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Fire Behaviour of Steel and Composite Floor Systems

Background of simple design method

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Dec. 2010

Content of presentation

- **Mechanical behaviour of composite floors in a fire situation**
- **Simple design method of reinforced concrete slabs at 20 °C**
  - Floor slab model
  - Failure modes
- **Simple design method of composite floors at elevated temperatures**
  - Resistance of concrete slab with plastic yield lines
  - Membrane effect at elevated temperatures
  - Enhancement in presence of supporting steel beams

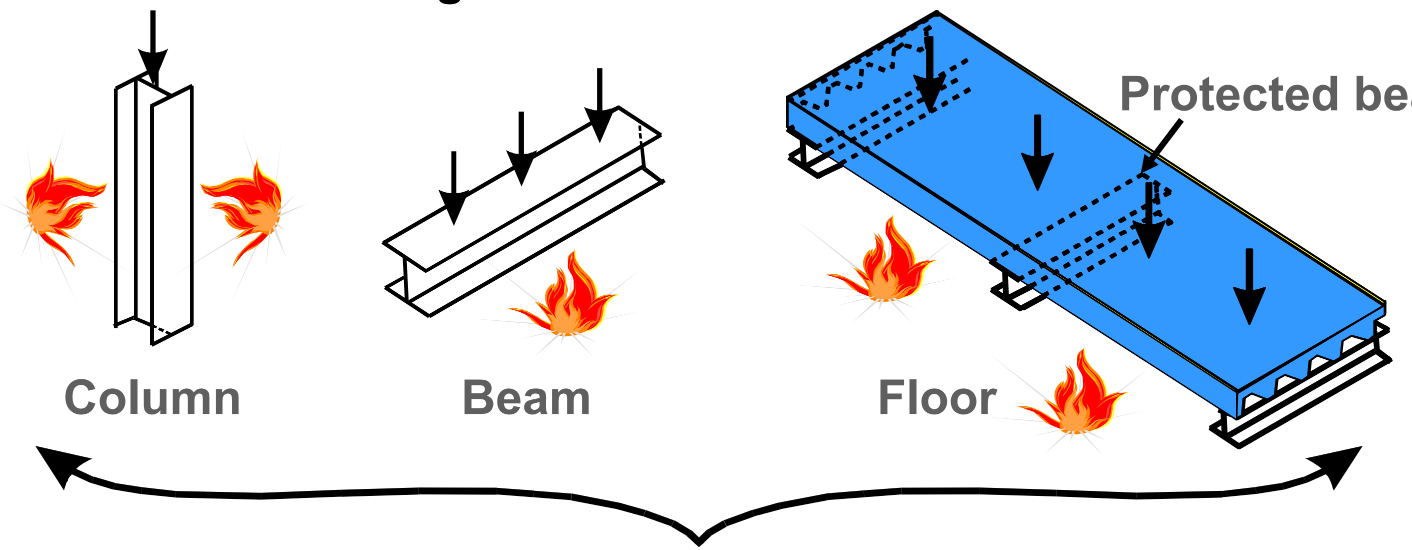
Mechanical behaviour of composite floors

Mechanical behaviour of composite floors

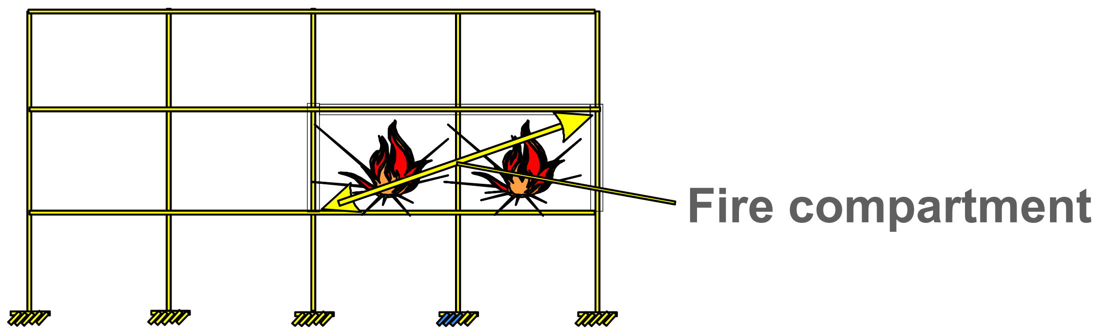
Simple design method of reinforced concrete slabs at 20°C

Simple design method of composite floors at elevated temperatures

- **Traditional design method**



Existing design methods assume isolated members will perform in a similar way in actual buildings

