EFFECT OF FIRE ON FRP REINFORCED CONCRETE STRUCTURES

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Summary

New type of composite CGFRP (Carbon-Glass Fibre Reinforced Polymers) reinforcement has been developed in recent years at Brno University of Technology, which is fit for standard reinforcing, strengthening and pre-stressing of concrete structures. Advantages of FRP reinforcement are namely resistibility against aggressive environment and possibility to use smaller cover of reinforcement. However high demands on durability and resistibility against outer influences are required in modern construction and therefore next part of the research is concentrated on resistibility of structures reinforced by CGFRP reinforcement under effects of fire.

The paper deals with experiments specially aimed on behaviour of pre-stressed and non pre-stressed panels subjected to fire effects. The behaviour of test panels during the fire was compared using different thickness of test structures together with the influence of the pre-stressing. These tests were completed with the tensile strength test under fire conditions of the reinforcement bars alone.

The results demonstrate that in case of good anchoring of CGFRP reinforcement it is possible to use this reinforcement for load transfer even after significant damage (even burn-out of epoxy matrix) done by fire.

Mathematical models was created to verify the behaviour of experimentally tested panels and to provide basic data for following detailed mathematical models. These models enable to predict the behaviour of other FRP reinforced structures under effect of fire.

Keywords: FRP, fire safety, pre-stressed concrete, effects of fire

1 Introduction

There are many advantages in using FRP materials as reinforcement. Probably the most important is the ratio between tensile strength and self-weight and their corrosion resistance compared to standard steel reinforcement. On the other hand its usage is often restrained by its higher costs and lower modulus of elasticity again in comparison with steel reinforcement. Also, there is relatively little knowledge about the behaviour of FRP reinforced structures considering long-term load effects and/or extreme situations, such as exposure to fire. With the fast degradation of material properties in mind, it is obvious that a special attention has to be paid when designing the structures that could be exposed to

such conditions. Research of the influences of higher temperatures and fire effects is one of the particular aims of the research projects currently on-going at Brno University of Technology.

General knowledge indicates the fibres in FRP materials have better resistance to high temperature than the binding matrix (in most cases epoxy resin) [1]. The mechanical properties of the fibres are relatively stable up to 1000°C temperature. On the contrary polymer matrix is flammable and very sensitive to higher temperatures. Mentioned deterioration of mechanical properties of the matrix causes a loss of interaction between individual fibres and therefore the loss of bond between FRP reinforcement and the surrounding material.

The overall behaviour of the FRP reinforcement starts to change in temperatures around 60 °C and 150 °C. In this temperature range the matrix softens and the internal friction between fibres decreases causing degradation of the whole system. At temperatures between 150 °C and 200 °C (so called the glass transformation temperature) there is a sharp deterioration of both strength and stiffness of the FRP material caused by behaviour of the matrix. At temperatures of 400 °C and higher the matrixes are very susceptible to inflammation as well as in direct contact with the flame.

2 Concrete Panels Reinforced with CGFRP Reinforcement

The verification of panels' behaviour was divided into two stages. In the first stage a static loading tests was performed without the influence of temperature loading. These tests served as initial verification of the bearing capacity of the specimens. The whole set of experiments was arranged so that the influence of different thickness of panels (150 mm and 200 mm) together with pre-stressing could be observed.

The test specimens were prepared in layout dimensions of 3600×500 mm (Fig. 1). The specimens were reinforced with the CGFRP composite reinforcement [2] – FRP reinforcement wit Carbon core and Glass fibres around the core. Each panel was reinforced with three CGFRP bars with diameter of 14 mm; the pre-stressing force was 35 kN in each reinforcement bar in case of pre-stressed test panels. Concrete cover was 25 mm. This type of reinforcement was already used in real structure of pedestrian bridge [3].

