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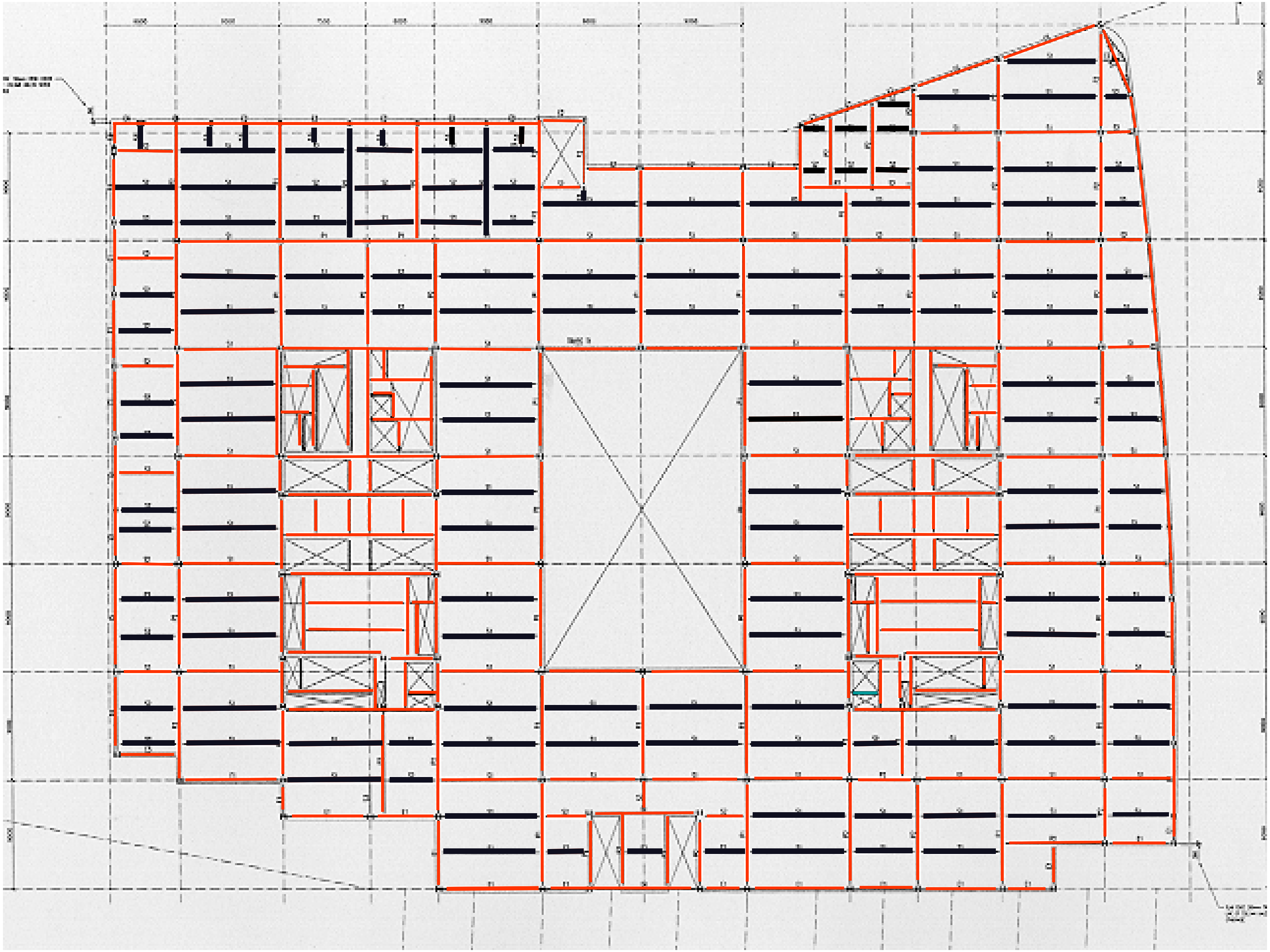
Fire Behaviour of Steel and Composite Floor Systems

Simple design method

Aim of the design method



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**
  - Extension to fire behaviour
  - Membrane effect at elevated temperatures
  - Contribution from unprotected beams
  - Design of protected beams

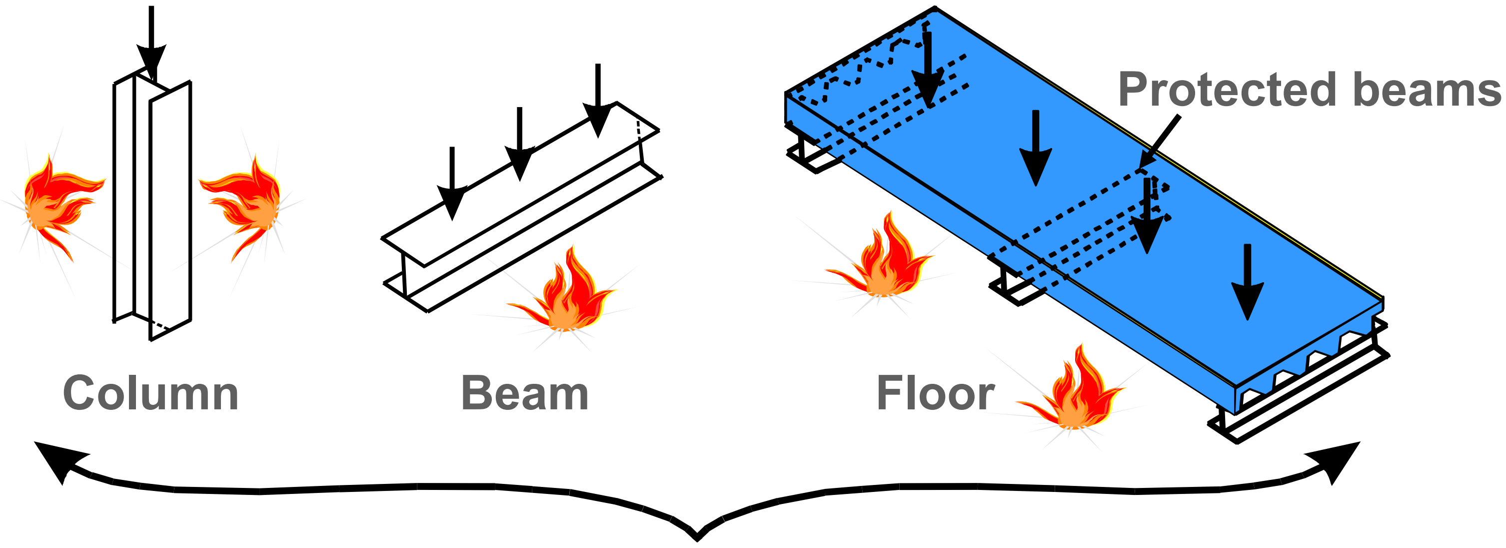
Mechanical behaviour of composite floors

