Conceptual Fire Design and assessment

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Part I

CONCEPTUAL FIRE DESIGN

(Fabienne ROBERT)
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
To prove compliance with Essential Requirements:

- Tests + extended applications of results
- Calculation and/or design methods
- Combination of tests and calculations

National fire regulations:
- Required class - or fire resistance time

Parametric fire:
- Fire resistance time

Nominal fire:
- European REI (M) classification

Fire parts of Eurocodes:
- Tabulated data
- Simplified calculation
- Advanced calculation

CE marking
REI (M)

EN 13501-2
Classification standard

EN 1363, EN 1365
Fire tests
EUROCODE 2
Background and Applications

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Alternative verification method

Project Design

Prescriptive Regulation
(Thermal Actions given by a Nominal Fire)

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

- Advanced Calculation Models
EUROCODE 2
Background and Applications

Alternative verification method

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Performance-Based Code
(Physically based Thermal Actions)

Selection of Simple or Advanced Fire Development Models

Member Analysis

Calculation of Mechanical Actions at Boundaries

Analysis of Part of the Structure

Calculation of mechanical Actions et Boundaries

Analysis of Entire Structure

Selection of Mechanical Actions

Simple Calculation Models (if available)

Advanced Calculation Models

Advanced Calculation Models

Advanced Calculation Models
Content of EN 1992-1-2

1 - General
   - Basic requirements
   - Actions
   - Design values of material $X_{d,fi}$
   - Verification methods

2 - Basis of Design
   - Mechanical and thermal properties

3 - Material Properties
   - Strength reduction
   - Temperature profiles
   - Reduced cross-section
   - General aspects
   - Thermal response
   - Mechanical response
   - Validation

4 - Design Procedures
   - Annex A
     - Temperature profiles
   - Annex B
     - Isotherm 500 zone method
     - Section in bending & axial load
   - Annex C
     - Tabulated data for columns
   - Annex D
     - Calculation methods for shear, torsion and anchorage
   - Annex E
     - Simplified calculation methods for beams and slabs

5 - Tabulated data

6 - High strength concrete
   - Concrete
   - Reinforcing steel
   - Prestressing steel
   - Simplified calculation methods
   - Advanced calculation methods
   - Spalling
   - Joints
   - Protective layers
   - Columns
   - Walls
   - Tensile members
   - Beams
   - Slabs
   - Spalling
   - Thermal properties
   - Structural design
Scope

- 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
  \[ X_{d,fi} = X_k / \gamma_{M,fi} \quad \text{(favourable)} \]
  \[ X_{d,fi} = X_k \cdot \gamma_{M,fi} \quad \text{(unfavourable)} \]
(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);

\( \eta_{fi} \) is the reduction factor for the design load level for the fire situation.
Verification method – member analysis

Example for $\eta_{fi}$

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

Note 2: As a simplification a recommended value of $\eta_{fi} = 0.7$ may be used.
• **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 $\varepsilon_{cu1,\theta}$

$\alpha_{CC} = 1,0$ in fire design
The same strength reduction values are given for simplified calculation methods in Section 4
1. Siliceous concrete
2. Calcareous concrete

\[ k_1(\theta) \]

\[ k_2(\theta) \]

\[ \theta \text{ [°C]} \]
Concrete compressive strength

Graph showing the ratio of strength \( f_{c,e} / f_{c,u} \) against strain \( \varepsilon_c \) for different temperatures: 20 °C, 100 °C, 300 °C, 500 °C, and 700 °C.
Reinforcing and prestressing steel: stress-strain relationship

\[ \varepsilon_{sp,\theta} = \frac{f_{sp,\theta}}{E_{s,\theta}} \quad \varepsilon_{sy,\theta} = 0.02 \]

Class A reinforcement:

\[ \varepsilon_{st,\theta} = 0.15 \quad \varepsilon_{su,\theta} = 0.20 \]

\[ \varepsilon_{st,\theta} = 0.05 \quad \varepsilon_{su,\theta} = 0.10 \]
Strength reduction \((f_{yk})\) for reinforcing steel

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**Background and Applications**

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**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 (hot rolled and cold worked) for strains \(\varepsilon_{s,fi} < 2\%\)

Recommended with experimental evidence.
Strength reduction ($\beta_{fpk}$) 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**