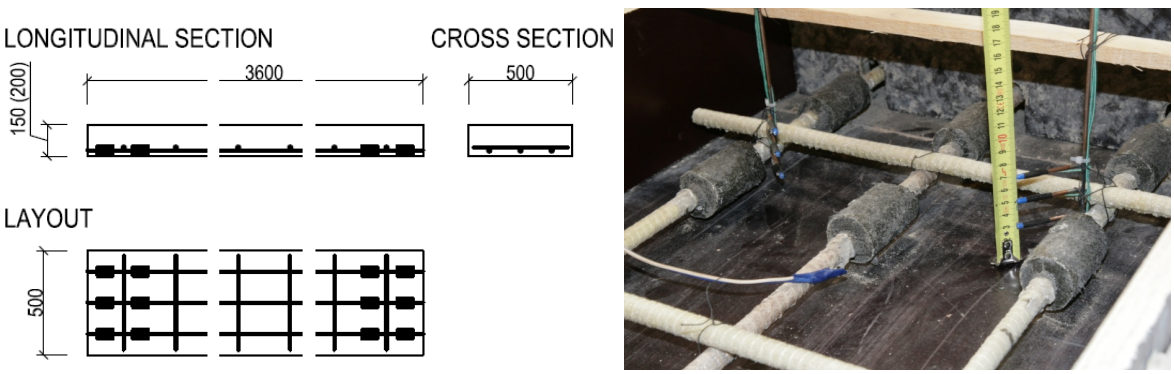


Fig. 1 *Scheme of test specimens (reinforcement placing is identical for pre-stressed and non pre-stressed variant); detail of built-in thermal sensors*

The specimens designed for fire experiments were equipped with built-in thermal sensors along the height of the cross section. In this way it was possible to measure the thermal

field and observe the actual temperature distribution in the material (the right-hand side of the Fig. 1).

The value of the loading force during the fire tests was determined according to the results (Fig. 2) of previous static tests. It was fixed on the value of 20 kN. This load level corresponds roughly with a serviceability limit state of the non-pre-stressed panel with the thickness of 200 mm. It is possible that such load value could be acting on the real structure during the initiation of the fire load. Other panels were loaded with the same force to allow the comparison of the influences of thickness and pre-stressing of structure.

