Title: Numerical modelling of membrane action of composite slabs in fire situation

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ABSTRACT

Membrane action in fire is now an intensively researched area, for which more improvement is always necessary. The paper presents some numerical simulations, done with the SAFIR program, in order to derive more simple models for representing the partially protected composite floors in fire situation. The numerical models are calibrated using the results of three full scale tests that have been performed in recent years.

INTRODUCTION

Several full-scale fire tests on composite steel-concrete slabs have shown that the load transfer mode in the slab, that relies essentially on bending at room temperature, changes to membrane behaviour in the fire situation, due to the large deflections created by thermal gradients. Appropriate understanding and modelling of this particular behaviour allows a safe approach, but also substantial savings on the thermal insulation that has to be applied on the underlying steel structure.

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 that have to be analyzed in shorter time.

The first objective of the research presented in this paper is to derive more simple models for representing the partially protected composite floors in fire situation that, on 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 second objective is to highlight the influence of some critical parameters on the behaviour and fire resistance of composite slabs such as the amount of reinforcing steel in the slab, the thickness of the slab, the load level and the flexibility of the protected edge beams.

The calibration of the numerical models is based on the results of three full scale tests that have been performed in recent years in order to investigate various aspects of the tensile membrane action: two have been performed by CTICM in France, FRACOF [1] and COSSFIRE [1], and one by the Czech Technical University in Prague, in the Czech Republic [3]. Different parametric analyses have been performed on these tests with the advanced calculation model SAFIR of the University of Liege [4].

FRACOF TEST AND NUMERICAL SIMULATION

Considering the size of used fire furnace, the designed test specimen covered an area of 7.35 m by 9.53 m[1], see Figure 1. The specimen comprised 4 secondary beams, 2 primary beams, 4 short columns and a 155 mm thick floor slab incorporating a reinforcing steel mesh of 256 mm²/m located at 47 mm over the steel sheet. The composite steel and concrete slab was realised with open trapezoidal steel sheet of 0.75 mm thickness. A uniformly distributed load of 3.87 kN/m² was applied on the slab. The two central secondary beams and the composite slab were unprotected, while all other beams and the columns were fire protected. The ISO fire exposure lasted up to 120 minutes, moment when the fire was stopped due to integrity failure of the floor.

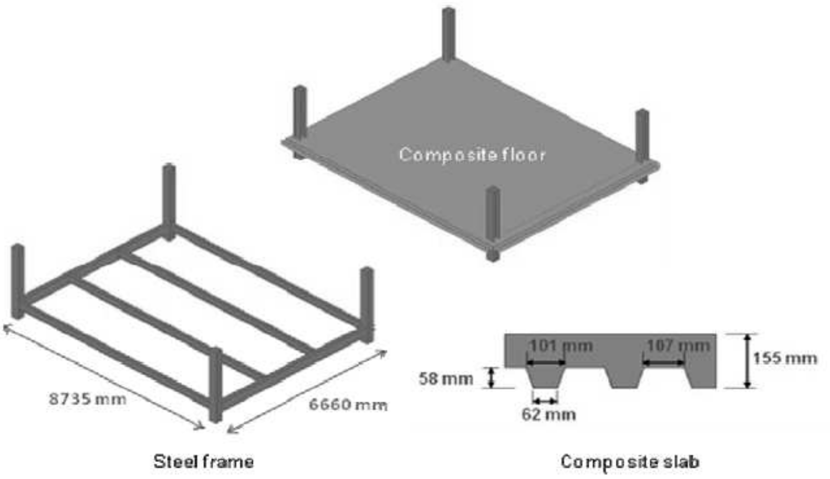


Figure 1. Tested structure

For the temperature in protected beams, there is a certain level of uncertainty for *a priori* simulations because only the nominal values of thermal properties are known and some differences can be observed between the predicted and the measured steel temperature. The predictions are much more reliable for unprotected beams. For the thermal analysis, the cross section of the slab containing ribs has been replaced by a section with an average thickness calculated according to EC4-1-2 Annex D [5] which, for this profile, yielded sufficiently accurate estimation of the temperature at the level of the bars, see Figure 4.

The beams have been idealised 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 bars have been modelled as smeared layer having only uniaxial strength and stiffness. For the material properties, the nominal values have been used, not the measured ones.