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

**Class B**

$\beta = 0.9$
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Thermal properties

Convective heat flux

Radiative heat flux

Percentage reduction of density

Specific heat [kJ/kg K]
(Moisture content, u = 3%)
(u = 1.5%)
(u = 0%)

Thermal conductivity

www.structuralfiresafety.org

www.structuralfiresafety.org

Figure 3.7 – Conductivité thermique du béton
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Thermal Conductivity

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Range for national definitions

Thermal Conductivity

Thermal conductivity [W/(mK)]

Temperature [°C]
Thermal Elongation

Total thermal elongation of concrete

Curve 1: Siliceous aggregate
Curve 2: Calcareous aggregate
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
• **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.
• 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 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
- Annex E
- Simplified method to calculate bending capacity for predominantly uniformly distributed loads
- This is some kind of extension of Tabulated data
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 $\theta_p$ 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).
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Background and Applications

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Spalling

CALCULATION METHODS
Define exposure class

X0 or XC1 (dry)

Moisture content ≤ 3 %

TABULATED DATA

Explosive spalling is covered by minimum requirements
No further check needed

Is moisture content known

No, or yes but > 3 %

Avoid spalling by more accurate assessment

Moisture content, type of aggregates, permeability of concrete, heating rate

Yes

OK

Has the correct behaviour been checked by tests

Solid slabs OK, some beams OK

No

Assume loss of cover and calculate R
Falling off of concrete

- Reinforcement
- Spacing ≤ 100 mm
- Diameter ≥ 4 mm
- Axis distance ≥ 70 mm
- Provide surface reinforcement mesh

Unless tests have proved that falling-off does not occur.
(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.
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 \( \eta_{fi} \) for use in a Country may be found in its National Annex.

For walls and columns load level \( \eta_{fi} \) or degree of utilisation \( \mu_{fi} \) 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 \( \leq 3 \) m and first order eccentricity \( \leq 0,15h \) 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 \( \leq 0,25h \) and \( \lambda_{fl} \leq 30 \n  
In Method A degree of utilisation:

\[
\mu_{fl} = \frac{N_{Ed,fl}}{N_{Rd}}
\]

In Method B load level is defined as:

\[
n = \frac{N_{0Ed,fl}}{l(0,7(A_{c} f_{cd} + A_{s} f_{yd}))}
\]

Slenderness, \( l_{o,fl} \)
- upper floor 0,7 l
- intermediate floor 0,5 l
### SECTION 5 – Tabulated data

#### TABULATED DATA FOR COLUMNS: tables for Method B

<table>
<thead>
<tr>
<th>Standard fire resistance</th>
<th>Mechanical reinforcement ratio $\omega$</th>
<th>Minimum dimensions (mm). Column width $b_{mn}$/axis distance $a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$n = 0.15$</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>R 30</td>
<td>0.100</td>
<td>150/25*</td>
</tr>
<tr>
<td></td>
<td>0.500</td>
<td>150/25*</td>
</tr>
<tr>
<td></td>
<td>1.000</td>
<td>150/25*</td>
</tr>
<tr>
<td>R 60</td>
<td>0.100</td>
<td>150/30:200/25*</td>
</tr>
<tr>
<td>R 120</td>
<td>0.100</td>
<td>250/50:350/25*</td>
</tr>
<tr>
<td></td>
<td>0.500</td>
<td>200/45:300/25*</td>
</tr>
<tr>
<td></td>
<td>1.000</td>
<td>200/40:250/25*</td>
</tr>
<tr>
<td>R 180</td>
<td>0.100</td>
<td>400/50:500/25*</td>
</tr>
<tr>
<td></td>
<td>0.500</td>
<td>300/45:450/25*</td>
</tr>
<tr>
<td></td>
<td>1.000</td>
<td>300/35:400/25*</td>
</tr>
<tr>
<td>R 240</td>
<td>0.100</td>
<td>500/60:550/25*</td>
</tr>
<tr>
<td></td>
<td>0.500</td>
<td>450/45:500/25*</td>
</tr>
<tr>
<td></td>
<td>1.000</td>
<td>400/45:500/25*</td>
</tr>
</tbody>
</table>

