Education and Culture DG
Lifelong Learning Programme
LEONARDO DA VINCI

1&4 ANEFORE

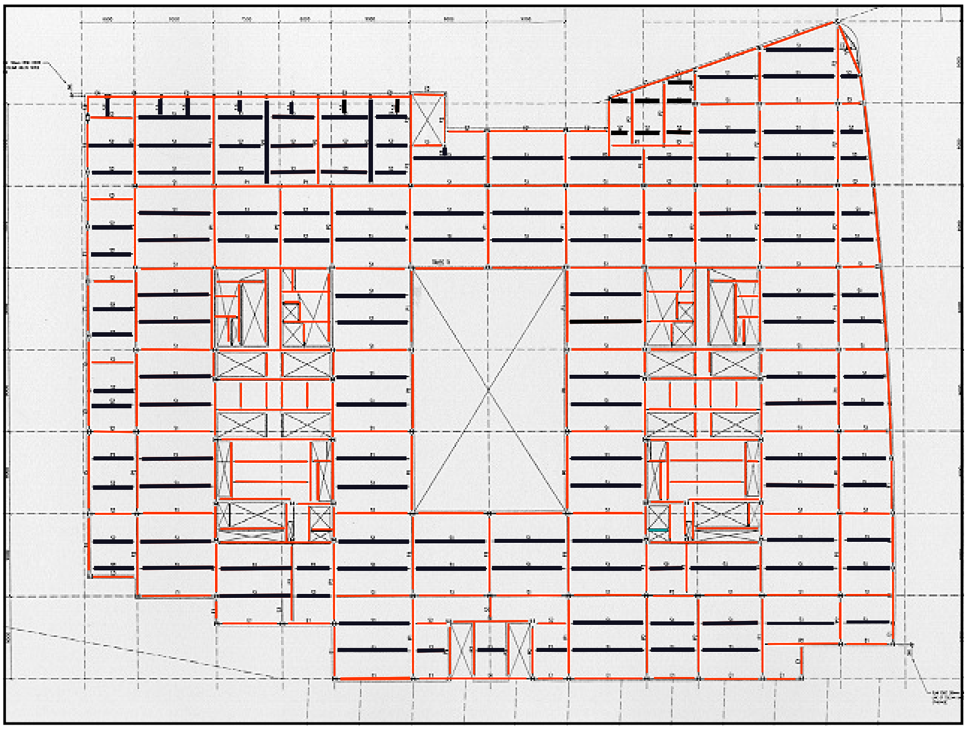
FRACOF

Fire Behaviour of Steel and Composite Floor Systems

Simple design method

Prof. Colin Bailey

26th of May 2011



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

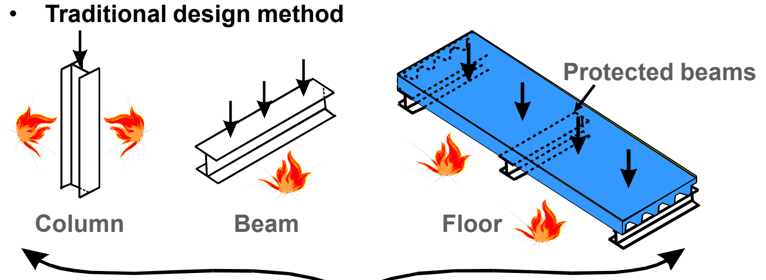
Mechanical behaviour of composite floors

Mechanical behaviour of composite floors

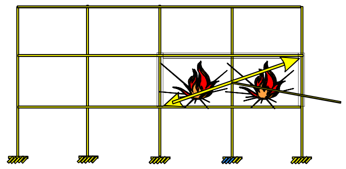
Simple design method of reinforced concrete slabs at 20°C

Simple design method of composite floors at elevated temperatures

- **Traditional design method**



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



Mechanical behaviour of composite floors

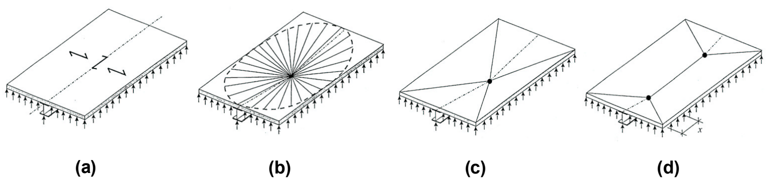
Mechanical behaviour of composite floors