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**



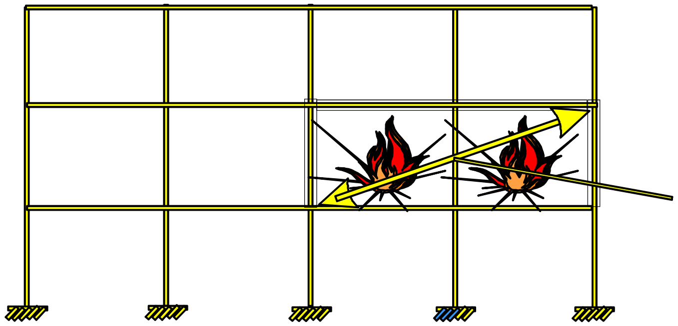
Protected beams

Column

Beam

Floor

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



Fire compartment

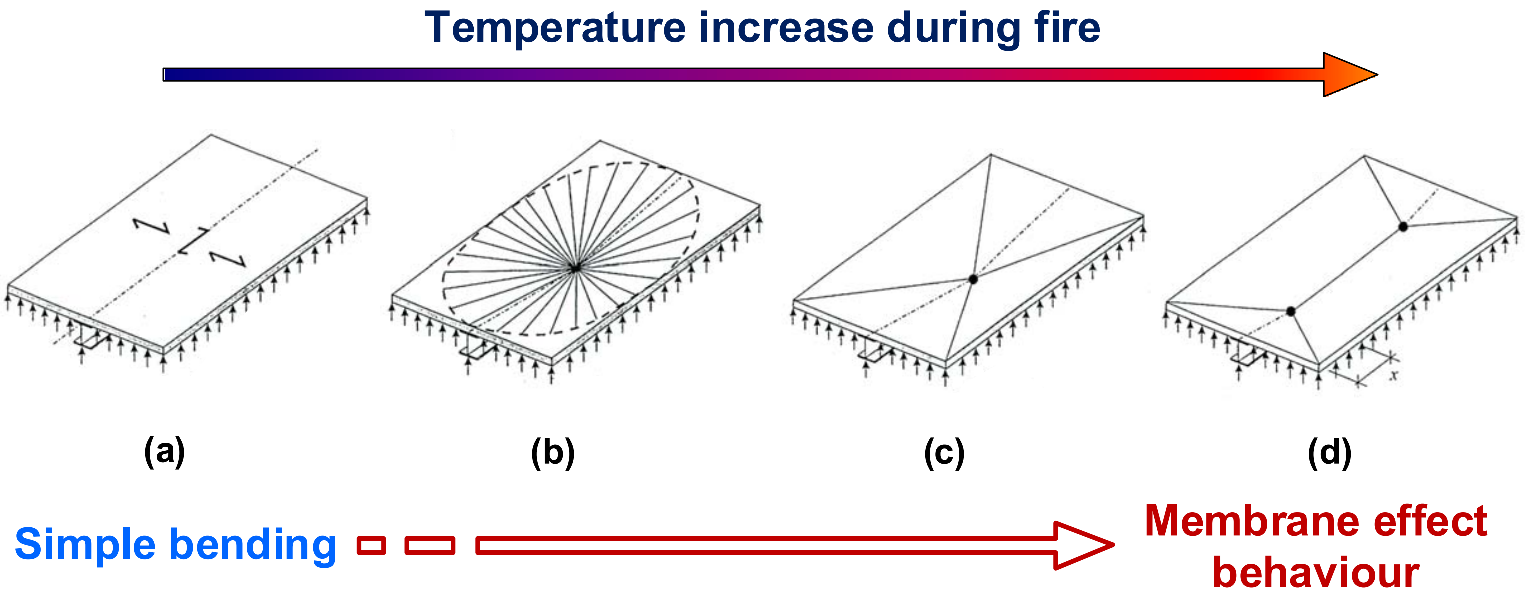
Mechanical behaviour of composite floors

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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



Temperature increase during fire

(a) (b) (c) (d)

Simple bending

Membrane effect behaviour

Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

Simple design method at 20°C

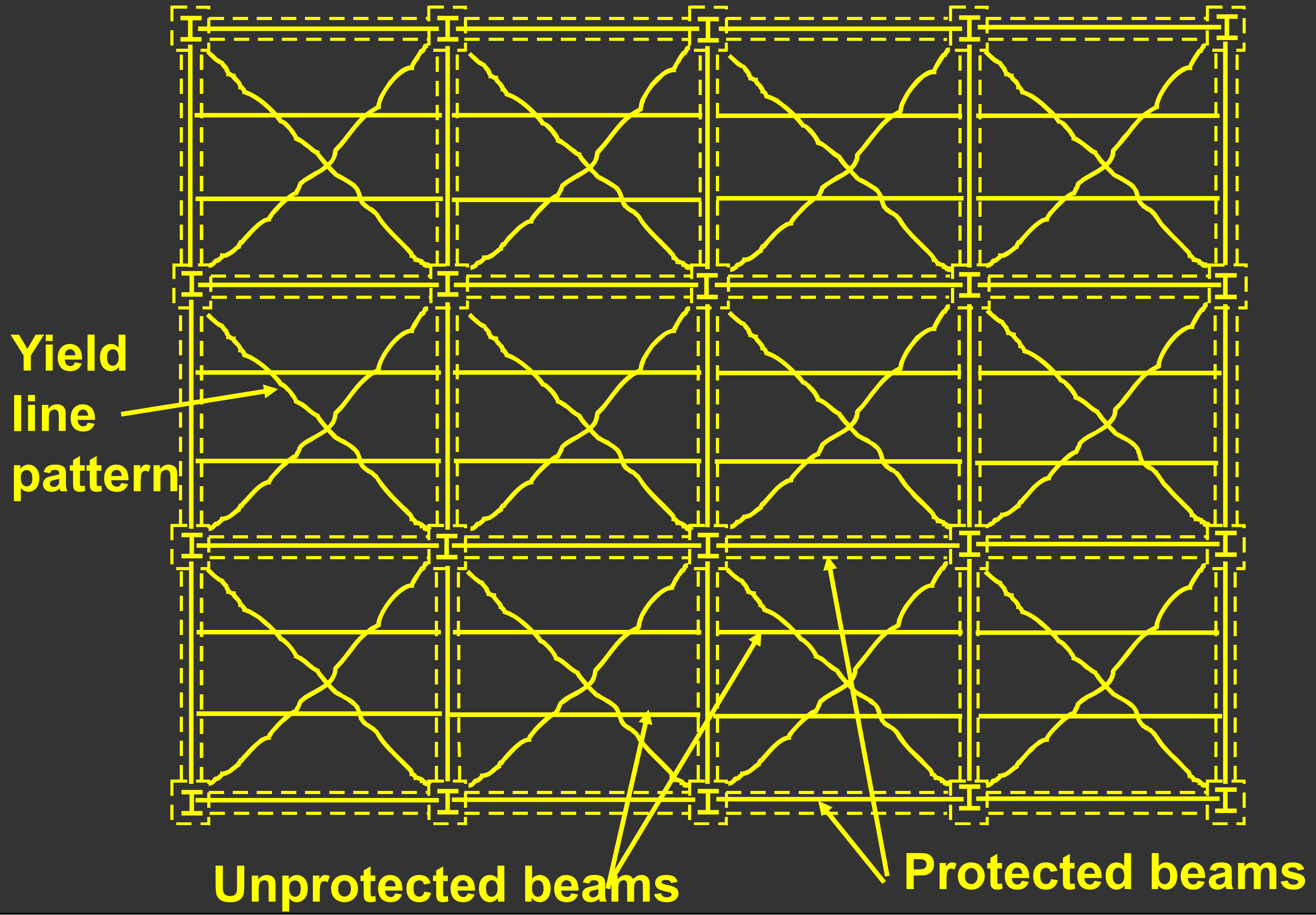
Simple design method at elevated temperatures

