FRACOF: FIRE RESISTANCE ASSESMENT OF PARTIALLY PROTECTED STEEL-CONCRETE COMPOSITE FLOORS

FRACOF: DETERMINAZIONE DELLA RESISTENZA AL FUOCO DI SOLAI MISTI ACCIAIO-CLS PARZIALMENTE PROTETTI

Riccardo ZANON, Mauro SOMMAVILLA, Olivier VASSART
ArcelorMittal Long Carbon Europe
riccardo.zanon@arcelormittal.com
mauro.sommavilla@arcelormittal.com
olivier.vassart@arcelormittal.com

Bin ZHAO
Fire Research Department
CTICM
Saint-Aubin, France
binzhao@cticm.com

Jean-Marc FRANSSEN
University of Liege
Argenco Department
Liege, Belgium
JM.Franssen@ulg.ac.be

ABSTRACT

Large-scale fire tests and observations of actual building fires have shown that the fire performance of composite steel framed buildings is much better than is indicated by fire resistance tests on isolated elements.

This contribution presents application of a simple design method, so-called FRACOF concept, for the analysis of non-sway steel-framed buildings with composite floors. Starting point were the outstanding results obtained in the BRE Cardington large-scale building fire test programme carried out during 1995 and 1996. The method was further validated by large-scale standard furnace tests in 2008 and 2009, as well as with natural fire tests in 2010. A recent test has also shown the possibility of application of this concept to composite floors with castellated beams.

The recommendations are in line with the reliability level imposed by current design rules and are limited to structures similar to that tested. The method permits designers to spare the fire protection for the framing elements for which it is not needed by keeping the same safety requirement than traditional codes.

SOMMARIO

Prove di resistenza al fuoco su grande scala e osservazioni di incendi in edifici reali hanno mostrato che le prestazioni in caso di incendio di edifici a telaio composti acciaio-calcestruzzo sono molto migliori di quanto indicato dalle prove di resistenza al fuoco su elementi isolati.

Questo contributo presenta l’applicazione di un semplice metodo di calcolo, denominato concetto FRACOF, per l’analisi al fuoco di telai controventati a struttura mista acciaio-calcestruzzo. Punto di partenza sono stati i risultati sorprendenti ottenuti nell’ambito del programma di prove sperimentali su grande scala condotto dal BRE sull’edificio di Cardington tra il 1995 e il 1996. Il metodo é stato in seguito validato da vari test in forni con temperatura ISO 834 nel 2008 e nel 2009, e da test con incendio naturale nel 2010. Recentemente prove su solai composti con travi alveolari hanno dimostrato la validità di tale metodo anche per questo tipo di strutture.

Le raccomandazioni sono conformi al livello di sicurezza richiesto dalle normative attuali e si limitano a strutture simili a quelle sottoposte a prova sperimentale. Il metodo permette facilmente ai progettisti di individuare se alcuni elementi del telaio possano restare non protetti mantenendo un livello di sicurezza equivalente a quello dei metodi tradizionali che prevedono una protezione dell’intera struttura.

1 INTRODUCTION

For buildings requiring severe fire resistance, it is common practice for all exposed structural members within a steel-framed building to have some form of applied fire protection to ensure that they retain their strength and stiffness. The use of applied fire protection is considered to be a distinct disadvantage for adopting a steel frame, compared to using other materials, due to the cost and time to apply the protection.

The natural fire tests on the eight-storey building at Cardington shows clearly that the stability of composite steel-framed floors with some unprotected steel beams can be fully maintained by the beam/slab interaction, despite the fact that the temperature of unprotected beams exceeds 1000º C. The analysis made after Cardington fire tests shows that this excellent fire behavior is due to both membrane and diaphragm effects of the reinforced composite slab together with steel beams once the steel beams attain temperatures at which they are no longer capable of supporting the applied load alone [1], [2], [3].

