Training School for Young Researchers

Fire Engineering Research – Key Issues for the Future II

Codes of practice – prescriptive rules or performance-based approach?
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COST Action TU0904 Naples, 6-9 June 2013

Scope

- Introduction
- Thermal Actions
- Mechanical Actions
- Thermal Analysis
- Mechanical Analysis
- Design procedures
- Examples using different design procedures: prescriptive and performance-based approaches
Prescriptive rules or performance-based approach?

Some background before to try to answer to this question.

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

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);

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

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

* 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 beginning 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)

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

![ISO 834 curve graph]

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.

Reference plane

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

<table>
<thead>
<tr>
<th>Purpose group of building</th>
<th>Minimum periods (minutes) for elements of structure in ac:</th>
<th>Basement storey $S_{basement}$</th>
<th>Ground or upper storey</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>More than 10</td>
<td>Not more than 10</td>
<td>More than 6</td>
</tr>
<tr>
<td>1. Residential (domestic):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Flats and maisonettes</td>
<td>90</td>
<td>Not relevant</td>
<td>30&quot;</td>
</tr>
<tr>
<td>b. and c. Dwellinghouses</td>
<td>90</td>
<td>Not relevant</td>
<td>30&quot;</td>
</tr>
<tr>
<td>2. Residential:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Institutional ex.</td>
<td>90</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>b. Other residential</td>
<td>90</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>3. Office:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Not sprinkler:</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>- Sprinkler (2)</td>
<td>90</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>4. Shop and commercial:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Not sprinkler:</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>- Sprinkler (2)</td>
<td>90</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>5. Assembly and recreation:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Not sprinkler:</td>
<td>90</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

INTERNAL FIRE SPREAD (STRUCTURE)

The Requirement

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

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Limits on application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal fire spread (structure)</td>
<td></td>
</tr>
<tr>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>(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.</td>
<td></td>
</tr>
<tr>
<td>(3) To inhibit the spread of fire within the building, it shall be subdivided with fire-resisting construction to an extent appropriate to the size and intended use of the building.</td>
<td></td>
</tr>
<tr>
<td>(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.</td>
<td></td>
</tr>
</tbody>
</table>

Requirement B3(1) does not apply to material alterations to any prison provided under Section 33 of the Prisons Act 1952.
- 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:

<table>
<thead>
<tr>
<th>Classification according to the occupancy</th>
<th>Risk categories</th>
<th>Function of the structural member</th>
</tr>
</thead>
<tbody>
<tr>
<td>I, III, IV, V, VI, VII, VIII, IX, X</td>
<td>R30, REI30</td>
<td>Only load bearing</td>
</tr>
<tr>
<td></td>
<td>R60, REI60</td>
<td>Load bearing and separating</td>
</tr>
<tr>
<td></td>
<td>R90, REI90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R120, REI120</td>
<td></td>
</tr>
<tr>
<td>II, XI and XII</td>
<td>R60, REI60</td>
<td>Only load bearing</td>
</tr>
<tr>
<td></td>
<td>R90, REI90</td>
<td>Load bearing and separating</td>
</tr>
<tr>
<td></td>
<td>R120, REI120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R180, REI180</td>
<td></td>
</tr>
</tbody>
</table>

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. Example
Portuguese regulation for fire safety of buildings

- Required fire resistance

- 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 or Standard fire ISO 834
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

Design Procedures

Prescriptive Rules
(Thermal Actions given by Nominal Fire)

Performance-Based Code
(Physically based Thermal Actions)

Nominal fire. Ex: Standard fire ISO 834

Natural fire
Introduction

Prescriptive or performance-based according the Eurocodes - 2

Design Procedures

Prescriptive Rules
(Thermal Actions given by Nominal Fire)

Performance-Based Code
(Physically based Thermal Actions)

Tabulated data
Simple calculation models or advanced calculation models

Simple calculation models or advanced calculation models

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
Prescriptive approach was used

Steel Structure

θ
 t

Standard fire ISO 834 has been used

Introduction
Performance-based approach was used

θ
 t

Natural fire

Steel Structure
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

- S, G, Q
- G, Q
- G, Q

Actions for temperature analysis
Thermal Action
FIRE

Actions for structural analysis
Mechanical Action
- Dead Load: G
- Imposed Load: Q
- Snow: S
- Wind: W
Eurocode 1:
Actions on Structures

Thermal actions
Heat transfer at surface of building elements

\[ \dot{h}_{\text{net},d} = \dot{h}_{\text{net},c} + \dot{h}_{\text{net},r} \]

Total net heat flux
Thermal actions
Heat transfer at surface of building elements

\[ \dot{h}_{\text{net},d} = \dot{h}_{\text{net},c} + \dot{h}_{\text{net},r} \]

**Total net heat flux**

\[ \dot{h}_{\text{net},c} = \alpha_c (\theta_g - \theta_m) \]

**Convective heat flux**

\[ \dot{h}_{\text{net},r} = \Phi \cdot \varepsilon_f \cdot \varepsilon_m \cdot \sigma \cdot \left[ (\theta_r + 273)^4 - (\theta_m + 273)^4 \right] \]

**Radiative heat flux**

\[ \theta_g \approx \theta_r \]

Temperature of the fire compartment

Prescriptive

Performance-based

Nominal fire

Natural fire

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
### Advanced Fire Models

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

### Localised Fire

- HESKESTADT
- HASEMI

\[ \theta(x, y, z, t) \]