- **Method developed by Professor Colin Bailey**

  University of Manchester

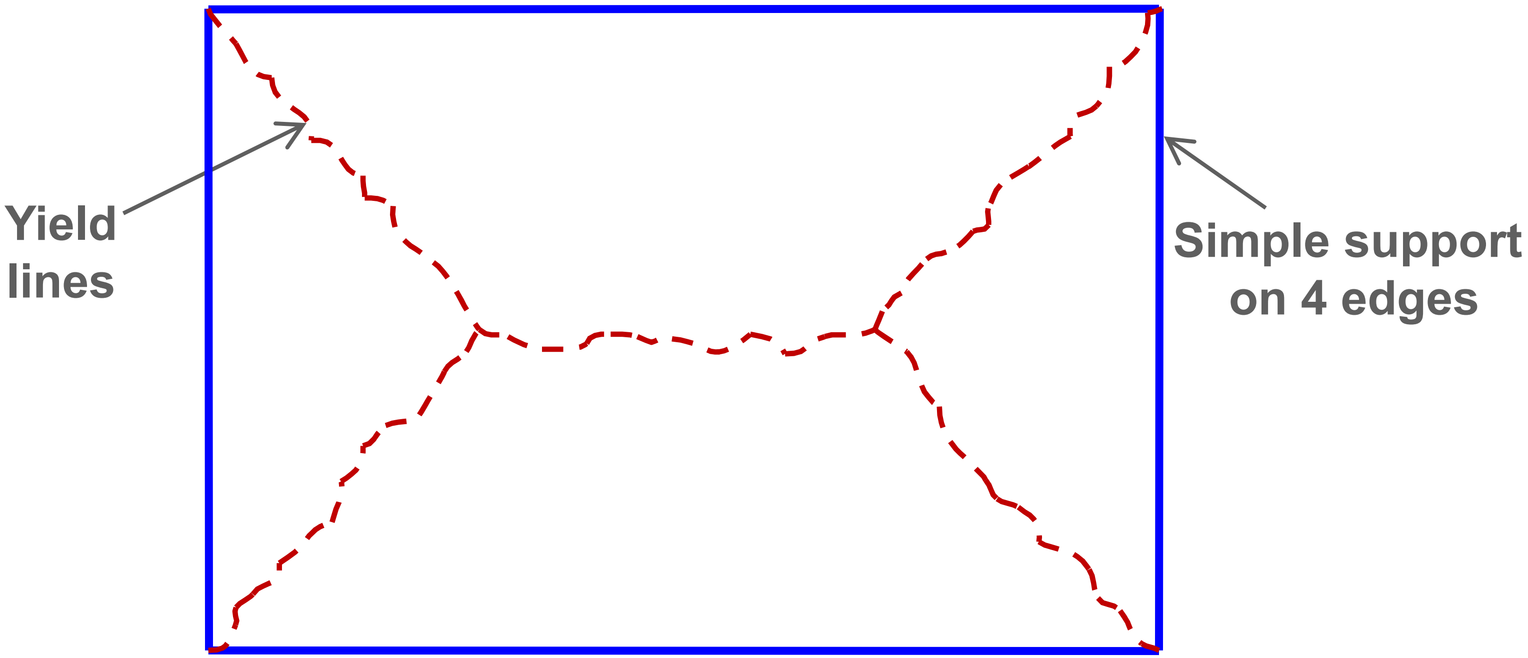
  formerly with Building Research Establishment (BRE)

Designing for membrane action in fire



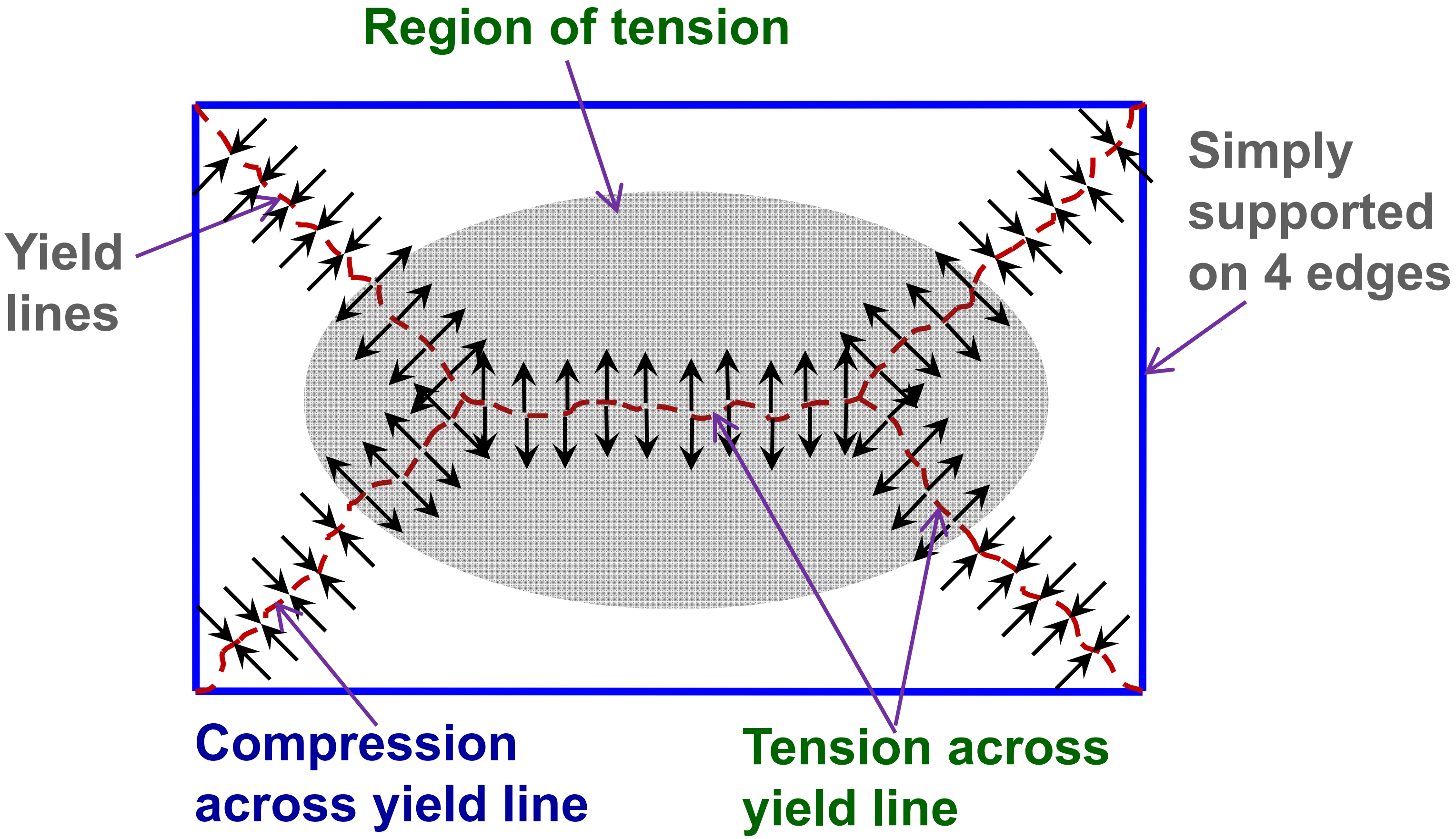
Simple design method of reinforced concrete slabs at 20 °C

- **Floor slab model with 4 vertically restrained sides** (Plastic yield lines) – horizontally unrestrained – very conservative assumption