Fig. 1. Cardington test building and one of the fire tests

Based on observation and analysis of the experimental results, a new fire design concept was developed in UK concerning modern multi-storey steel-framed buildings using composite construction, i.e. the floors are constructed using composite slabs with profiled steel decking attached by shear connectors like headed studs to downstand beams [7]. This design concept allows designers to take advantage of whole building behavior and allows them to determine which members can remain unprotected while maintaining the same safety levels, as far as the expected overall stability from fully fire protected structures.

On the basis of above evolution in UK the project FRACOF was launched with the main objective to extend this design concept to other European national markets, especially under ISO fire condition with the purpose of getting the maximum benefit from this new design concept for the daily practice.

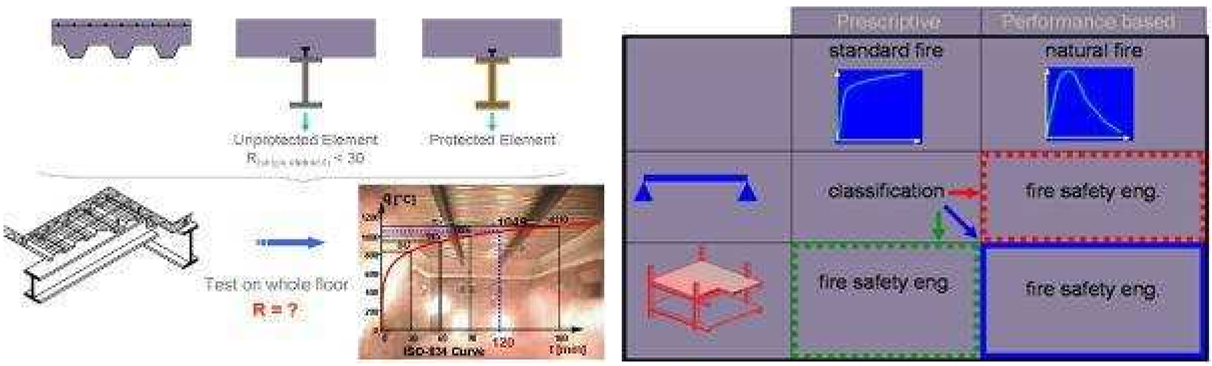

Fig. 2. Starting point of the Fracof concept

2 FRACOF: FULL SCALE TEST UNDER ISO FIRE CONDITION

2.1 Design of the fire test

The fire test was conceived with the objective to provide the evidence that a steel and concrete composite floor if some of its steel beams are not protected may ensure, with an adequate reinforcing steel mesh embedded in the concrete slab, a good fire performance even exposed to severe ISO fire. Considering the size of used fire furnace, it is decided to adopt a specific test specimen shown in figure 3 (detailed test description can be found in [8]).

Fig. 3: Layout of the specimen tested in the Fracof project

In fact, the specimen is with a composite floor supported by four short steel columns. The composite floor is composed of four secondary beams and two primary beams covered by a steel and concrete composite slab, all of which are linked together with help of headed studs, a very commonly used type of shear connectors for composite structures. In addition to this shear connection, all steel members are linked together with two common types of steel joints. It can be found that all structural members of a composite floor are present in this specimen leading therefore to a structure within real buildings. Also, in order to simulate the continuity condition of composite floor, the reinforcing steel mesh of two sides of the slab is welded to two additional steel beams which are in turn fixed to furnace structure. The global dimensions of the specimen can be summarized as follows:

- span of secondary beam: 8.735 m;
- span of primary beam: 6.66 m;
- span of composite slab: 2.22 m;
- total length of steel column: 2.5 m, with 0.8 m below composite slab.