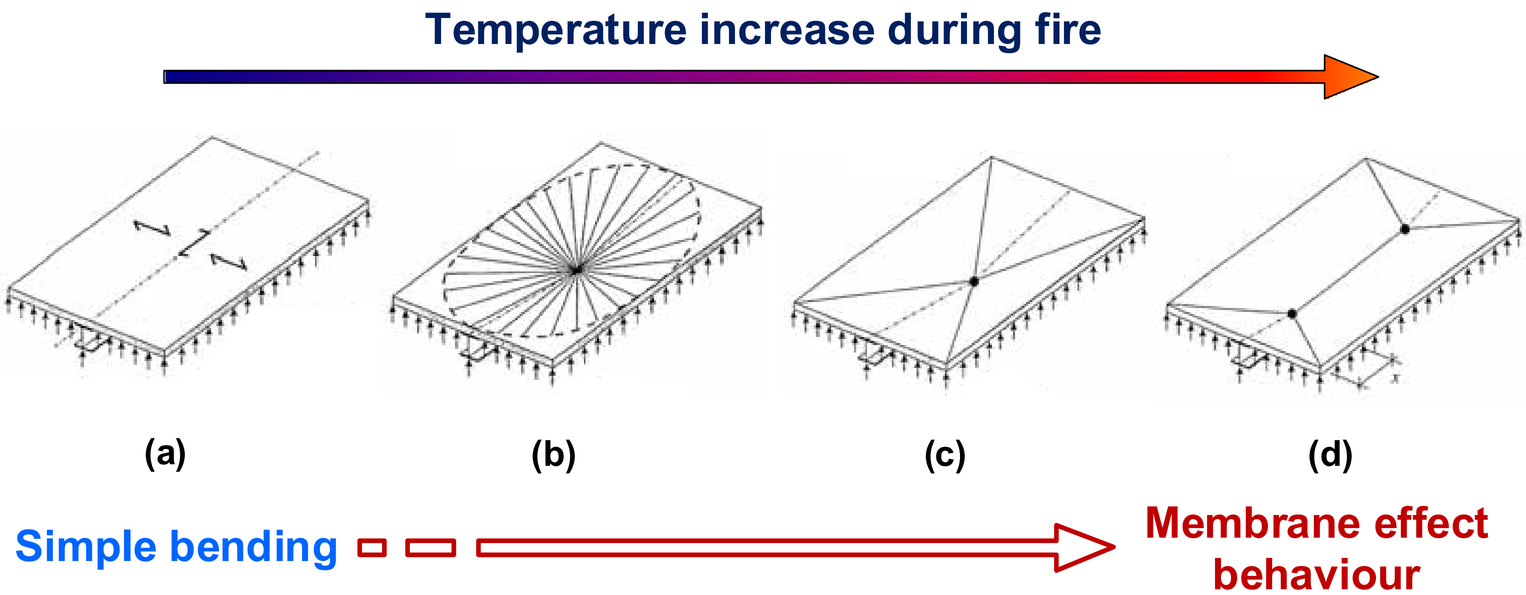


Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Real behaviour in case of composite floor with strong reinforcing steel mesh in concrete slab**



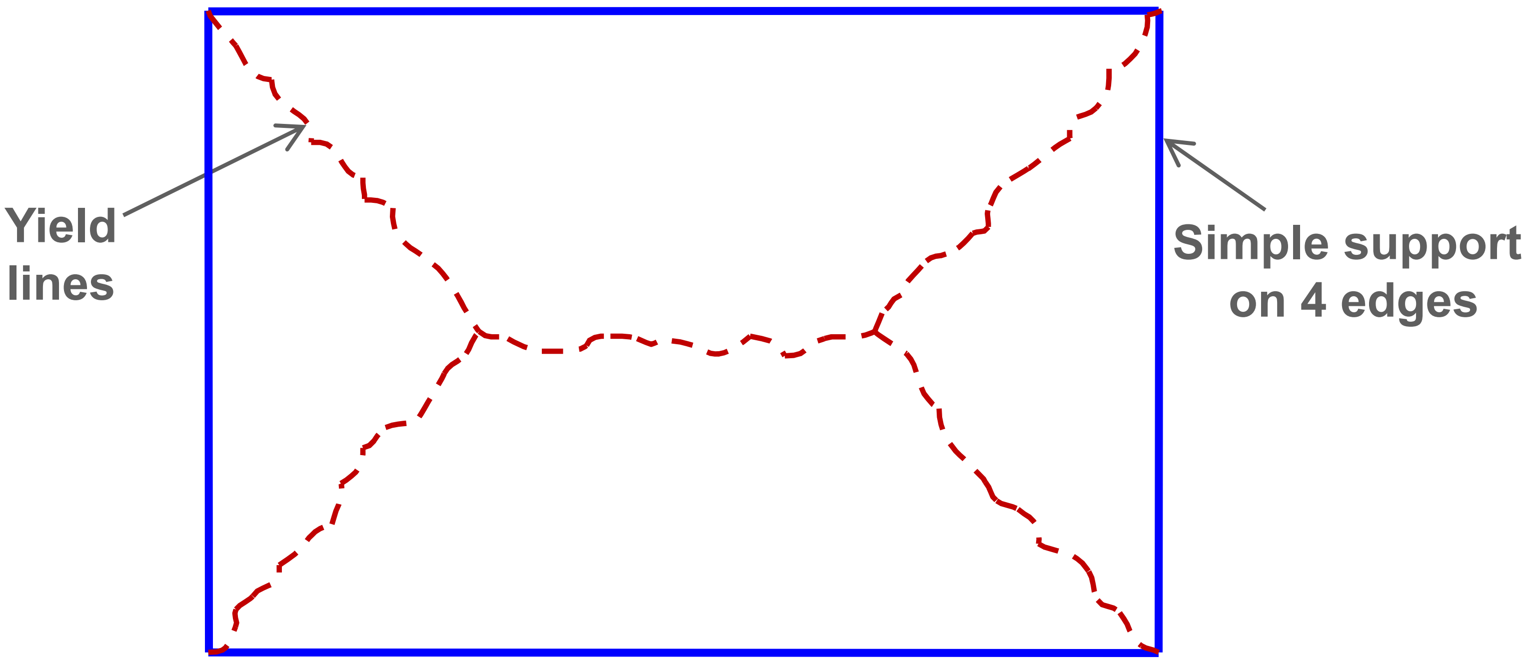
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

Simple design method at 20°C

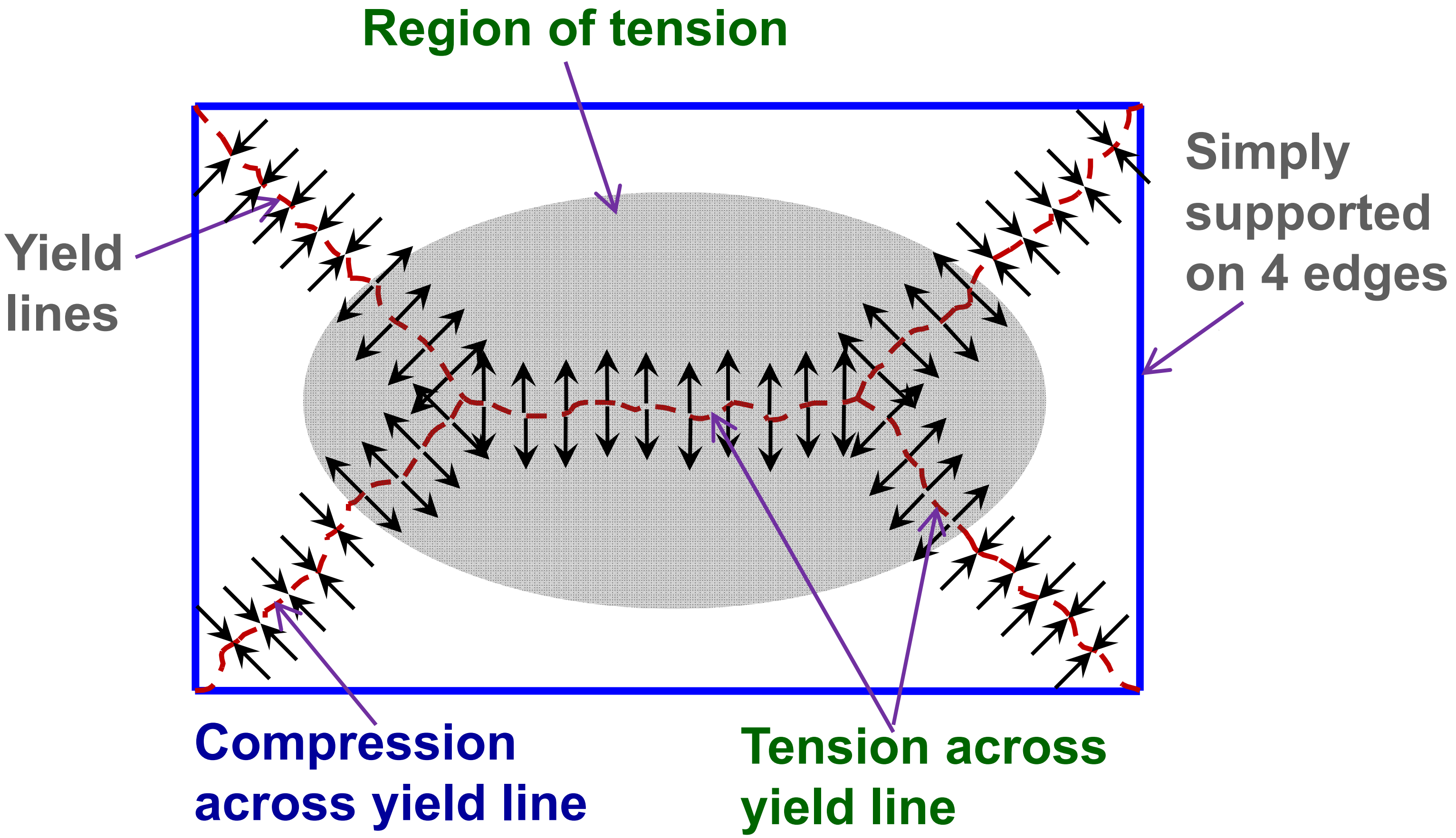
Simple design method at elevated temperatures