Simple design method of reinforced concrete slabs at 20 °C

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



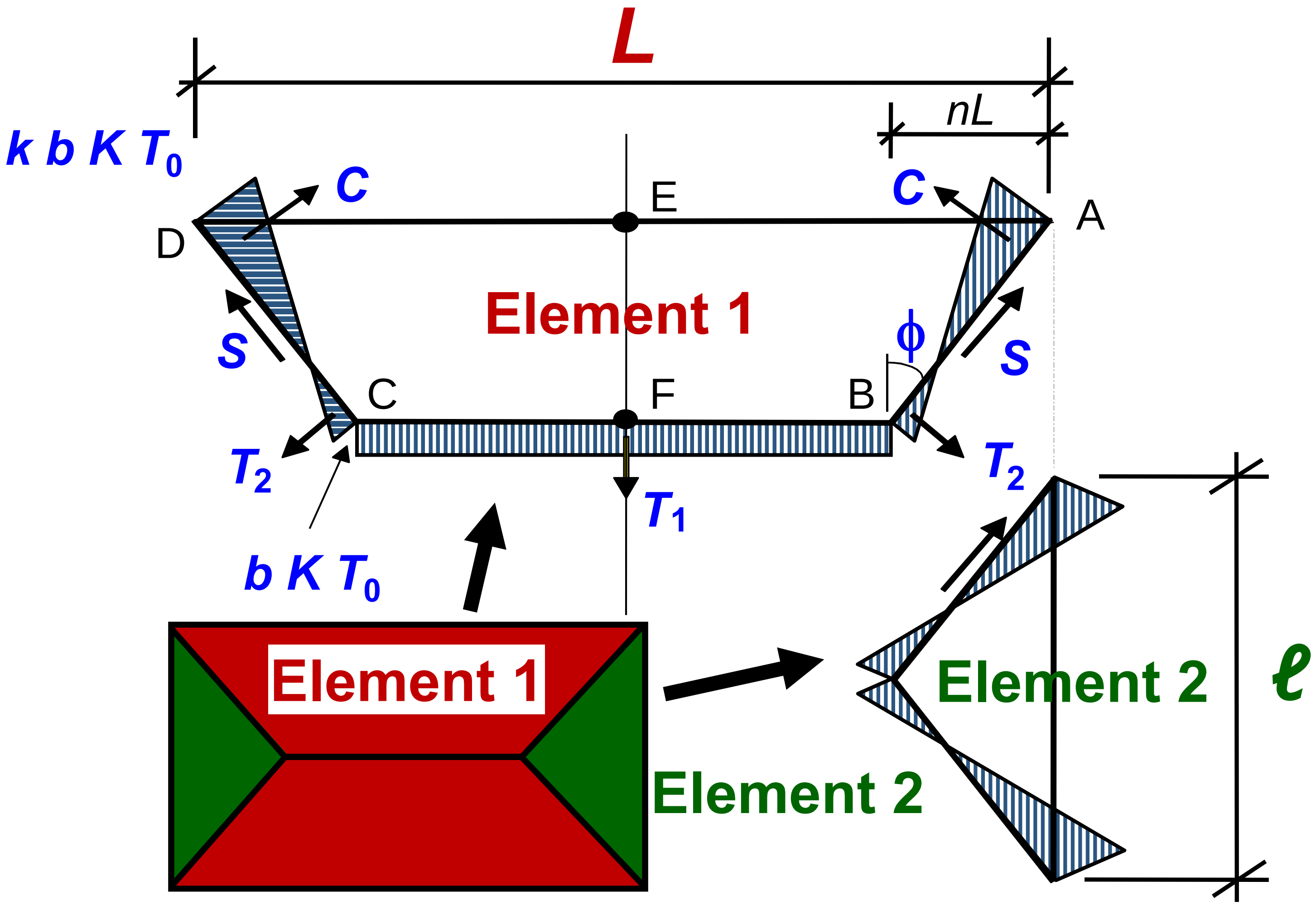
Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

Simple design method of reinforced concrete slabs at 20 °C

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



Simple design method of reinforced concrete slabs at 20 °C

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

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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,
KT_0	is the resistance of the steel reinforcing mesh per unit width,
T_1, T_2, C, S	are resulting membrane forces along yield lines.

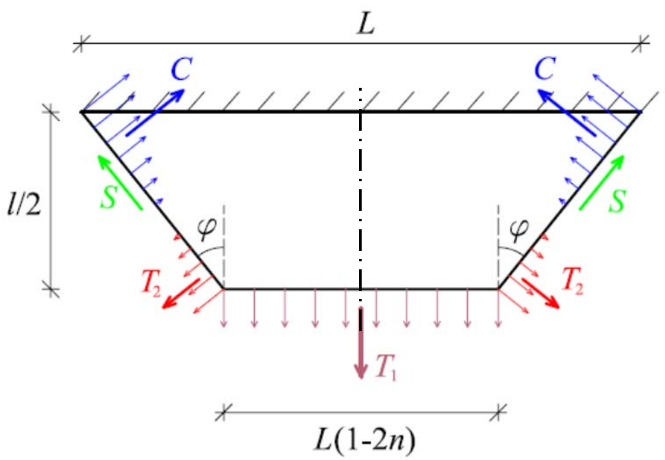
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

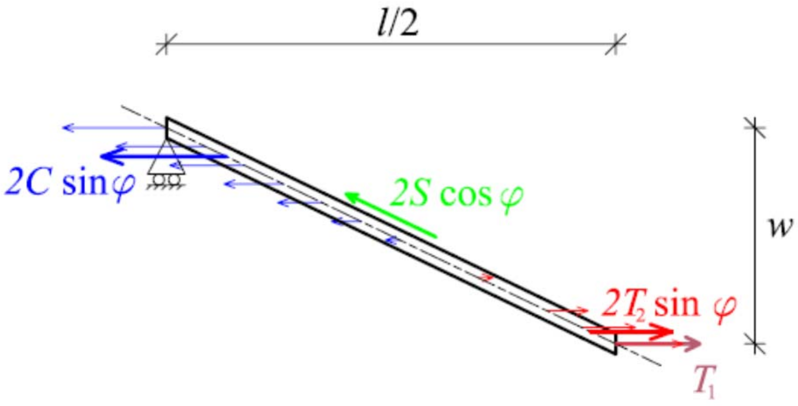
Simple design method at 20°C

Simple design method at elevated temperatures

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



In-plane view of the resulting membrane forces



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

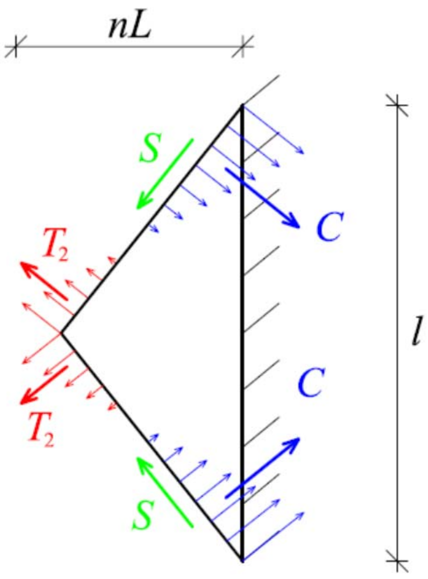
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