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

(1) Requires width greater than 600 mm. Particular assessment for buckling is required.
• 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
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.
• Thermal properties (thermal conductivity)
• Specific structural design

<table>
<thead>
<tr>
<th>Increase of minimum cross section by factor</th>
<th>Class 1</th>
<th>Class 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Walls and slabs exposed on one side</td>
<td>1,1</td>
<td>1,3</td>
</tr>
<tr>
<td>- Other structural members</td>
<td>1,2</td>
<td>1,6</td>
</tr>
<tr>
<td>Increase of axis distance by factor</td>
<td>1,1</td>
<td>1,3</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Moment capacity reduction factors for beams and slabs</th>
<th>$k_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>Class 2</td>
</tr>
<tr>
<td>Beams</td>
<td>0,98</td>
</tr>
<tr>
<td>Slabs exposed to fire in the compression zone</td>
<td>0,98</td>
</tr>
<tr>
<td>Slabs exposed to fire in the tension side, $h_s \geq 120$ mm</td>
<td>0,98</td>
</tr>
<tr>
<td>Slabs exposed to fire in the tension side, $h_s = 50$ mm</td>
<td>0,95</td>
</tr>
</tbody>
</table>
References of the presentation

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


Part II

CASE STUDY (Caroline MORIN)
Objective
Apply the design methods presented in the Eurocode 2 ‘Design of concrete structures ‘ Part 1-2 ‘Structural fire’ on a structure exposed under fire

Methodology
Selection of 2 elements in the selected structure
- A continuous beam
- A column

Verification of the design of the structure under a fire with:
- Tabulated data
- Simplified calculation method
- Advanced calculation method
Structure
Reinforcing steel of the intermediate selected span

INTRODUCTION

Reinforcing steel of the intermediate selected span
**Sections**

**Beam**
- $b=0.30$ m * $h=0.43$ m
- Bars in tension in the middle of the span: $6\Phi 16$, $a=48$ mm
- Bars near the support (west side): $2\Phi 16$ ($a=68$ mm) & $4\Phi 20$ ($a=50$ mm)
- Bars near the support (east side): $4\Phi 20$ ($a=50$ mm)

**Column**
- $b=0.30$ m, $l=2.80$ m, $a=45$ mm
- Longitudinal reinforcing steel: $8\Phi 20$

![Diagram of beam and column sections with measurements](image)
**Scope (EN 1992-1-2, section 5.1 & 5.2)**

Design solutions for the fire exposure **up to 240 minutes**

Normal weight concrete made with **siliceous aggregates**

No further checks are required concerning shear, torsion, anchorage

No further checks are required concerning spalling, except for surface reinforcement

**General design rules**

For load bearing function, minimum requirements concerning **section sizes and axis distance of steel reinforcement** are given

Symbol used in tables
Column characteristics

300/45, reinforcing steel 8Φ20, length =2.80 m
normal weight concrete made with siliceous aggregates
Standard fire exposure of 120 minutes, exposed on more than one side
Braced structure
G= 232.3 kN, Q= 48.31 kN et ψ₂,₁=0.3 (ψ₁,₁=0.5 EN 1992-1-2/NAF)

Method A (Table 5.2a)

Validity of the method:

- Effective length of the column under fire conditions: l₀,fi=1.40 m ≤ 3 m
- First excentricity under fire conditions: e=0.0021 m ≤ 0.15b=0.045 m
- Amount of reinforcement: Aₛ=25,13 cm² ≤ 0.04 A_c=36 cm²
- Reduction factor for the design level in the fire situation: μₕ₁=Nₑd,fi/Nᵣd=0.1

<table>
<thead>
<tr>
<th>Standard fire resistance</th>
<th>Minimum dimensions (mm) Column width bₘᵢₙ/axis distance a of the main bars</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Column exposed on more than one side</td>
</tr>
<tr>
<td></td>
<td>μₕ₁ = 0.2</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>R 120</td>
<td>250/40</td>
</tr>
<tr>
<td></td>
<td>Linear interpolation ➔ 300/37.5</td>
</tr>
</tbody>
</table>
Column characteristics

300/45, reinforcing steel 8Φ20, length = 2.80 m
Normal weight concrete made of siliceous aggregates
Standard fire exposure of 120 minutes, exposed on more than one side
Braced structures
G = 232.3 kN, Q = 48.31 kN