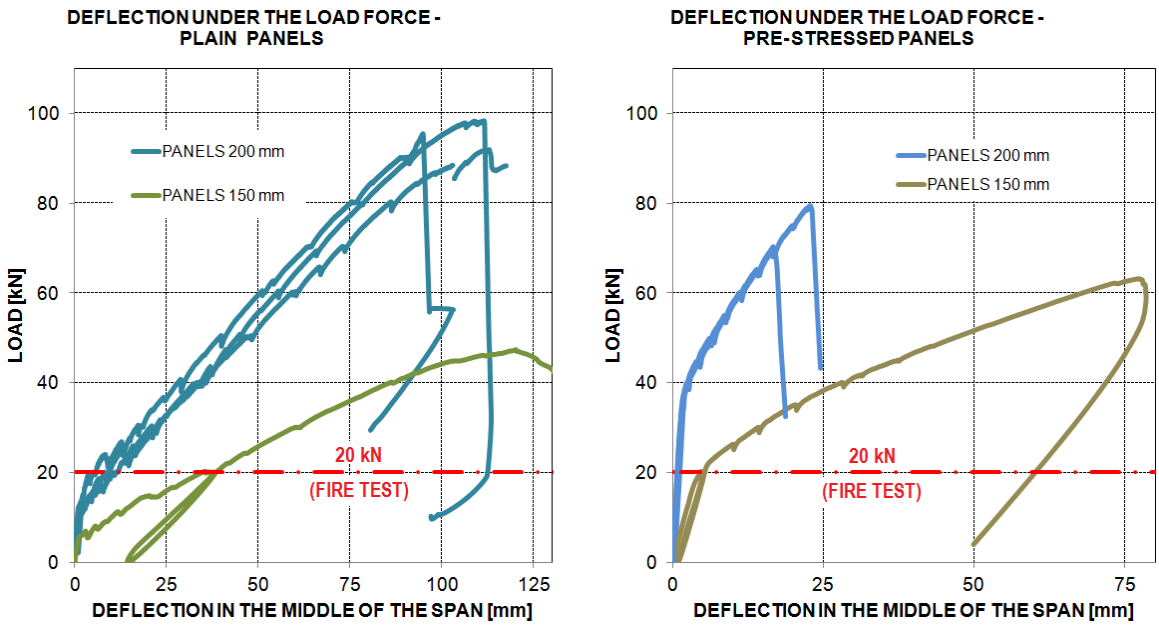


Fig. 2 *Results of the static loading without the influence of high temperature*

3 Fire Experiments

3.1 Arrangement of the experiment

All experiments were not performed sooner than four months after the production (concrete casting) of the specimens. This time laps was supposed to ensure sufficient dry out of the material so to minimize the risk of concrete cover spalling and thus premature exposure of reinforcement bars to the flame (direct contact between the flame and FRP material dramatically increases the danger of inflammation of the epoxy matrix). Direct access of the flame to the bars was expected later during the test due to the opening of cracks in wake of the increase of deflection of the panels. To improve the drying of the material the panels were also warmed using air heaters.

The fire experiment as such was designed in order to allow simultaneous testing of loaded concrete panels and loaded discrete reinforcement bars. This requirement affected the final layout of the fire test furnace (Fig. 3). The concrete panels were loaded with the force of 20 kN located in the middle of their span. Also un-loaded reference specimens were observed during the test. Measured variables were temperatures (in the furnace i.e. actual temperature load, on the surface of the specimens and inside the panels), the tensile

stress in the reinforcement bars, compressive stress in the concrete and deflection of the panels.

The tensile strength test was performed on a similar way – reinforcement bars were loaded by a tensile force of 50 kN during the fire test. This tensile force represents roughly 50% of tensile strength under normal conditions, while the approximate tensile stress in the pre-stressed bars reinforcing the loaded test panels. The only difference in comparison with test panels was added protection of the bars provided by plasterboard. This protection prevented the direct contact between the bars and flame and provided certain inhibition of the temperature increase in comparison with fire curve. It was meant as a partial simulation of the concrete cover in case of reinforcement bars embedded in real structures.