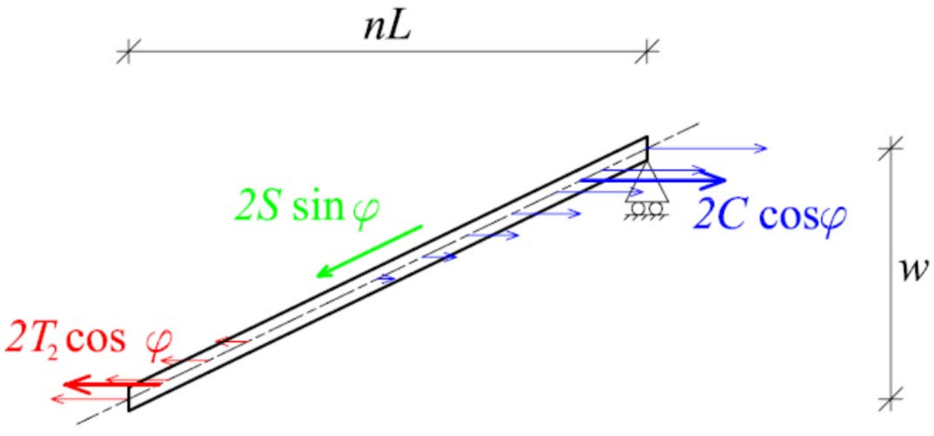
Simple design method at 20°C

Simple design method at elevated temperatures

- **Contribution of membrane action (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**

$e_{i,\ i=1,2} =$ e_{im} : enhancement due to membrane forces on element i +
e_{ib} : Enhancement due to the effect of in-plane forces on the bending capacity.

  - **Overall enhancement**

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

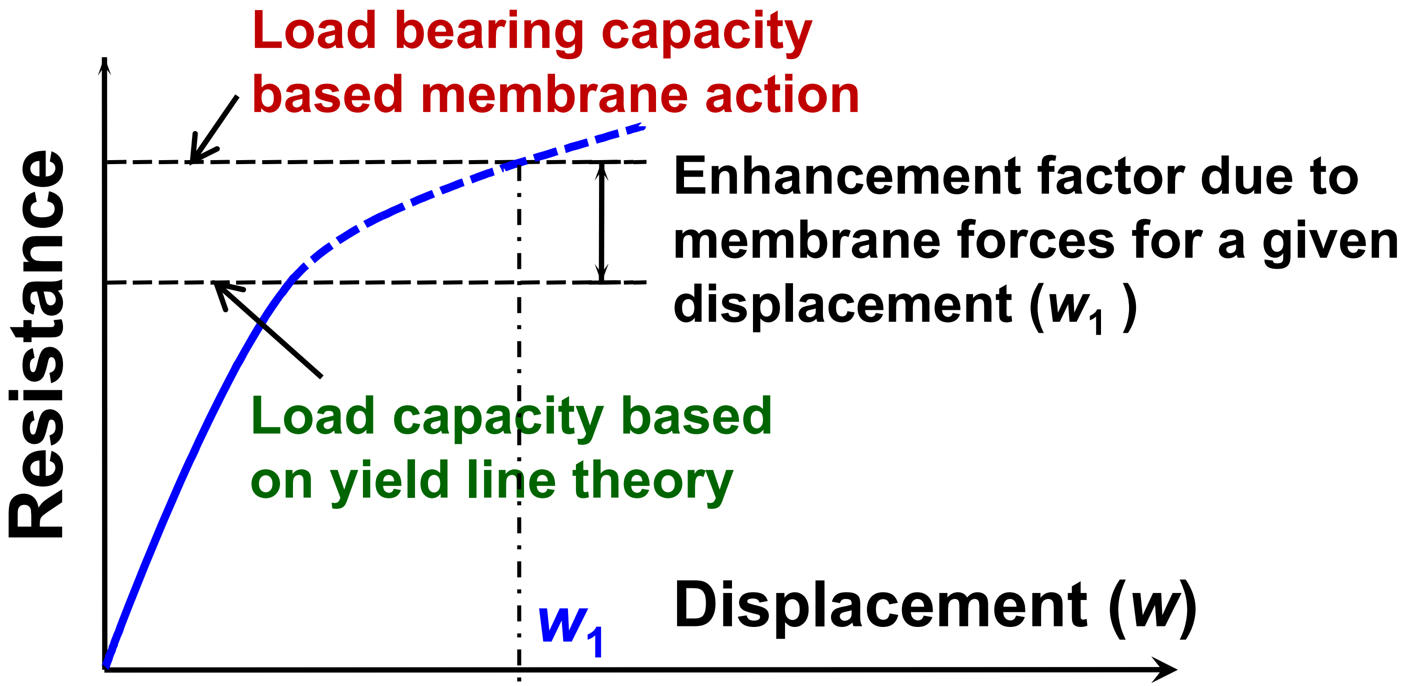
where:

μ is the coefficient of orthotropy of the reinforcement

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

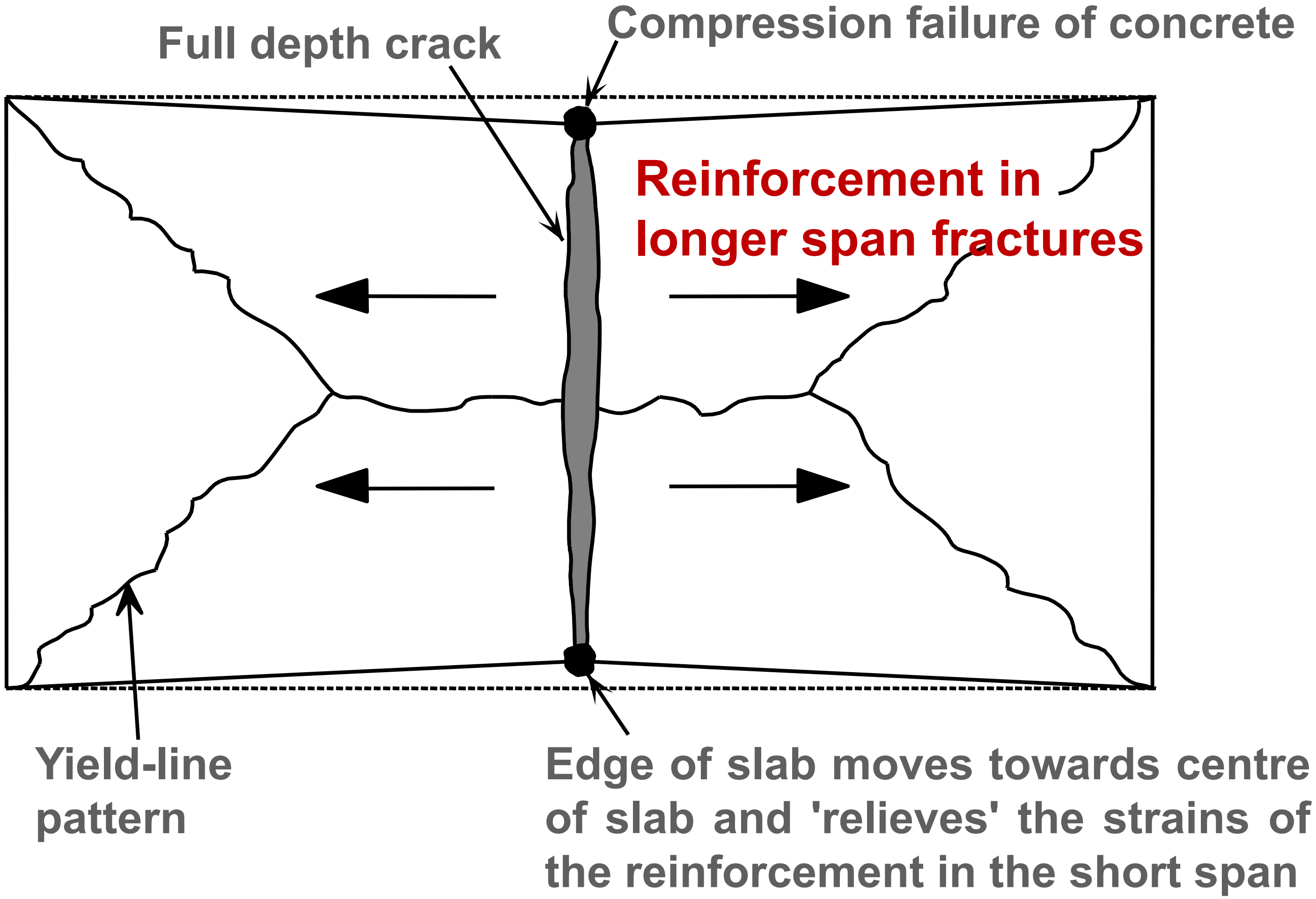
Simple design method of reinforced concrete slabs at 20 °C