Method B (Table 5.2b)

Validity of the method:

- Load level at normal temperature conditions: \( n = 0.14 \)
- First eccentricity under fire conditions: \( e = 0.0021 \) m, \( e/b = 0.013 \leq 0.25 \)
- Slenderness of the column under fire conditions: \( \lambda_{fi} = l_{0,fi}^\prime / i = 11.55 \leq 30 \)
- Mechanical reinforcement ratio at normal temperatures conditions: \( \omega = 0.73 \)

<table>
<thead>
<tr>
<th>Standard fire resistance</th>
<th>Mechanical reinforcement ratio ( \omega )</th>
<th>Minimum dimensions (mm). Column width ( b_{min} )/axis distance ( a )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( n = 0.15 )</td>
<td>( n = 0.3 )</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>R 120</td>
<td>0.100</td>
<td>250/50:350/25*</td>
</tr>
<tr>
<td></td>
<td>0.500</td>
<td>200/45:300/25*</td>
</tr>
<tr>
<td></td>
<td>1.000</td>
<td>200/40:250/25*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100/100/600/30</td>
</tr>
</tbody>
</table>

OK R120 (300/45)
Beam characteristics

300/48, reinforcing steel 6Φ16
Normal weight concrete made with siliceous aggregates,
Standard fire exposure of 120 minutes, exposed to fire on three sides
G= 40.85 kN.m, Q= 8.7 kN.m

Method for continuous beam (Table 5.6)
Minimum values of axis distance $a$ to the soffit and sides of continuous beams together with minimum values of length $b$
Redistribution of bending moment for normal temperature design <15 %
Area of top reinforcement should be: $A_{s,\text{req}(x)} = A_{s,\text{req}(0)} \cdot (1 - 2.5x/l_{\text{eff}})$

<table>
<thead>
<tr>
<th>Standard fire resistance</th>
<th>Minimum dimensions (mm)</th>
<th>Web thickness $b_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Possible combinations of $a$ and $b_{\text{min}}$ where $a$ is the average axis distance and $b_{\text{min}}$ is the width of beam</td>
<td>Class WA</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>R 120</td>
<td>$b_{\text{min}}= 200$</td>
<td>$300$</td>
</tr>
</tbody>
</table>
General (section 4.2)
Simplified cross-section calculations methods may be used to determine the ultimate load-bearing capacity of a heated cross section and to compare the capacity with the relevant combination

- Informative Annex B: 2 alternatives methods for calculating the resistance to bending moments: « 500°C isotherm method » and « Zone method »

Standard fire exposure
Temperature profiles determined from calculation or tests
Reduced cross-section
Strength reduction of materials

Note: for shear and anchorage, when minimum dimensions given in tabulated data are followed, further checks for shear and anchorage are not required (section 4.4)
Continuous beam

Recall of data

- $l=6.43 \text{ m}$, $b=0.30 \text{ m}$, $h=0.40 \text{ m}$, $h_{\text{slab}}=0.18 \text{ m}$
- Hot rolled reinforcing steel: $6\Phi 16$, $a=48 \text{ mm}$
- West top reinforcement: $4\Phi 20 + 2\Phi 16$, $a_1=50 \text{ mm}$ et $a_2=68 \text{ mm}$
- East top reinforcement: $4\Phi 20$, $a=50 \text{ mm}$
- Siliceous aggregates, $f_{ck}=25 \text{ MPa}$
- G= 40.85 kN.m, Q= 8.7 kN.m et $\psi_{1,1}=0.5$

**Method B1** valid with a minimum cross-section $b=0.30 \text{ m} > 0.16 \text{ m}$

<table>
<thead>
<tr>
<th>Fire resistance</th>
<th>R 60</th>
<th>R 90</th>
<th>R120</th>
<th>R180</th>
<th>R240</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum width of cross-section mm</td>
<td>90</td>
<td>120</td>
<td>160</td>
<td>200</td>
<td>280</td>
</tr>
</tbody>
</table>

Temperature profiles: Fire exposure up to 120 min

- Reduced cross section
  - **500°C isotherm method**\(\Rightarrow a_{500\text{°C}}\)
  - $b_{fi}=0.210 \text{ m}$
  - $h_{fi}=0.365 \text{ m}$
Continuous beam

