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NUMERICAL MODEL FOR STEEL–CONCRETE COMPOSITE SLABS IN FIRE, CONSIDERING THE MEMBRANE EFFECT

BY

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Abstract. Membrane action in fire for composite steel–concrete slabs is now an intensively researched area, for which more improvement is always necessary. Simplified methods exist for determining the fire resistance of composite slabs considering this effect, but a complex finite element analysis cannot be avoided in all particular situations. The paper presents some numerical simulations, in which simplified hypothesis were considered for representing the partially protected composite steel concrete slabs in fire situation. The numerical models are calibrated using the results of two full scale tests that have been performed in recent years.

Key words: fire design; composite slabs; membrane action; numerical analysis.

1. Introduction

Large-scale fire tests conducted in a number of countries and observations of actual building fires have shown that the fire performance of composite steel framed buildings with composite floors (concrete slabs connected to steel beams by means of headed studs) is much better than indicated by standard fire resistance tests on composite slabs or composite

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beams as isolated structural elements, due to the membrane effect of the composite slabs that develops in fire situation. Recent full-scale fire tests on composite steel–concrete slabs confirmed that a steel and composite floor, if some of its steel beams are not protected, may ensure, with an adequate reinforcing steel mesh in concrete slab, a good fire performance even exposed to long ISO fire (COSSFIRE, 2006; Zhao *et al*., 2008).

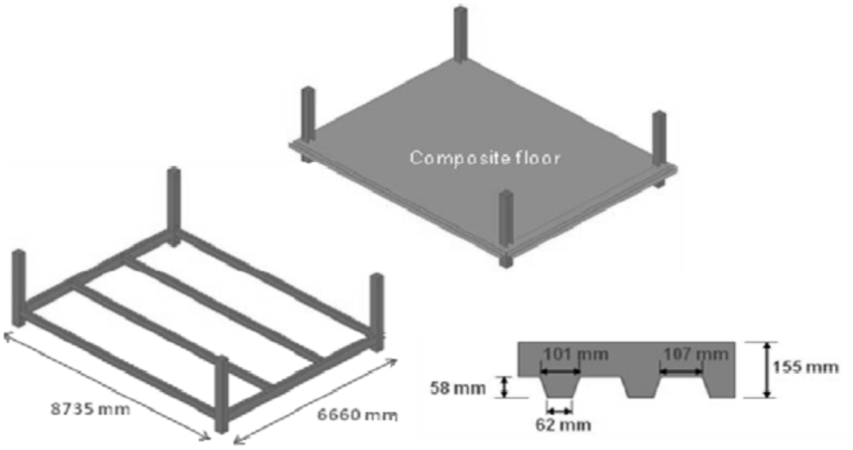
Researchers at the Building Research Establishment of UK, developed a simple design method for composite steel concrete floor slabs, considering the membrane effect (Bailey & Moore, 2000). However, this method cannot cover all the situations that may arise in practice and a finite element analysis cannot be avoided in all particular situations. A complete and detailed numerical modelling of the membrane effect is quite complex and CPU time consuming, due to the simultaneous presence of beams and of orthotropic shells. If such a numerical simulation can be done in research centres and universities, it is not practically applicable for real projects to be analysed in shorter time. Appropriate understanding and modelling of this particular behaviour of composite slabs allows a safe approach, but also substantial savings on the thermal insulation that has to be applied on the underlying steel structure.

The aim of this paper is to derive the simplest possible models for representing the partially protected composite floors in fire situation that, with the price of simplifications and approximations, would nevertheless yield a sufficiently close to reality representation of the structural behaviour and a safe estimate of the load bearing capacity. The numerical analyses were made with SAFIR (Franssen, 2005), a special purpose computer program, developed for the analysis of structures under ambient and elevated temperature conditions, at the University of Liège. The calibration of the numerical models is based on the results of two full scale tests that have been performed in recent years in order to investigate various aspects of the tensile membrane action, performed by CTICM in France: COSSFIRE (2006) and FRACOF (Zhao *et al*., 2008).

2. Numerical Analysis of FRACOF Test

Considering the size of used fire furnace, the designed test specimen covered an area of 7.35 m × 9.53 m, so around 60 m². A specific test specimen shown in Fig. 1 (Zhao *et al*., 2008) was adopted for this test. The composite steel and concrete floor comprised four secondary beams, two primary beams, four short columns and a 155 mm thick floor slab, for a fire resistance of 120 min according to EN1994-1-2 (Vulcu *et al*., 2010), incorporating a reinforcing steel mesh of 256 mm²/m located at 50 mm from the top of the slab. All steel beams were linked to the concrete slab with help of headed studs, and to columns with two common types of steel joints (flexible end plate and double angle web cleats using bolts of M20 in grade 8.8). The composite steel and concrete slab was realized with trapezoidal steel sheet of 0.75 mm thickness.