In Figure 2, the calculated deformed shape and the membrane stresses in the slab are shown, at 165 minutes, i.e. just before failure was reached in the numerical the simulation. At this moment, the structure failed due to large deflections of the secondary edge beams. The membrane action, characterised by the equilibrium between the compression of the concrete on the edges of the slab and the tension in the bars in the middle of the slab, was overreached, and the slab could not support the load any longer. The chart shows the comparison between the measured and the calculated deflection at the centre of the slab.

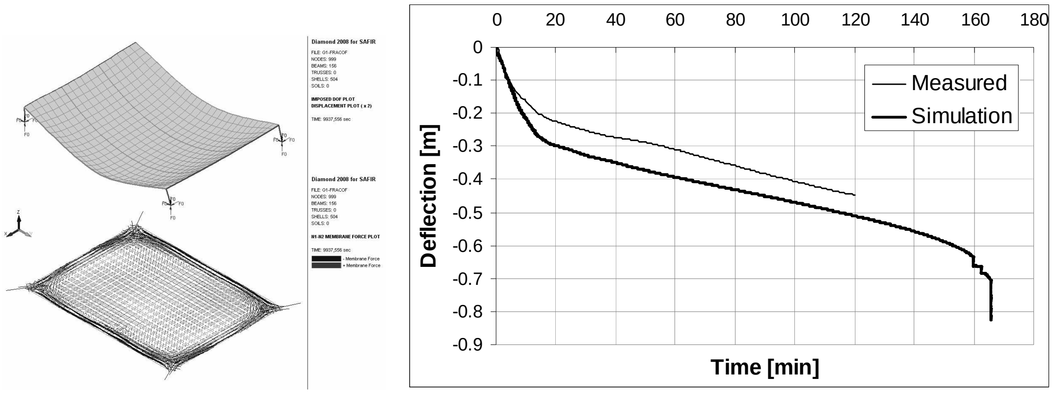


Figure 2. Deformed shape and membrane forces – Deflection in the middle of the slab

COSSFIRE TEST AND NUMERICAL SIMULATION

The COSSFIRE test [2] was part of a project with the objective to propose design rules for the beam-to-column connections when exposed to a natural fire. The designed test specimen covered an area of 6.66 m by 8.5 m. A specific test specimen shown in Figure 3 was adopted, composed of 5 secondary beams, 4 primary beams, 6 short columns and a 135 mm thick deck incorporating a reinforcing steel mesh of 251 mm²/m located at 35 mm over the trapezoidal steel sheet Cofraplus60, with 0.75 mm thickness. A uniformly distributed load of 3.75 kN/m² was applied on the slab. The two middle secondary beams and the composite slab were unprotected, while all the boundary beams of the floor were fire protected. The ISO fire exposure lasted up to 120 minutes.

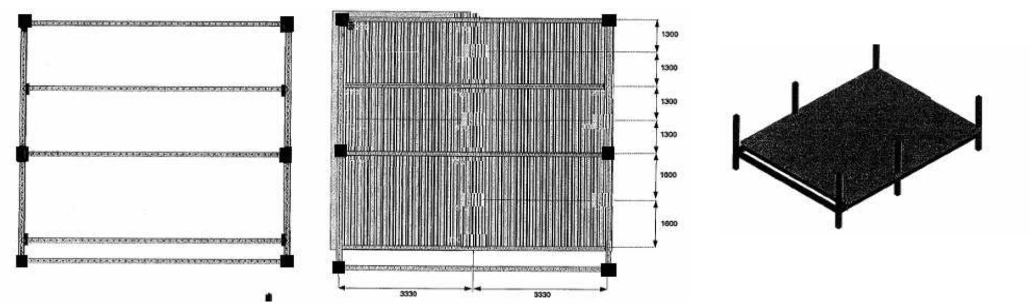


Figure 3. Tested structure

Here also, the temperatures calculated in the unprotected beams were closer to the observed temperatures than those calculated in the protected edge beams and the temperatures calculated in the bars of the slab on the base of the equivalent thickness as recommended by Eurocode 4 were reasonably close to the temperatures observed during the test, see Figure 5.

