Fire resistance of concrete slabs acting in compressive membrane action

No need for steel anymore?

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Introduction

• Bearing capacity of (existing) slabs?

• Experiences in building renovations with a surprising low capacity following classic bending theory, mostly with rather thin slabs.

• No excessive deformations noted before => no tensile membrane action involved but probably compressive membrane action.

• What about fire resistance of such slabs?
Compressive membrane action (CMA)

- The arch effect – compressive membrane action

- Lateral restraint capable to withstand compressive forces
Compressive membrane action (CMA)

- CMA mechanism fails due to concrete crushing => TMA or failure
CMA at elevated temperature

• Isothermal lines

• Behaviour at the origin of arches?
CMA with FEM models?

- By the aid of plane elements with bending and membrane behaviour.
- Advanced material model (Explicit Transient Creep).
- At ambient conditions, time dependent load function (20s)

- Stops at 70%
- Doesn’t work
CMA with FEM models?

• Vertical section with superimposed layers of shell elements
• Advanced material model (Explicit Transient Creep).
• At ambient conditions, time dependent load function (20s)
• Rebar elements

• Adding elevated temperature profile pro layer is quiet simple
Case study – building description

• Leopold tower in Brussels near the NATO (Evere).
• Office building in the past with screed and mobile load of 3 kN/m²
• Slab of 0.14 m, 5.04 m span, width 16.5m, upper (curtailed) and lower principal reinforcement = Ø8/0.15 (335 mm²/m)
Case study – building description

• Transformation into an apartment building with reduced mobile loads but increased super imposed dead loads.

• Out of bending theory; insufficient reinforcement even for the existing situation.

• But restraints available at the extremes => CMA possible?

• Due to high costs of external reinforcement + fire protection and possible benefits the owner agreed with a load test.
Case study – Test set-up

• Load test done till ULS-values (for ambient conditions); 11.58 kN/m²
• Swimming pools of 0.8 m + DL.
Case study – Bearing capacity

• Elastic bending theory

\[ M_{Rd} = (h - c_{centre} - \frac{x}{2})A_s f_{yd} = (h - c_{centre} - \frac{A_s f_{yd}}{2b f_{cd}})A_s f_{yd} \]

• Span 13.17 kNm, hogging moments 11.52 kNm with sum 24.69 kNm
• With \( \Sigma M = wL^2/8 \Rightarrow w < 7.78 \text{ kN/m}^2 \) and needed + test 11.58 kN/m\(^2\)?
• Only dead loads are representing already 6.18 kN/m\(^2\) (factored)

• Plastic analysis with membrane action results in 0.35 m deformation!
• Measured deformations of only a few mm
• Only CMA can explain this behaviour
Case study – FEM @ ambient temperature

- CMA simulation without reinforcement
- Full load available after 20 s with equal increments/time step
- Principal stresses at 10.7 s (about DL) & 12.5 s
Case study – FEM @ ambient temperature

- Principal stresses at 13.5 s

- Principal stresses at 20.0 s
Case study – FEM @ ambient temperature

• Measured deformations related to computed values

• Seems to correspond on a reasonable way 😊
Case study – FEM @ elevated temperature

• Temperature profiles out of NBN EN 1992-1-2

• Reduced load 8.08 kN/m² (due to fire conditions)
Case study – FEM @ elevated temperature

• Principal stresses at 20.0 s with layered shell elements

• Principal stresses at 900 s (delaminating starts)

Delaminating or splitting of concrete, due to high normal compressive forces.
Case study – FEM @ elevated temperature

• Principal stresses at 1200 s
  Works as canti-lever

• Principal stresses at 1750 s (cracks on top and termination/failure)
  Reinforcement fails
  Delaminating of concrete becomes really important. Is this already noticed by somebody during experiments?
Case study – Failure time with protection

• Temperature profiles out of NBN EN 1992-1-2

• Protection time

![Graph showing temperature profiles and protection time](image-url)
Case study – Failure time with protection

• Protection material; presume the same efficiency as one layer of 23 mm of concrete:
Simplifications – engineering judgement

•Let’s try the simple way:

1. At ambient temperature, the horizontal reaction force is computed as: \( H_{Sd} = \frac{M_{Sd}}{z} = \frac{p_{sd} \cdot L^2}{8 \cdot z} \) with \( z \) = the lever arm or arch camber, \( p_{sd} \) = design load and \( L \) the span.