Normal weight concrete C30/37 was adopted in the design. The reinforcing steel mesh used in the composite slab was with S500 steel grade and had a grid size of 150 × 150 mm and 7 mm diameter. During the fire test, the mechanical loading of the floor was applied using fifteen sand bags distributed over the floor leading to an equivalent uniform load of 3.87 kN/m². The two secondary beams and the composite slab were unprotected, while all the boundary beams of the floor, namely all beams in direct connection with columns, were fire protected to ensure a global structural stability under fire situation. The main measurements were related to temperature and the deflected shape of the floor. Approximately 170 thermocouples were used to monitor the temperature of the steel frame and the temperature distribution in the slab. For the measurement of the floor deformation, nine displacement transducers of which seven vertical displacement transducers were installed.



Steel frame Composite slab

Fig. 1 – Tested structure (Zhao *et al.*, 2008).

The ISO fire exposure lasted up to 120 min, moment when the fire was stopped due to integrity failure of the floor.

Because the edge beams were placed on the boundary of the slab, the fire exposure was just on two faces. The properties of the insulation material that have been used in the simulation were the nominal ones (those given by the producer). For the unprotected beams, the fire exposure was considered on three faces (without the top flange). Fig. 2 shows the comparison between the calculated temperatures and the measured ones in the web, at the point in which thermocouples were placed.

For the thermal distribution, in order to obtain a simpler numerical model, the cross section of the slab containing ribs has been replaced by a section with an average thickness calculated according to EN1994-1-2 Annex D

(2005). Fig. 3 shows a good agreement between the evolution of the measured and simulated temperature in the slab at the rebar level.

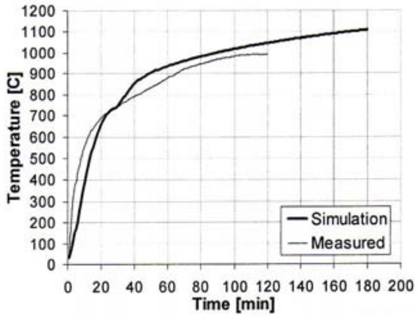


Fig. 2 – Temperature in the secondary unprotected beams (web).

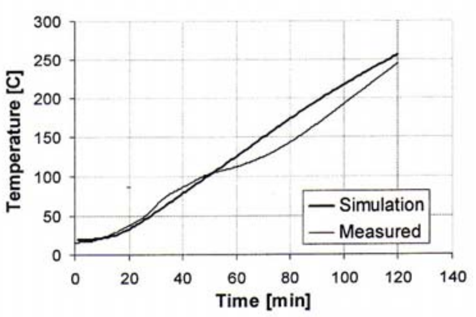


Fig. 3 – Temperature evolution in the slab at rebar level.

The primary and secondary beams have been idealized using beam elements, and the slab using shell elements. According to the connection details from the test, the beam-to-column and beam-to-beam joints were modelled as simple connections. The rebars Ø7/150/150, placed at 50 mm from the top, have been modelled as an equivalent steel layer on the thickness of the shell element, in amount of 256 mm²/m. Even though at the test the load was "concentrated" by using sand bags, in the simulation the load was considered uniformly distributed. For the material properties, the nominal values have been used, not the measured ones.

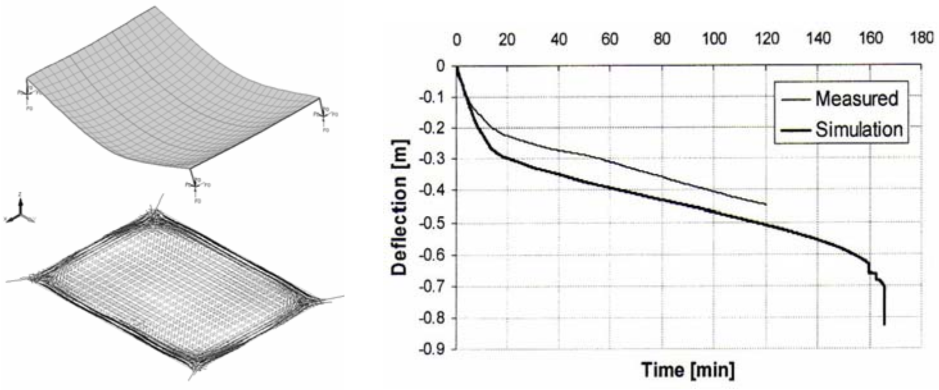


Fig. 4 – Deformed shape and membrane forces – deflection in the middle of the slab.

