Some Information on Eurocode 4 – part 1.2

(mainly from DIFESEK project report)

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Coordinator CEN TC 250 / Horizontal Group "FIRE"
Composite slabs & beams
Options

- Flat concrete slab or composite slab with profiled steel sheeting
- Profiles with or without Fire protection material
- Reinforcing bar
- Shear connectors
- Optional slab
- Stirrups welded to web of profile
- Reinforcing bar
- Beams
- Slabs
Composite columns
Options

(a) steel embedded in concrete (traditional approach)
(b) concrete between flanges (f.r. dependent on reinforcement)
(c) concrete filled SHS
- without reinforcement (f.r. ca. 30 minutes or less)
- with reinforcement (f.r. dependent on reinforcement)
Non-uniform temperature distribution
Load bearing and (possibly) separating function

- Load bearing capacity
- Thermal insulation
- Integrity

Options

- tabulated data
- simple calculation model
- advanced calculation model
## Tabulated data
(steel and concrete composite members)

<table>
<thead>
<tr>
<th>Composite beams</th>
<th>Composite columns</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Composite beam" /></td>
<td><img src="image2" alt="Composite column" /></td>
</tr>
<tr>
<td><img src="image3" alt="Concrete for insulation" /></td>
<td><img src="image4" alt="Concrete for insulation" /></td>
</tr>
<tr>
<td>Standard Fire Resistance</td>
<td>( \eta_{fi,t} \leq 0.28 )</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Minimum ratio of web to flange thickness ( e_w/e_f )</td>
<td>0.5</td>
</tr>
<tr>
<td>Minimum cross-sectional dimensions for load level</td>
<td>( \eta_{fi,t} \leq 0.47 )</td>
</tr>
<tr>
<td>Minimum ratio of reinforcement ( A_s/(A_c+A_s) ) in %</td>
<td>( \eta_{fi,t} \leq 0.66 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load level</th>
<th>R30</th>
<th>R60</th>
<th>R90</th>
<th>R120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum dimensions ( h ) and ( b ) [mm]</td>
<td>160</td>
<td>200</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Minimum axis distance of reinforcing bars ( u_s ) [mm]</td>
<td>-</td>
<td>50</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Minimum ratio of reinforcement ( A_s/(A_c+A_s) ) in %</td>
<td>-</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

**Composite Columns – prEN1994-1-2**

**Abstract**

- Tabulated data and relevant parameters
- Standard fire resistance
- Load level
- Section dimension
- Reinforcing steel
- Concrete cover

**Diagram**

- Diagram of composite columns
- Symbols: \( A_c \), \( A_s \), \( u_s \), \( e_w \), \( e_f \), \( h \)
**Composite Beams**

**Condition for application:**
- slab: \( h_c \geq 120 \text{ mm} \)
- \( b_{eff} \leq 5 \text{ m} \)
- steel section: \( b / e_w \geq 15 \)
- \( e_f / e_w \leq 2 \)

**Additional reinforcement area, related to total area between the flanges:**
\[ A_s / (A_c + A_s) \leq 5\% \]

### Standard Fire Resistance

<table>
<thead>
<tr>
<th>Load Level</th>
<th>R30</th>
<th>R60</th>
<th>R90</th>
<th>R120</th>
<th>R180</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>70/0,0</td>
<td>100/0,0</td>
<td>170/0,0</td>
<td>200/0,0</td>
<td>260/0,0</td>
</tr>
<tr>
<td>1.2</td>
<td>150/0,0</td>
<td>170/0,0</td>
<td>200/0,0</td>
<td>200/0,0</td>
<td>240/0,0</td>
</tr>
<tr>
<td>1.3</td>
<td>150/0,0</td>
<td>170/0,0</td>
<td>200/0,0</td>
<td>200/0,0</td>
<td>240/0,0</td>
</tr>
</tbody>
</table>

### Minimum cross-sectional dimensions for load level \( \eta_{fl,t} \leq 0,3 \)

- \( \min b \) [mm] and additional reinforcement \( A_s \) in relation to the area of flange \( A_f / A_f \)

<table>
<thead>
<tr>
<th>Load Level</th>
<th>R30</th>
<th>R60</th>
<th>R90</th>
<th>R120</th>
<th>R180</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>80/0,0</td>
<td>170/0,0</td>
<td>250/0,4</td>
<td>270/0,5</td>
<td>-</td>
</tr>
<tr>
<td>2.2</td>
<td>150/0,0</td>
<td>200/0,2</td>
<td>240/0,3</td>
<td>300/0,5</td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>120/0,0</td>
<td>180/0,2</td>
<td>220/0,3</td>
<td>280/0,3</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>100/0,0</td>
<td>170/0,2</td>
<td>200/0,3</td>
<td>250/0,3</td>
<td></td>
</tr>
</tbody>
</table>
### Totally encased steel sections