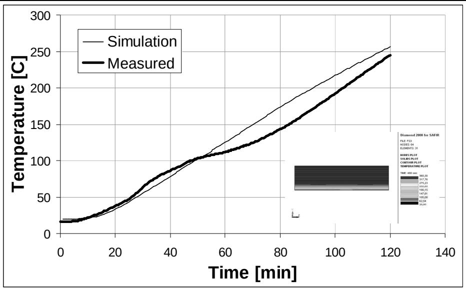


Figure 4. Temperature variation in the slab at rebar level (FRACOF)

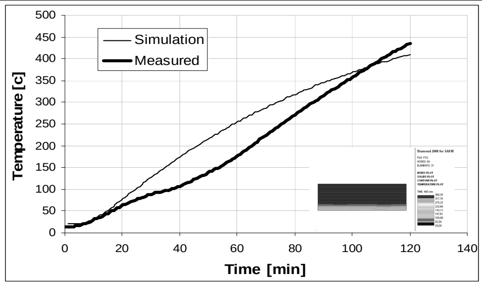


Figure 5. Temperature variation in the slab at rebar level (COSSFIRE)

In Figure 6, the deformed shape and the membrane forces of the slab after 150 minutes are shown. 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.

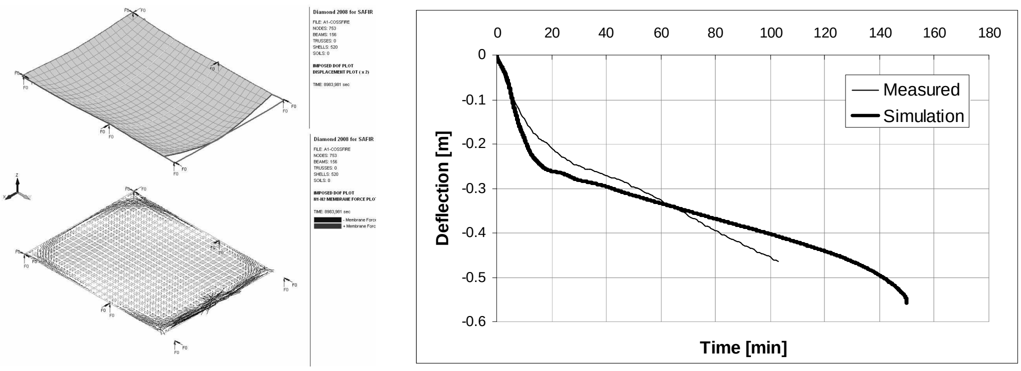


Figure 6. Deformed shape and membrane forces – Deflection in the middle of the slab

PRAGUE TEST AND NUMERICAL SIMULATION

The aim of the fire test was to observe the overall behaviour of the structure, which may not be observed in tests performed on separate elements. Three types of flooring systems [3] and six wall structures with mineral wool were tested. The construction of the experimental building is documented on Figure 7.

The experimental structure represents one floor of an administrative building of 18 x 12 m. The composite slab on the castellated covered an area of 9 x 12 m² and beams with corrugated webs an area of 9 x 6 m². The deck was a simple trapezoidal composite profile of 60 mm depth with 60 mm of concrete over the profile, reinforced by a smooth mesh of ø5 mm 100/100 mm (i.e. 196 mm²/m) located 20 mm over the profile.

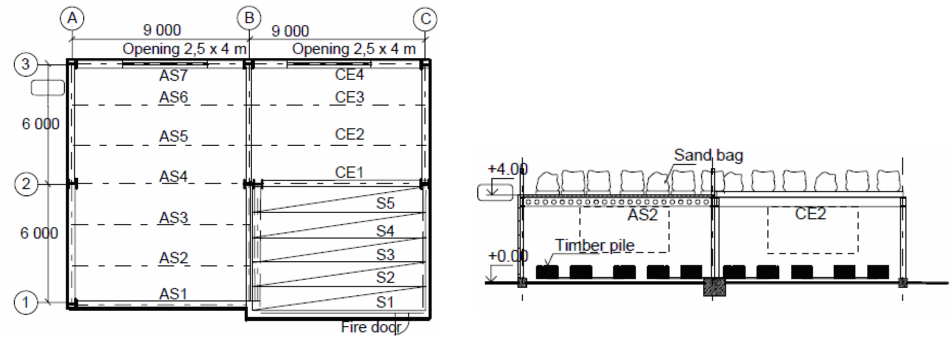


Figure 7. Tested structure

The dead load of the tested structure reached 2,6 kN/m². The variable load of 3,0 kN/m² was simulated by sand bags. The fire load of 620 MJ/m² for this natural fire tests consisted wooden cribs. The openings of 2.54 m height and a total length of 8.00 m ventilated the compartment. To allow a smooth development of fire, no glazing was installed.