- **Floor slab model with 4 vertically restrained sides** (Plastic yield lines)



Simple design method of reinforced concrete slabs at 20 °C

- **Floor slab model**
  - Membrane effect enhancing yield lines resistance



Mechanical behaviour of composite floors

Simple design method at 20°C

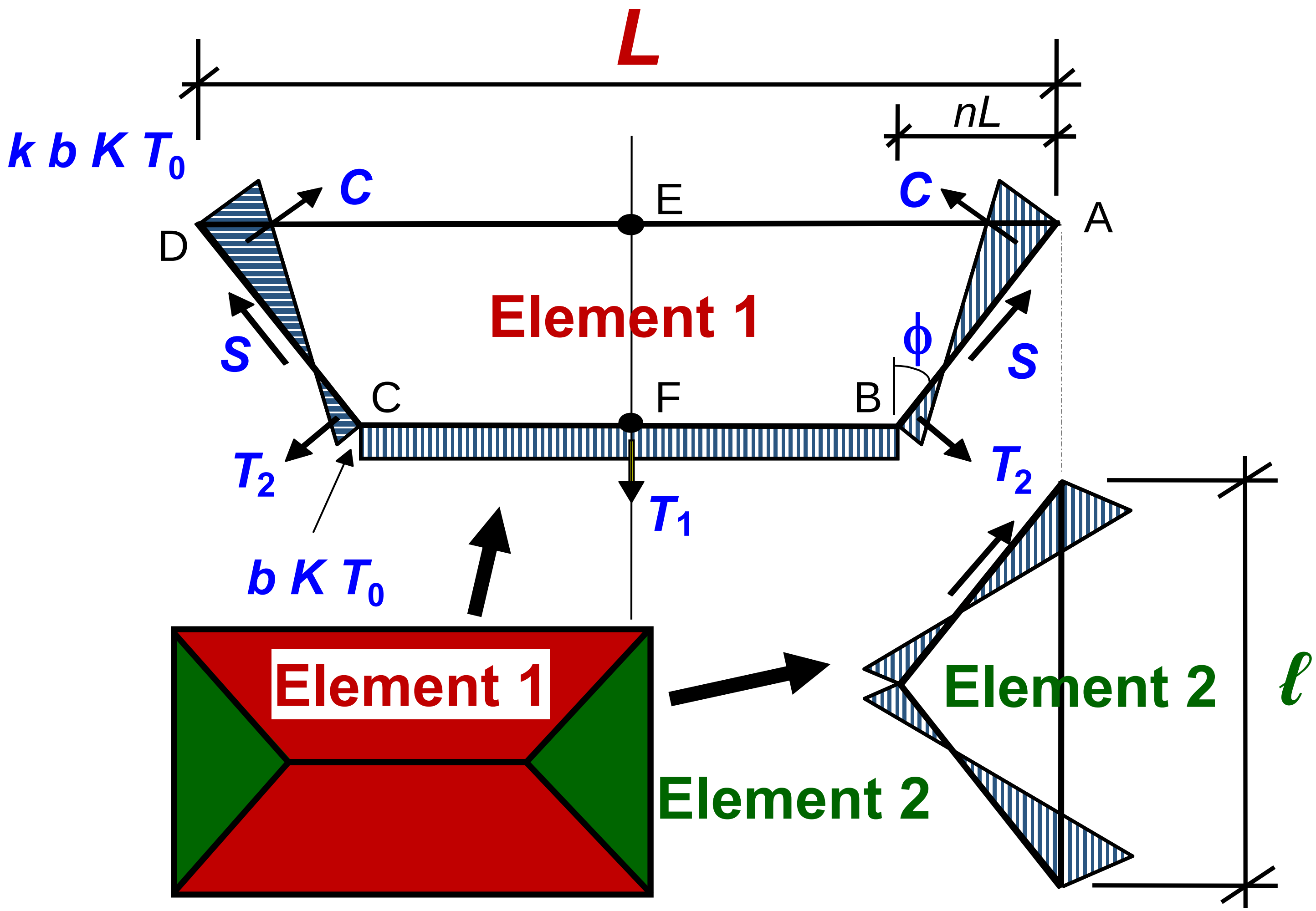
Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Membrane forces along yield lines (1)**



- **Membrane forces along yield lines (2)**

k, b	are parameters defining magnitude of membrane forces,
n	is a factor deduced from yield line theory,
K	is the ratio of the reinforcement in the shorter span to the reinforcement in the longer span,
T_0	is the reinforcement per unit width in the longer span,
T_1, T_2, ***C, S***	are resulting membrane forces along yield lines.