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



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

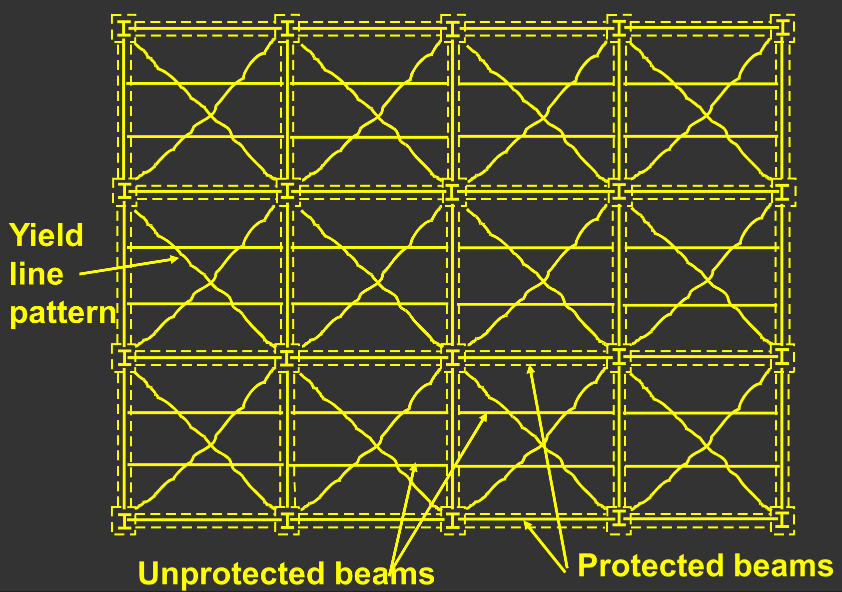
Simple design method at elevated temperatures

- **Method developed by Professor Colin Bailey**

  University of Manchester

  formerly with Building Research Establishment (BRE)

Designing for membrane action in fire



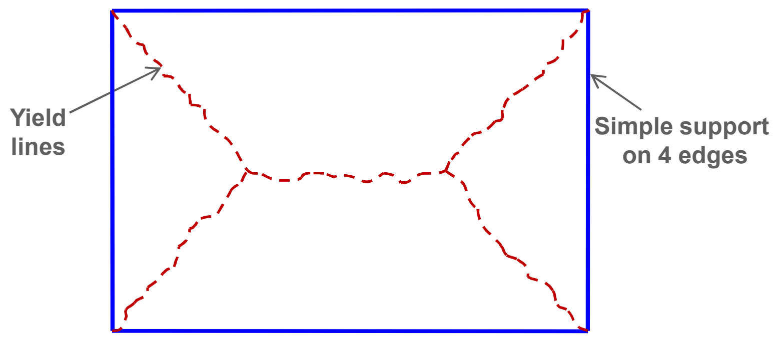
Simple design method of reinforced concrete slabs at 20 °C

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) – horizontally unrestrained – very conservative assumption



26th of May 2011 Background of simple design method 9

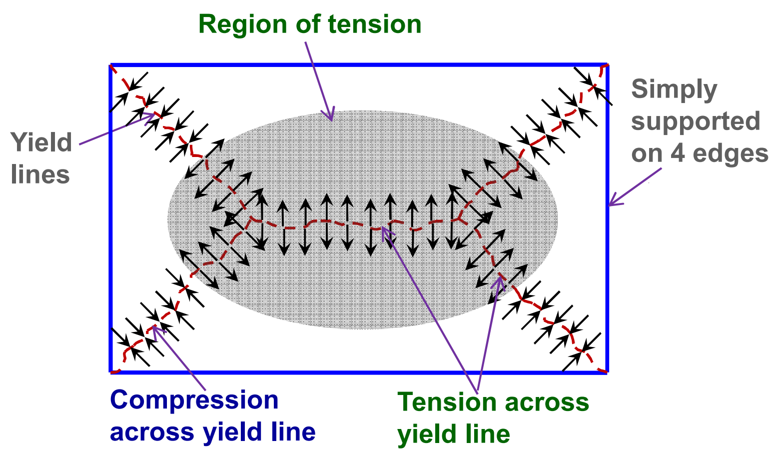
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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