Under the composite slab with castellated beams, a temperature of 935°C was measured after 60 minutes. The collapse of the slab occurred after 62 minutes, at the beginning of the cooling phase of the fire, with the measured temperature of the lower flange of the beam at the mid span equal to 895 °C.

The numerical simulation was performed for the 9x6 m² zone where the slab is supported by Angelina beams. The columns and the cross braces were not modelled. Therefore, the analysis was realised only for the Angelina beams, the composite slab, and two types of protected edge beams.

A fire curve has first been obtained with OZone program and used further in the thermal analysis. This curve is compared in Figure 8.a) with the measured gas temperatures at the test. Figure 8.b) shows the comparison for the temperature in the lower flange of the Angelina beams.

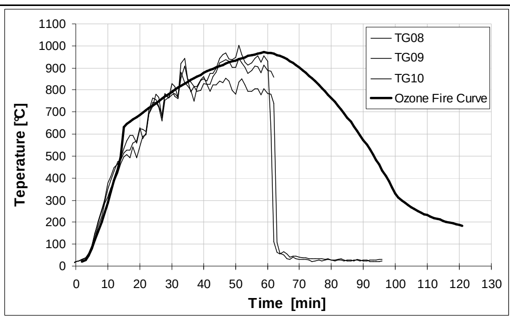


Figure 8.a). Comparison between the Ozone fire curve and the gas measurements

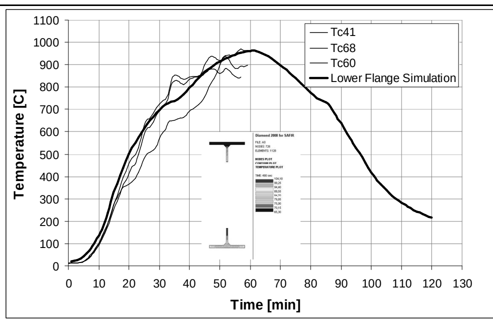


Figure 8.b) Temperature in lower flange of the Angelina beams

The castellated beams were modelled using the “minimum section” for the entire length of the beam. For the thermal distribution, the section of the slab containing ribs has also been replaced by a section with an average thickness.

In the numerical model, the edge beams and the unprotected Angelina beams were idealised using beam elements, and the slab using shell elements. Vertical supports have been used instead for the columns, and horizontal restrains for the cross braces and for the continuity of the slab.

Figure shows the deformed shape and the membrane forces of the slab at failure, namely a concrete failure in the corner of the slab, see Figure 9. The chart shows the deflection curve from the simulation compared to the measured deflection from the test for the middle area of the slab.

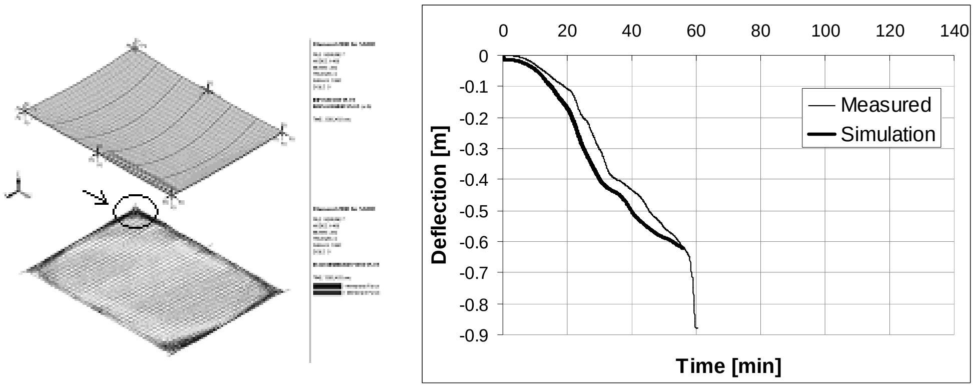


Figure 9. Deformed shape and membrane forces – Deflection in the middle of the slab

PARAMETRIC STUDY

For the tree tests, a sensitive analysis has been performed in order to see the influence of a number of parameters on the mechanical response of a composite slab. For the Prague test, the study aimed also to identify what could have improved the behaviour of the slab. For each parameter, one or more simulations have been done and then compared with the reference numerical models presented above. The investigated parameters are:

- the vertical supports on the edges;
- the thickness of the slab;
- the amount of reinforcement;
- the modelling of the unprotected beam;
- the influence of the lateral restraints of the slab;

Influence of the vertical supports on the edges

For the three tests, a model was built in which all the edges of the composite slab were fully restrained vertically. The aim was to see how important the stiffness of the edge beam is. In all three cases, the slab with full vertical fixity on the edges resisted a longer time to the fire exposure, see Figure 10, because the plastic hinge that otherwise formed in the secondary edge beams was avoided. For the Fracof and Cossfire tests the collapse of the slab was not reached after 4 and respectively 3 hours of ISO fire exposure. For the Prague test, the collapse at 61 minutes was also avoided.