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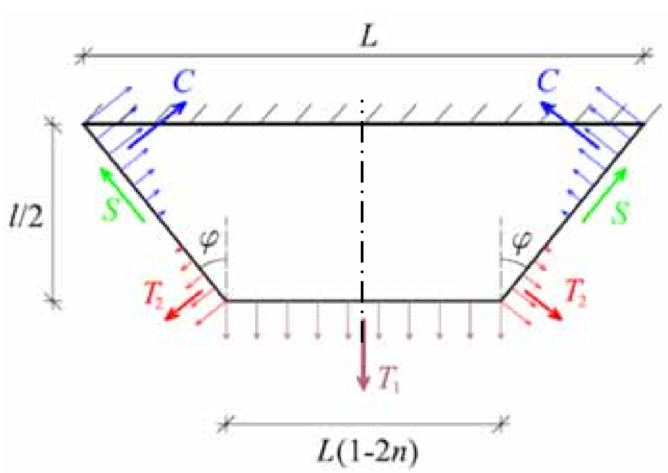
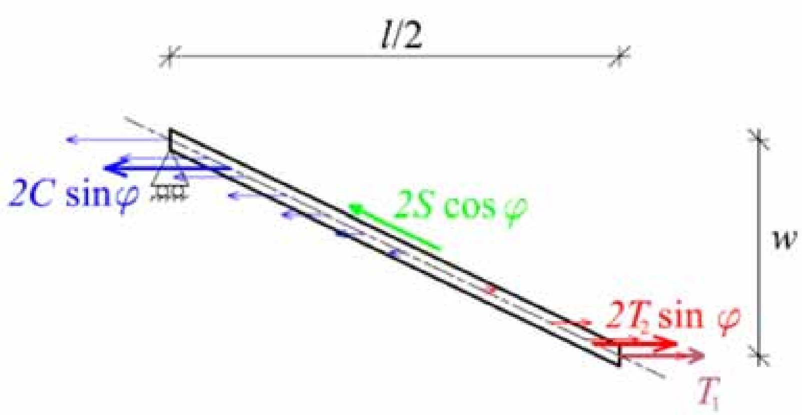
Simple design method at 20°C

Simple design method at elevated temperatures

- **Contribution of membrane action (1)**
  - **Element 1**

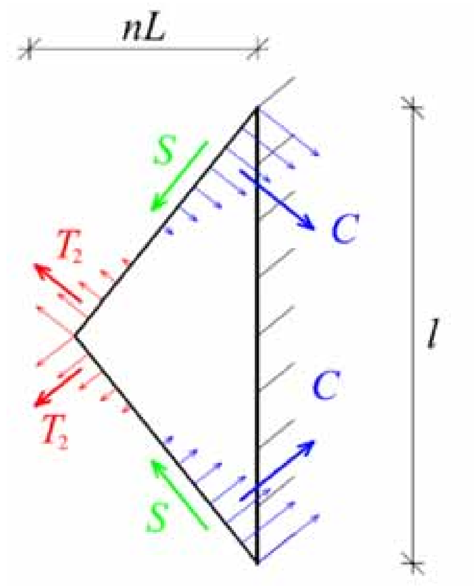


In-plane view of the resulting membrane forces

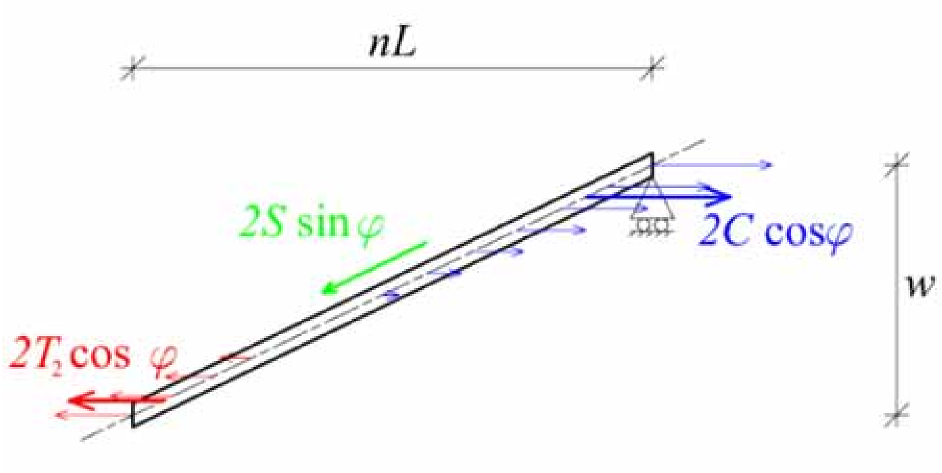


Side-view of the resulting membrane forces under a deflection equal to *w*

- **Contribution of membrane action (2)**
  - **Element 2**



In-plane view of the resulting membrane forces



Side-view of the resulting membrane forces under a deflection equal to w

Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Contribution of membrane action (3)**
  - **Enhancement factor for each element**

$e_{i,\ i=1,2} = \begin{cases} e_{im} : \text{moment resistance of element i about the support} \\ + \\ e_{ib} : \text{moment resistance of element i yield lines} \end{cases}$

  - **Overall enhancement**

$$e = e_1 - \frac{e_1 - e_2}{1 + 2\mu a^2}$$

where:

μ is the coefficient of orthotropy of the reinforcement

a is the aspect ratio of the slab = *L/ℓ*

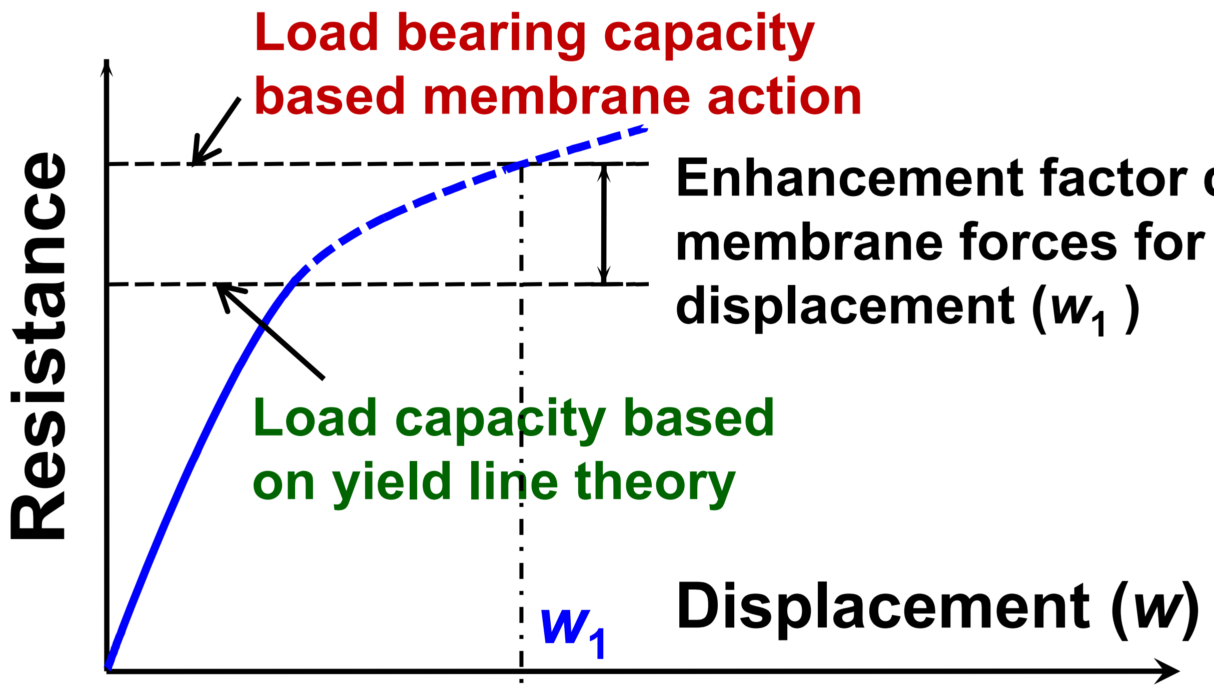
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

