Application of Structural Fire Design, 29 April 2011, Prague, Czech Republic

MUNICH FIRE TESTS ON MEMBRANE ACTION
of Composite Slabs in Fire – Test Results and Recent Findings

Martin Stadler [a], Martin Mensinger [b], Peter Schaumann [c], Jörg Sothmann [c]

[a] Technische Universität München, Chair for Metal Structures, Munich, Germany, Member of TUM Graduate School
[b] Technische Universität München, Chair for Metal Structures, Munich, Germany
[c] Leibniz Universität Hannover, Institute for Steel Construction, Hannover, Germany

INTRODUCTION

Composite beam slab systems show a very good behaviour in case of fire. Due to large deformations membrane forces are activated inside the slab and wider spans can be bridged. Secondary beams are not necessary at elevated temperatures and can be left unprotected. In several European countries research projects were carried out to analyse this phenomenon. In Great Britain and Switzerland membrane action is already used to design slab systems in fire. To enable such design rules in Germany further investigations are required. Available design methods need to be adapted to German design rules and some remaining issues have to be clarified. For this reason the research project "Nutzung der Membranwirkung von Verbundträger-Decken-Systemen im Brandfall" (Utilisation of membrane action for design of composite beam-slab-systems in fire) was initiated by the authors.

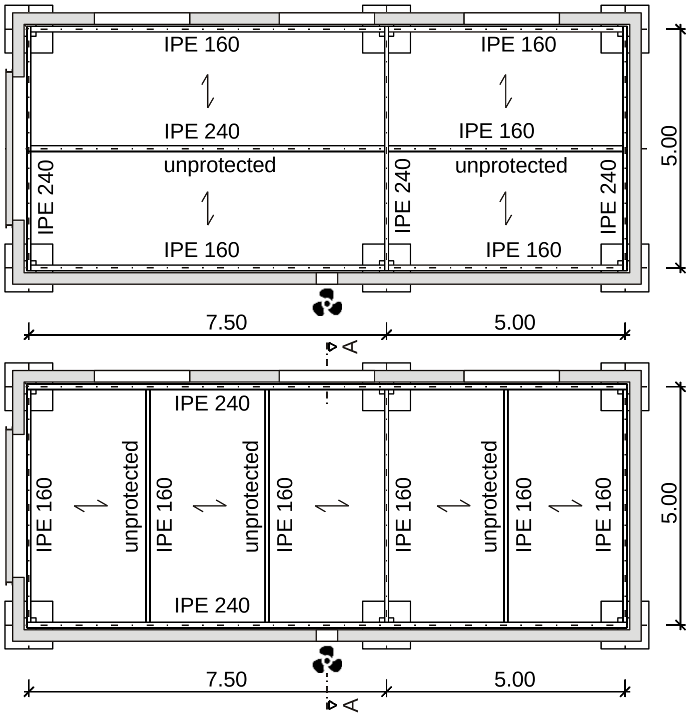
Main objective of the project is to understand the behaviour of intermediate beams between two slab panels. Large rotations lead to huge cracks in the concrete chord above the edge beams. That may reduce the load bearing capacity of these beams. Two large scale fire tests have been performed in Munich (Fig. 1 and Fig. 2) to analyse this issue, to calibrate numerical models and to validate analytical assumptions. Test results and latest findings of the project are presented in this paper.

Fig. 1 First Munich fire test

Fig. 2 Second Munich fire test

1 TEST ARRANGEMENT

The test arrangements should represent office buildings and similar multi storey structures. The specimens both consisted of two slab panels with overall dimensions of 5.0 m by 12.5 m (Fig. 3 and Fig. 4). They were supported by hot rolled I-beams and six reinforced concrete columns. The columns were not part of the investigation. All edge beams were protected with intumescent coating for a fire resistance of 60 minutes. The secondary beams were left unprotected. Two tests with slightly different arrangements have been performed. Only the orientation of the secondary beams, the flooring system and the intumescent coating system has been varied. The first specimen was built with a lattice girder precast slab and the second one with a profiled steel sheeting composite slab. The cross sections and reinforcement amount have been designed for an office building at ambient temperature according to EN 1994-1-1. The utilization factors S_d/R_d were chosen very close to 100% to avoid structural integrity based on oversizing.