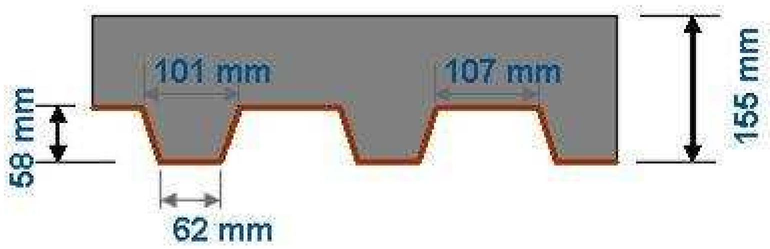

Fig. 4: Detail of the composite slab used in the test

The composite slab is with the profiled steel sheet COFRAPLUS60 (trapezoidal), a steel decking largely used on the French market. According to EN1994-1-2 [6], the total depth of the slab should be 155 mm (see figure 4 for more detail) for a fire resistance of 120 minutes. In compliance with the span of the slab (2.22 m), the thickness of the steel sheet is 0.75 mm. The concrete is predicted in normal weight concrete with a quality of C30/37. The cross sections as well as the headed studs of all steel beams are defined in accordance with the requirements of EN1994-1-1 for room temperature design of composite structures. As far as steel joints are concerned, they are designed according to the requirements of EN1993-1-8. Two common types of steel joints, that is flexible end plates and double angle web cleats using bolts of M20 in grade 8.8, are adopted for this steel frame.

In addition to the self weight of the structure, the floor construction was designed for a dead load of 1.20 kN/m^2 and an imposed load of 5.00 kN/m^2. With all above data, the design has led to following cross sections of steel beams:
• secondary beam: IPE300 with the steel grade of S235;
• primary beam: IPE400 with the steel grade of S355;
• column: HEB260 with the steel grade of S235.

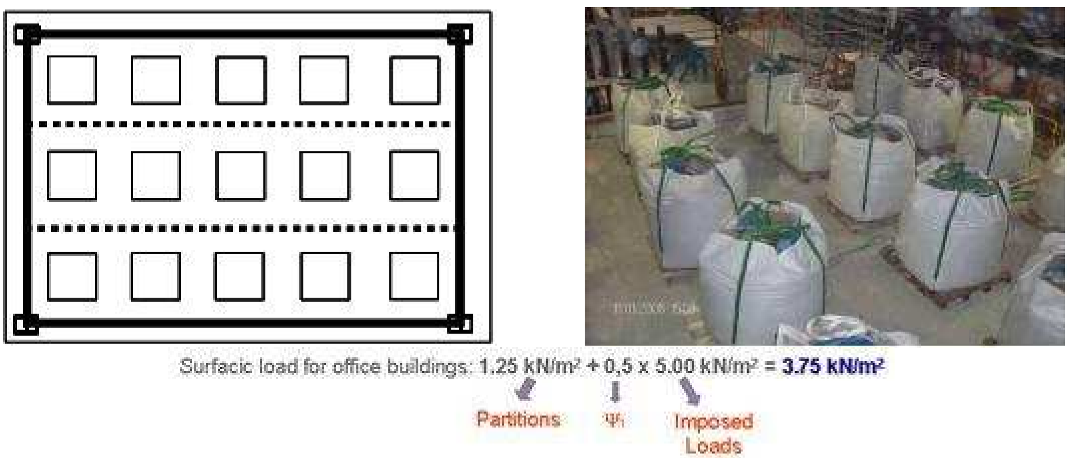

Fig. 5: Mechanical loading used for the Fracof test

2.2 Fire test condition

For fire test, three different aspects are of main importance in order to have a correct execution: 1) mechanical loading condition; 2) heating condition; 3) fire protection system.

The mechanical loading of the floor is applied with help of fifteen sand bags uniformly distributed over the floor (see figure 5). Each of sand bags weighs exactly 15.0 kN leading therefore to an equivalent uniform load of 3.87 kN/m². This value is higher than design load of 3.75 kN/m² derived from Eurocode load combination in fire situation for office buildings.

The floor, occupying an area of more than 60 m², was exposed, from below, to the ISO fire condition using a standard fire resistance testing furnace (see figure 6). In compliance with the fire design concept of such type of floor, the two secondary beams and the composite slab are unprotected. However, all the boundary beams of the floor (all beams in direct connection with columns) are fire protected to ensure a global structural stability for a fire rating of 120 minutes.

