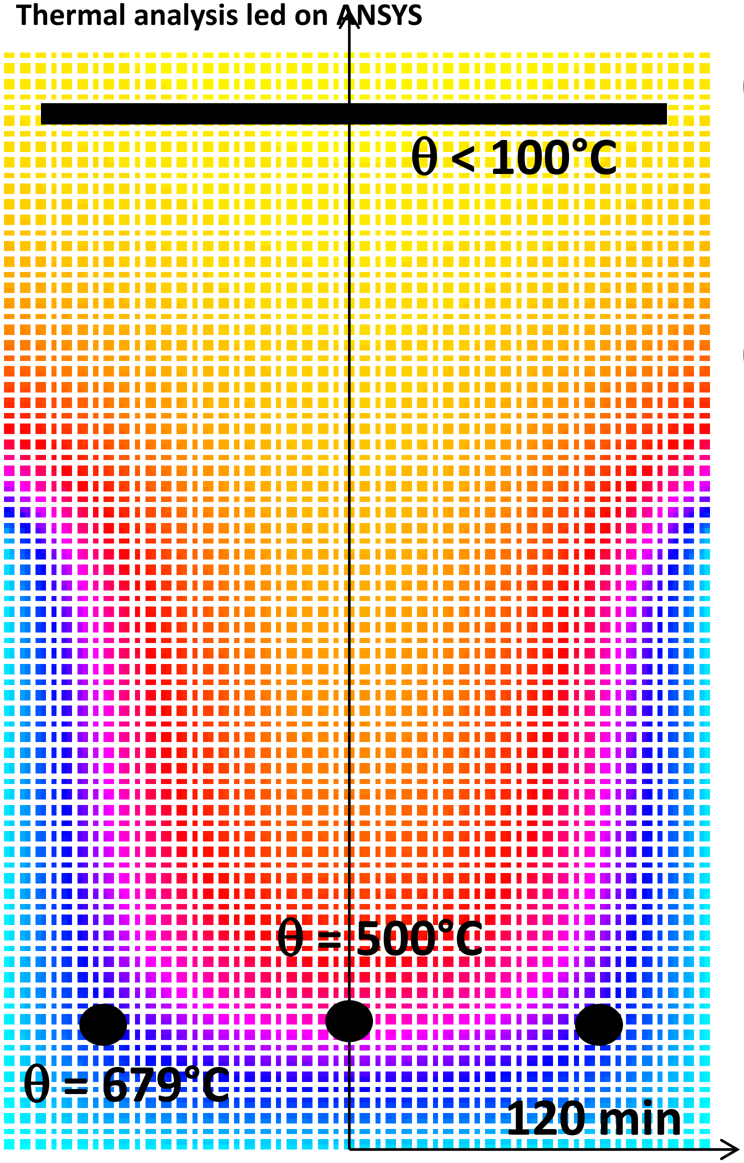
Annex B.1 : 500°C isotherm method

(a) Determine the isotherm of 500°C for the specified fire exposure, standard fire or parametric fire;

(b) Determine a new width b_{fi} and a new effective height d_{fi} of the cross-section by excluding the concrete outside the 500°C isotherm. The rounded corners of isotherms can be regarded by approximating the real form of the isotherm to a rectangle or a square

Verification method for beam

Thermal analysis led on ANSYS



(a) Determine the isotherm of 500°C for the specified fire exposure, standard fire or parametric fire;

(b) Determine a new width b_{fi} and a new effective height d_{fi} of the cross-section by excluding the concrete outside the 500°C isotherm. The rounded corners of isotherms can be regarded by approximating the real form of the isotherm to a rectangle or a square

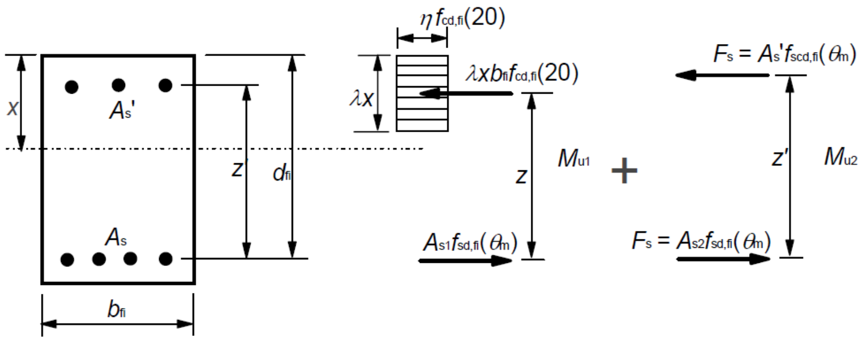
(c) Determine the temperature of reinforcing bars in the tension and compression zones. The temperature of the individual reinforcing bar is taken as the temperature in the centre of the bar.

Verification method for beam

(d) Determine the reduced strength of the reinforcement due to the temperature according to 4.2.4.3.

at 120 minutes, b_{fi} = 18 cm		T°C	k_s	F_s(kN)
At mid-span	1Ø16	500	0,78	78,4
	2Ø16	679	0,28	56,3
	Σ			**134,7**
At intermediate support	9Ø12	<100°C	1	**508,9**
At end support	7Ø12	<100°C	1	**395,8**

(e) Use conventional calculation methods for the reduced cross-section for the determination of the ultimate load bearing capacity with strength of the reinforcing bars, as obtained in (d).