- Parametric Fire
- \( \theta(t) \) uniform in the compartment

### Fully Engulfed Compartment

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

\[ \text{Exact geometry} \]

---

### Nominal Temperature-Time Curve

**Simplified Fire Models**

- Nominal Temperature-Time Curve

<table>
<thead>
<tr>
<th>Gas temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
</tr>
<tr>
<td>1100</td>
</tr>
<tr>
<td>1000</td>
</tr>
<tr>
<td>900</td>
</tr>
<tr>
<td>800</td>
</tr>
<tr>
<td>700</td>
</tr>
<tr>
<td>600</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>200</td>
</tr>
</tbody>
</table>

- External Fire
- Standard Fire
- Hydrocarbon Fire

**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

Boundary properties
Ceiling height
Opening Area
Fire area
Rate of heat release
Fire load density

Geometry

Fire

Characteristics of the Fire Compartment
Natural Fire Model

Fire resistant enclosures defining the fire compartment according to the national regulations

Material properties of enclosures: $c$, $\rho$, $\lambda$

Definition of openings

From DIFISEK+
### Characteristics of the Fire Load from EN 1991-1-2
#### Natural Fire Model

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

### Design value of the fire load density
#### Natural Fire Model

\[
q_{f,d} = q_{f,k} \cdot m \cdot \delta_{q1} \cdot \delta_{q2} \cdot \delta_n
\]  

[ MJ/m² ]

- $m$ – 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.

- $\delta_{q1}$ – factor taking into account the fire activation risk due to the size of the compartment

- $\delta_{q2}$ – factor taking into account the fire activation risk due to the type of occupancy

- $\delta_n$ – 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**

#### Rate of Heat Release Curve from EN 1991-1-2

**Natural Fire Model**

\[
Q(t) = \left( \frac{t}{t_{\alpha}} \right)^2
\]

- **Decay phase**

\[
Q_{\text{max}} = A_i \times RHR_i
\]

- **70% (q_{f,d} \cdot A_i)**

#### Table: Compartment floor area vs. Danger of Fire Activation

<table>
<thead>
<tr>
<th>Compartment floor area $A_f$ [m²]</th>
<th>Danger of Fire Activation $\delta_{q1}$</th>
<th>Danger of Fire Activation $\delta_{q2}$</th>
<th>Examples of Occupancies</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1,10</td>
<td>0,78</td>
<td>Art gallery, museum, swimming pool</td>
</tr>
<tr>
<td>250</td>
<td>1,50</td>
<td>1,00</td>
<td>Residence, hotel, office</td>
</tr>
<tr>
<td>2500</td>
<td>1,90</td>
<td>1,22</td>
<td>Manufacture for machinery &amp; engines</td>
</tr>
<tr>
<td>5000</td>
<td>2,00</td>
<td>1,44</td>
<td>Chemical laboratory, Painting workshop</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Manufacture of fireworks</td>
</tr>
</tbody>
</table>

\[
q_{f,d} = \delta_{q1} \cdot \delta_{q2} \cdot \prod \delta_{n_i} \cdot m \cdot q_{f,k}
\]

- Automatic Fire Suppression
- Independent Water Supplies
- Automatic Water Extinguishing System
- Automatic Fire Detection
- Automatic Fire Detection & Alarm
- Automatic Alarm Transmission to Fire Brigade
- Manual Fire Suppression
- Work Fire Brigade
- Off Site Fire Brigade
- Safe Access Routes
- Fire Fighting Devices
- Smoke Exhaust System

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

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

<table>
<thead>
<tr>
<th>Class 3</th>
<th>Time (min)</th>
<th>Rate of heat release (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>0</td>
</tr>
</tbody>
</table>

From ECSC Project: Demonstration of real fire tests in car parks and high buildings.
Annex C of EN 1991-1-2:
• Flame is not impacting the ceiling of a compartment ($L_f < H$)
• Fires in open air

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

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

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

Hasemi method

Horizontal distances

$$r_i = \sqrt{d_1^2 + d_2^2}$$
Temperature development
Gas and steel temperature

Scenario 1: unprotected steel
\( \theta_{a,\text{max}} = 710.9 \, ^\circ\text{C} \)

Scenario 1: protected steel
\( \theta_{a,\text{max}} = 527 \, ^\circ\text{C} \)

Scenario 2
\( \theta_{a,\text{max}} = 466.7 \, ^\circ\text{C} \)

Scenario 3
\( \theta_{a,\text{max}} = 466.7 \, ^\circ\text{C} \)

Scenario 4
\( \theta_{a,\text{max}} = 510.9 \, ^\circ\text{C} \)

Scenario 3
\( \theta_{a,\text{max}} = 528.5 \, ^\circ\text{C} \)

Fire load density - \( q_{t,d} \)
Opening factor - \( O = A_v \sqrt{h/A_t} \)
Wall factor - \( b = \sqrt{\rho c \lambda} \)

Temperature \( \theta = \theta(t) \)

Natural Fire Model

Parametric fire. Needed parameters

Limitations:
- \( A_{\text{floor}} \leq 500 \, \text{m}^2 \)
- No horizontal openings
- \( H \leq 4 \, \text{m} \)
- Wall factor from 1000 to 2200
- Fire load density, \( q_{t,d} \) from 50 to 1000 MJ/m\(^2\)
Annex A of EN 1991-1-2