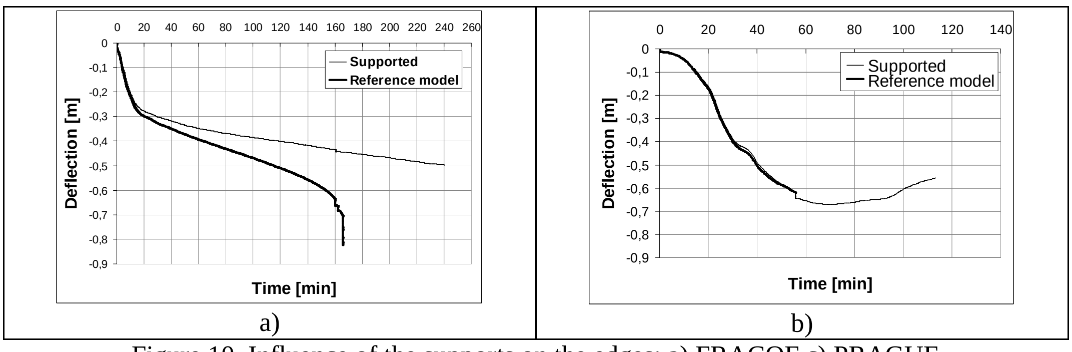
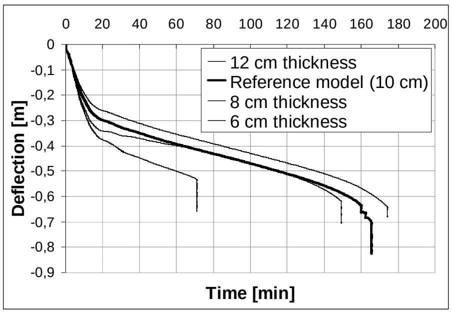


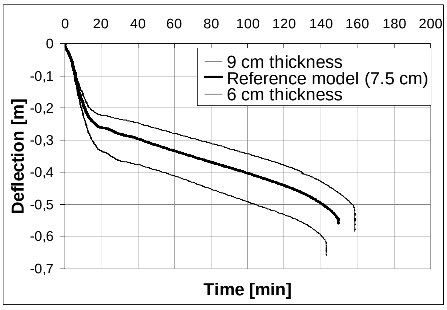
Figure 10. Influence of the supports on the edges: a) FRACOF c) PRAGUE

Influence of the thickness of the slab

Models with different thickness of the slab were considered. Figure 11 shows that a higher thickness leads to lower deflections, with a minimum thickness being required to achieve stability, the value of this minimum thickness being somehow different in each test.



a)



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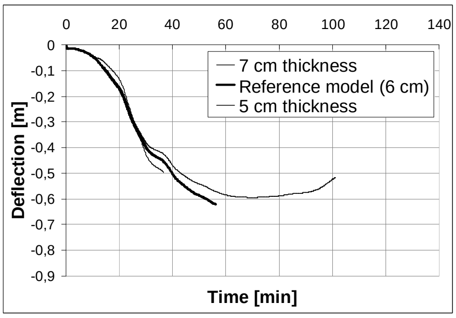
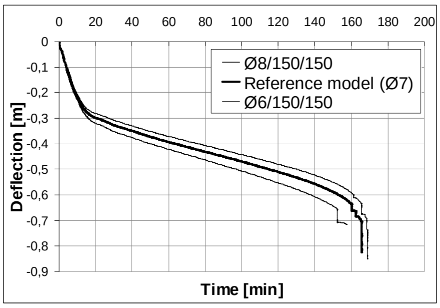


c)

Figure 11. Influence of the slab thickness: a) FRACOF b) COSSFIRE c) PRAGUE

Influence of the amount of reinforcement



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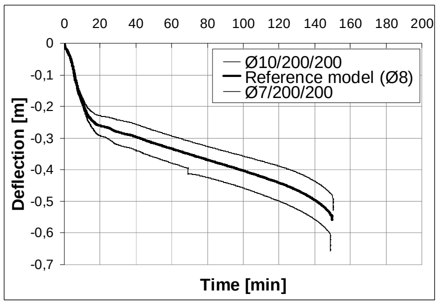