Verification method for beam

✓ **Mid-span :**

$F_{s,\ fi,\ mid\text{-}span} = 134{,}7$ kN

$d_{fi} = 356$ mm ; $z = 345$ mm

} $M_{Rd,\ fi,\ mid\text{-}span} = 46$ kN.m

✓ **Intermediate support :**

$F_{s,\ fi,\ intermediate\ support} = 508{,}5$ kN

$d_{fi} = 300$ mm ; $z = 244$ mm

} $M_{Rd,\ fi,\ inter.\ support} = 123{,}8$ kN.m

✓ **End support :**

$F_{s,\ fi,\ end\ support} = 395{,}8$ kN

$d_{fi} = 300$ mm ; $z = 256$ mm

} $M_{Rd,\ fi,\ end\ support} = 101{,}3$ kN.m

$$M_{Rd,fi\ 120'} = M_{Rd,\ fi,\ mid\text{-}span} + (M_{Rd,\ fi,\ inter.\ sup.} + M_{Rd,\ fi,\ end\ sup.})/2 = 158{,}5 \text{ kN.m}$$

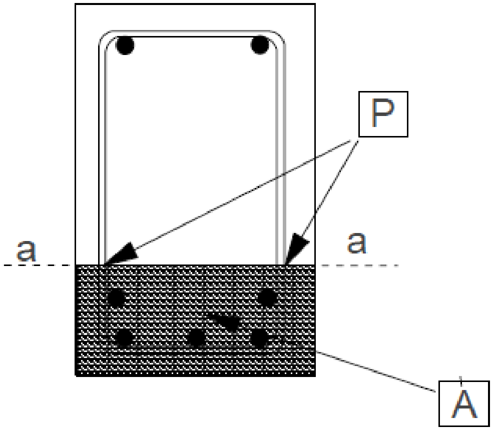
> M0Ed,fi = 80 kN.m

D.3 Design procedure for assessment of shear resistance of a reinforced concrete cross-section

(A) Compute the reduced geometry of the cross section as in Annex B.1 or B.2

(B) Determine the residual compression strength of concrete

(C) Determine the residual tensile strength of concrete (full strength $f_{ctd,fi} = f_{ctd,fi(20)}$ inside the isotherm of 500°C when applying the 500°C isotherm method).



A Effective tension area

(D) Determine the effective tension area (see EN 1992-1-1, Section 7) above delimited by the Section a-a.

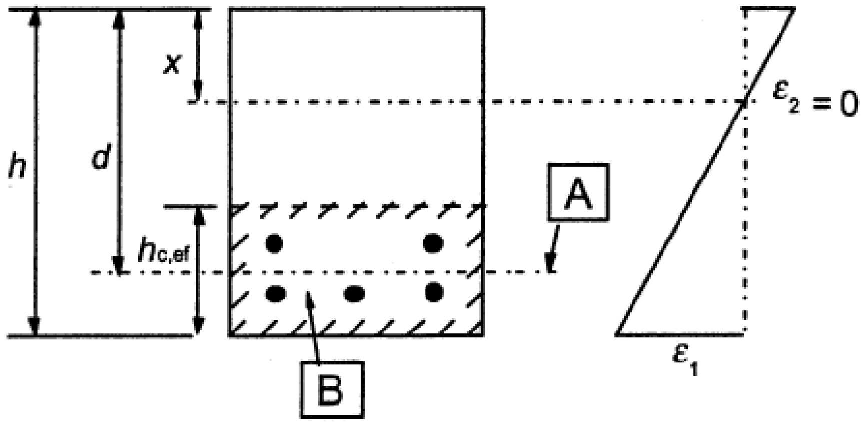
(E) Determine the reference temperature, θ_P, in links as the temperature in the point P (intersection of Section a-a with the link)

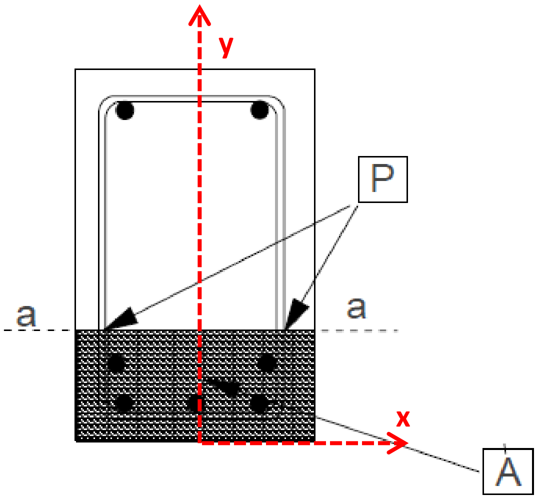
(F) The reduction of design strength of steel in links should be taken with respect to the reference temperature $f_{sd,fi} = k_s(\theta)\, f_{sd}(20)$.

(G) Calculation methods for design and assessment for shear, as in EN 1992-1-1, may be applied directly to the reduced cross-section.

Verification method for beam

Determination of the effective tension area (see EN 1992-1-1, Section 7) :





A Effective tension area

$h_{c,ef}$ = min {2,5(h – d), (h – x)/3 , h/2}

At 120 minutes :

$h_{c,ef,fi}$ = min {2,5(400 – 356); (400 – 50)/3 , 400/2}

$h_{c,ef,fi}$ = {110 ; 117 ; 200 }

$h_{c,ef,fi}$ = 110 mm ⟶

θ_P = {-92mm;110 mm}

θ_P = 547 °C

k_s (547) = 0,46 (§4.2.4.3)

Verification method for beam

Where shear reinforcement is provided :

$V_{Rd,fi} = \min \{ V_{Rd,sfi} = (A_{sw} / s) \cdot z_{fi} \cdot f_{ywd,fi} \cdot \cot \theta \quad ; \quad V_{Rd,max} = \alpha_{cw} \, b_{w,fi} \, z_{fi} \, \nu_1 f_{cd,fi} / (\cot \theta + \tan \theta) \}$

$A_{sw} = 2 \times \pi \times 3^2 = 56{,}5$ mm²
$s = 175$ mm
$z_{fi} = 345$ mm
$f_{ywd,fi} = k_s(\theta_P) \times 500/1 = 230$ Mpa
$\theta = 21{,}8°$ (assumption for cold design)

$\alpha_{cw} = 1$ (non prestressed structures)
$b_{w,fi} = 180$ mm (500°C isotherm method)
$z_{fi} = 345$ mm
$\nu_1 = 0{,}6\,(1-f_{ck}/250) = 0{,}54$
$f_{cd,fi} = 25$ Mpa (500°C isotherm method)
$\theta = 21{,}8°$ (assumption for cold design)