2. The depth of the compression area is: \( x = \frac{H_{Sd}}{b \cdot f_{cd}} \) with \( b \) the slab width and \( f_{cd} \) the design concrete strength in compression.

3. The lever arm is modified to account for the depth \( x \): \( z = h - \frac{x}{2} \) with \( h \) the slab height; some iterations may be required from 1 to 3 to find the final value of the lever arm.
Simplifications – engineering judgement

• Let’s try the simple way:
  1. In case of fire, the applied load is lower than the design load at ambient temperature; hence the horizontal reaction force is reduced as: \( H_{fi} = p_{fi} \cdot L^2 / (8 \cdot z_{fi}) \) with \( z_{fi} \) = lever arm and \( p_{fi} \) = load in case of fire.
  2. The depth of the compression area in case of fire is: \( x_{fi} = H_{fi} / (b \cdot f_{\theta}) \). Looking to Fig. 1a, the temperature \( \theta \) of the lower part of the slab will be important at the origins of the arch.
  3. The lever arm is modified to account for the depth \( x_{fi} \): \( z_{fi} = h - (x_{fi}/2) \); some iterations may be required from 1 to 3 to find the final value of the lever arm in case of fire.
  4. Finally, the verification of structural safety in the fire situation is performed as: as long as \( H_{fi} < H_{Sd} \), the slab is able to sustain the load in the fire situation.
Simplifications – engineering judgement

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1. In case of fire, the applied load is lower than the design load at ambient temperature; hence the horizontal reaction force is reduced as: $H_{fi} = p_{fi} \cdot L^2/(8 \cdot z_{fi})$ with $z_{fi} = \text{lever arm and } p_{fi} = \text{load in case of fire.}$

2. The depth of the compression area in case of fire is: $x_{fi} = H_{fi}/(b \cdot f_{\theta})$. Looking to Fig. 1a, the temperature $\theta$ of the lower part of the slab will be important at the origins of the arch.

3. The lever arm is modified to account for the depth $x_{fi}$: $z_{fi} = h - (x_{fi}/2)$; some iterations may be required from 1 to 3 to find the final value of the lever arm in case of fire.

4. Finally, the verification of structural safety in the fire situation is performed as: as long as $H_{fi} < H_{Sd}$, the slab is able to sustain the load in the fire situation.
Simplifications – engineering judgement

• Case study => doubtful result?

1. \( H_{sd} = M_{sd}/z = 11.58 \cdot 5.04^2/(8 \cdot 0.133) = 276.46 \text{ kN/m} \) with \( z = 0.95 \cdot 0.140 = 0.133 \)
2. \( x = 276.46/(0.85 \cdot 30/1.5) = 16.26 \text{ mm} \), hence take 16 mm.
3. \( z = 0.140 - 0.016/2 = 0.132 \text{ m} \) which can be considered as converged, taking into account 1% deviation compared with 0.133.
4. \( H_{fi} = 8.08 \cdot 5.04^2/(8 \cdot z_{fi}) \leq 276.46 \text{ kN/m} \) which leads to \( z_{fi} \geq 0.093 \text{ m} \)
5. \( z_{fi} = 0.140 - (x_{fi}/2) \geq 0.093 \text{ or } x_{fi} \leq 0.093 \text{ m} \)
6. \( x_{fi} = 276.46/(f_{c\theta}/f_{ck} \cdot 30) \leq 93 \text{ mm} \), the maximum allowable reduction to respect this equilibrium is obtained if \( f_{c\theta}/f_{ck} \geq 0.10 \) and can be applied at the origin of the arch. Take this equal to the one corresponding to the temperature in the ultimate fiber of the layer as a rough and save simplification. Following table 3.1 of EC2-1-2 [4] this means 871 °C would be acceptable, which appears at R57 < R120 required but > R29 following SAFIR analysis.
Further developments

• Punching problem:
  • Has the same failure behaviour
  • Is related to the same mechanism
  • But we even don’t understand and agree about at ambient conditions.
  ...
  • ...
  • ...
Conclusions

• CMA can play a major role in restrained structures. With advanced FEM-analysis and suitable material models this can be simulated with a reasonable agreement for the vertical deformations.

• Modelling at elevated temperatures is even more challenging, however maximum surface temperatures could be derived for a practical case study and subsequently the needed fire protection.

• Our understanding of CMA is still to limited to built up simple engineering models.
Thanks for the kind attention

Q&A?

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