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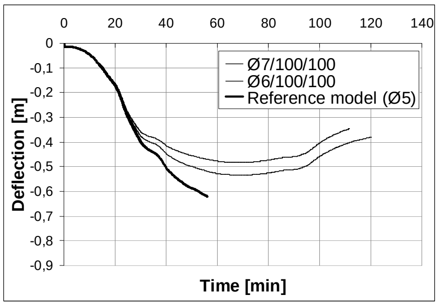


c)

Figure 12. Influence of the reinforcement: a) FRACOF b) COSSFIRE c) PRAGUE

Models with different quantities of reinforcements were considered with nearly unchanged results for the first 2 tests and a dramatic improvement in the test of Prague, see Figure 12.

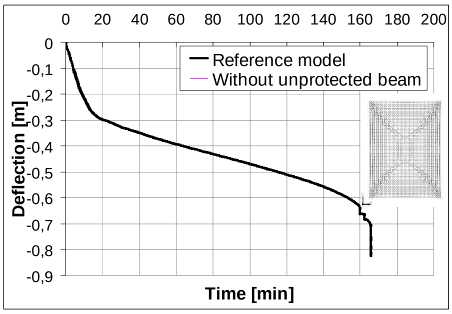
Modelling of the unprotected beam

For the three tests, besides the reference model, a second model has been considered, in which the unprotected secondary beams were neglected, or just a part of the section has been modelled. For the Prague test, the secondary beams were castellated beams, and the question was how to model these, or whether it is really necessary to model these at all. Figure 13 shows the deflection for the reference models and the models without unprotected beam.

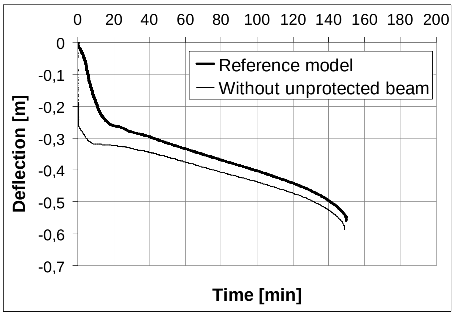
For the Fracof test, in case the unprotected beams were neglected, the transition from the compressive membrane to the tensile membrane was “violent” so that the yield lines formed leading to the failure of the slab before the total load could be applied.

For the Cossfire test, in case the unprotected beams were not present, the slab entered from the beginning into tensile membrane. As the fire develops, the deflection curve converged towards the same curve as the one obtained when the unprotected beams are present in the model.

For Prague test, using just the upper T for the castellated beams lead to large deflections at the beginning of the test, but the deflection curve did not converged to the same displacement and time resistance. Using the minimum section (the upper and lower T) for the Angelina beams lead to a good correlation with the test, but in the case where just the upper T was used, an early failure of the slab occurred.



a)



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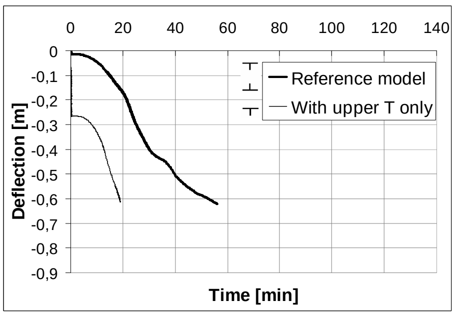

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Figure 13. Modelling of the unprotected beam: a) FRACOF b) COSSFIRE c) PRAGUE

Influence of the lateral restraints of the slab

For the three tests, beside the reference model, a second model has been considered in which the composite slab was laterally restrained on the four edges, with the aim to simulate an eventual continuity of the slab, assuming that there is no rupture of the bars on the supports. Figure 14 shows that the Fracof structure resisted up to 4 hours, while for the other structures a numerical failure occurred and the simulation could not be run until failure.