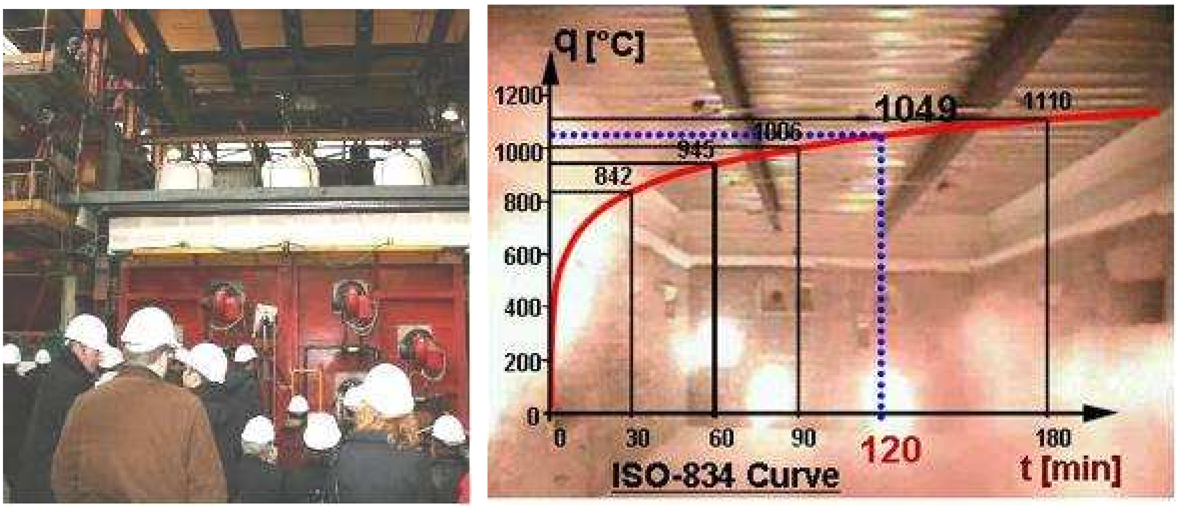

Fig. 6: Photos taking during the test and the ISO-834 fire curve used

2.3 Real material properties

The different material investigation performed before the fire test allows to know the real material properties of the specimen as follows:

- Secondary beams: mean value yield strength 311 MPa;
- Primary beams: mean value yield strength 423 MPa;
- Reinforcing steel mesh: mean value yield stress 594 MPa with 14.5% elongation at rupture;
- Concrete: mean value of cylinder compressive strength is 36.7 MPa.

It must be noted that the reinforcing steel mesh used was class A (B500A according EN10080) so no specific requirement concerning ductility of rebar steel was imposed.

2.4 Measurement of test results

A total of 194 measurements were used to record the specimen's behavior. The main measurements are 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 through the slab. 9 displacement transducers of which 7 vertical displacement transducers were installed to measure the deflection of the floor. The two remained transducers were used to measure the horizontal movement of the floor. Moreover, a special high temperature video camera was put inside the furnace which can record visually the floor deformations versus time.

3 EXPERIMENTAL OBSERVATIONS FROM THE FRACOF TEST

The test lasted for more than 120 minutes and the fire was stopped due to integrity failure of the floor. However, the recording of specimen's behavior continued until 900 minutes allowing also to know the performance of the floor during the cooling phase of the fire.

3.1 Thermal response

The furnace temperature was controlled during the test with plate thermal meters just below the floor and the recorded temperatures in different places of the furnace show that the ISO standard fire curve is closely followed. As far as the heating of steel beams is concerned, the unprotected steel beams were heated up to around 1040 °C. On the contrary, the protected steel beams were heated up to around 300 °C which is less than predicted due to reduced exposure of these members located at the edge parts of the furnace (see figure 7).

The heating of composite slab was also recorded during the test at different location through the slab thickness. The temperature recorded at the unexposed side of the composite slab after 120 minutes of fire is slightly higher than 100 °C, which is still less than 140 °C, the criterion of insulation performance.