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



Simple design method of reinforced concrete slabs at 20 °C

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



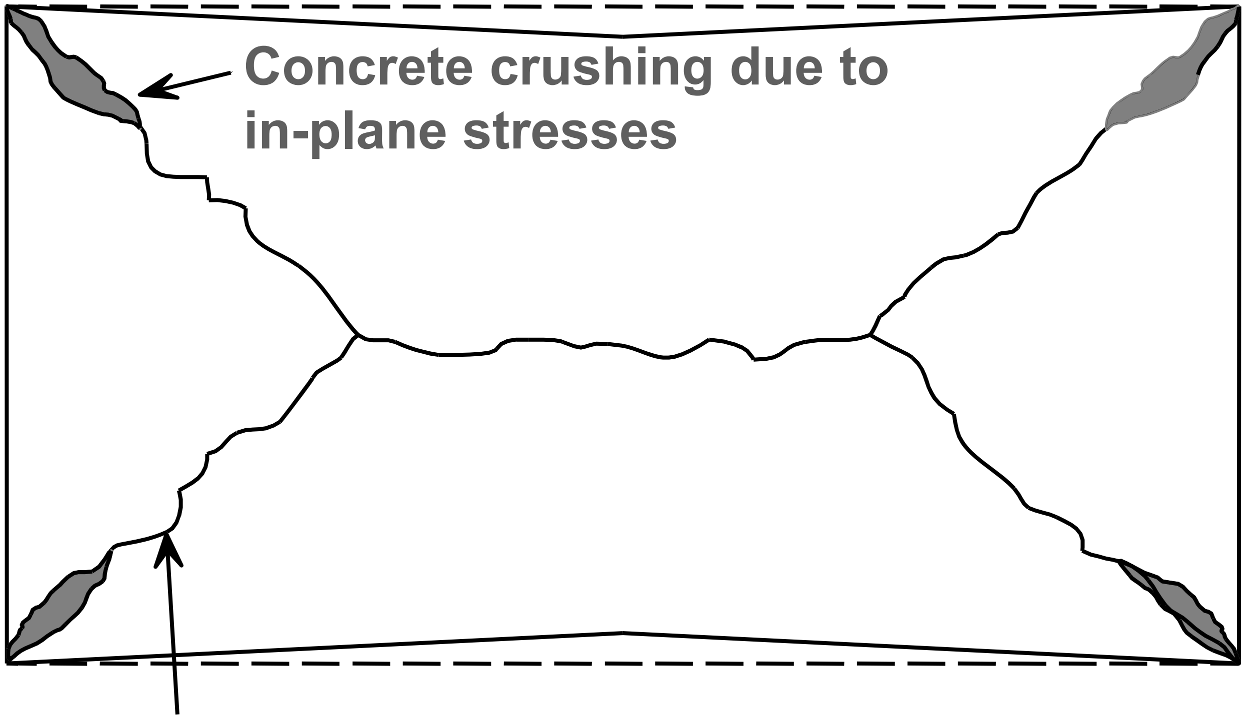
Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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



Concrete crushing due to in-plane stresses

Yield-line pattern

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

- **Failure modes** (experimental evidence)

Tensile failure of reinforcement

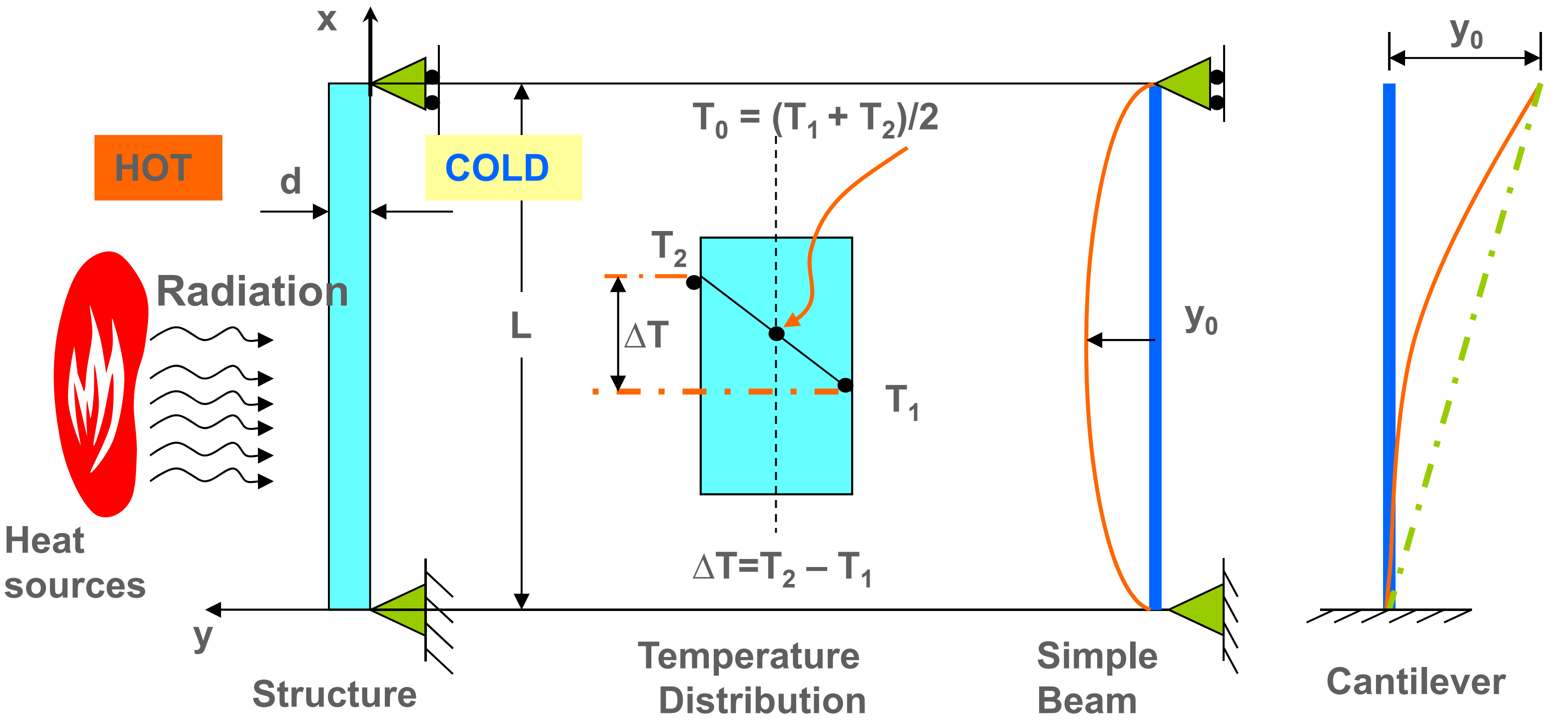
Compressive failure of concrete

Simple design method at elevated temperatures

- **Floor slab model at elevated temperatures (1)**
  - On the basis of the same model at room temperature
  - Account taken of temperature effects on material properties.