26th of May 2011 Background of simple design method 10

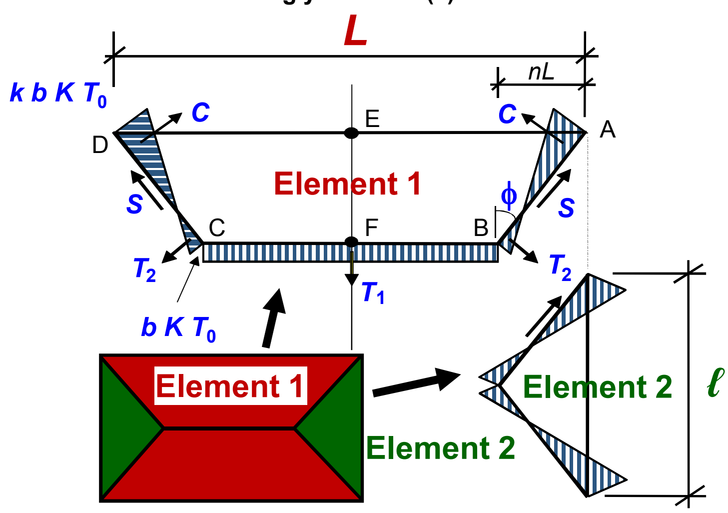
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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



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

- **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.

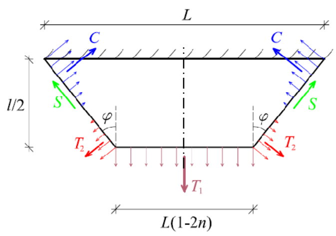
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

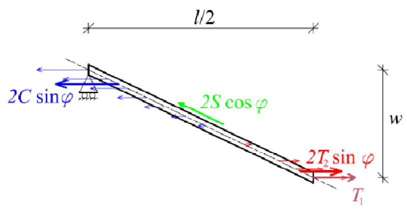
Simple design method at 20°C

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*

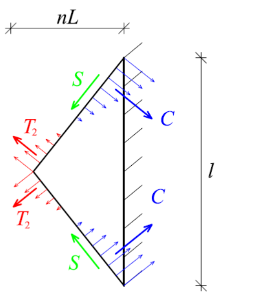
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

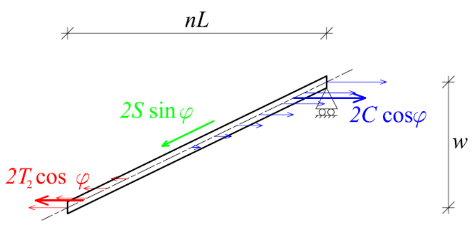
Simple design method at 20°C

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

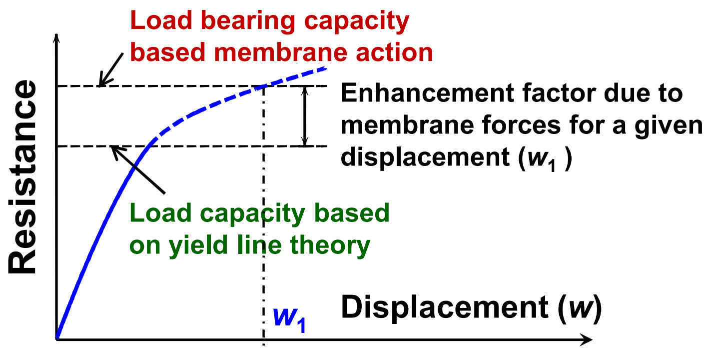
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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