**Standard Fire Resistance**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>R30</th>
<th>R60</th>
<th>R90</th>
<th>R120</th>
<th>R180</th>
<th>R240</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 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>1.2 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>1.3 Minimum axis distance of reinforcing bars $u_s$ [mm]</td>
<td>20*</td>
<td>30</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

*Or *

<table>
<thead>
<tr>
<th>Requirement</th>
<th>R30</th>
<th>R60</th>
<th>R90</th>
<th>R120</th>
<th>R180</th>
<th>R240</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 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>2.2 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>2.3 Minimum axis distance of reinforcing bars $u_s$ [mm]</td>
<td>-</td>
<td>20*</td>
<td>20*</td>
<td>30</td>
<td>40</td>
<td>-</td>
</tr>
</tbody>
</table>

**NOTE:** *) These values have to be checked according to 4.4.1.2 of EN 1992-1-1
How to apply tabulated data in fire design (two different situations)

**VERIFICATION**

1. $R_d$ of $\theta_{20^\circ C}$
2. $E_{fi.d}$
3. $\eta_{fi,t} = \frac{E_{fi.d}}{R_d}$
4. Section dimension reinforcing steel concrete cover
5. Standard fire rating

**PRE-DESIGN**

1. $E_{fi.d}$ and $E_d$
2. $\eta_{fi,t} = \frac{E_{fi.d}}{E_d}$
3. Standard fire rating
4. Section dimension reinforcing steel concrete cover
5. $R_d \geq E_d$
Concrete with only insulation function

<table>
<thead>
<tr>
<th>Standard Fire Resistance</th>
<th>R30</th>
<th>R60</th>
<th>R90</th>
<th>R120</th>
<th>R180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete cover c [mm]</td>
<td>0</td>
<td>25</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

Diagram showing concrete for insulation and slab with standard fire resistance values.
Composite elements
Calculation rules thermal response

Similar to concrete elements
Complications due to shape
Simple calculation rules available
Thermal response composite elements
Advanced model (illustration)

computer simulation
test vs. simulation
Semi-empirical approach

Parameter study based on systematic calculation with advanced calculation model

Direct application of advanced calculation model
Simple calculation models
Semi-empirical approach

Components cross section:
- flanges steel section
- web steel section
- concrete
- re-bars

For each component:
- reduced strength
- and/or reduced area

Reduced cross section
Simple calculation models
Parameter study approach

Composite slabs with profiled steel sheet

<table>
<thead>
<tr>
<th>Decking type</th>
<th>Concrete depth $H_B$ [mm]</th>
<th>Concrete type</th>
</tr>
</thead>
<tbody>
<tr>
<td>re-entrant (6x)</td>
<td>50, 60, 70, 80, 90, 100, 110, 120</td>
<td>NCW and LWC ENV 1994-1-1</td>
</tr>
<tr>
<td>trapezoidal (49x)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- standard fire conditions
- profiled shape deckings taken into account
- thermal properties according to EC
- average moisture content: 4% (NWC) and 5% (LWC)

Note: total number of simulations: 880
Typical temperature distribution at the unexposed side of a composite slab

**Insulation criterion:**

\[-\Delta \Theta_{av} \leq 140 \, ^\circ C\]

\[-\Delta \Theta_{max} \leq 180 \, ^\circ C\]
Issues:

\[ t_f = t_f (l_1, l_2, \ldots, A/L_r, \phi) \]

with:
- \( l_1, l_2, \ldots \) geometry slab
- \( A \) volume rib
- \( L_r \) exposed surface rib
- \( \phi \) configuration factor

\[ t_f = a_0 + a_1 \cdot h_1 + a_2 \cdot \phi + a_3 \cdot A/L_r + a_4 \cdot 1/L_3 + a_5 \cdot A/L_r \cdot 1/l_3 \text{ [min]} \]

with:
- \( a_i \) coefficients, depending on duration of s.f.c. exposure
Thermal insulation composite slabs
Verification simple calculation rule

Fire resistance (Eurocode 4) => Fire resistance (adv. model)

- (a) ENV rule
- (b) new rule
Composite slabs
Thermal response positive reinforcement