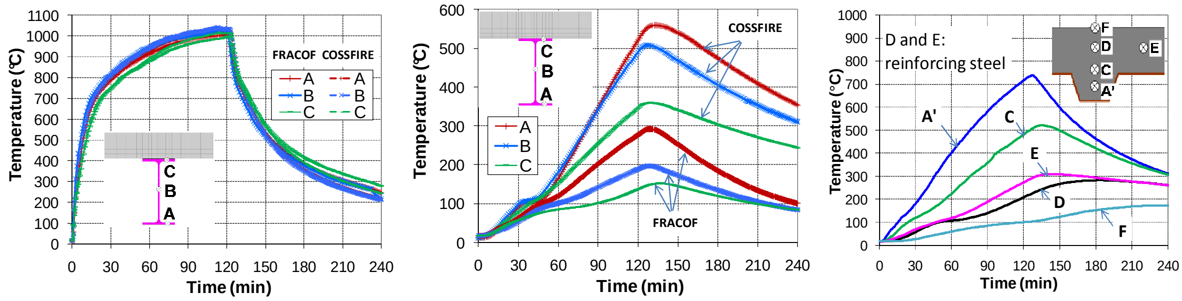

Fig. 7: Recorded temperature of unprotected beams (left), protected beams (center), and slab (right).

3.2 Mechanical response

The various displacement transducers installed on the floor permit to know in detail the displacement of the floor. The vertical displacements of the floor are shown in figure 8 over the whole period of recording. It can be observed that the maximum deflection rise of the floor after 120 minutes of fire is about 460 mm and those of the two unprotected secondary beams are approximately 420 mm so less than the twentieth of their span.

During the cooling phase of the fire, the deflection increased still slightly and reached the maximum value at about 135 minutes. At this moment, the furnace temperature has dropped from 1050 °C to only 600 °C (see figure 7). This phenomenon can be explained by the fact that the main component providing the necessary load bearing capacity of the floor, that is the reinforcing steel mesh in concrete slab is still heated up until 135 minutes (see figure 7). Regarding the displacement of edge beams, as they were very few heated, their deflection rise remains also low and does not exceed 100 mm. In addition, the deflection of edge secondary beams is much more increased than that of two primary beams, which complies fully with the load redistribution principle of the floor under membrane effect once subjected to fire.

From the deflection recording of the floor, one can understand easily that it fulfill its load-bearing capacity during the whole period of fire. Apparently after 120 minutes of ISO fire, the resistance capacity of the floor is still strong enough to bear the applied load.

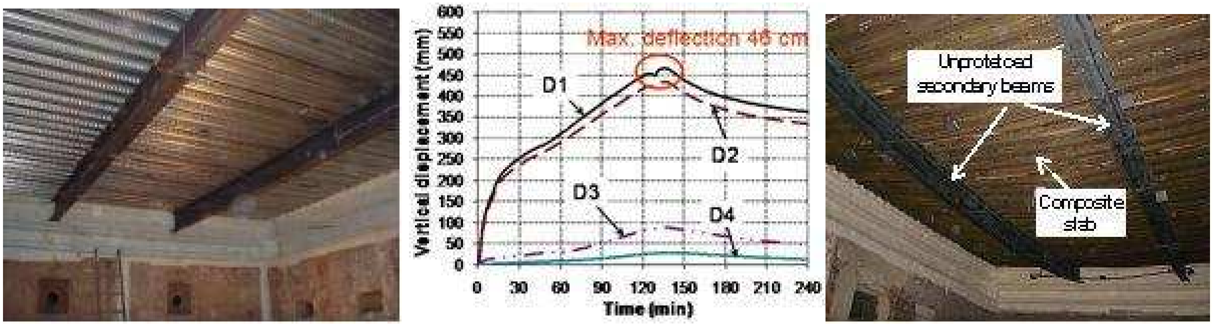

Fig. 8: Deformation of the steel-concrete composite floor during the fire test

3.3 Cracking of the concrete

Another important parameter to be mentioned here is the cracking of the composite floor which has a direct influence on fire performance of the floor. Therefore, the cracking of concrete was followed closely during the test and the main observed results are as follows:

• Small cracks occurred in the concrete, particularly around steel columns and continuous edges of the slab, at an early stage of the fire test;

• There was some enlargement of these cracks during the heating phase of the test, but this did not significantly influence the integrity performance of the floor;

• A more significant crack occurred after 105 minutes of fire exposure.