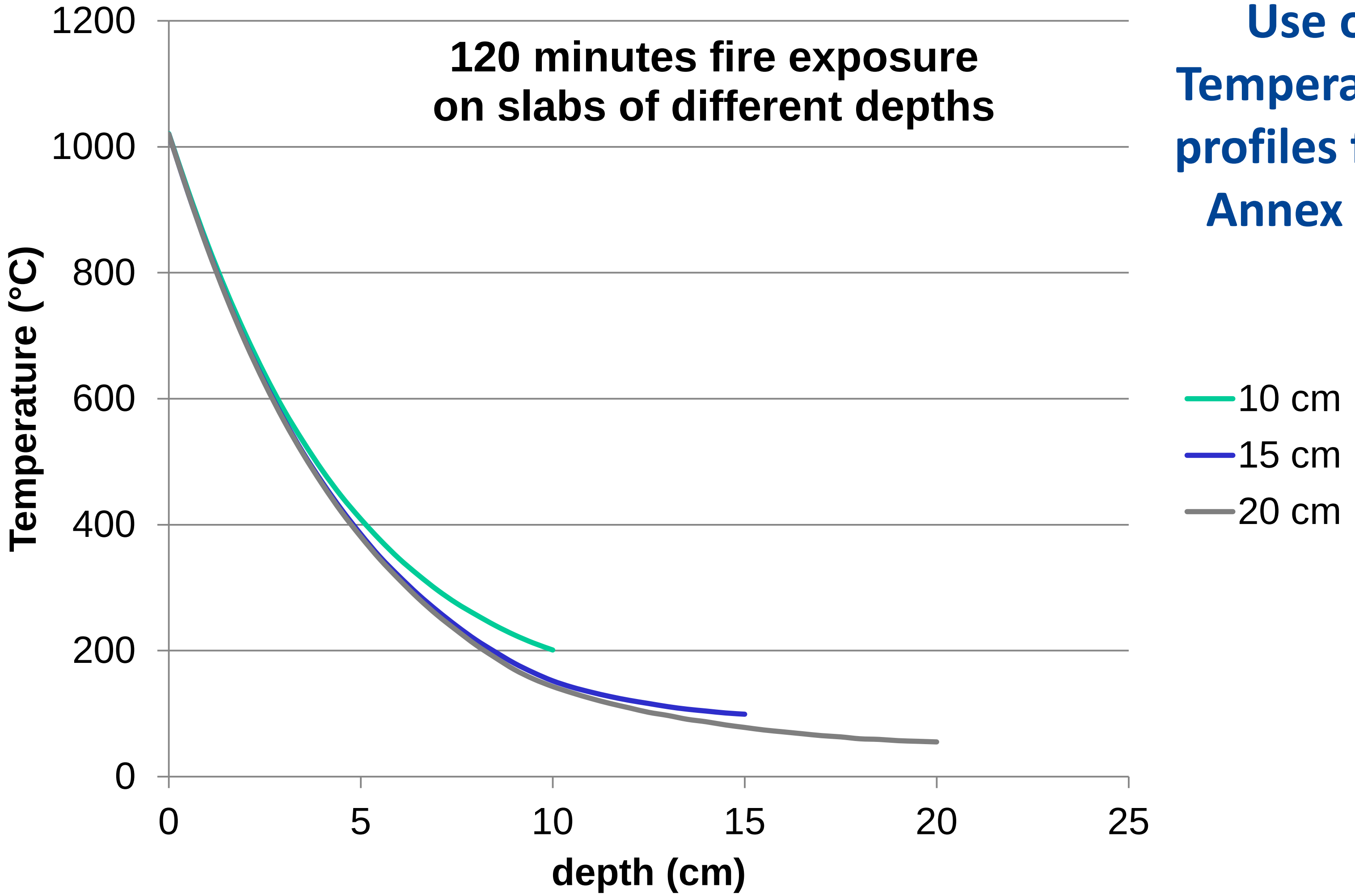
$V_{Rd,sfi}$ = 64 kN

$V_{Rd,max}$ = 289 kN

➔ $V_{Rd,fi} < V_{Ed,\,red,fi}$ = 69,3 kN, the beam is not verified for R120

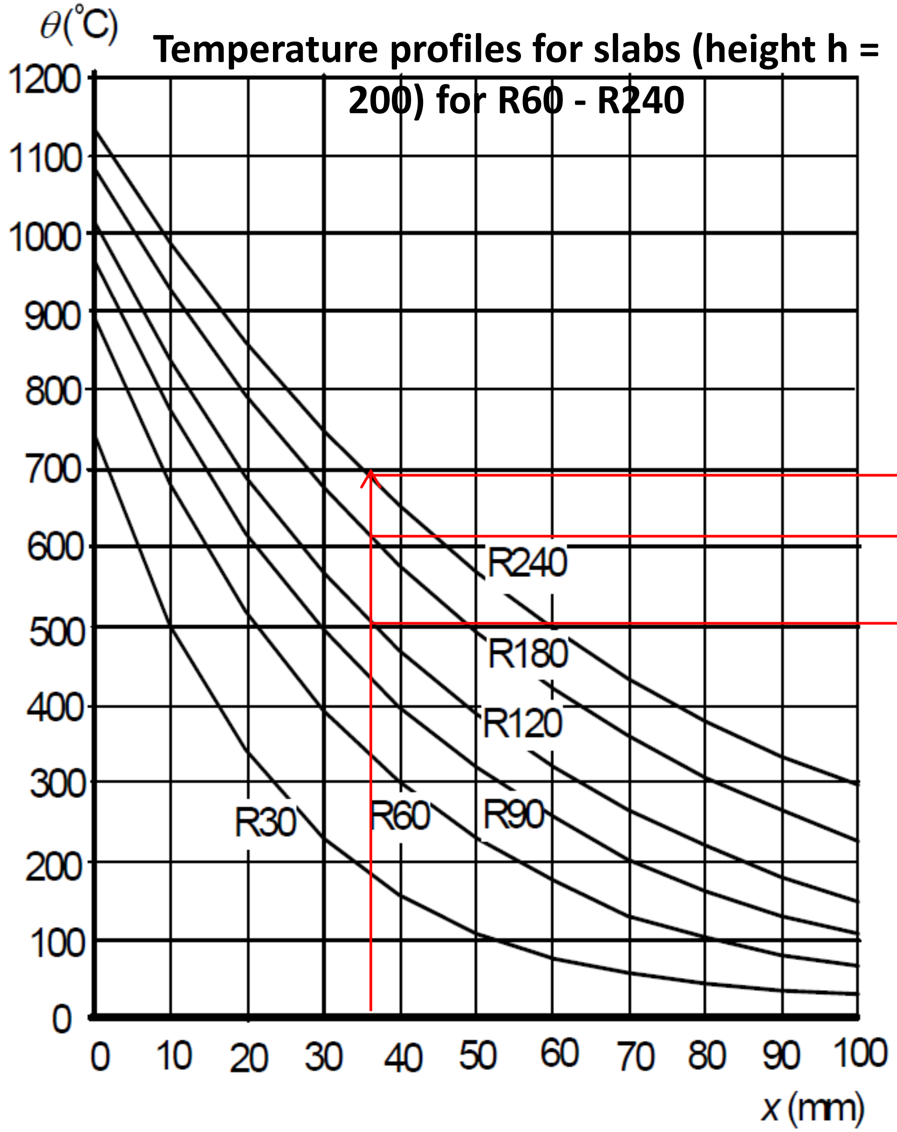
The spacing of the stirrups should be reduced to a minimal value of 160 mm
or the stirrups diameter should be increased to Ø8 mm