Simple design method at 20°C

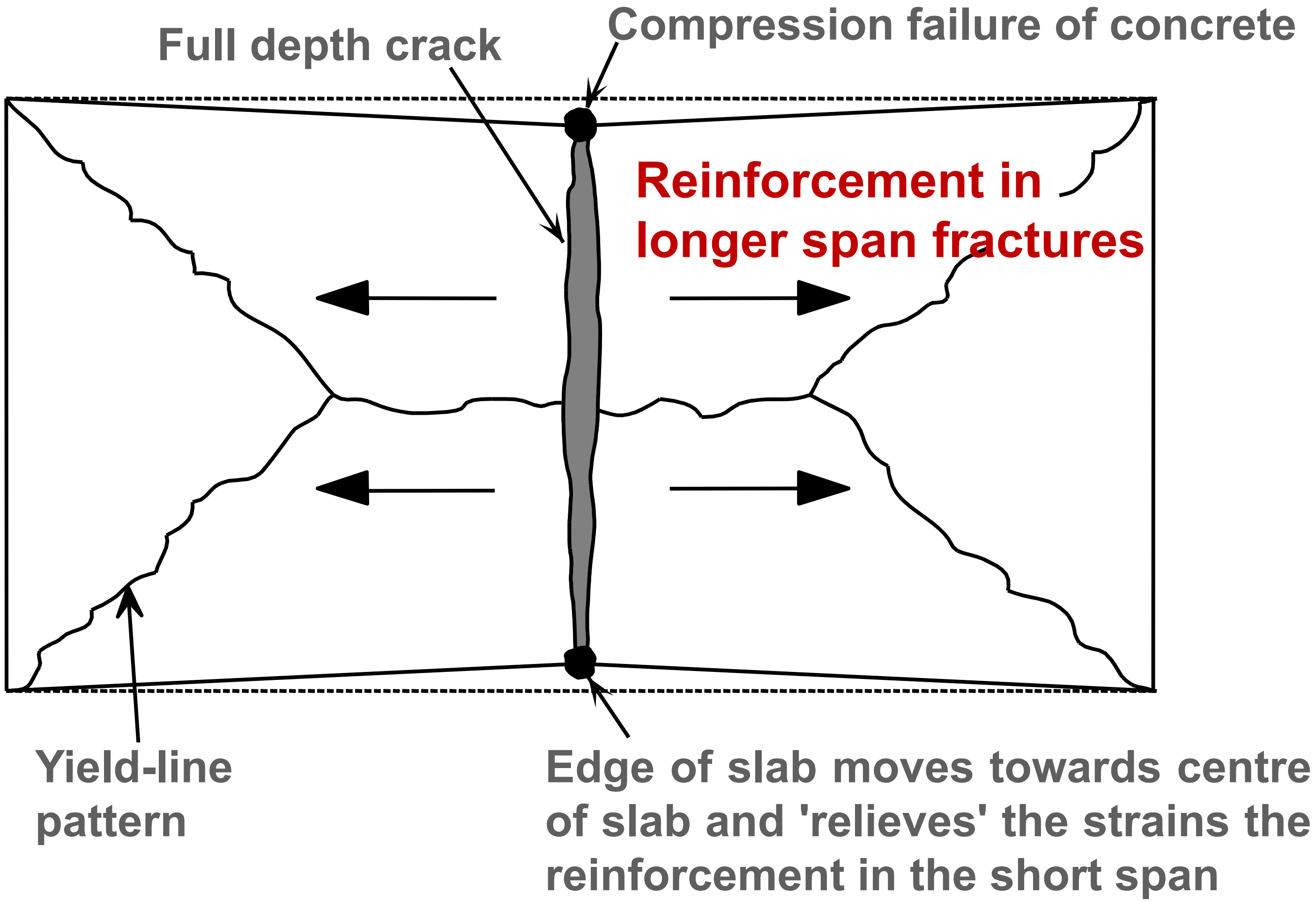
Simple design method at elevated temperatures