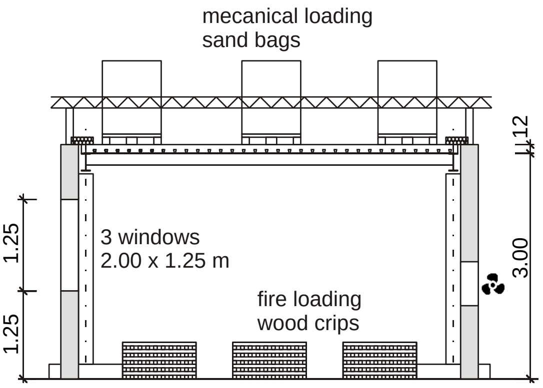


Fig. 3 Plan view of test 1 (above) and 2 (below)

Fig. 4 Section A-A

The fire exposure of the slabs was intended to follow as close as possible the ISO 834 fire curve. The edge beams also have been inside the furnace to be able to deform freely and to investigate the influence of the edge beams on membrane action. The loading should be representative for office buildings. To ensure these boundary conditions a 3.0 m high temporary furnace was built by aerated concrete bricks. Sandbags were placed on top of the slab to simulate a uniform distributed load of 2.1 kN/m². Wood cribs consisting of 4.9 m³ spruce timber constituted the fire load. Three windows in one wall provided natural ventilation and a fan was installed in the opposite wall to readjust the ventilation.

2 TEST RESULTS

2.1 Test 1

At the first test with the lattice girder precast slab the gas temperatures exceeded 1000°C. Due to slightly non-uniform temperature distribution the maximum average gas temperature was about 900°C after 40 minutes (Fig. 5). The longer secondary beam heated up to 900°C the shorter beam even up to 950°C. The temperature in the edge beams remained below 500°C. Partially the intumescent coating detached from the lower flange. Therefore the lower flange of the intermediate beam reached almost gas temperature. The upper flange and the web stayed cooler than 500°C. The larger panel reached a maximum deformation of 260 mm after 60 minutes and the shorter panel about 200 mm. After 19 minutes a huge crack appeared in the smaller panel close to the intermediate beam (Fig. 6). The upper reinforcement layer ruptured completely in this crack and smoke passed through the gap. The slab did not collapse during the whole test but it lost its integrity (criterion “E”).

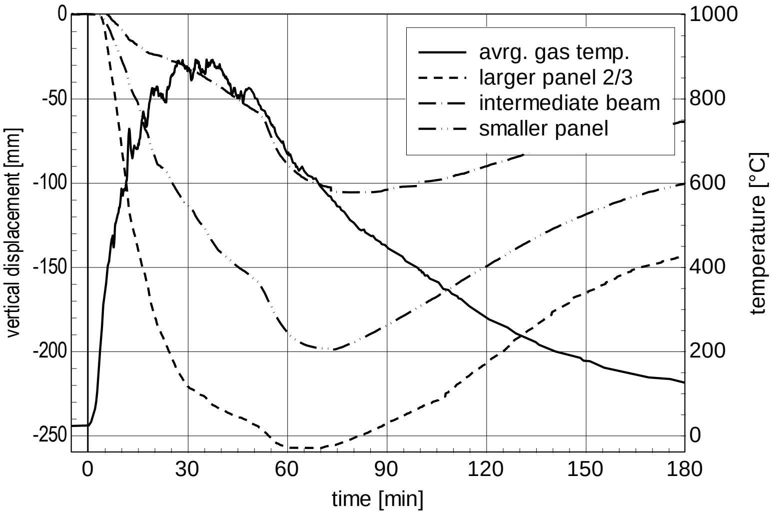


Fig. 5 Gas temperature and displacements first test

Fig. 6 Crack above intermediate beam first test

2.2 Test 2

The second test showed a very good behaviour of the composite slab during the whole experiment. The gas temperatures reached their maximum of more than 900°C after 40 minutes. The unprotected secondary beams reached over 800°C and the protected edge beams remained below 350°C. A maximum temperature of about 500°C was measured in the intermediate beam. The larger panel deformed vertically more than 250 mm and the smaller panel about 190 mm after 60 minutes (Fig. 7). The intermediate beam achieved the same deformation as the smaller panel after three hours. A large crack appeared above the intermediate beam (Fig. 8). However, all three criterions (REI) for fire resistance were kept during the whole test.