Such cracking has certainly an impact on integrity performance of the floor. Investigation of the crack after the test showed that the crack was caused by the failure of a welded joint between two steel reinforcing meshes. This type of failure can be fully avoided if appropriate construction details for lapping tension reinforcement are adopted in accordance with EN1992-1-1. Despite the occurrence of such an important crack and failure of steel reinforcing mesh in the longitudinal direction in the central part of the floor, its load bearing capacity was still adequate to achieve a fire resistance in excess of 120 minutes.

3.4 Numerical simulation

After the test numerical simulations were performed to calibrate numerical models. Without efforts it was possible to find an outstanding correspondence between experimental records and FE-results. A description of these numerical simulations can be found in [10], [12].

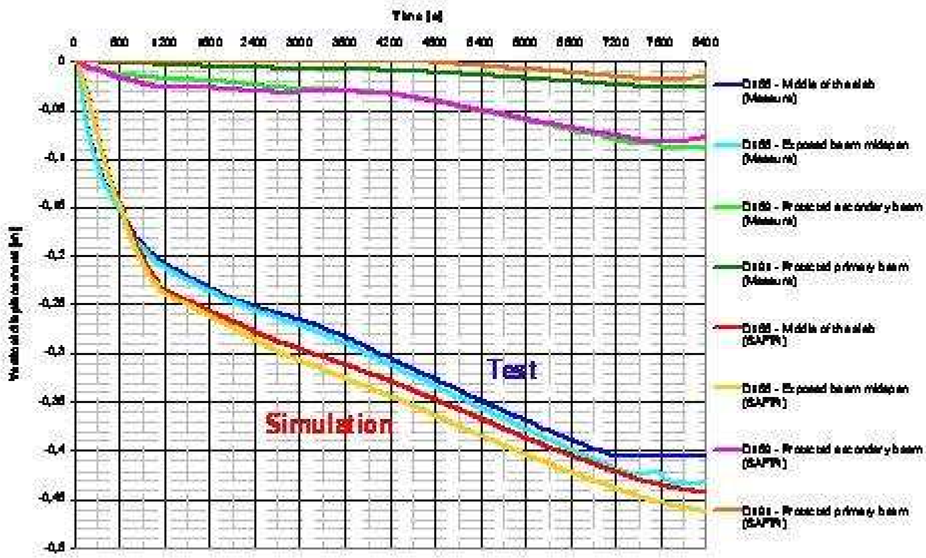

Fig. 9: Comparison between experimental and numerical results concerning displacement – Fracof test

4 OTHER RECENT EXPERIMENTAL TESTS

4.1 Maizieres-les-Metz test (France)

One year after the Fracof test another full scale test was made in the furnace of Maizieres-les-Metz (16/01/2009) in the scope of the European research project COSSFIRE. The specimen and the test conditions were similar to the FRACOF test, with the considerable difference that in this case the connections were left unprotected and the slab was even more optimized for the cold condition. Also in this test a fire rating of 120 minutes under ISO fire could be achieved without structural collapse. For more information see [14].

Fig. 10: Some pictures of the Cossfire test (16/01/2009)

4.2 Dachau tests (Germany)

In the scope of national AIF project "*Nutzung der Membranwirkung von Verbundträger-Decken-Systemen im Brandfall*", a small building (about 12.5 x 5.0 m) was build and two tests (07/07/2010 and 03/09/2010) on partially protected steel-concrete composite systems exposed to natural fire were executed. Though temperature exceeding 1000°C no collapse was registered.

Fig. 11: Some pictures of the Dachau tests (07/07/2010)

4.3 Belfast test (United Kingdom)

In the scope of the European Research Project FICEB+, a full scale fire test was performed (27/02/2010) on a composite floor for analyzing the possibility of tensile membrane action to develop when the steel beams of the floor are made of cellular beams. A huge floor of 15.0 x 9.0 m was exposed to natural fire created by a wood crib fire load of 700 MJ/m². The structure survived the fire that peaked at 1000°C and lasted for 90 minutes (see [11], [13]).