- **Contribution of membrane action (4)**



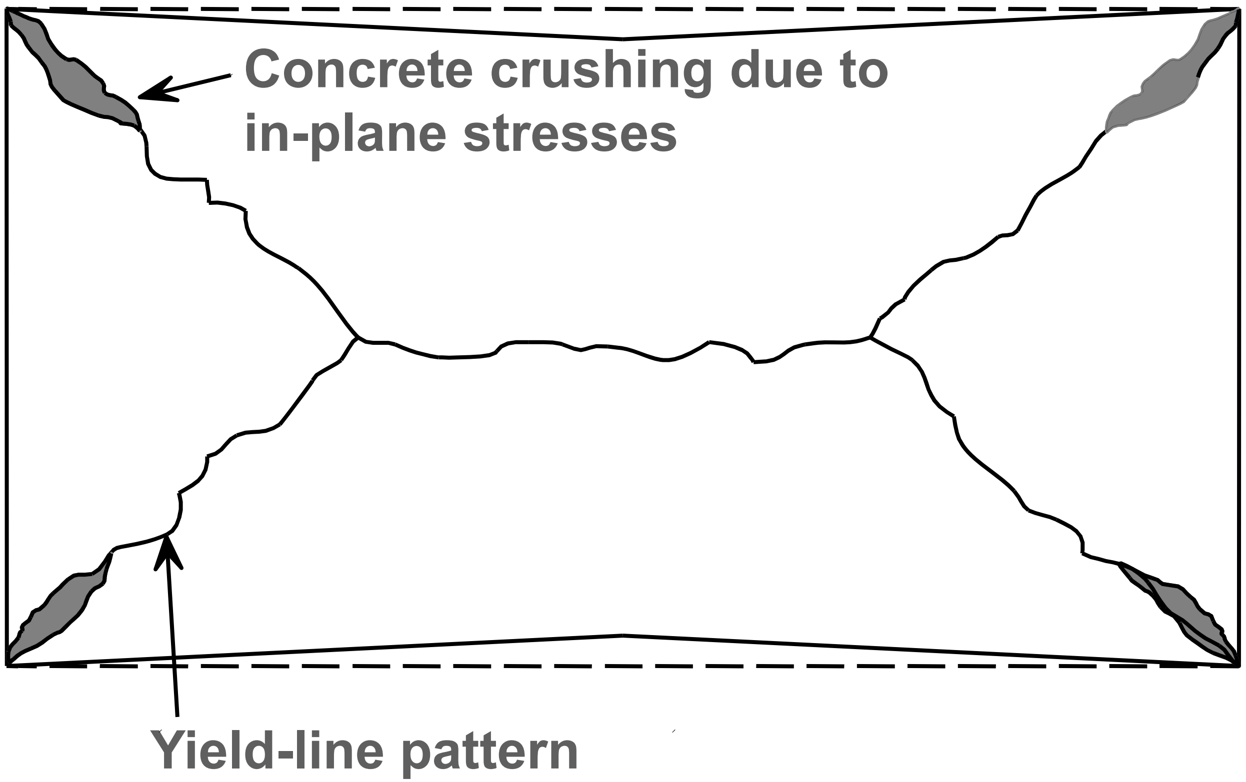
Simple design method of reinforced concrete slabs at 20 °C

- **Failure modes** (tensile failure of reinforcement)



Simple design method of reinforced concrete slabs at 20 °C

- **Failure modes** (compressive failure of concrete)
  - More likely to occur in case of strong reinforcement mesh



Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Failure modes** (experimental evidences)

Tensile failure of reinforcement

Compressive failure of concrete

Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Floor slab model at elevated temperatures (1)**
  - On the basis of the same model at room temperature
  - Account for thermal bowing of the slab due to temperature gradient in depth which equals to:

$$w_{\theta} = \frac{\alpha (T_2 - T_1)\ell^2}{19.2\, h}$$

where:

h is the effective depth of the slab

ℓ is the shorter span of the slab

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Floor slab model at elevated temperatures (2)**

and:

α is the coefficient of thermal expansion for concrete

For LW concrete, EN 1994-1-2 value is taken

$\alpha_{LWC} = 0.8 \times 10^{-5}$ °K^{-1}

For NW concrete, a conservative value is taken

$\alpha_{NWC} = 1.2 \times 10^{-5}$ °K^{-1} $< 1.8 \times 10^{-5}$ °K^{-1} (EN 1994-1-2 value)

T_2 is the temperature of the slab bottom side (fire-exposed side)

T_1 is the temperature of the slab top side (unexposed side)

- **Floor slab model at elevated temperatures (3)**
  - **Assuming mechanical average strain at a stress equal to half the yield stress at room temperature**
  - **Deflection of slab on the basis of a parabolic deflected shape of the slab due to transverse loading:**

$$w_\varepsilon = \sqrt{\left(\frac{0.5\, f_{sy}}{E_s}\right)\frac{3L^2}{8}} \leq \frac{\ell}{30}$$

where:

E_s is the elastic modulus of the reinforcement at 20°C

f_{sy} is the yield strength of the reinforcement at 20°C

L is the longer span of the slab

Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Floor slab model at elevated temperatures (4)**
  - Hence, the maximum deflection of the floor slab is:

$$w = \frac{\alpha(T_2 - T_1)\ell^2}{19.2\,h} + \sqrt{\left(\frac{0.5\,f_{sy}}{E_s}\right)\frac{3L^2}{8}}$$

  - However, the maximum deflection of the floor slab is limited to:

$$w \leq \frac{L + \ell}{30}$$

- **Conservativeness of the floor slab model at elevated temperatures**
  - The estimated vertical displacements due to thermal curvature are underestimated compared to theoretical values
  - The thermal curvature is calculated based on the shorter span of the slab
  - Any additional vertical displacements induced by the restrained thermal expansion when the slab is in a post buckled state are ignored
  - Any contribution from the steel decking is ignored
  - The increase of the mesh ductility with the temperature increase is ignored

Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Load bearing capacity of the floor slab model enhanced in presence of unprotected steel beams (1)**
  - **Catenary action of unprotected beams is neglected**
  - **The bending moment resistance of unprotected beams is taken into account with following assumptions:**
    - Simple support at both ends
    - Heating of the steel cross-section calculated according to EN1994-1-2 4.3.4.2, considering shadow effect
    - Thermal and mechanical properties for both steel and concrete given in EN 1994-1-2

Simple design method at elevated temperatures

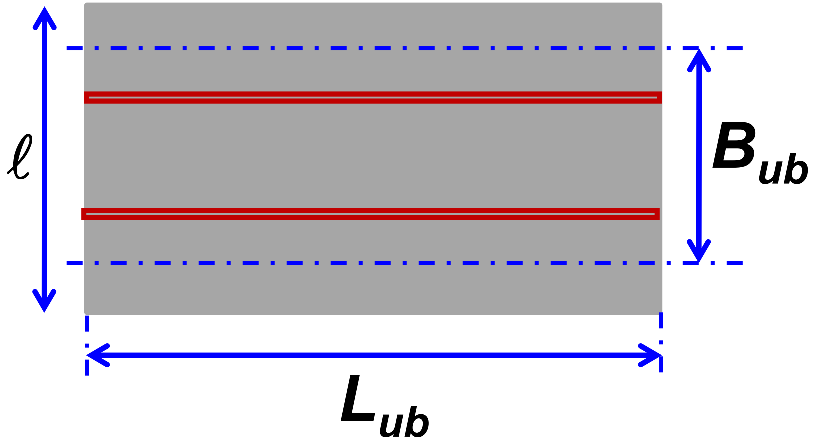
Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Load bearing capacity of the floor slab model enhanced in presence of unprotected steel beams (2)**
  - **Enhancement of load bearing capacity from unprotected beams is:**

$$\frac{8M_{Rd,fi}}{L_{ub}^{2}}\frac{n_{ub}}{B_{ub}} = \frac{8M_{Rd,fi}}{L^{2}}\frac{1+n_{ub}}{\ell}$$