Temperature reinforcement has significant impact on $M^+_p,\Theta$

$\Theta_r = \Theta_r (u_1, A/O, l_3, z ..)$

$z = z(u_1, u_2, u_3)$

Note: steel sheet may significantly contribute to the load bearing capacity!
Thermal response positive reinforcement
Simple calculation rule

(a) ENV rule

(b) new rule
Composite slabs

Thermal Insulation (ISO fire) | Equivalent thickness $h_{eff}$[mm]
---|---
I 30 | 60 – $h_3$
I 60 | 80 – $h_3$
I 90 | 100 – $h_3$
I 120 | 120 – $h_3$
Concrete filled SHS columns
Resistance to fire (traditional approach)

Design charts available
Unpractical
Need for “user friendly” design tool

⇒ e.g. POTFIRE

<table>
<thead>
<tr>
<th>no.</th>
<th>concrete</th>
<th>rebar</th>
<th>quality</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>C20</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>C20</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>C20</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>C30</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>C30</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>C30</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>C40</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>C40</td>
<td>2.5</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>C40</td>
<td>4</td>
</tr>
</tbody>
</table>
Validation POTFIRE

assumptions:
- $\alpha_{\text{conv}} = 25 \text{ W/m}^2\text{k}$
- $\varepsilon_{\text{res}} = 0.7$

Concrete Filled Steel Hollow Section
Logiciels de calcul

Logiciels « AFcolumn » et « AFbeam »

Développés par ProfilARBED

Peuvent être obtenus sur le site

www.arcelormittal.com
Simple calculation model (steel and composite members)

<table>
<thead>
<tr>
<th>Beams (steel or composite)</th>
<th>Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Beam Diagram 1" /></td>
<td><img src="image2" alt="Column Diagram 1" /></td>
</tr>
<tr>
<td><img src="image3" alt="Beam Diagram 2" /></td>
<td><img src="image4" alt="Column Diagram 2" /></td>
</tr>
<tr>
<td><img src="image5" alt="Beam Diagram 3" /></td>
<td><img src="image6" alt="Column Diagram 3" /></td>
</tr>
<tr>
<td><img src="image7" alt="Beam Diagram 4" /></td>
<td><img src="image8" alt="Column Diagram 4" /></td>
</tr>
</tbody>
</table>
Simple calculation model (composite beam) - plastic resistance theory

\[ F_c^+ = F_t^+ \times D^+ \]
Composite beams

- **bare**
- **insulated**
Simple calculation model (composite column) - buckling curve

Load capacity: \( N_{fi.Rd} = \chi(\bar{\lambda}_\theta) \cdot N_{fi.pl.Rd} \)

\( \chi(\bar{\lambda}_\theta) \leftrightarrow \text{strength and rigidity of effective section} + \text{column buckling length} \ L_{fi} \)
Construction details shall be respected in order to consistent with numerical models

Reinforcing bars between slab and edge columns

Maximum gap of 15 mm between beam and column and between lower flange of the beam

Maximum gap of 15 mm between beam and column and between lower flange of the beam

Reinforcing bars between slab and edge columns

Maximum gap of 15 mm between beam and column and between lower flange of the beam

Reinforcing bars between slab and edge columns

Maximum gap of 15 mm between beam and column and between lower flange of the beam

φ12 in S500

Maximum gap of 15 mm between beam and column and between lower flange of the beam
Construction details to get hogging moment resistance in fire situation

- Join detail - Example

- Continuous reinforcing bar
- Studs
- Sections with infilled concrete

A limited gap allowing to develop a hogging moment in the fire situation
Connection between steel profile and encased concrete

- Welding of stirrups to the web:
  - $\phi_r \geq 8\,\text{mm}$
  - $\phi_s \geq 6\,\text{mm}$
  - $l_w \geq 4\,\phi_s$

- Welding of studs to the web:
  - Studs:
    - $d \geq 10\,\text{mm}$
    - $h_v \geq 0.3b$

- Welding properties:
  - $a_w \geq 0.5\,\phi_s$
  - $b$
Fire design by global structural analysis

- Application requirement of advanced calculation models
  - Requirement on material models
    - strain composition
    - kinematical material model
    - strength during cooling phase
  - Step by step iterative solution procedure
  - Check of possible failure untreated in direct analysis
    - rupture due to excessive steel elongation
    - cracking and crushing of concrete
Global analysis of steel and concrete composite floor under localised fire

