Thermal simulation of fire tests on steel-concrete composite slabs

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Introduction

• Tests were performed on steel-concrete composite slabs to evaluate their performance in fire scenarios.
• A permanent load is maintained on a slab while the gas temperatures under the slab evolve for 2.5 hours according to the history given in ISO 834.
• Analyses (using Abaqus) were conducted involving both blind simulations and post-test calculations of the fire tests.
C30/37 concrete
B500S steel for rebars
S355 steel plates
Nelson studs
• Requirements:
  – The temperature in the unexposed surface is limited to 160 ºC.
  – Failure will be assumed if the peak deflection of the slab reaches 1/20th of the span.
Model

- Purely thermal analyses were conducted first
- Using the thermal information, mechanical analyses were carried out
- The models generated comprise:
  - Concrete
  - Plate skins
  - Beams
  - Reinforcing bars (only in the mechanical one)
  - Connecting studs
Symmetry plane

Fire
• Thermal properties of concrete

\[ \lambda_c = 2 - 0.2451 \left( \frac{\theta}{100} \right) + 0.0107 \left( \frac{\theta}{100} \right)^2 \ \text{W/m K} \]

\[ \lambda_c = 1.36 - 0.136 \left( \frac{\theta}{100} \right) + 0.0057 \left( \frac{\theta}{100} \right)^2 \ \text{W/m K} \]
• Thermal properties of steel

- for $20^\circ C \leq \theta_a < 800^\circ C$:
  \[ \lambda_a = 54 - 3.33 \times 10^{-2} \theta_a \text{ W/mK} \]

- for $800^\circ C \leq \theta_a \leq 1200^\circ C$:
  \[ \lambda_a = 27.3 \text{ W/mK} \]

- for $20^\circ C \leq \theta < 600^\circ C$:
  \[ c_s = 425 + 7.73 \times 10^3 \theta_a - 1.69 \times 10^5 \theta_a^2 + 2.22 \times 10^6 \theta_a^3 \text{ J/kgK} \]

- for $600^\circ C \leq \theta < 735^\circ C$:
  \[ c_s = 666 + \frac{13602}{738 - \theta_a} \text{ J/kgK} \]

- for $735^\circ C \leq \theta < 900^\circ C$:
  \[ c_s = 545 + \frac{17820}{\theta_a - 731} \text{ J/kgK} \]

- for $900^\circ C \leq \theta < 1200^\circ C$:
  \[ c_s = 650 \text{ J/kgK} \]
• Thermal expansion
• Mechanical properties of concrete
• Mechanical behaviour of structural steel
• Mechanical behaviour of rebars
• Embedded studs in the concrete are joined to the steel shell with a planar connector with nonlinear behaviour.

• Frictional contact exists between steel shells and the concrete with a friction coefficient of 0.2, which is considered low and thus conservative.
• The evolving thermal problem is analysed by implicit integration using Abaqus/Standard.

• Heat transfer coefficients govern the heat exchanges of the surfaces.

• The resulting temperatures are interpolated and supplied to the mechanical analyses as required.
• The mechanical problem is highly nonlinear:
  – The material behaviour (the more important nonlinearities)
  – Contacts
• Problem awkward for the implicit methods in Abaqus/Standard → An explicit integration seemed more appropriate (mass scaling to expedite the computations)
• Procedure:
  – 1\textsuperscript{st} step: gravity loads and the mechanical loads are introduced smoothly.
  – 2\textsuperscript{nd} step: the thermal load is applied lasting 150 min.
  – 3\textsuperscript{rd} step: the mechanical loads are increased gradually until failure.
Results

Heat transfer coefficient 100 W/m²°C for the exposed surface (10 W/m²°C for the unexposed)

Temperature (°C)
• Temperatures at steel plates
• Temperatures in concrete
• Evolution of the deformation
State at 150 min

Longitudinal stress (Pa)

Plastic strain (-)

(0.01 ⇒ ~0.3 mm)
• Sensitivity to concrete expansion

![Graph showing sensitivity to concrete expansion](image-url)
• Sensitivity to stud stiffness
Conclusions

• The thermal variables have a strong influence on the mechanical behaviour, but no influence of the mechanical variables on the thermal problem. This allows dealing with the problem sequentially.

• The thermal problem is only moderately nonlinear and can be solved implicitly; by contrast, the mechanical models include highly nonlinear effects and an explicit solver was used.
• The conductivity and specific heat for steel and concrete proposed in the Eurocodes are appropriate.

• A heat transfer coefficient on the order of 100-200 W/m² °C is adequate for modelling the heat exchange across the exposed surface of the structure. This coefficient represents a complex combination of radiation, convection and conduction processes.
• The mechanical properties of steel and concrete derived from the Eurocodes are adequate. In the material properties provided for the steel, creep effects are not considered separately.

• Most of the deformations taking place are controlled by the thermal expansion of the steel plates. Indeed, the calculations match better the measurements if the concrete expansion is neglected. Standard calculations tend to overestimate the effective thermal expansion of cracked concrete, which is likely to be rather small.