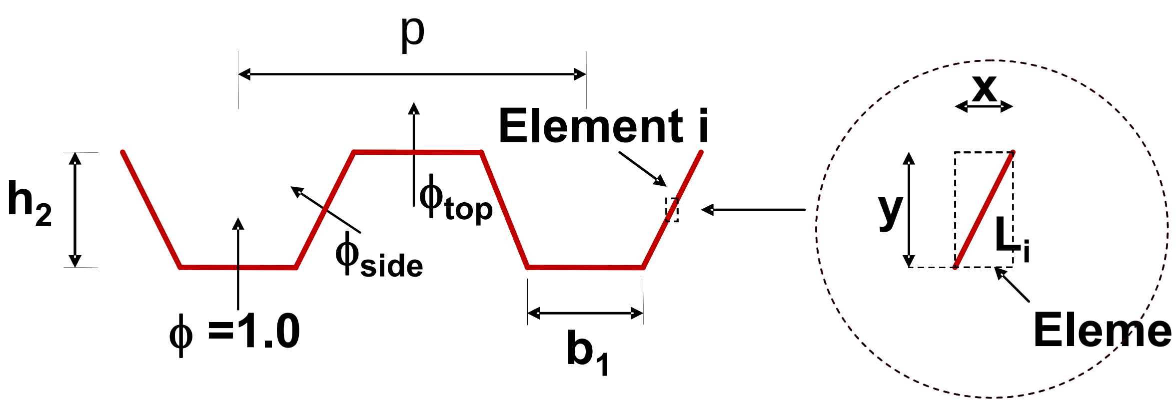


where:

n_{ub} is the number of unprotected beams

$M_{Rd,fi}$ is the moment resistance of each unprotected composite beam

- **Temperature calculation of composite slab**
  - **On the basis of advanced calculation models**
    - 2D finite difference method
    - Material thermal properties from EN 1994-1-2 for both steel and concrete
    - Shadow effect is taken into account for composite slabs



Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Load bearing capacity of protected perimeter beams**
  - **Load level $\eta_{fi,t}$**
    - Additional load on secondary beams
  - **Critical temperature method**
    - Composite beams (EN 1994-1-2)
      - R30
      - Other fire resistance ratings
    - Steel beams (EN 1993-1-2)

$$0.9\,\eta_{fi,t} = \frac{f_{ay,\theta cr}}{f_{ay}} = \left.\frac{M_{Rd,fi,b,i}}{M_{Rd,b,i}}\right|_{i=1,2}$$

$$\eta_{fi,t} = \frac{f_{ay,\theta cr}}{f_{ay}} = \left.\frac{M_{Rd,fi,b,i}}{M_{Rd,b,i}}\right|_{i=1,2}$$

$$\eta_{fi,t} = \frac{f_{ay,\theta cr}}{f_{ay}} = \left.\frac{M_{Rd,fi,b,i}}{M_{Rd,b,i}}\right|_{i=1,2}$$

Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Load bearing capacity of protected perimeter beams on the basis of global plastic mechanism**
  - **Primary beams and secondary beams are designed separately**
  - **For both primary and secondary beams**
    - An alternative single yield line pattern linking the plastic hinges is considered
    - The required moment resistance $M_{Rd,fi,b}$ is the same on all parallel perimeter beams, regardless of their actual cross-section
    - 2 cases are studied
      - 2 edge beams
      - at least 1 internal beam
    - The principle of virtual work is applied

Simple design method at elevated temperatures

- **Load bearing capacity of primary beams (1)**

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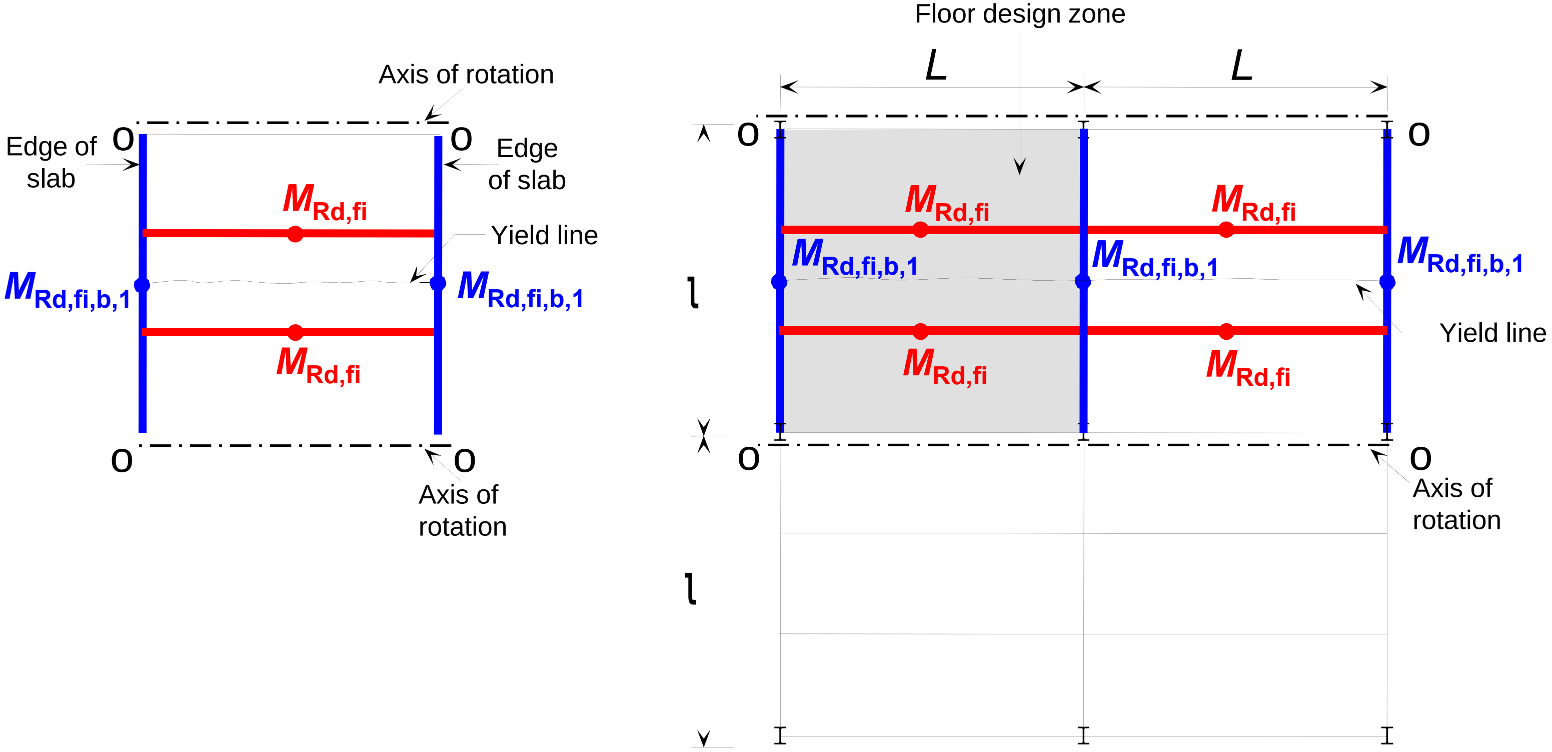
Simple design method at 20°C