Standard part of the floor system

Composite slab
Steel deck: 0.75 mm

3.2 m
4.2 m
15 m
10 m
15 m
10 m
10 m
Two different structural models may be adopted

- **2D composite frame model (beam elements)**
  - membrane effect is limited to one direction due to 1D effect slab model
  - load redistribution is not possible between parallel beams

- **3D composite floor model (multi-type element)**
  - membrane effect over whole floor area
  - load redistribution becoming possible with help of shell elements

More realistic to apply 3D composite floor model
Validity of 3D composite floor model

- Test
- Cal. 3D
- Cal. 2D

3D calculation model

Vert. Disp. (mm)

Time (min)

Hori. Disp. (mm)

Time (min)
Strategy of 3D composite floor modelling

Global structure without composite slab

Fire area

Detail of numerical modelling
Mechanical loading and boundary conditions

Uniformly distributed load: $G + \Psi_{1,1} Q$

Continuity condition of concrete slab

$\theta = 0$

Continuity condition of columns

$\theta = 0$
Mechanical response of the structure

- Total deflection of the floor and check of the corresponding failure criteria
Mechanical response of the structure

➢ Total deflection of the floor and check of the corresponding failure criteria

![Diagram showing deflection and time graphs with failure criteria]

- For the main beam, the failure criteria is met when:
  \[ 110 \text{ mm} \leq \frac{L}{20} = 500 \text{ mm} \]

- For the secondary beam, the failure criteria is met when:
  \[ 280 \text{ mm} \leq \frac{L}{20} = 750 \text{ mm} \]
Mechanical response of the structure

➢ Check of failure criteria: elongation of reinforcing steel

1.4 % ≤ 5 %

Strain of reinforcing steel // slab span

1.3 % ≤ 5 %

Strain of reinforcing steel ⊥ slab span
Unbraced frame – R + 3
Design

Unbraced frame
Edge column temperature

Time: 90 minutes

Temperature (°C)

External Column
Central column temperature

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>140</td>
<td>70</td>
</tr>
<tr>
<td>160</td>
<td>80</td>
</tr>
<tr>
<td>180</td>
<td>90</td>
</tr>
</tbody>
</table>

The diagram shows central column temperature changes over time, with temperature values ranging from 0 to 1000 °C and time values ranging from 0 to 90 minutes.
**Bean-slab temperature**

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>40</td>
<td>400</td>
</tr>
<tr>
<td>50</td>
<td>500</td>
</tr>
<tr>
<td>60</td>
<td>600</td>
</tr>
<tr>
<td>70</td>
<td>700</td>
</tr>
<tr>
<td>80</td>
<td>800</td>
</tr>
<tr>
<td>90</td>
<td>900</td>
</tr>
</tbody>
</table>

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**Graphical Representation:**

- **A**
- **B**
- **C**
- **D**

---

**Legend:**

- **A**: High temperature area
- **B**: Medium temperature area
- **C**: Low temperature area
- **D**: Very low temperature area
Deformations of the frame

Horizontal displacement HD (mm)
Braced frame
Deformation of frame
## Comparison

<table>
<thead>
<tr>
<th>Case</th>
<th>Restraint condition</th>
<th>Dimension of external column</th>
<th>Dimension of central column</th>
<th>Dimension of beam</th>
<th>Fire resistance of the frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unbraced</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
<td>37.5 minutes</td>
</tr>
<tr>
<td>2</td>
<td>Unbraced</td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
<td>44.5 minutes</td>
</tr>
<tr>
<td>3</td>
<td>Unbraced</td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
<td><img src="image9" alt="Diagram" /></td>
<td>60.5 minutes</td>
</tr>
<tr>
<td>4</td>
<td>Unbraced</td>
<td><img src="image10" alt="Diagram" /></td>
<td><img src="image11" alt="Diagram" /></td>
<td><img src="image12" alt="Diagram" /></td>
<td>64.0 minutes</td>
</tr>
<tr>
<td>5</td>
<td>Braced</td>
<td><img src="image13" alt="Diagram" /></td>
<td><img src="image14" alt="Diagram" /></td>
<td><img src="image15" alt="Diagram" /></td>
<td>47.5 minutes</td>
</tr>
<tr>
<td>6</td>
<td>Braced</td>
<td><img src="image16" alt="Diagram" /></td>
<td><img src="image17" alt="Diagram" /></td>
<td><img src="image18" alt="Diagram" /></td>
<td>60.0 minutes</td>
</tr>
</tbody>
</table>