Verification method for slab



Use of Temperature profiles from Annex A ?

Verification method for slab



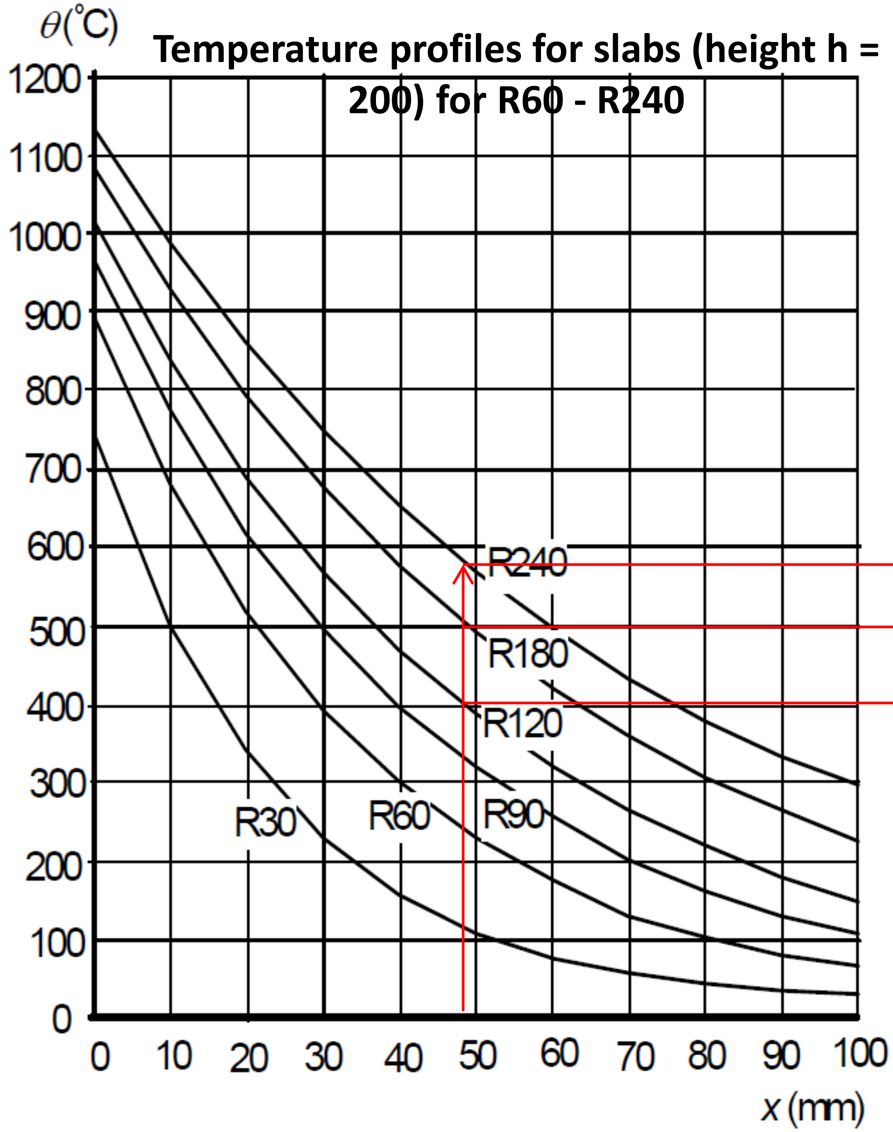
x is the distance from the exposed surface