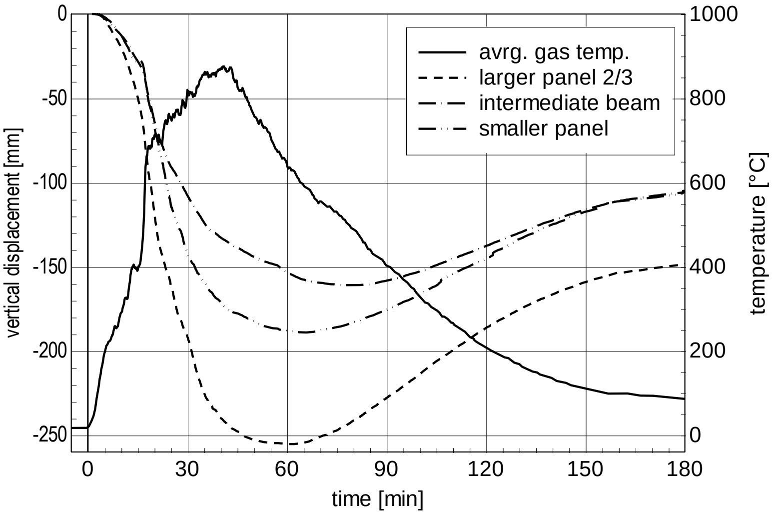


Fig. 7 Gas temperature and displacements second test

Fig. 8 Crack above intermediate beam second test

3 FIRE SIMULATION

In order to dimension the ventilation conditions the zone-model based software OZone developed by the University of Liege was used. The predicted temperature-time-curve matches the test data closely (Fig. 9). However, some differences occurred between measured and predicted temperature-time-curve mainly caused by the humidity of the wood. The humidity considerably influences the combustion heat of fuel (c.h.o.f.) of the wood. The predicted curve was computed with the OZone default value for a c.h.o.f. of 17.5 MJ/kg. At the first test the wood had a measured humidity of 11.2%. This humidity leads to a reduced c.h.o.f. of 16.3 MJ/kg. With this reduction the simulated curve is very close to the measured curve in the heating phase. Only the cooling phase differs from the test data (Fig. 9).

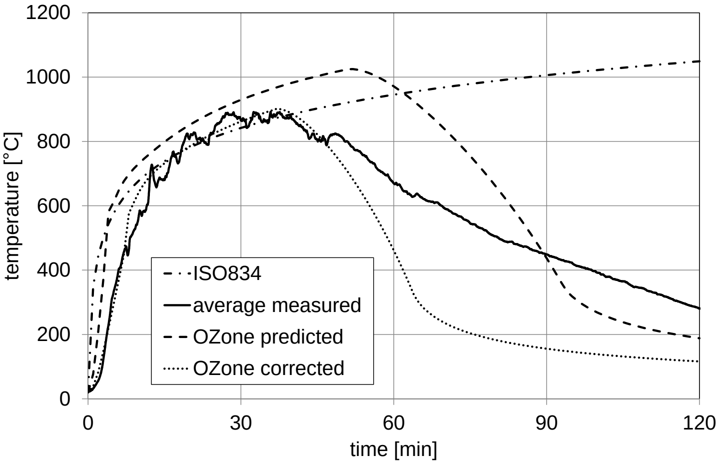


Fig. 9 Comparison of simulated and measured gas temperatures

4 EDGE BEAM BEHAVIOUR

The load bearing mechanism of the slab-beam-system is very complex. It will be discussed in the context of the first test. Assuming the slab has rigid vertical support and no edge beams the typical membrane force distribution occurs (Fig. 10). In each panel tensile membrane forces appear in the centre of the panel and a compression ring around the perimeter. This force distribution was described in former works and simplified design methods are based on it (e.g. Newman et al, 2000). But the forces change considerably when taking the edge beams into account (Fig. 11). A compression ring does not exist anymore. The edge beams elongate due to thermal expansion. This elongation is restrained by the slab and leads to compression in the beams and tension in the slab. In the model with rigid support the highest compression stresses in the concrete arise in the middle of the longer edge and the highest tensile forces occur in the middle of the slab in longitudinal direction. Whereas by including the edge beams the highest concrete compression emerges diagonal at the corners and considerable tensile forces occur above the intermediate beam.