Simple design method at elevated temperatures

Free Bowing of a concrete slab



Simple Beam $y = \dfrac{\alpha L^2}{8}\dfrac{(T_2 - T_1)}{d}$

Cantilever $y = \dfrac{\alpha L^2}{2}\dfrac{(T_2 - T_1)}{d}$

Bowing is caused by Temperature Difference **$\Delta T = T_2 - T_1$** **Or Gradient** **$\Delta T/d$**

Simple design method at elevated temperatures

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

α is the coefficient of thermal expansion for concrete

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

α_{LWC} **= 0.8 × 10^{-5} °K^{-1}**

For NW concrete, a conservative value is taken

α_{NWC} **= 1.2 × 10^{-5} °K^{-1} < 1.8 × 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)

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 (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:

$$w < \frac{\alpha\left(T_2 - T_1\right)l^2}{19.2h} + l/30$$

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

Simple design method at elevated temperatures

- **Conservativeness of the floor slab model at elevated temperatures**
  - Reinforcement over supports is assumed to fracture.
  - 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

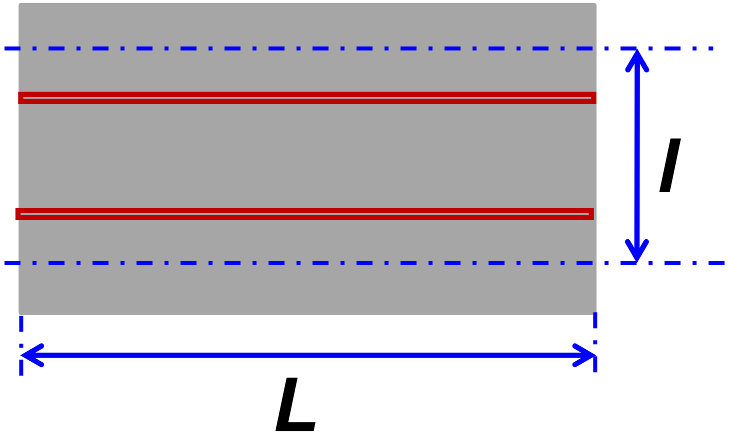
Mechanical behaviour of composite floors

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:**

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



where:

n_{ub} is the number of unprotected beams

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

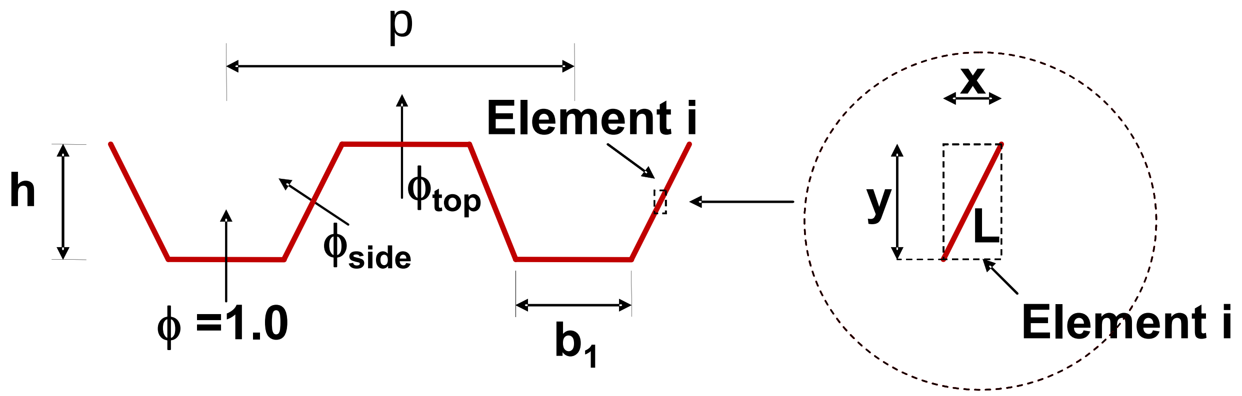
Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Temperature calculation of composite slab**
  - **On the basis of advanced calculation models**
    - ❑ 2D finite difference method
    - ❑ Material thermal properties from Eurocode 4 part 1-2 for both steel and concrete
    - ❑ Shadow effect is taken into account for composite slabs



Simple design method at elevated temperatures

- **Load bearing capacity of protected perimeter beams**
  - **Overall floor plastic mechanism based on beam resistance**
  - **Load ratio in fire situation**
    - ☐ Additional load on protected beams
  - **Critical temperature simple calculation method (EN 1994-1-2)**

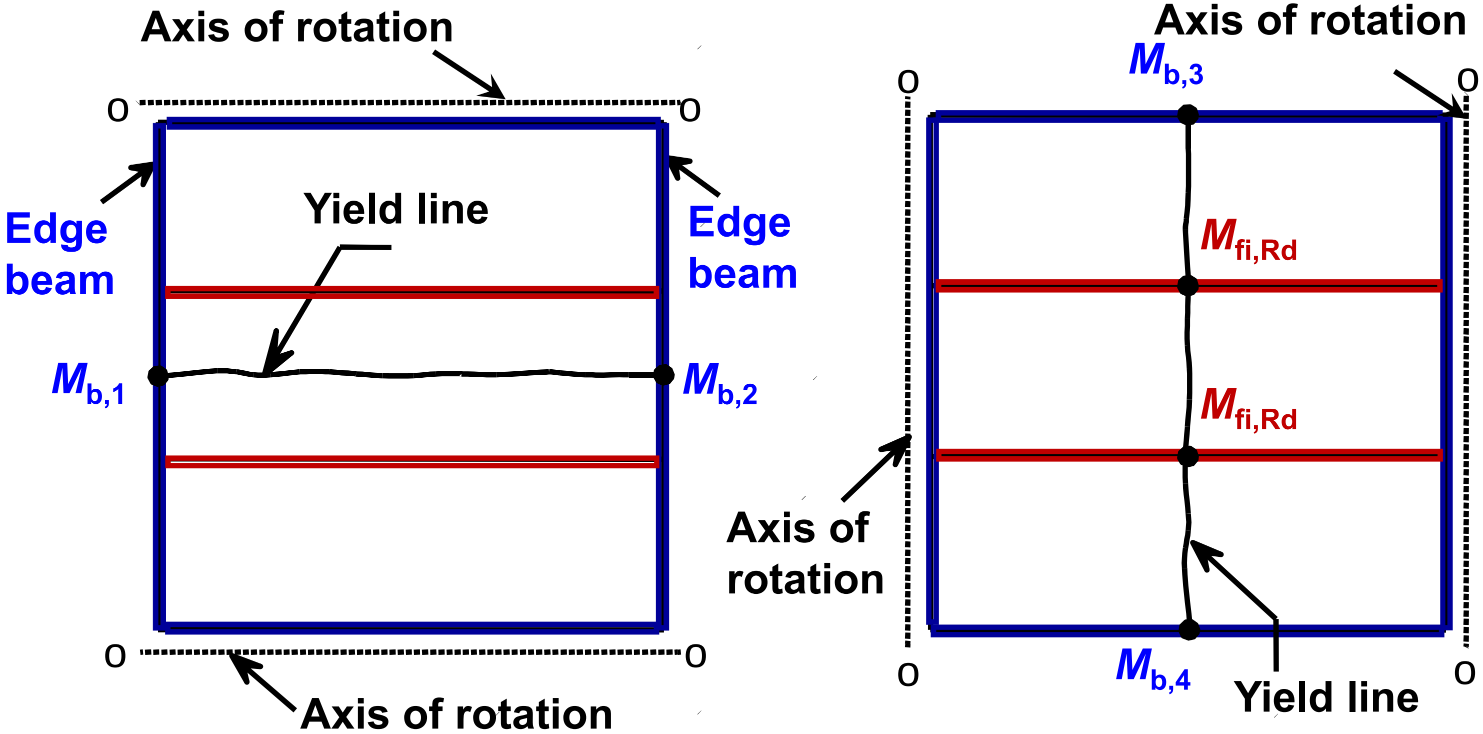
Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