At 36 mm axis distance

- 690°C – R 240
- 615°C – R 180
- 500°C – R 129

Verification method for slab

Temperature profiles for slabs (height h = 200) for R60 - R240



x is the distance from the exposed surface

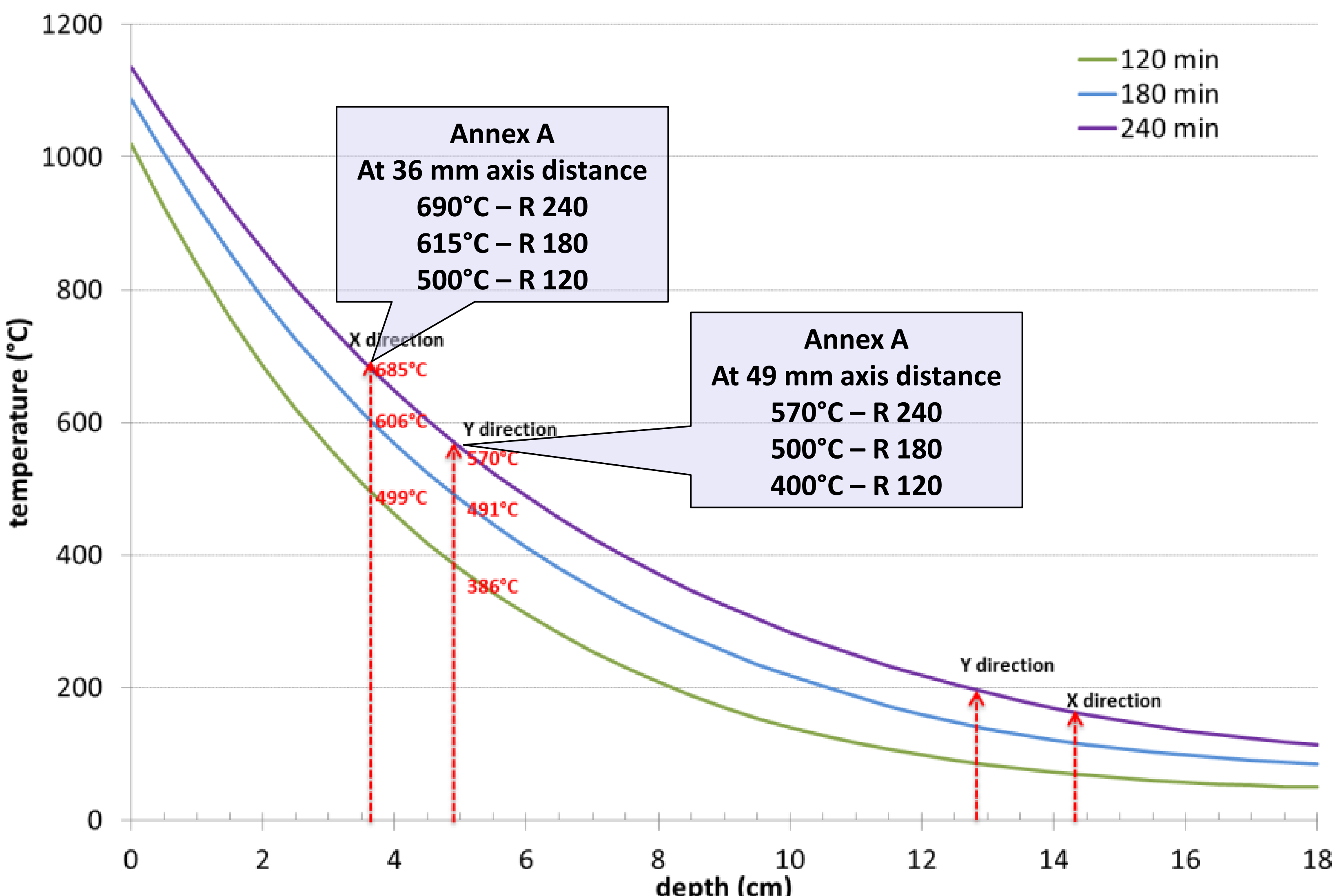
At 49 mm axis distance

570°C – R 240

500°C – R 180

400°C – R 120

Verification method for slab



Thermal analysis led on code_Aster

Verification method for slab

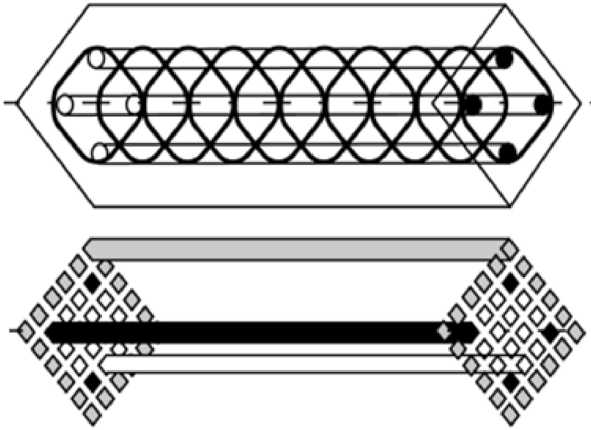
	Span		Intermediate support	
Direction	X	Y	X	Y
Temp steel (°C)	606	491	<200	<200
k_s	0,456	0,8	1	1
$A_{s,span} \times f_{sd,fi}(\theta_m)$ (kN/m)	206,3	427,3	615,7	804,2
z_{fi} (mm)	140	122	98	77
M_{fi} (kN.m/m)	29	52	60	62

	X	Y
$M_{Rd,fi}$ (kN.m/m)	59	83
$M_{0Ed,fi}$ (kN.m/m)	15,7	10,5
Check	**OK**	**OK**

The load-bearing capacity of the two-way slab is assumed verified under fire at 180 minutes. However, the rotational capacity of the slab at the intermediate support should be checked. Some complementary information may be given in National annexes to perform these calculations.

- Utilization of Code_ASTER (finite element model)