Temperature of reinforcing bars in tension
Reduced strength of the reinforcement due to the temperature

- $k_{moy}=0.515$
- $f_{yd,fi}=k_{moy}*f_{yk}/\gamma_{s,fi}=0.515*500/1=257.37$ MPa
- $d_{fi}=d=0.390$ m
- $A_{s}*f_{yd,fi}=A_{s}*k_{moy}*f_{yk}/\gamma_{s,fi}=12.06*10^{-4}*257.37=0.310$ MN

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>T (°C)</th>
<th>Asi (mm²)</th>
<th>ksi</th>
<th>ks.As (mm²)</th>
<th>ai.ksi.As (mm³)</th>
</tr>
</thead>
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<td>692</td>
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<td>617</td>
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<td>86</td>
<td>4142</td>
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<tr>
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<td>48</td>
<td>461</td>
<td>201</td>
<td>0.8658</td>
<td>174</td>
<td>8356</td>
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<tr>
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<td>260</td>
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</tr>
</tbody>
</table>

Bending strength moment: $M_{Rd,fi}=z*A_{s}*k_{moy}*f_{yk}/\gamma_{s,fi}=116.39$ kN.m

Comparison with a software CIM’feu EC2: $M_{Rd,fi}=121.04$ kN.m (+4%)
Continuous beam

Temperature of reinforcing bars (in the west side)
Reduced strength of the reinforcement due to the temperature

- \( k_{\text{moy}}=1 \)
- \( f_{y_{\text{d,fi}}} = k_{\text{moy}} \times f_{y_k}/\gamma_{s,\text{fi}} = 1 \times 500/1 = 500 \text{ MPa} \)
- \( d_{\text{f,i}}=0.309 \text{ m} \)
- \( A_{\text{s}} \times f_{y_{\text{d,fi}}} = A_{\text{s}} \times k_{\text{moy}} \times f_{y_k}/\gamma_{s,\text{fi}} = 17.59 \times 10^{-4} \times 500 = 0.880 \text{ MN} \)

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>( x ) (mm)</th>
<th>( y ) (mm)</th>
<th>( T ) (°C)</th>
<th>( A_{\text{s}} ) (mm²)</th>
<th>( k_{\text{s}} )</th>
<th>( k_{s,\text{As}} ) (mm²)</th>
<th>( a_{i,k_{\text{s}},A_{\text{s}}} ) (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>50</td>
<td>69</td>
<td>314</td>
<td>1</td>
<td>314</td>
<td>15708</td>
</tr>
<tr>
<td>2</td>
<td>140</td>
<td>50</td>
<td>43</td>
<td>314</td>
<td>1</td>
<td>314</td>
<td>15708</td>
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<tr>
<td>1'</td>
<td>160</td>
<td>50</td>
<td>43</td>
<td>314</td>
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<td>1</td>
<td>314</td>
<td>15708</td>
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<tr>
<td>3</td>
<td>40</td>
<td>68</td>
<td>82</td>
<td>251</td>
<td>1</td>
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<td>17090</td>
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<tr>
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<td>68</td>
<td>82</td>
<td>251</td>
<td>1</td>
<td>251</td>
<td>17090</td>
</tr>
</tbody>
</table>

Strength moment: \( M_{Rd,w,\text{fi}} = z \times A_{\text{s}} \times k_{\text{moy}} \times f_{y_k}/\gamma_{s,\text{fi}} = 206.64 \text{ kN.m} \)

Comparison with a software CIM’feu EC2: \( M_{Rd,w,\text{fi}} = 199.57 \text{ kN} \) (- 3 %)
Continuous beam

Temperature of reinforcing bars (in the east side)
Reduced strength of the reinforcement due to the temperature

- $k_{moy} = 1$
- $f_{yd,fi} = k_{moy} * f_{yk} / \gamma_{s,fi} = 1 * 500 / 1 = 500 \text{ MPa}$
- $d_{fi} = 0.315 \text{ m}$
- $A_s * f_{yd,fi} = A_s * k_{moy} * f_{yk} / \gamma_{s,fi} = 12.56 \times 10^{-4} * 500 = 0.628 \text{ MN}$