- **Load bearing capacity of protected perimeter beams on the basis of global plastic mechanism**



Validation against test data

7 Full-scale Cardington Tests

1 large-scale BRE test (cold but simulated for fire)

10 Cold tests carried out in the 1960/1970s

15 small –scale tests conducted by Sheffield University in 2004

44 small-scale cold and fire tests carried out by the University of Manchester

FRACOF and COSSFIRE ISO Fire tests

Full-scale test carried out by Ulster University 2010.

Small – Scale Experimental Behaviour and Design of Concrete Floor Slabs

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

22 Cold Tests and 22 Identical Hot tests (Both MS and SS mesh reinforcement)

Results obtained applying the methodology

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

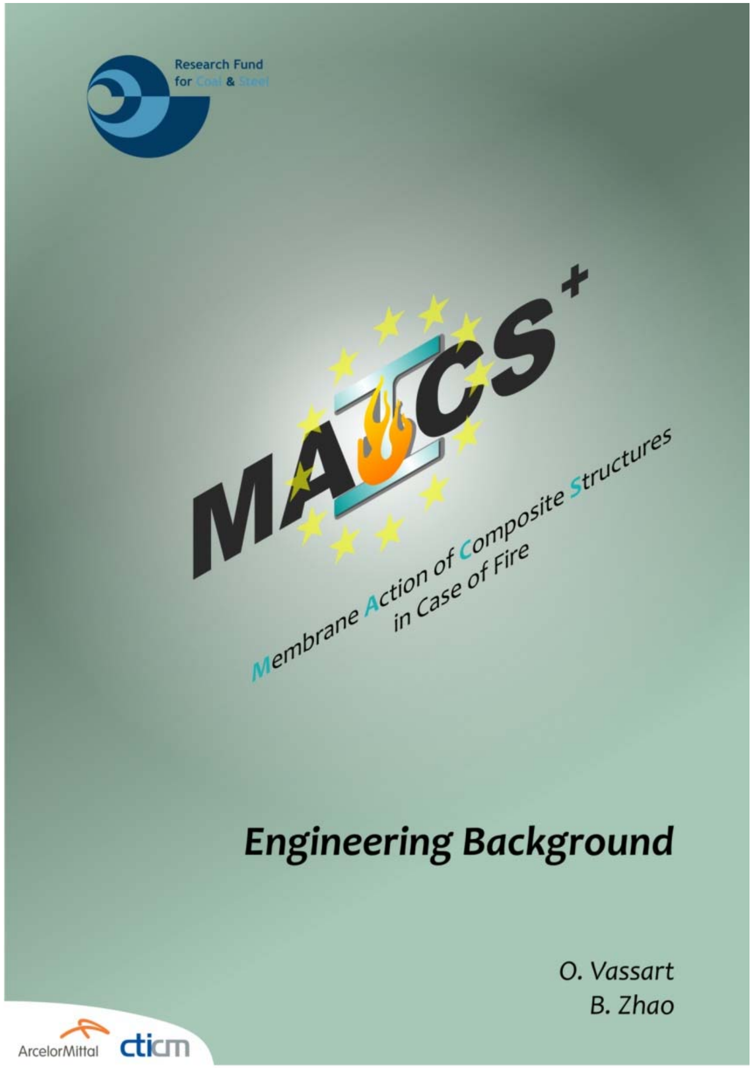
40 to 55% of beams can be left unprotected by placing protection where it is needed.

Available documents

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures



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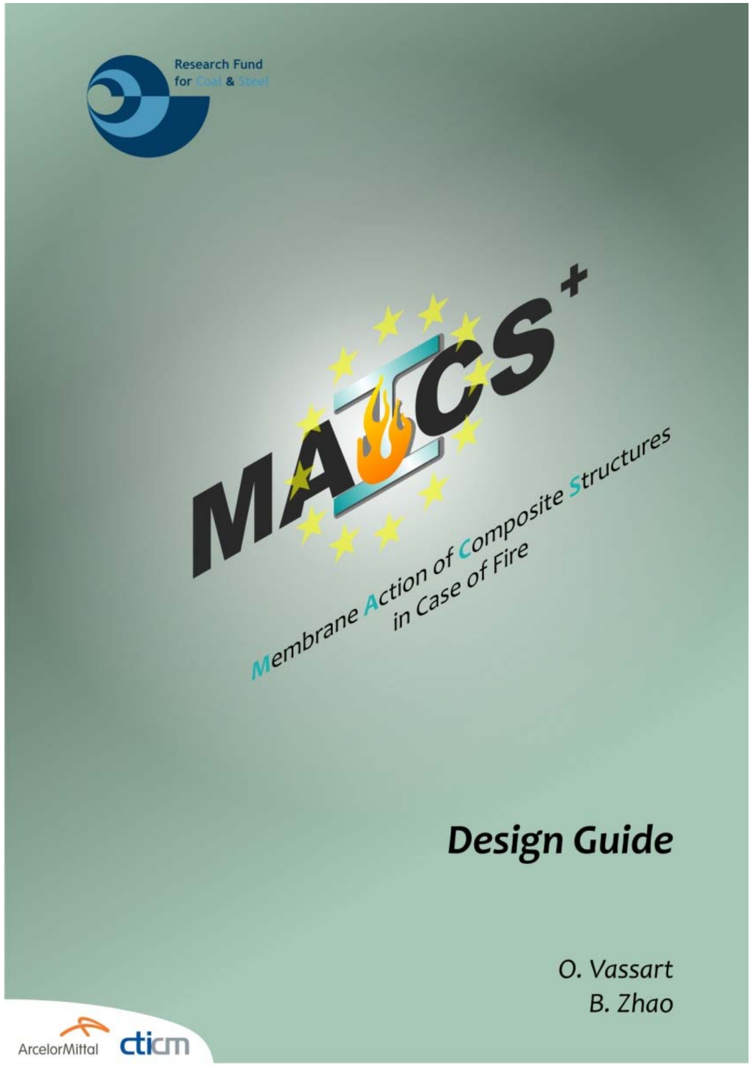
Membrane Action of Composite Structures in Case of Fire

Engineering Background

O. Vassart
B. Zhao

ArcelorMittal cticm



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Design Guide

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