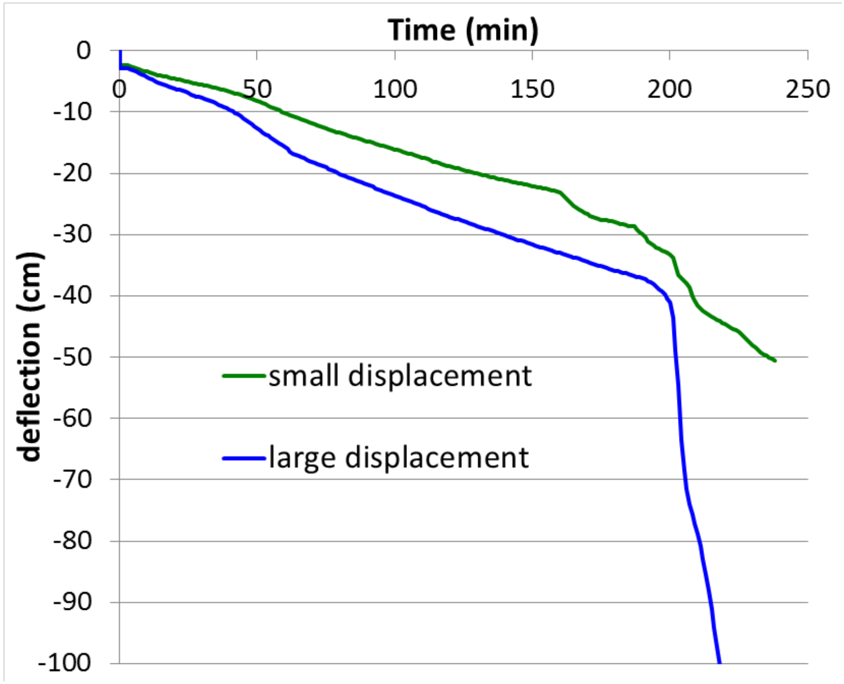
- Transient thermal modelling non linear analysis (2D, cross-section analysis)
- Temperature projection on the fibre of the beam element and/or on shell elements
- Transient non linear mechanical calculation (3D analysis) with large displacement assumptions



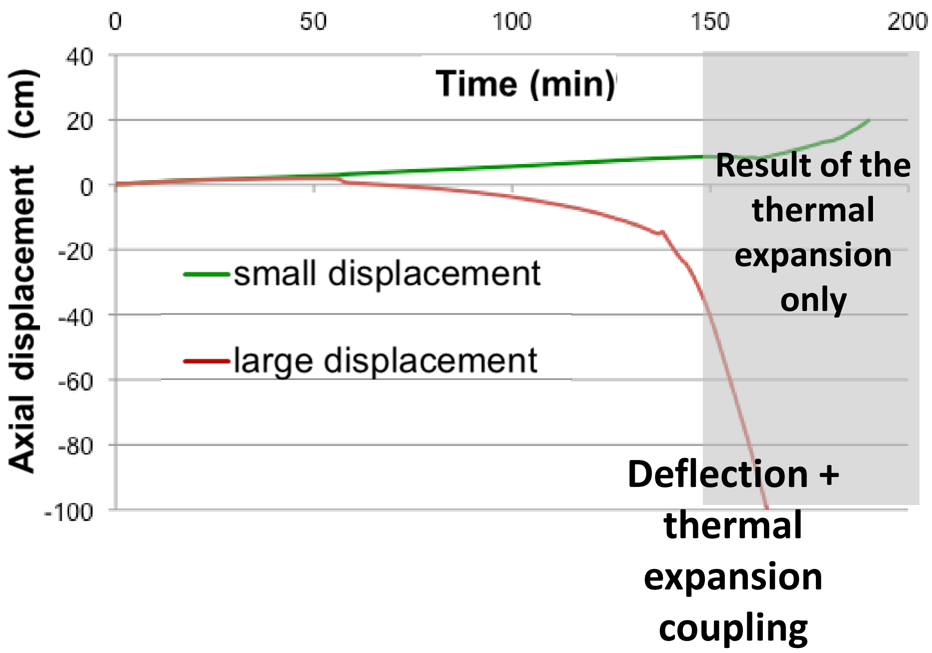
- **What about the large displacements ?**

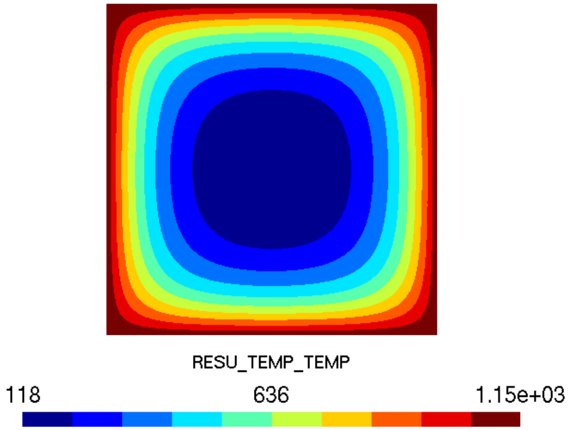
  →geometry readjustment for each time step (more realistic behaviour)