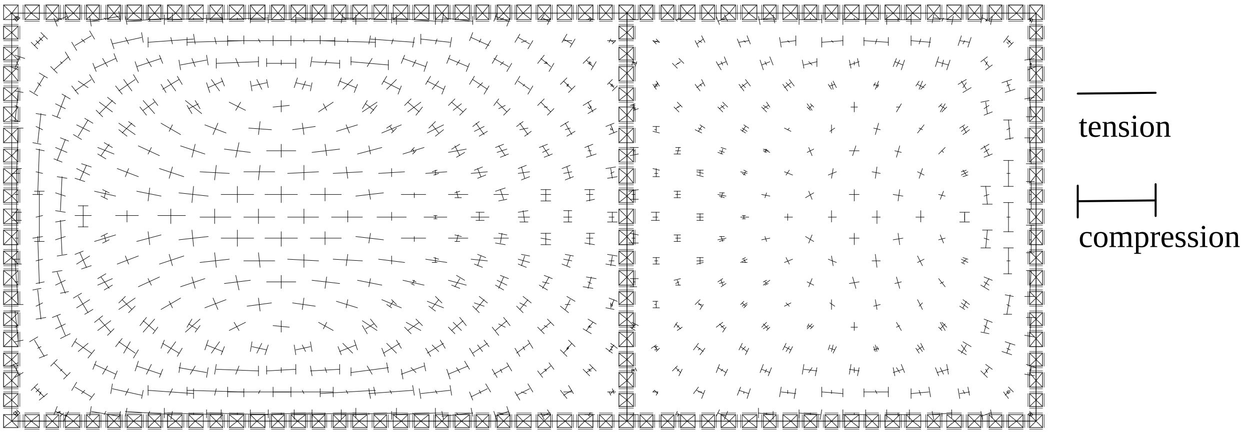


Fig. 10 Membrane forces, slab with rigid support

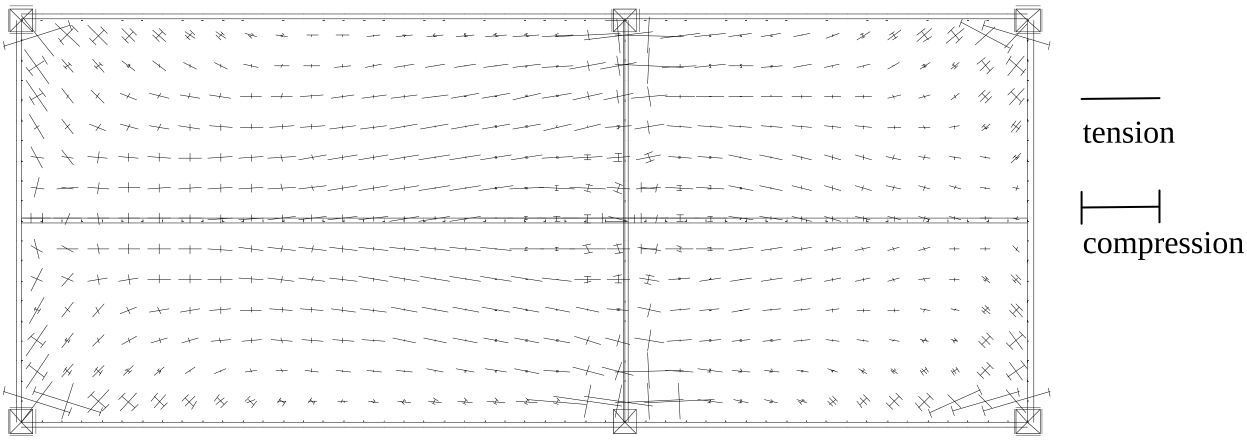


Fig. 11 Membrane forces, slab supported by edge beams

The tensile forces in the reinforcement above the intermediate beam are mainly caused by the hogging moment. This can be shown by considering the stresses in the top layer of the slab (Fig. 12a). Material nonlinearities reduce these stresses but even a bending hinge above the intermediate beam is not sufficient. The tensile forces are reduced but do not disappear (Fig. 12b). A possible explanation is that the slab acts like a three times supported cable in longitudinal direction. During the test all this led to cracking of the concrete above the intermediate beam, yielding and finally even to rupture of the reinforcement in the crack. With the ruptured reinforcement in the tension-zone the slab was not able to bear shear forces anymore and a huge shear crack was formed close to the intermediate beam. After that all the constraint forces have been removed and the slab again got into equilibrium with a different force distribution (Fig. 12c). To prevent this kind of failure further research is necessary.