In Fig. 4 the deformed shape and the membrane stresses of the slab are shown, at 165 min. At this moment the structure failed due to large deflections of the secondary edge beams. The membrane action, characterized by the equilibrium between the compression of the concrete on the edges of the slab and the tension in the rebars from the middle of the slab, was overreached, and the slab could not uphold the load any longer. The chart shows the comparison between the measured and the calculated deflection for the middle of the slab.

3. Numerical Analysis of COSSFIRE Test

Considering the size of the fire furnace, the designed test specimen covered an area of 6.66 m × 8.5 m, so around 56 m². A specific test specimen shown in Fig. 5 (COSSFIRE, 2006) was adopted for this test. The composite steel and concrete floor was composed of five secondary beams, four primary beams, six short columns and a 135 mm thick deck incorporating a reinforcing steel mesh of 251 mm²/m located at 40 mm from the top of the slab. All the beams were linked on the one hand to concrete slab with help of headed studs, and on the other hand to the columns. The composite steel and concrete slab was realized with a trapezoidal steel sheet with 0.75 mm thickness.

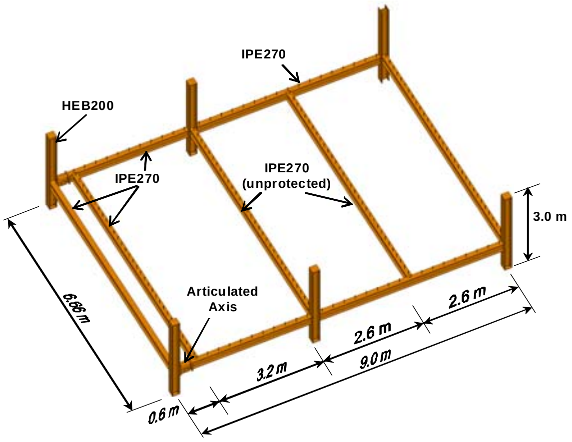


Fig. 5 – Tested structure (COSSFIRE, 2006).

Normal weight concrete C30/37 was adopted in the design. The reinforcing steel mesh used in the composite slab was realized of S500 steel grade and with a grid size of 200 × 200 mm and 8 mm diameter.

During the fire test, the mechanical loading of the floor was applied using sand bags, distributed over the floor, leading to an equivalent uniform load of 3.75 kN/m². The two middle secondary beams and the composite slab were unprotected. All the boundary beams of the floor were fire protected in order to ensure a global structural stability under fire situation.

The main measurements were related to temperature and the deflected shape of the floor. Approximately 146 thermocouples were used to measure the temperature of the connections, 56 thermocouples for the temperature distribution in the slab, 11 thermocouples for the gas temperature in the furnace and 20 displacement transducers of which 16 vertical displacement transducers were installed to measure the deflection of the floor. The ISO fire exposure lasted up to 120 min.

The protected beams were placed on the edges, leading to a fire exposure on two faces. For the unprotected secondary beams, the fire exposure was considered on three faces, as in case of FRACOF model. Fig. 6 shows the very good agreement between the calculated temperatures and the measured ones in the web of the secondary beams, at the point in which thermocouples were placed.

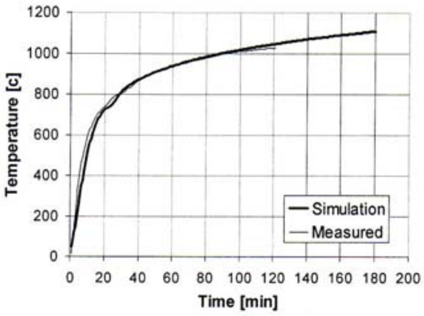


Fig. 6 – Temperature in the secondary unprotected beams (web).

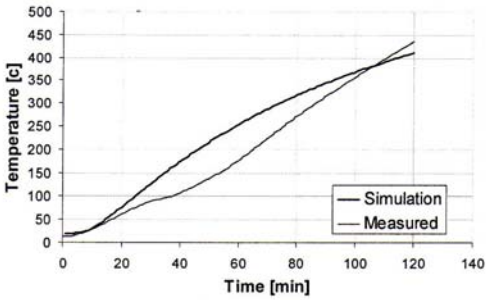


Fig. 7 – Temperature variation in the slab at rebar level.

For the thermal distribution, as in case of the FRACOF numerical model, the cross section of the slab containing ribs has been replaced by a section with an average thickness calculated according to EN1994-1-2 Annex D (2005). Fig. 7 shows the variation of the measured and the calculated temperature in the slab at the rebar level.

The primary and secondary beams have been idealized with beam elements and the slab with shell elements. The beam-to-column and beam-to-beam joints have been modelled as simply connected. The rebars Ø8/200/200, placed at 40 mm from the top, have been idealized as a steel layer in amount of 251 mm²/m. In the simulation the load was considered uniformly distributed in the amount of 6.25 kN/m². For the material properties, the nominal values were considered.