Fig. 12: Some pictures of the Belfast tests (27/02/2010)

5 CONCLUSIONS

The FRACOF concept aims at determining the fire performance of partially protected steel-concrete composite floors utilizing the membrane action. This method has proven its adequateness in several tests under nominal as well as natural fires in various European countries. Its field of application has been enlarged thanks to an extensive campaign of FE-simulations with numerical models which were calibrated on experimental evidences.

Nowadays important dissemination activities are taking place to make designers aware of these recent developments in the field of fire engineering [9], [10]. To mention the dissemination project FRACOF+ funded through the *"Leonardo da Vinci - Transfer of Innovation"* programme, during which 6 seminars were organized in 2010/2011 (www.fire.fsv.cvut.cz/fracof/), and the new MACS+ valorization project funded through RFCS, in which 18 seminars are foreseen in countries around Europe in the forthcoming years (www.macs_web.eu). To further support this scientific dissemination, ArcelorMittal in collaboration with CTICM and SCI provides the designers an user-friendly tool in which the FRACOF concept has been implemented for classical building layouts. This software can be downloaded free of charge on the web-site (www.arcelormittal.com/sections).

The authors consider that the FRACOF concept can be a significant step to further increase the competitiveness of steel-concrete composite floors in buildings, optimizing the design in fire condition even under nominal fire actions. This will allow to spread the benefits of steel construction to a wider range of multi-storey buildings.

Fig. 12: Example of use of FRACOF concept for fire design: Centre Acier Flémalle at Liege (BE)

REFERENCES

[1] "The behaviour of multi-storey steel framed buildings in fire", A European joint Research Programme, British Steel Swinden Research Centre, 1999.

[2] Bailey, C. G. and Moore, D. B. "The structural behaviour of steel frames with composite floor slabs subject to fire, Part 1: Theory" The Structural Engineer, June 2000.

[3] Bailey, C. G. and Moore, D. B. "The structural behaviour of steel frames with composite floor slabs subject to fire, Part 2: Design" The Structural Engineer, June 2000.

[4] EN 1991-1-2:2002 "Eurocode 1: Actions on structures – Part 1 2: General actions. Actions on structures exposed to fire" CEN.

[5] EN 1993-1-2:2005 "Eurocode 3. Design of steel structures. General rules. Structural fire design" CEN.

[6] EN 1994-1-2:2005 "Eurocode 4. Design of composite steel and concrete structures. Structural fire design" CEN.

[7] Newman, G.M., Robinson, J.T. and Bailey C.G., "Fire Safe Design: a New Approach to Multi-Storey Steel-Framed Buildings" (second edition), SCI Publication P288, 2006.

[8] Zhao, B.; Roosefid, M.; Vassart, O.; Full scale test of a steel and concrete composite floor exposed to ISO fire, Fifth International workshop Structures in Fire2008.

[9] Vassart, O. and Zhao, B. "Fire Resistance Assessment of Partially Protected Composite Floors (FRACOF) Design guide", Leonardo Da Vinci European Program, 2009.

[10] Vassart, O. and Zhao, B. "Fire Resistance Assessment of Partially Protected Composite Floors (FRACOF) Engineering Background", Leonardo Da Vinci European Program, 2009.

[11] Vassart, O., Bailey, C. G., Hawes, M., Nadjai A., Simms W. I. Zhao, B., Gernay T., Franssen, J.-M.: "Large-scale fire test of unprotected cellular beam acting in membrane action", Sixth International workshop Structures in Fire2010.

[12] R. Zanon, L-G. Cajot, M. May, H. Girkes; "Robuste Stahlbauten im Brandfall", Der Stahlbau, August 2010.

[13] Final report of European research project: "RFS2-CT-2007-00042: FICEB+: Fire Resistance of long span cellular beams made of hot rolled sections" (under publication).

[14] Final report of European research project: "RFSR-CT-2006-00028 : COSSFIRE - Connections of steel and composite structures under natural fire conditions" (under publication).

KEYWORDS

Fire Design, Membrane Action, Unprotected Steel Beams, Composite Floor Slabs, Cellular Beams.