Parametric fire curves function of $O$

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

Ventilation controlled fires
Fuel controlled fires

Office
$A_f = 45,0 \, m^2$
$O = 0,08 \, m^{1/2}$
$q_{f,k} = 511 \, MJ/m^2$
$m = 0,8$
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 for temperature analysis
Thermal Action
FIRE

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

Actions for structural analysis

Mechanical Action

- Dead Load: G
- Imposed Load: Q
- Snow: S
- Wind: W

Actions for temperature analysis

Thermal Action

FIRE

Actions on Structures

\[ S, G, Q \]

G, Q

G, Q

Fire

\[ \sum_{j=1}^{2} \gamma_{G,j} G_{k,j} + \gamma_{Q,1} \cdot Q_{k,1} + \sum_{i>1} \gamma_{Q,1} \psi_{0,i} \cdot Q_{k,i} \]

Combination Rules for Mechanical Actions

EN 1990: Basis of Structural Design

- At room temperature (20 °C)

- In fire situation

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

\[ \sum_{j=1} G_{k,1} + (\psi_{1,1} \text{ or } \psi_{2,1}) \cdot Q_{k,1} + \sum_{i>1} \psi_{2,i} \cdot Q_{k,i} + A_d \]

\[ \psi_{1,1} Q_{k,1} \] – Frequent value of the representative value of the variable action \( Q_i \)

\[ \psi_{2,1} Q_{k,1} \] – Quasi-permanent value of the representative value of the variable action \( Q_i \)

\( A_d \) – 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**

\[
\sum_{j \geq 1} \frac{G_{k,1}}{\psi_1} + (\psi_1 \text{ ou } \psi_2) \cdot Q_{k,1} + \sum_{j \geq 1} \psi_{2,j} \cdot Q_{k,j} + A_d
\]

<table>
<thead>
<tr>
<th>Action</th>
<th>(\psi_1)</th>
<th>(\psi_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imposed loads in buildings, category</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>(see EN 1991-1-1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imposed loads in congregation areas and</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>shopping areas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imposed loads in storage areas</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Vehicle weight (\leq 30) kN</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>(30 \text{ kN} \leq) vehicle weight (\leq 160) kN</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Imposed loads in roofs</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Snow (Norway, Sweden …)</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Wind loads on buildings</td>
<td>0.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>

In some countries the National Annex recommends \(\psi_1, Q_1\), 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**
4. **Calculation of the mechanical behaviour of the structure exposed to fire - EC3**
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

$$q_c = h_c (\theta - \theta_\infty) \quad \text{convection}$$

$$q_r = \beta \varepsilon (\theta^4 - \theta_a^4) = \beta \varepsilon (\theta^2 + \theta_a^2)(\theta + \theta_a)(\theta - \theta_a) = h_r (\theta - \theta_a) \quad \text{radiation}$$

Thermal response

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

Concrete (30x30 cm²)

Steel (IPE300)

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

$$\Delta T = 794 \, ^\circ C$$

$$\Delta T = 22 \, ^\circ C$$
Temperature increase in time step $\Delta t$:

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

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

**Radiation:**

$$\dot{h}_{net,r} = 5.67 \times 10^{-8} \Phi \varepsilon_f \varepsilon_m \left( (\theta_r + 273)^4 - (\theta_m + 273)^4 \right)$$

**Convection:**

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

**Section factor $A_m/V$**

Unprotected steel members

$$\Delta \theta_{a,t} = k_{sh} \frac{A_m/V}{c_a \rho_a} \dot{h}_{net,d} \Delta t$$
Correction factor for the Shadow effect $k_{sh}$

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

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

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

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

---

**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:

(a) - Spray or intumescent
(b) - Board
(c) - Beam
Structural fire protection
Intumescent paint

Structural fire protection
Cementitious Sprays
Structural fire protection

Insulating Board

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 \( \Delta t \)

\[ \Delta \theta_{a.t} = \frac{\lambda_p}{c_a \rho_a} \frac{A_p}{V} \left( \frac{1}{1 + \phi/3} \right) (\theta_{g.t} - \theta_{a.t}) \Delta t - (e^{\phi/10} - 1) \Delta \theta_{g.t} \]
Section factor \( A_p/V \)
Protected steel members

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

Steel perimeter
inner perimeter of board
2(b+h)

inner perimeter of board

Steel 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

- 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

<table>
<thead>
<tr>
<th>Steel Temperature $\theta$</th>
<th>Reduction factor relative to $f_y$ for effective yield strength $k_{y,\theta} = f_y,\theta / f_y$</th>
<th>Reduction factor relative to $f_y$ for proportional limit $k_{p,\theta} = f_p,\theta / f_y$</th>
<th>Reduction factor relative to $E_a$ for the slope of the linear elastic range $k_{E,\theta} = E_a,\theta / E_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>100°C</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>200°C</td>
<td>1.000</td>
<td>0.807</td>
<td>0.900</td>
</tr>
<tr>
<td>300°C</td>
<td>1.000</td>
<td>0.613</td>
<td>0.800</td>
</tr>
<tr>
<td>400°C</td>
<td>1.000</td>
<td>0.420</td>
<td>0.700</td>
</tr>
<tr>
<td>500°C</td>
<td>0.780</td>
<td>0.360</td>
<td>0.600</td>
</tr>
<tr>
<td>600°C</td>
<td>0.470</td>
<td>0.180</td>
<td>0.350</td>
</tr>
<tr>
<td>700°C</td>
<td>0.230</td>
<td>0.075</td>
<td>0.250</td>
</tr>
<tr>
<td>800°C</td>
<td>0.110</td>
<td>0.050</td>
<td>0.100</td>
</tr>
<tr>
<td>900°C</td>
<td>0.060</td>
<td>0.0375</td>
<td>0.0675</td>
</tr>
<tr>
<td>1000°C</td>
<td>0.040</td>
<td>0.025</td>
<td>0.0450</td>
</tr>
<tr>
<td>1100°C</td>
<td>0.020</td>
<td>0.0125</td>
<td>0.0225</td>
</tr>
<tr>
<td>1200°C</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Yield Strength $k_{y,\theta} = f_y,\theta / f_y$