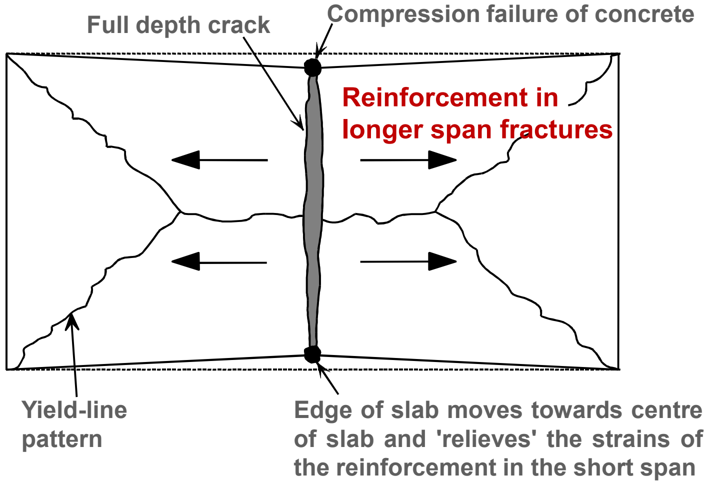
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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



26th of May 2011 | Background of simple design method | 17

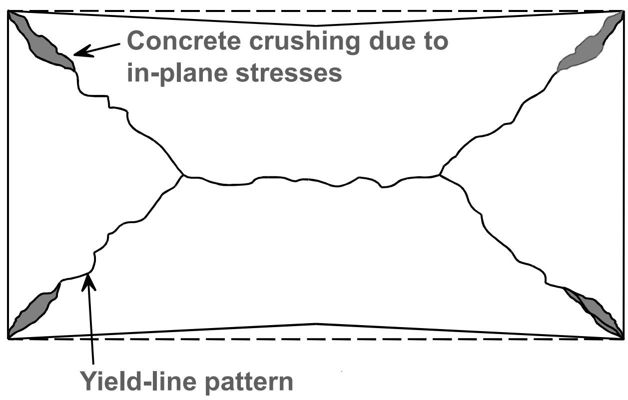
Simple design method of reinforced concrete slabs at 20 °C

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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



26th of May 2011 | Background of simple design method | 18

Simple design method of reinforced concrete slabs at 20 °C

- **Failure modes** (experimental evidence)

Tensile failure of reinforcement

Compressive failure of concrete

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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.
  - 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

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

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)

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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

Mechanical behaviour of composite floors

Simple design method at 20°C

Simple design method at elevated temperatures

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:

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

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

26th of May 2011 | Background of simple design method | 23

Simple design method at elevated temperatures

Mechanical behaviour of composite floors

Simple design method at 20°C

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

26th of May 2011 | Background of simple design method | 24

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

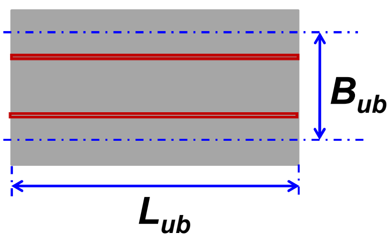
Mechanical behaviour of composite floors

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

Basic Strength (Energy) Calculation.

Load Capacity at the Fire Limit State =

$$e\left[\frac{\text{Internal work done by the slab}}{\text{External work per unit load}}\right] + \frac{\text{Internal work done by the beam(s)}}{\text{External work per unit load}}$$

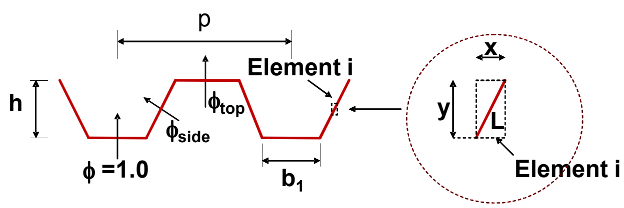
Simple design method at elevated temperatures

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

Mechanical behaviour of composite floors

Simple design method at 20°C

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)