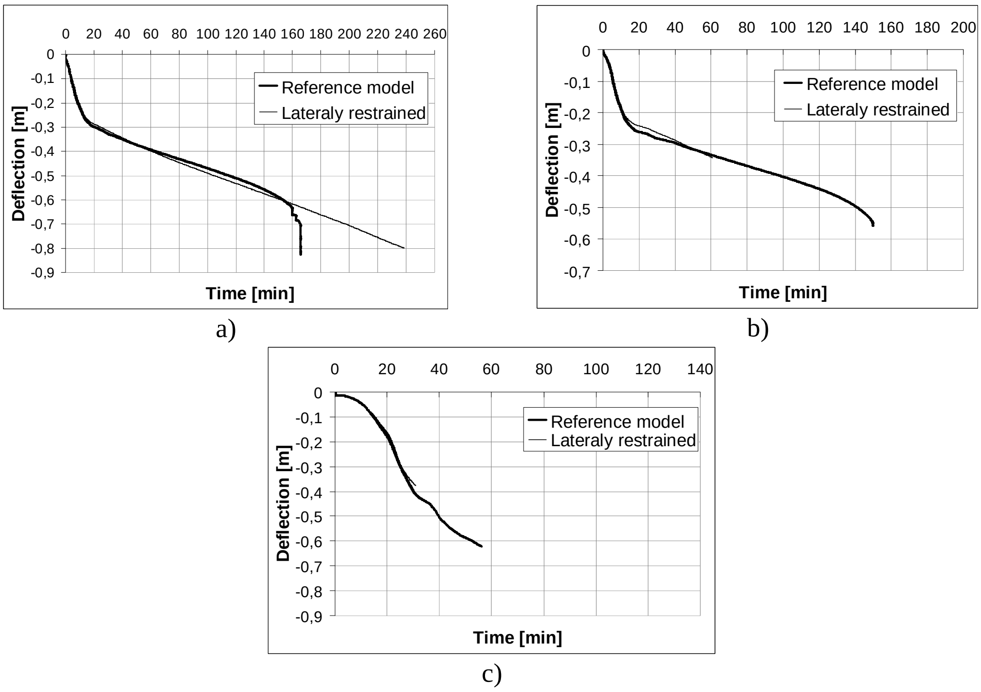

Figure14. Influence of the lateral restrains of the slab: a) FRACOF b) COSSFIRE c) PRAGUE

CONCLUSIONS

Using the available information from the three tests, Fracof, Cossfire and Prague, numerical simulations have been done using the SAFIR program. Differences of time resistance for Fracof and Cossfire tests could not be emphasised because the fire exposure in the tests was stopped after 120 minutes. For the Prague structure, the fire resistance time in the *a priori* numerical simulation is almost the same as the failure time observed in the test, with a difference of 5 minutes.

In order to see the influence of different parameters on the behaviour of the composite slabs when exposed to fire, a parametric study has been performed for each test.

Increasing the thickness of the slab improves the behaviour of the slab, with lower vertical deflections and higher fire resistance times. The average thickness for the section of the slabs containing ribs, calculated according to Annex D of EC4-1-2, may be used for the thermal distribution in the numerical simulation, at least with the open trapezoidal sections used in these tests.

For the Fracof and Cossfire tests the failure was caused by plastic hinge forming in the secondary edge beams. When the edges of the slabs are considered as completely restrained vertically, the plastic hinge forming in the secondary edge beams is avoided and the fire resistance time is increased for the three slabs.

If lateral restrains are used in the numerical simulation, the failure is not reached after 4 hours of ISO fire exposure in the Fracof test. For the other two tests (Cossfire and Prague), the use of lateral restrains leads to early numerical failure.

If the secondary beams are not present in the numerical simulation, the transition from the compressive membrane to the tensile membrane is “violent” For the Fracof test so that the yield lines lead to early failure of the slab. For the Cossfire test, if the secondary beams are neglected, the slab enters from the beginning into tensile membrane. However, the failure time and evolution of vertical deflections are nearly the same than for the reference model. For Prague structure, using just the upper T for the castellated Angelina beams, large deflections are obtained at the beginning, like in the Cossfire test, but the vertical deflection curve does not converge to the same displacement and time resistance as in the reference numerical model. For the Prague test, using the minimum section (the upper and lower T) for the Angelina beam showed good correlation with the test.

Increasing the amount of reinforcement improves the behaviour of the slab (less vertical displacement and higher fire resistance times). However, if the collapse is not caused by failure of reinforcement but by compression in the concrete, using more reinforcement will not lead to a significant improvement (as can be seen in the case of the Fracof and Cossfire tests). For Prague test, using a higher amount of rebars lead to lower vertical deflection and the collapse was avoided.

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