Young Modulus $k_{E,\theta} = E_a,\theta / E_a$

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 period of time defining the fire resistance must be accepted by the authorities.

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, \( t_{fi,req}^{1} \)
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

<table>
<thead>
<tr>
<th>Standard fire resistance</th>
<th>Minimum dimensions (mm)</th>
<th>With thickness $t_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class WA</td>
<td>Class WB</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>R 30</td>
<td>40</td>
<td>120</td>
</tr>
<tr>
<td>R 60</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>R 90</td>
<td>150</td>
<td>250</td>
</tr>
<tr>
<td>R 120</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>R 180</td>
<td>240</td>
<td>340</td>
</tr>
</tbody>
</table>

- $a_0 = a + 10mm$ (see note below)

For prestressed beams, the increase of axis distance according to 5.2(b) should be noted. $a_0$ is the axis distance to the side of beam for the inwards (tension or wye) of beams with only one layer of reinforcement. For values of $b_{wx}$ greater than that given in Column 4, an increase of $a_0$ is required.

* Normally the cover required by EN 1992-1-1 will control.
### 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 axes distance of the reinforcing bars, of composite columns made of totally encased steel sections.

<table>
<thead>
<tr>
<th></th>
<th>R 30</th>
<th>R60</th>
<th>R90</th>
<th>R 120</th>
<th>R180</th>
<th>R240</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.1</strong> Minimum dimensions $h_c$ and $b_c$ [mm]</td>
<td>150</td>
<td>180</td>
<td>220</td>
<td>300</td>
<td>350</td>
<td>400</td>
</tr>
<tr>
<td><strong>1.2</strong> minimum concrete cover of steel section $c$ [mm]</td>
<td>40</td>
<td>50</td>
<td>50</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td><strong>1.3</strong> minimum axes distance of reinforcing bars $u_k$ [mm]</td>
<td>20*</td>
<td>30</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>2.1</strong> Minimum dimensions $h_c$ and $b_c$ [mm]</td>
<td>-</td>
<td>200</td>
<td>250</td>
<td>350</td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td><strong>2.2</strong> minimum concrete cover of steel section $c$ [mm]</td>
<td>-</td>
<td>40</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td><strong>2.3</strong> minimum axes distance of reinforcing bars $u_k$ [mm]</td>
<td>-</td>
<td>20*</td>
<td>20*</td>
<td>30</td>
<td>40</td>
<td>-</td>
</tr>
</tbody>
</table>

**Standard Fire Resistance**

- **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

\[ M_{f_i,Rd} = T (y_F - y_T) \]

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

Temperature profiles from Annex A

Effective section

T = 100 °C

T = 200 °C

T = 300 °C

R60

Eurocode 2

Sagging moment resistance of a RC beam
Steel profiles can be considered as an assembly of individual plates:

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

Internal and outstanding elements:
- a) Rolled section
- b) Hollow section
- c) Welded section

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

\[
\lambda_p = \frac{f_y}{\sigma_{cr}} = \frac{f_y}{k_\sigma \frac{\pi^2}{12(1-v^2)b^2} \frac{E}{t_k^2}} \approx \frac{b/t}{\frac{1}{28.4 \sqrt{k_\sigma}} \frac{1}{\sqrt{235 \frac{E}{210000}}}} = \frac{b/t}{\frac{1}{28.4 \sqrt{k_\sigma}} \frac{1}{\sqrt{235 \frac{E}{210000}}}} \approx \frac{b/t}{28.4 \sqrt{k_\sigma}} \sqrt{\frac{235}{f_y}} \sqrt{\frac{E}{210000}}}
\]

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

This parameter is widely 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 \[ \Rightarrow \text{See next slide} \]

Classification of the cross-sections - 4

\[ \varepsilon_\theta = \sqrt{\frac{235}{f_y,\theta}} \sqrt{\frac{E_\theta}{210000}} = \frac{235}{k_{y,\theta} f_y} \sqrt{\frac{k_{E,\theta} E}{210000}} = \sqrt{\frac{k_{E,\theta}}{k_{y,\theta}}} \sqrt{\frac{235}{f_y}} \sqrt{\frac{E}{210000}} = \sqrt{\frac{k_{E,\theta}}{k_{y,\theta}}} \frac{235}{f_y} \approx 0.85 \sqrt{\frac{235}{f_y}} = 0.85 \varepsilon \]

\[ \varepsilon_\theta = 0.85 \sqrt{\frac{235}{f_y}} = 0.85 \varepsilon \]
**Classification of the cross-sections - 5**