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>$x$ (mm)</th>
<th>$y$ (mm)</th>
<th>$T$ (°C)</th>
<th>$A_s$ (mm$^2$)</th>
<th>$ksi$</th>
<th>$ks.A_s$ (mm$^2$)</th>
<th>$ai.ksi.Asi$ (mm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>50</td>
<td>69</td>
<td>314</td>
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</tbody>
</table>

Strength moment: $M_{Rd,e,fi} = 172.61 \text{ kN.m}$
Comparison with a software CIM’feu EC2: $M_{Rd,e,fi} = 169.01 \text{ kN.m} (-2\%)$

Bending moment for a simply supported beam: $M_{Ed0,fi} = 241 \text{ kN.m}$

Total bending strength: $M_{Rd,fi} = 306 \text{ kN.m} > M_{Ed0,fi} = 241 \text{ kN.m}$ **OK R120**
Comparison with CIM’feu EC2: $M_{Rd,fi} = 305.33 \text{ kN.m} (-0.2\%)$
**Column**

**General data**
- $b=0.30 \text{ m}$, $l=2.80 \text{ m}$
- Hot rolled reinforcing steel: $8\Phi20$, cover $=35 \text{ mm}$ ($a=45 \text{ mm}$)
- Siliceous aggregates, $f_{ck}=25 \text{ MPa}$
- $N_G=232.3 \text{ kN.m}$, $N_Q=48.31 \text{ kN.m}$ et $\psi_{1,1}=0.5$

« 500 °C isotherm method », $b=0.30 \text{ m} > 0.16 \text{ m}$

<table>
<thead>
<tr>
<th>Fire resistance</th>
<th>R 60</th>
<th>R 90</th>
<th>R120</th>
<th>R180</th>
<th>R240</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum width of cross-section mm</td>
<td>90</td>
<td>120</td>
<td>160</td>
<td>200</td>
<td>280</td>
</tr>
</tbody>
</table>

Temperature profiles: Fire exposure up to 120 min

**Reduced cross section**
- 500°C isotherm method $\Rightarrow a_{500°C}=55 \text{ mm}$
- $b_{fi}=0.190 \text{ m}$
Column

Taking into account of the 2\textsuperscript{nd} order effect?

- $A = 0.7$
- Mechanical reinforcement ratio under fire exposure $\omega = 0.77 \Rightarrow B = 1.597$
- $C = 0.7$
- $n = N_{ed,fi} / A_c, f_{cd} = 0.284$
- Limit slenderness $\lambda_{lim} = 29.36$
- Slenderness $\lambda = l_{0,fi} / i = 25.52 < \lambda_{lim} \Rightarrow$ we can neglect the 2\textsuperscript{nd} order effect

Strength of the cross-section: $N_{Rd,fi} = 1.60 \text{ MN}$

Design normal effort: $N_{Ed,fi} = 0.256 \text{ MN}$

$N_{Ed,fi} = 0.256 \text{ MN} < N_{Rd,fi} = 1.60 \text{ MN} \Rightarrow \text{OK R120}$
General
A realistic analysis of the structure exposed to fire

Reliable approximation of the expected behaviour of the structure

Include calculation models for:

- Development and distribution of the temperature within structural members = thermal response
- Mechanical behaviour of the structure = mechanical response
Hypothesis for the modelling

Thermal response (EC1-1-2)

- Based on principles and assumptions of the theory heat transfer
  - Convection, radiation
  - Thermal transfer coefficient on the unexposed face ($\alpha_c=4$ W/m²K)
  - Thermal transfer coefficient on the exposed face ($\alpha_c=25$ W/m²K)
  - Standard fire exposure

\[ \theta_g = 20 + 345 \log_{10} (8t + 1) \quad [\degree C] \]

- Include the relevant thermal actions (EN 1991-1-2), the temperature dependent thermal properties of the materials, the influence of
Hypothesis for the modelling

Mechanical response

- Based on the principles and assumptions of the theory of structural mechanics, taking into account the changes of mechanical properties with temperature
- Loads G, Q
Modeling of the structure

Aster Code

Meshes using multi-fibre beam elements
Results & analysis in terms of deflections

Vertical deflection of the middle of the beam (< 10 cm)
Horizontal displacement at the head of the column

Calculations $\Rightarrow$ structure strength during 180 minutes (> 120 minutes)