Slab

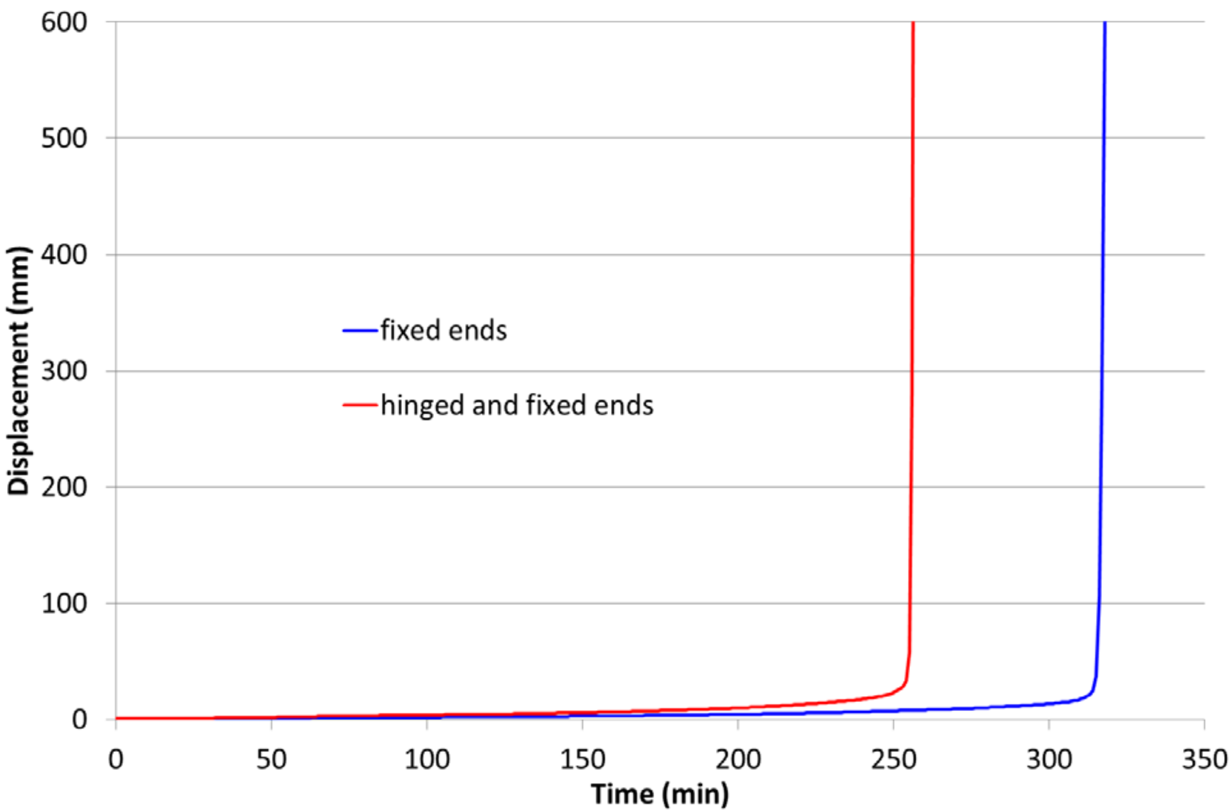


Beam



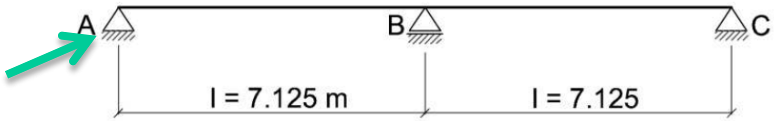


Results on the column

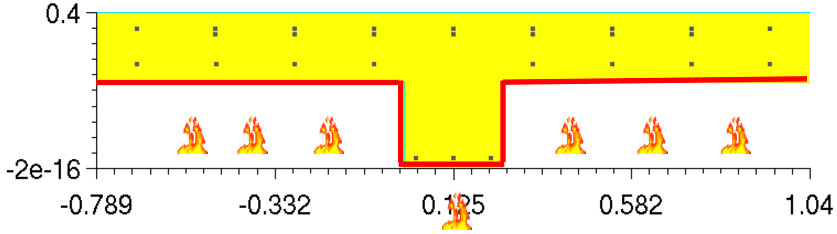


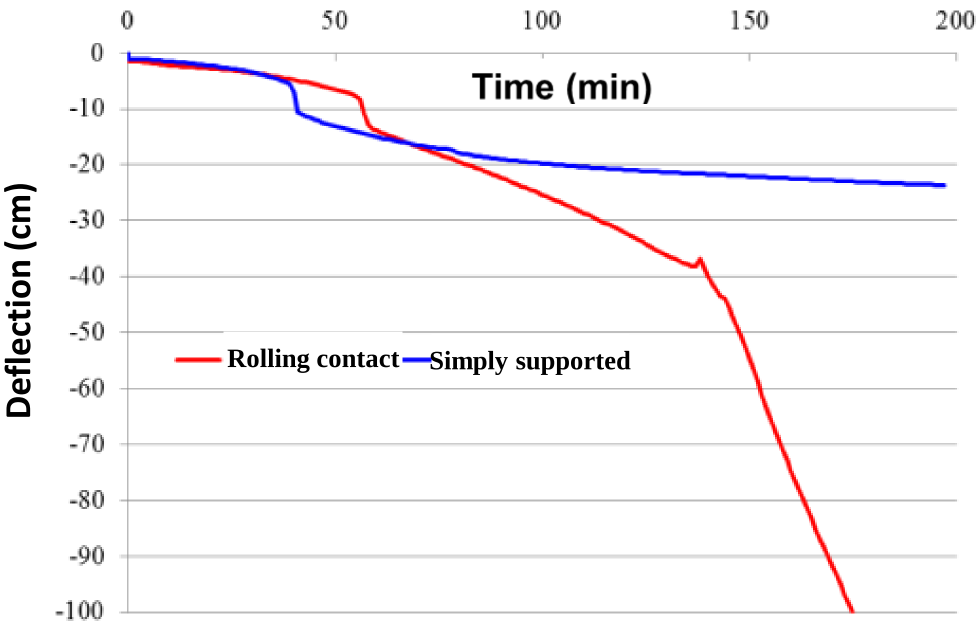
Vertical displacement allowed to make possible buckling