For carbon steel:

\[
e = 0.85 \sqrt{\frac{235}{f_y}} \text{ and tables from EN 1993-1-1}
\]

<table>
<thead>
<tr>
<th>Element</th>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange</td>
<td>( c / t = 9e )</td>
<td>( c / t = 10e )</td>
<td>( c / t = 14e )</td>
</tr>
<tr>
<td>Web subjected to compression</td>
<td>( c / t = 33e )</td>
<td>( c / t = 38e )</td>
<td>( c / t = 42e )</td>
</tr>
<tr>
<td>Web subjected to bending</td>
<td>( c / t = 72e )</td>
<td>( c / t = 83e )</td>
<td>( c / t = 124e )</td>
</tr>
</tbody>
</table>

For stainless steel:

\[
e_\theta = 0.85 \sqrt{\frac{235}{f_y}} \frac{E}{210000} \text{ and tables from EN 1993-1-4}
\]

**Eurocode 3: Fire Resistance:**

**Tension members - 1**

- The design resistance of a tension member with uniform temperature \( \theta_a \) is:

\[
N_{fi,\theta,\text{Rd}} = k_{y,\theta} \frac{A_{f_y}}{\gamma_{M,fi}}
\]

or

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

\( N_{\text{Rd}} = \) design resistance of the cross-section \( N_{\text{pl,Rd}} \) 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 $\theta_a$ is

$$ N_{b,fi,0,Rd} = \chi_{fi} A k_{y,0} f_y \frac{1}{\gamma_{M,fi}} $$

With

$$ \chi_{fi} = \frac{1}{\phi_0 + \sqrt{\phi_0^2 - \bar{\lambda}_0^2}} $$

$$ \phi_0 = \frac{1}{2} \left[ 1 + \alpha \bar{\lambda}_0 + \bar{\lambda}_0^2 \right] $$

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

• Non-dimensional slenderness:

$$ \bar{\lambda}_0 = \bar{\lambda} \sqrt{k_{y,0} / k_{E,0}} $$

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

• The design moment resistance of a Class 1, 2 or Class 3 cross-section with a uniform temperature $\theta_a$ is:

$$ M_{fi,0,Rd} = M_{Rd} k_{y,0} \left( \frac{\gamma_{M0}}{\gamma_{M,fi}} \right) $$

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

$$ M_{Rd} = M_{el,Rd} \quad \text{– Class 3 cross-sections} $$
Adaptation factors to take into account the non-uniform temperature distribution

Moment Resistance:

$$M_{f_{i,0,Rd}} = M_{Rd} \gamma_{y,0} \left( \frac{\gamma_{M0}}{\gamma_{M,fi}} \right) \frac{1}{k_1k_2}$$

$\kappa_1$ is an adaptation factor for non-uniform temperature across the cross-section

- $\kappa_1 = 1.0$ for a beam exposed on all four sides
- $\kappa_1 = 0.7$ for an unprotected beam exposed on three sides
- $\kappa_1 = 0.85$ for a protected beam exposed on three sides

$\kappa_2$ is an adaptation factor for non-uniform temperature along the beam.

- $\kappa_2 = 0.85$ at the supports of a statically indeterminate beam
- $\kappa_2 = 1.0$ in all other cases
Eurocode 3: Fire Resistance: Laterally unrestrained beams - 1

Lateral-torsional buckling


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

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

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

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

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

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

(Curves a, b, c, d)
Design shear resistance

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

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

\( \theta_{web} \) is the average temperature in the web of the section.

\( k_{y,0,web} \) is the reduction factor for the yield strength of steel at the steel temperature \( \theta_{web} \).

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

\[ \frac{N_{f_{,Ed}}}{\chi_{min,fi} A k_{y,0} f_y/\gamma_{M,fi}} + \frac{k_y M_{y,fi,Ed}}{W_{pl,y} k_{y,0} f_y/\gamma_{M,fi}} + \frac{k_z M_{z,fi,Ed}}{W_{pl,z} k_{y,0} f_y/\gamma_{M,fi}} \leq 1 \]

Class 3

\[ \frac{N_{f_{,Ed}}}{\chi_{min,fi} A k_{y,0} f_y/\gamma_{M,fi}} + \frac{k_y M_{y,fi,Ed}}{W_{el,y} k_{y,0} f_y/\gamma_{M,fi}} + \frac{k_z M_{z,fi,Ed}}{W_{el,z} k_{y,0} f_y/\gamma_{M,fi}} \leq 1 \]
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

\[
\frac{N_{\text{f,Ed}}}{\chi_{z,\text{f}} A k_{y,\theta} \frac{f_y}{\gamma_{M,\text{f}}}} + \frac{k_{LT} M_{y,\text{f,Ed}}}{\chi_{LT,\text{f}} W_{pl,y} k_{y,\theta} \frac{f_y}{\gamma_{M,\text{f}}}} + \frac{k_z M_{z,\text{f,Ed}}}{W_{pl,z} k_{y,\theta} \frac{f_y}{\gamma_{M,\text{f}}}} \leq 1
\]

Class 3

\[
\frac{N_{\text{f,Ed}}}{\chi_{z,\text{f}} A k_{y,\theta} \frac{f_y}{\gamma_{M,\text{f}}}} + \frac{k_{LT} M_{y,\text{f,Ed}}}{\chi_{LT,\text{f}} W_{el,y} k_{y,\theta} \frac{f_y}{\gamma_{M,\text{f}}}} + \frac{k_z M_{z,\text{f,Ed}}}{W_{el,z} k_{y,\theta} \frac{f_y}{\gamma_{M,\text{f}}}} \leq 1
\]