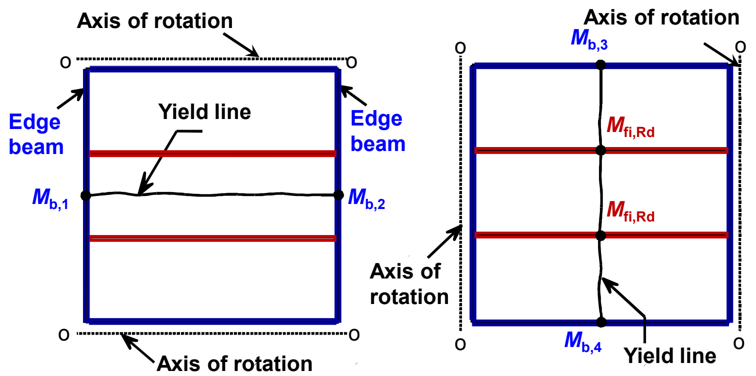
Simple design method at elevated temperatures

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

Full-scale test carried out by Ulster University 2010.

Plus more……

Small – Scale Experimental Behaviour and Design of Concrete Floor Slabs

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

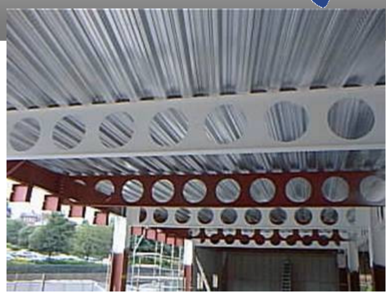
BRE Digest 462 (2001):

Allowable vertical displacement

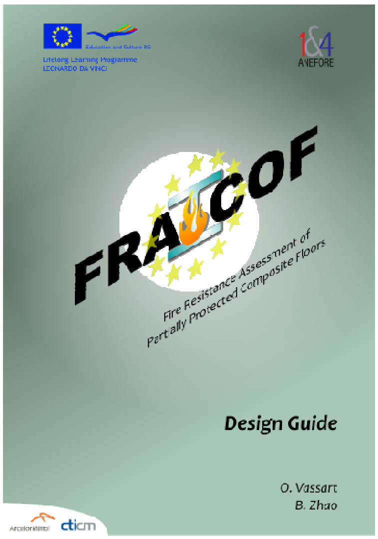
$$\upsilon = \frac{\alpha (T_2 - T_1) l^2}{19.2\,h} + \sqrt{\left(\frac{0.5 f_y}{E}\right)_{\text{Reinf } 20^\circ C} \frac{3L^2}{8}}$$

Slab	ν mm	T_{pred} °C	T_{test} °C	Ratio
MF1	56.82	643	764	**0.84**
MF2	39.51	680	694	**0.98**
MF3	45.48	558	727	**0.77**
MF4	32.80	526	686	**0.77**
MF5	46.39	648	722	**0.90**
MF6	35.53	622	760	**0.82**
MF7	47.57	446	556	**0.80**
MF8	34.72	548	650	**0.84**

Slab	ν mm	T_{pred} °C	T_{test} °C	Ratio
SF1	54.11	863	893	**0.97**
SF2	40.18	863	885	**0.97**
SF4	40.04	852	>840	**-**
SF6	34.44	709	903	**0.79**
SF8	29.81	774	877	**0.88**
SF9	41.82	722	885	**0.82**
SF10	30.40	619	873	**0.71**
SF11	43.46	609	826	**0.74**
SF12	31.13	630	836	**0.75**



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



26th of May 2011 Background of simple design method 35

References

- Bailey C.G. and Moore D.B. The structural behaviour of steel frames with composite floorslabs subject to fire: Part 1: Theory. The Structural Engineer Vol. 78 No. 11 June 2000 pp. 19 – 27
- Bailey, C. G, Membrane action of unrestrained lightly reinforced concrete slabs at large displacements, Engineering Structures, 23, pp. 470-483, 2001.
- Bailey C G, Toh W.S. "Behaviour of concrete floor slabs at ambient and elevated temperatures". Fire Safety Journal. Vol. 42. Issue 6-7. 2007 pp 425-436.
- **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.**

26th of May 2011 Background of simple design method 36