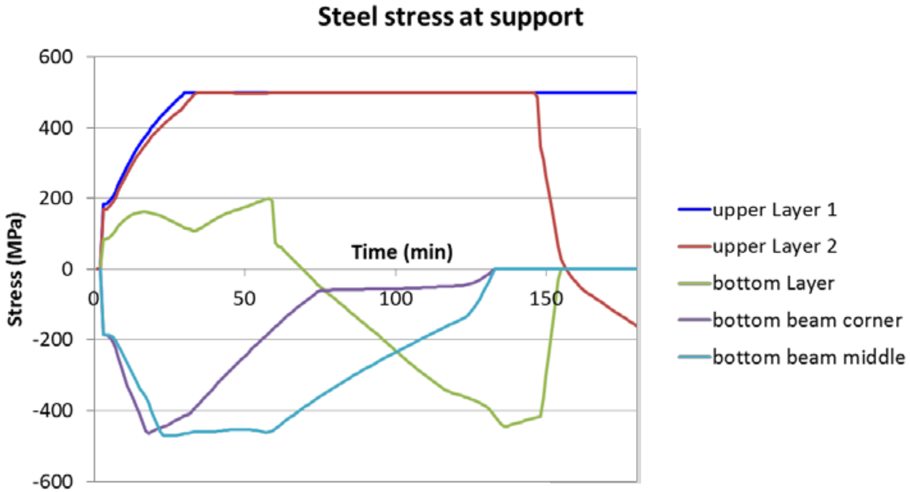
Results on the beam



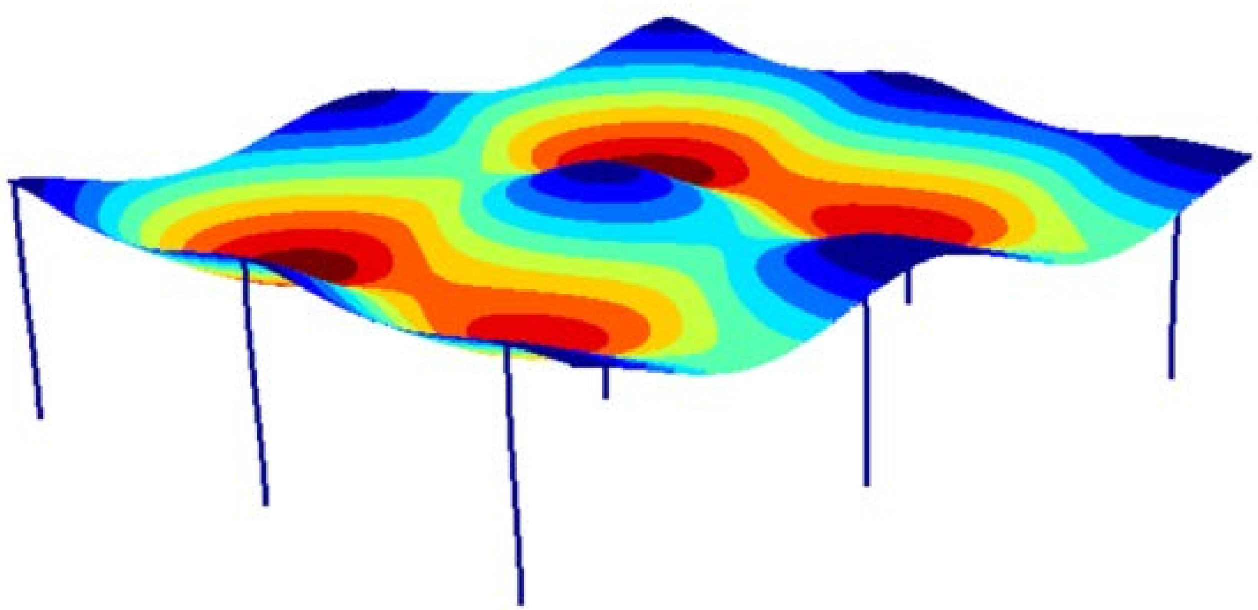
Intermediate support







Results on the beam-slab-column assembly

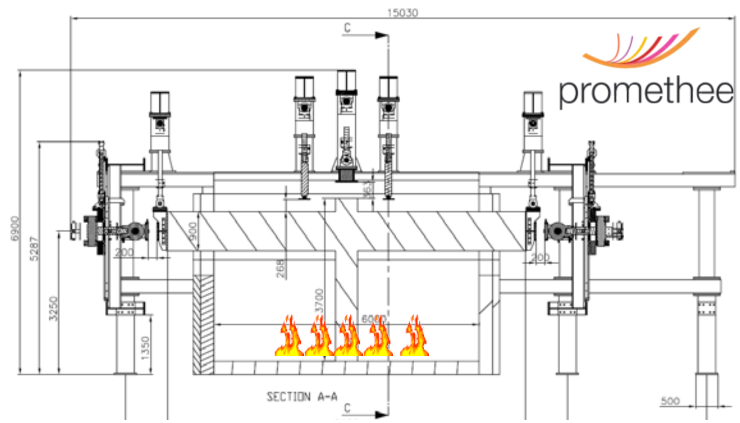


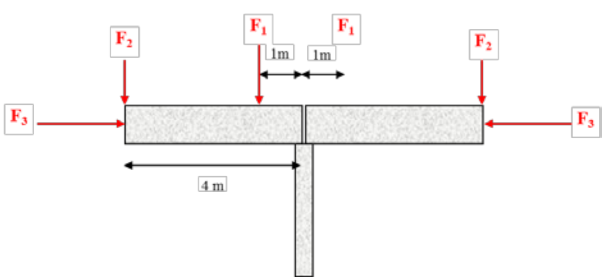
The failure (fast deflection growth in the middle of the slab) will appear at about 200 minutes (deflection is about 32 cm)

→ Global analysis allow to take into account localised fires (fire safety engineering)

News horizons…

- What about behavioural laws for the connections ?





News horizons…

- What about load induced thermal strain ?

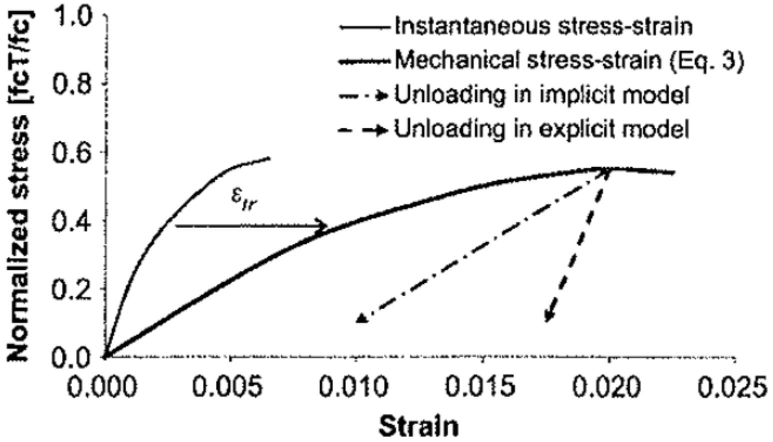


Fig. 1. Strain components in implicit and explicit models at 500 °C.

A formulation of the Eurocode 2 concrete model at elevated temperature that includes an explicit term for transient creep

T. Gernay[a,*], J.-M. Franssen[b]

Fire Safety Journal 51 (2012) 1–9

THE END !

Thank you for your attention...