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.
For class 1 and class 2

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

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

For class 3

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

Example: a purlin
Eurocode 3: Fire Resistance

**Design yield strength to be used with simple calculation models.**

Cross-sectional Class 1, 2 and 3

Cross-sectional Class 4

Annex E of EN 1993-1-2

---

**Eurocode 3: Fire Resistance**

Members with Class 4 cross-sections

**Two procedures:**

1. In the absence of calculation, a **critical temperature of 350 °C** 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.

\[
\bar{\lambda}_{p,\theta} \approx \bar{\lambda}_{20°C} \quad \text{(Slenderness of the plates)}
\]

(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

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

\[ \frac{k_{y,\theta} f_y}{\sqrt{k_{E,\theta}}} \cdot \frac{\pi^2 E_{\theta} t^2}{12(1-\nu^2)b^2} = \bar{\lambda}_p \sqrt{k_{y,\theta}} \frac{k_{0.2 p,\theta}}{k_{E,\theta}} \]

Eurocode 3: Fire Resistance
Non-dimensional slenderness of plates at elevated temperature

Class 1, 2, 3

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

Class 4

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

\[ \bar{\lambda}_{p,\theta} = \bar{\lambda}_{p,20^\circ C} \]

0 200 400 600 800 1000 1200
0 0.2 0.4 0.6 0.8 1 1.2 1.4
ºC

Class 4

1.0

1.0

\[ \sqrt{k_{0.2 p,\theta}} \approx 1.0 \]
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.

---

**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 $\theta_{cr}$ 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 $\mu_0$ at time $t = 0$ using:

$$\theta_{cr} = 39.19 \ln \left( \frac{1}{0.9674 \mu_0^{1/3} - 1} \right) + 482$$  \hspace{1cm} (4.22)

where $\mu_0$ must not be taken less than 0.013.

What is the meaning of this equation?
The best fit curve to the points of this table can be obtained as:

\[ k_{y,\theta} = \left( \frac{\theta_y - 482}{39.19} + 1 \right)^{-\frac{1}{3.833}} \leq 1 \]

The table provides reduction factors at temperature \( \theta \) relative to the value of \( f_y \) or \( E_a \) at 20°C.

### Table

<table>
<thead>
<tr>
<th>Steel Temperature ( \theta )</th>
<th>Reduction factor (relative to ( f_y )) for effective yield strength ( k_{y,\theta}f_y/\theta_f )</th>
<th>Reduction factor (relative to ( f_y )) for proportional limit ( k_{p,\theta}f_y/\theta_f )</th>
<th>Reduction factor (relative to ( E_a )) for the slope of the linear elastic range ( k_{E,\theta}E_a/\theta_E )</th>
<th>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_y/\theta_{0.2p} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 °C</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>100 °C</td>
<td>1.000</td>
<td>0.807</td>
<td>0.900</td>
<td>0.890</td>
</tr>
<tr>
<td>200 °C</td>
<td>1.000</td>
<td>0.420</td>
<td>0.700</td>
<td>0.650</td>
</tr>
<tr>
<td>300 °C</td>
<td>0.780</td>
<td>0.340</td>
<td>0.600</td>
<td>0.530</td>
</tr>
<tr>
<td>400 °C</td>
<td>0.470</td>
<td>0.180</td>
<td>0.310</td>
<td>0.300</td>
</tr>
<tr>
<td>500 °C</td>
<td>0.230</td>
<td>0.075</td>
<td>0.130</td>
<td>0.130</td>
</tr>
<tr>
<td>600 °C</td>
<td>0.110</td>
<td>0.030</td>
<td>0.090</td>
<td>0.070</td>
</tr>
<tr>
<td>700 °C</td>
<td>0.060</td>
<td>0.0175</td>
<td>0.0675</td>
<td>0.050</td>
</tr>
<tr>
<td>800 °C</td>
<td>0.040</td>
<td>0.0125</td>
<td>0.0450</td>
<td>0.030</td>
</tr>
<tr>
<td>900 °C</td>
<td>0.020</td>
<td>0.0125</td>
<td>0.0225</td>
<td>0.020</td>
</tr>
<tr>
<td>1000 °C</td>
<td>0.000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**Notes:** For intermediate values of the steel temperature, linear interpolation may be used.
Fire Resistance: Concept of critical temperature for a member in tension -1

- Resistance at normal temperature:
  \[ N_{Rd} = A_{f_{y}}/\gamma_{M0} \]

- Resistance in fire situation:
  \[ N_{fi,Rd} = A_{k_{y,\theta}} f_{y}/\gamma_{M,fi} \leq 1 \]

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

Concept of critical temperature for a member in tension - 3

Collapse occurs when:

\[ N_{fi, Rd, t} = N_{fi, Ed} \]

\[ A k_{y, \theta} f_{y} / \gamma_{M, fi} = N_{fi, Ed} \]

\[ k_{y, \theta} = N_{fi, Ed} / (A f_{y} / \gamma_{M, fi}) \]

\[ \theta_{a, cr} \]

\[ N_{fi, Rd, t} = N_{fi, Ed} \]

\[ N_{fi, Ed} \]