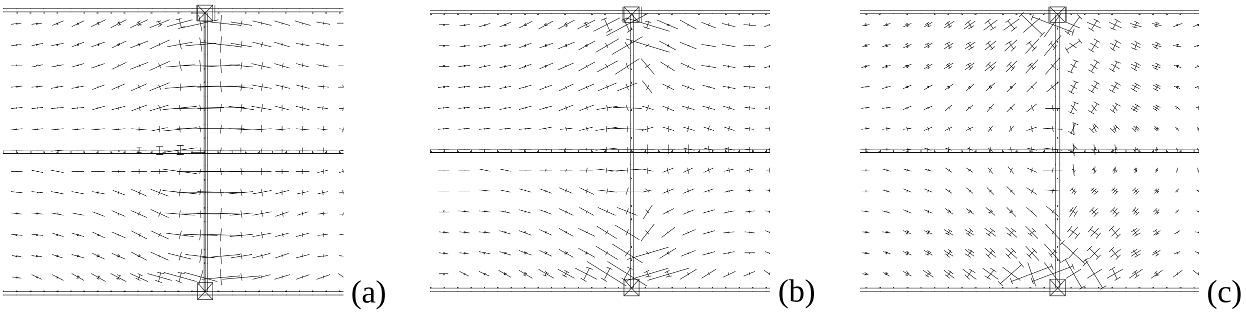


Fig. 12 Principal stresses top layer of slab, continuous (a) hinge (b) ruptured reinforcement (c)

5 SUMMARY

An on-going research project shall enable the use of membrane action for fire design of composite slabs in Germany. Within this project two large scale fire tests have been performed in Munich in 2010. The tests confirmed that membrane forces enhance the load bearing capacity considerably. In the test with the lattice girder precast slab a huge crack occurred above the intermediate beam. The slab lost its integrity and smoke streamed out of the crack. The provided explanation of the authors is that the reinforcement above the intermediate beam yielded due to the hogging moment and tensile membrane forces. No reinforcement was available anymore to transfer shear forces, a huge crack opened close to the intermediate beam and the reinforcement ruptured in the crack. Further research work is necessary to identify the parameters that induce this kind of failure and to develop design rules to avoid it in future.

6 ACKNOWLEDGEMENT

The authors would like to thank the sponsors of the project. Special thanks go to the German steel construction association DASt, the German ministry of economy and technology represented by the AiF and the construction company Max Bögl that enabled with big effort the assembly of the tests. Further supporters of the projects are: ArcelorMittal, Montana Bausysteme, Rütgers Organics, Sika, Xella, Hilti, stahl + verbundbau, Köco and HBM.

Das IGF-Vorhaben 16142 N der Forschungsvereinigung Deutscher Ausschuß für Stahlbau e.V. – DASt, Sohnstraße 65, 40237 Düsseldorf wurde über die AiF im Rahmen des Programms zur Förderung der industriellen Gemeinschaftsforschung und –entwicklung (IGF) vom Bundesministerium für Wirtschaft und Technologie aufgrund eines Beschlusses des Deutschen Bundestages gefördert.
(The IGF-research project 16142 N of the research association "Deutscher Ausschuß für Stahlbau e.V. – DASt, Sohnstr. 65, 40237 Düsseldorf" was supported via the AiF within the framework of the programme to support the cooperative industrial research and development (IGF) from the federal ministry of economy and technology due to a resolution of the German Bundestag.)

REFERENCES

Abu A. K., Burgess I. W., Plank R. J.: Slab panel vertical support and tensile membrane action in fire. In: Steel and Composite Structures 8 (2008), pp. 217–230

Abu A. K.: Behaviour of Composite Floor Systems in Fire. University of Sheffield, Department of Civil & Structural Engineering, Diss. 2009

Bailey C. G.: Membrane action of slab / beam composite floor systems in fire. In: Engineering Structures 26 (2004), pp. 1691-1703

Mensinger M., Schaumann P., Stadler M., Sothmann J.: Membranwirkung von Verbunddecken bei Brand – Stand der Technik. In: Stahlbau 79 (2010), Nr. 4, pp. 298–305

Newman G. M., Robinson J. T., Bailey C. G.: Fire safe design: A new approach to multi-storey steel-framed buildings, Steel Construction Institute, Ascot 2000 (SCI publication 288)

Tesar C. N.: Zum Tragverhalten von Verbunddeckensystemen im Brandfall, Diss. Zürich: vdf Hochsch.-Verl. an der ETH (IBK-Bericht, 309) (2008)