Simple design method at elevated temperatures

2 edge beams

1 internal beam



Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Load bearing capacity of primary beams (2)**
  - **2 edge beams**

$$M_{Rd,fi,b,1} = \frac{pL^2\ell - 8\mu M_0 L_{eff}}{16}$$

  - **At least one internal beam**

$$M_{Rd,fi,b,1} = \frac{pL^2\ell - 8\mu M_0 L_{eff}}{12}$$

where:

p is the maximum of the applied load and the floor loadbearing capacity

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Load bearing capacity of primary beams (3)**

and:

L_{eff} is the effective length of the yield line

- 2 edge steel beams

$$L_{eff} = L$$

- only 1 composite beam

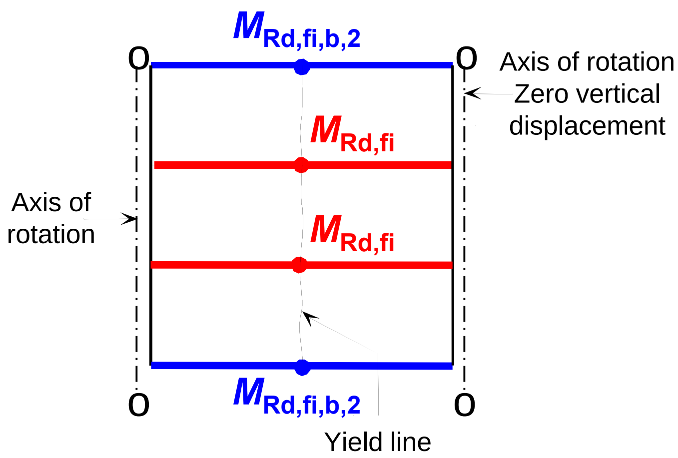
$$L_{eff} = L - min\left(\frac{L}{2};\frac{\ell}{8}\right)$$

- 2 composite beams

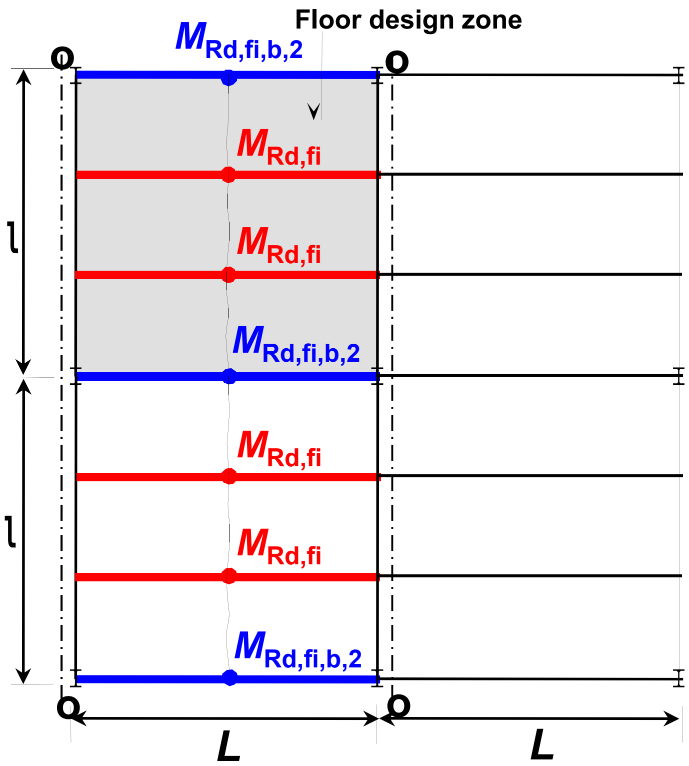
$$L_{eff} = L - 2 \times min\left(\frac{L}{2};\frac{\ell}{8}\right)$$

- **Load bearing capacity of protected secondary beams (1)**

2 edge beams



1 internal beam



Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Load bearing capacity of protected secondary beams (2)**
  - **2 edge beams**

$$M_{Rd,fi,b,2} = \frac{pL\ell^2 - 8\left(M_0\ell_{eff} + n_{ub}M_{Rd,fi}\right)}{16}$$

  - **At least one internal beam**

$$M_{Rd,fi,b,2} = \frac{pL\ell^2 - 8\left(M_0\ell_{eff} + n_{ub}M_{Rd,fi}\right)}{12}$$

where:

p is the maximum of the applied load and the floor loadbearing capacity

Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

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- **Load bearing capacity of protected secondary beams (3)**

  and:

  ℓ_{eff} is the effective length of the yield line

  - 2 edge steel beams

$$\ell_{eff} = \ell - n_{ub}\, min\left(\frac{\ell}{1+n_{ub}};\frac{L}{4}\right)$$

  - only 1 composite beam

$$\ell_{eff} = \ell - \left(n_{ub}+\frac{1}{2}\right) min\left(\frac{\ell}{1+n_{ub}};\frac{L}{4}\right)$$

  - 2 composite beams

$$\ell_{eff} = \ell - \left(n_{ub}+1\right) min\left(\frac{\ell}{1+n_{ub}};\frac{L}{4}\right)$$

References

- **Johansen, K.W.** ***Yield-line formulae for slabs.*** **Cement and Concrete Association. London: Taylor & Francis, 1972.**
- **Bailey, C.G.** ***Membrane action of slab/beam composite floor systems in fire.*** **Engineering Structures, October 2004, Vol. 26, Issue 12, pp. 1691-1703.**
- **EN 1994-1-2 :** ***Eurocode 4 : Design of composite steel and concrete structures – Part 1-2 : General rules – Structural fire design*****, CEN.**
- ***Fire Resistance Assessment of partially protected COmposite Floors (FRACOF): Engineering background*****. Technical Report, CTICM, SCI, 2009.**