**Eurocode 3: Fire Resistance**

**Concept of critical temperature for a member in tension - 4**

**By interpolation**

<table>
<thead>
<tr>
<th>Steel Temperature ( \theta_a )</th>
<th>Reduction factor (relative to ( f_y )) for effective yield strength ( k_{y, \theta} f_{y} / \gamma_{M, fi} )</th>
<th>Reduction factor (relative to ( f_y )) for proportional limit ( k_{y, \theta} f_{y} / \gamma_{M, fi} )</th>
<th>Reduction factor (relative to ( E_a )) for the slope of the linear elastic range ( k_{y, \theta} E_{a} / \gamma_{E, fi} )</th>
<th>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} / \gamma_{f, fi} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 °C</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>100 °C</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>200 °C</td>
<td>1.000</td>
<td>0.907</td>
<td>0.900</td>
<td>0.890</td>
</tr>
<tr>
<td>( \theta_{a, cr} ) = k_{y, \theta}</td>
<td>0.613</td>
<td>0.800</td>
<td>0.780</td>
<td>0.630</td>
</tr>
<tr>
<td>600 °C</td>
<td>0.470</td>
<td>0.310</td>
<td>0.310</td>
<td>0.300</td>
</tr>
<tr>
<td>700 °C</td>
<td>0.420</td>
<td>0.700</td>
<td>0.680</td>
<td>0.600</td>
</tr>
<tr>
<td>800 °C</td>
<td>0.420</td>
<td>0.600</td>
<td>0.530</td>
<td>0.530</td>
</tr>
<tr>
<td>900 °C</td>
<td>0.420</td>
<td>0.600</td>
<td>0.530</td>
<td>0.530</td>
</tr>
<tr>
<td>1000 °C</td>
<td>0.420</td>
<td>0.600</td>
<td>0.530</td>
<td>0.530</td>
</tr>
<tr>
<td>1100 °C</td>
<td>0.420</td>
<td>0.600</td>
<td>0.530</td>
<td>0.530</td>
</tr>
<tr>
<td>1200 °C</td>
<td>0.420</td>
<td>0.600</td>
<td>0.530</td>
<td>0.530</td>
</tr>
</tbody>
</table>

\[ \theta_{a, cr} = 39.19 \ln \left( \frac{1}{0.9674 f_{y, \theta}^{0.33}} + 1 \right) + 482 \]

**NOTE:** For intermediate values of the steel temperature, linear interpolation may be used.
Eurocode 3: Fire Resistance
Concept of critical temperature for a member in tension - 5

\[ \theta_{a,cr} = 39.19 \ln \left[ \frac{1}{0.9674 \mu_0^{3.833}} - 1 \right] + 482 \]

For the case of tension

\[ \mu_0 = \frac{E_{f,i,d}}{R_{f,i,d,0}} = k_{y,\theta} \]

\[ k_{y,\theta} = \frac{N_{f,i,Ed}}{(A_{f,i}/\gamma_{M,fi})} \]

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

\[ \theta_d \leq \theta_{crit} ! \]
Checking Fire Resistance in the temperature domain:
Strategy for natural fires

\[ \theta_{\text{max}} \leq \theta_{\text{crit}} \]
* - or using active fire fighting measures

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

\[ t_{\text{req}} \leq t_{f_{i,d}} \]
* - 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 (collapse 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

IPE500
\[ \theta_{cr} = ? \]
Intumescent = ?
**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**

<table>
<thead>
<tr>
<th>Section</th>
<th>( N ) [kN]</th>
<th>( M_y ) [kNm]</th>
<th>( M_z ) [kNm]</th>
<th>( q ) [kN/m]</th>
<th>( I_{x,y} ) [m]</th>
<th>( I_{x,z} ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPE 500</td>
<td>-139.4</td>
<td>0</td>
<td>135.9</td>
<td>0</td>
<td>16.300</td>
<td>-4.075</td>
</tr>
<tr>
<td></td>
<td>-139.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Program Elefir-EN
Critical temperature for load combination 1

Critical temperature for load combination 2

<table>
<thead>
<tr>
<th>Section</th>
<th>N</th>
<th>M1</th>
<th>M2</th>
<th>q</th>
<th>l0y</th>
<th>l0z</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPE 500</td>
<td>-135.9</td>
<td>0</td>
<td>170.9</td>
<td>0.69</td>
<td>16.300</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-135.9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>4.075</td>
</tr>
</tbody>
</table>
Critical temperature for load combination 2

**Results**

IPE 500 (Class 1)

- **Buckling resistance of the element**
  Critical temperature: 637.6 °C (Reduction factor: $k_{v0} = 0.380$)

- **Resistance of the cross-section**
  Critical temperature: 706.8 °C (Reduction factor: $k_{v0} = 0.219$)

**Critical temperature used in the next calculations:** 637.6 °C
Critical temperature of the column IPE 500

\[ \theta_{a,cr} = \min(656 \text{ ºC}; 638 \text{ ºC}) = 638 \text{ ºC} \]

Critical time with ISO 834 Using Elefir-EN
Critical time with ISO 834
Using Elefir-EN

\[ t_{fi,d} < t_{req} = 60 \text{ min} \quad \rightarrow \quad \text{Fire protection is needed for a critical temperature of } \theta_{a,cr} = 638 \text{ °C} \]
This Company has sheets for the temperatures: 350, 400, 450, 500, 550, 600, 620, 650 and 700°C
### Thickness of intumescent painting

... 600°C, 620°C, 650°C, ...