In Fig. 8, the deformed shape and the membrane forces of the slab after 149 min are represented. At this moment the composite slab failed, in the same manner as for the model of FRACOF structure, due to the large deflections of the secondary edge beam. In the chart, a comparison between the measured and the calculated deflection of the middle of the slab is shown.

After about 60 min a difference can be observed between the measured and the calculated deflection curves. In the test, for one of the secondary edge beams, damage of the insulation was observed, which was confirmed by an increase in temperature near the upper flange. For the mentioned edge beam, the measurements also show an increase of deflection at the middle of the span (s. Fig. 9), affecting in this way the deflection in the middle of the slab. This effect was not considered in the numerical analysis.

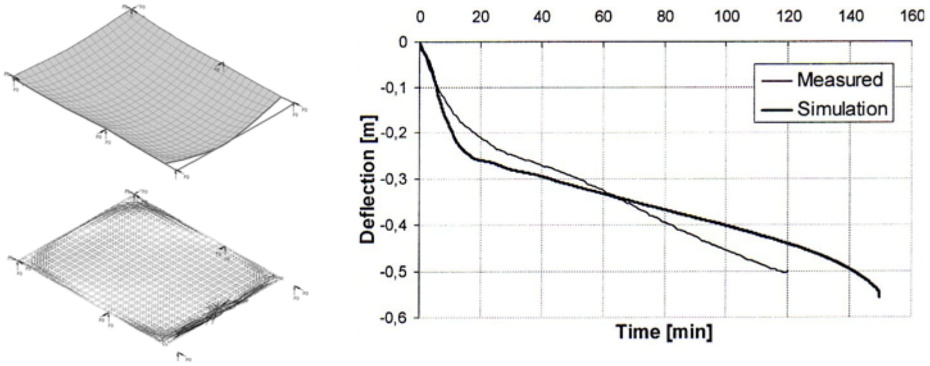


Fig. 8 – Deformed shape and membrane forces; deflection in the middle of the slab.

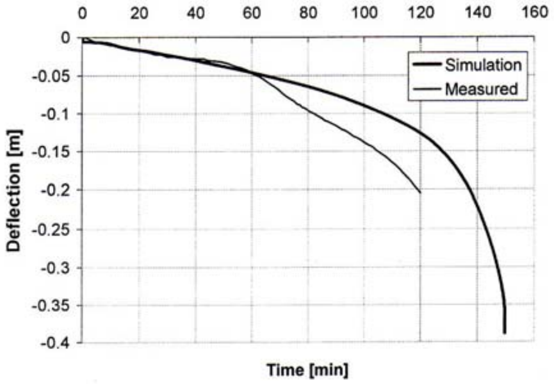


Fig. 9 – Deflection of the secondary edge beam.

4. Conclusions

Numerical simulations of composite slabs in fire have been done in order to calibrate a numerical model as simple as possible, but which would yield to a good approximation of the reality. The study emphasized that for the thermal distribution, in order to obtain a simpler numerical model, the cross section of the slab containing ribs may be replaced by a section with an average thickness calculated according to EN1994-1-2. The primary and secondary beams may be idealized using beam elements, and the slab using shell elements. Considering these approximations, the numerical models showed good agreement with the test results, at the level of time *vs*. displacement characteristics. Differences of time resistance between the numerical simulation and the tests could not be emphasized because the fire exposure in the tests was stopped after 120 min.

Acknowledgment. This research was made in the frame of a B. Sc. work carried out by the student Vulcu Cristian from the “Politehnica” University of Timişoara, supervized by the author within an ERASMUS project between the University of Liège, Belgium, and the „Politehnica” University of Timişoara, Romania.

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MODEL NUMERIC PENTRU PLANŞEELE COMPOZITE OŢEL–BETON ÎN SITUAŢIA DE INCENDIU, CONSIDERÂND EFECTUL DE MEMBRANĂ

(Rezumat)

Efectul de membrană care apare la planşeele compozite oţel–beton în situaţia de incendiu poate fi considerat în proiectare cu ajutorul unor modele analitice consacrate, care însă nu pot acoperi toate situaţiile care pot sa apară în practică. O analiză complexă cu element finit a planşeului solicitat la acţiunea focului nu poate fi întotdeauna evitată. Lucrarea prezintă două simulări numerice în care pentru modelare s-au considerat câteva ipoteze simplificatoare, pentru a reprezenta comportamentul planşeelor compozite cu elementele din oţel parţial protejate la foc. Modelele numerice sunt calibrate prin comparaţie cu două încercări experimentale la foc, la scară reală, efectuate recent.