θ_{a,cr} = 638 °C

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

<table>
<thead>
<tr>
<th>Section factor up to m²</th>
<th>Thickness mm</th>
<th>Section factor up to m²</th>
<th>Thickness mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>0.255</td>
<td>85</td>
<td>0.518</td>
</tr>
<tr>
<td>50</td>
<td>0.244</td>
<td>80</td>
<td>0.530</td>
</tr>
<tr>
<td>65</td>
<td>0.254</td>
<td>80</td>
<td>0.643</td>
</tr>
<tr>
<td>70</td>
<td>0.263</td>
<td>100</td>
<td>0.555</td>
</tr>
<tr>
<td>85</td>
<td>0.272</td>
<td>70</td>
<td>0.887</td>
</tr>
<tr>
<td>90</td>
<td>0.281</td>
<td>70</td>
<td>1.619</td>
</tr>
<tr>
<td>100</td>
<td>0.291</td>
<td>80</td>
<td>0.650</td>
</tr>
<tr>
<td>110</td>
<td>0.300</td>
<td>85</td>
<td>0.882</td>
</tr>
<tr>
<td>120</td>
<td>0.309</td>
<td>90</td>
<td>0.714</td>
</tr>
<tr>
<td>135</td>
<td>0.318</td>
<td>95</td>
<td>0.745</td>
</tr>
<tr>
<td>150</td>
<td>0.326</td>
<td>100</td>
<td>0.776</td>
</tr>
<tr>
<td>165</td>
<td>0.335</td>
<td>105</td>
<td>0.800</td>
</tr>
<tr>
<td>180</td>
<td>0.344</td>
<td>110</td>
<td>0.834</td>
</tr>
<tr>
<td>200</td>
<td>0.355</td>
<td>120</td>
<td>0.865</td>
</tr>
<tr>
<td>220</td>
<td>0.364</td>
<td>125</td>
<td>0.898</td>
</tr>
<tr>
<td>250</td>
<td>0.374</td>
<td>135</td>
<td>0.939</td>
</tr>
<tr>
<td>275</td>
<td>0.382</td>
<td>160</td>
<td>1.063</td>
</tr>
<tr>
<td>300</td>
<td>0.391</td>
<td>190</td>
<td>1.245</td>
</tr>
</tbody>
</table>

θ_{a,cr} = 638 °C => e = 0.402 mm  
θ_{a,cr} = 500 °C => e = 0.605 mm

More than 50%

---

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 500°C is suggested.

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

Temperature development for different fire scenarios

Temperatures obtained using the program Ozone
Unit B - Jumbo

Combination of actions:

\[ 1.0G_k + \psi_{1,1}Q_{k,1} = 1.0G_k + 0.0Q_{k,1} = G_k \]

<table>
<thead>
<tr>
<th></th>
<th>( N_{\text{ed}} ) (kN)</th>
<th>( M_1 ) (kN.m)</th>
<th>( M_2 ) (kN.m)</th>
<th>( L ) (m)</th>
<th>( \theta_{cr} ) (ºC)</th>
<th>( t_{\text{ed}} ) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEA 260</td>
<td>80</td>
<td>0.00</td>
<td>23</td>
<td>1.0</td>
<td>672.9</td>
<td>19.25</td>
</tr>
<tr>
<td>HEA 240</td>
<td>34</td>
<td>0.00</td>
<td>45</td>
<td>1.0</td>
<td>593.5</td>
<td>15.23</td>
</tr>
<tr>
<td>IPE 360</td>
<td>0.00</td>
<td>76.0</td>
<td>0.0</td>
<td>-</td>
<td>682.8</td>
<td>17.92</td>
</tr>
</tbody>
</table>

Without fire protection

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

<table>
<thead>
<tr>
<th></th>
<th>( \theta_{cr} ) (ºC)</th>
<th>ISO (min)</th>
<th>Natural Fire + Simplified Method (min)</th>
<th>Natural Fire + Advanced Method (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEA 260</td>
<td>672.9</td>
<td>&gt; 90</td>
<td>&gt; 90</td>
<td></td>
</tr>
<tr>
<td>HEA 240</td>
<td>593.5</td>
<td>80.8</td>
<td>&gt; 90</td>
<td>&gt; 90</td>
</tr>
<tr>
<td>IPE 360</td>
<td>682.8</td>
<td>&gt; 90</td>
<td>&gt; 90</td>
<td></td>
</tr>
</tbody>
</table>
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
Required fire resistance 120 minutes (R120)

Zona A
Zona B
Zona C

Main Portal Frame
56.0 m 30.0 m

Main Structure
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 critical temperature of 350°C;
- Using **performance-based approach** with advanced calculation 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

Software: SAFIR

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 500°C, 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 350°C 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

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

The shard in London
References

- MACS + (2012), Membrane Action in fire design of Composite Slab with solid and cellular steel beams - Valorisation.
- Ozone V2.2.6, (2009), http://www.arcelormittal.com/sections/.
- Vila Real, P. M. M.; Lopes, N. “Shopping Centre Oeiras, Portugal”, to Martifer, S.A., LERF - Laboratório de Estruturas e Resistência ao Fogo, Universidade de Aveiro, Junho de 2009.
Thank you for your attention

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