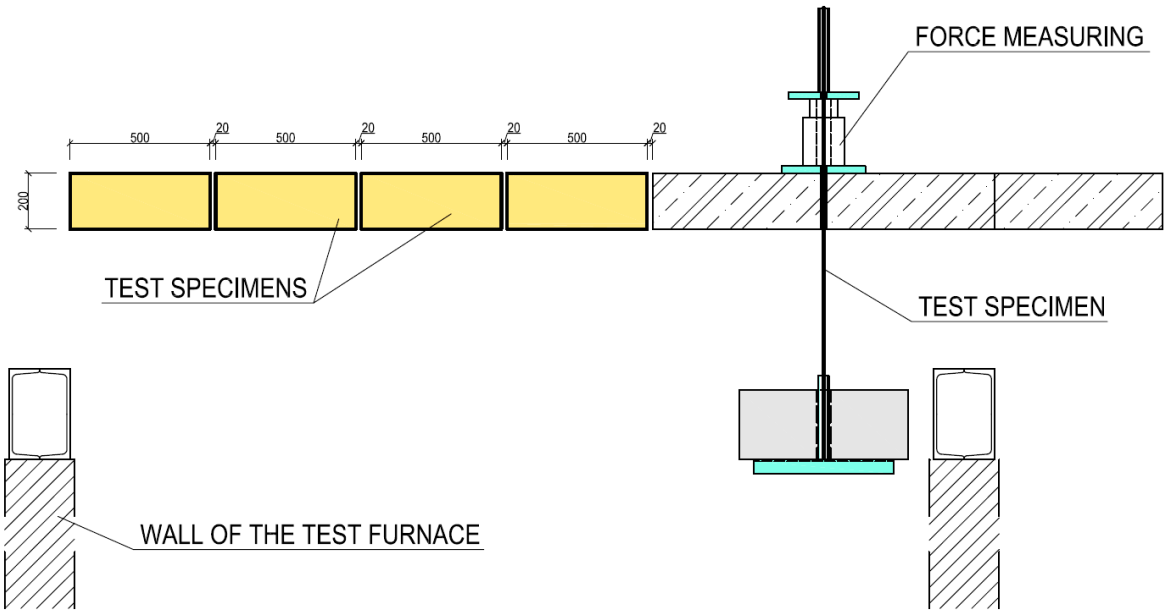


Fig. 3 *Scheme of the arrangement of the fire experiment*

3.2 Tensile strength of FRP reinforcement exposed to high temperature

The tensile strength test results show the anticipated [1] outcomes. In all observed cases the flame penetrated to the reinforcement bars eventually (as was planned), which caused total burn-out of the epoxy matrix of the reinforcement's cross-section. The remaining fibres were anchored in the gripping devices on both ends of the test specimens and were protected against high temperature. During the continuing increase in heat and flame their tensile strength decreased slowly and eventually this deterioration was followed by the sudden rupture of loose fibres (Fig. 4).

Looking at the results (Tab. 1) it is clear that reinforcement based on glass-fibres has better resistance to high temperatures than the reinforcement based on carbon-fibres. In the current research the works are in progress in modification of material composition to achieve a longer working life under fire, or more precisely to increase the critical temperature during which the collapse of material occurs (CGFRP).

a) *b)*

Fig. 4 *Burnt FRP reinforcement after the experiment – a) CFRP bar; b) GFRP bar (both loaded with the same tensile stress corresponding to approximately 50 % of their initial strength)*

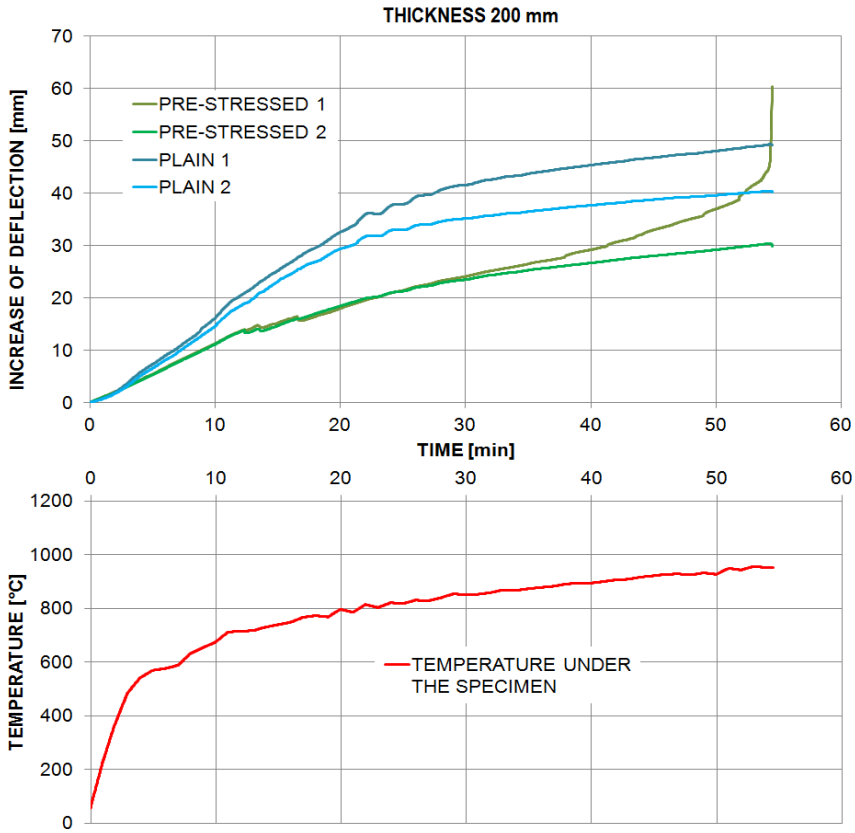
Tab. 1 *Summary of fire resistibility of FRP reinforcement*

Material type	Loading [% of initial strength]	Total elongation [mm]	Max. temperature [°C]
GFRP (ø14 mm)	50	40	370
CFRP (ø6 mm)		33	160

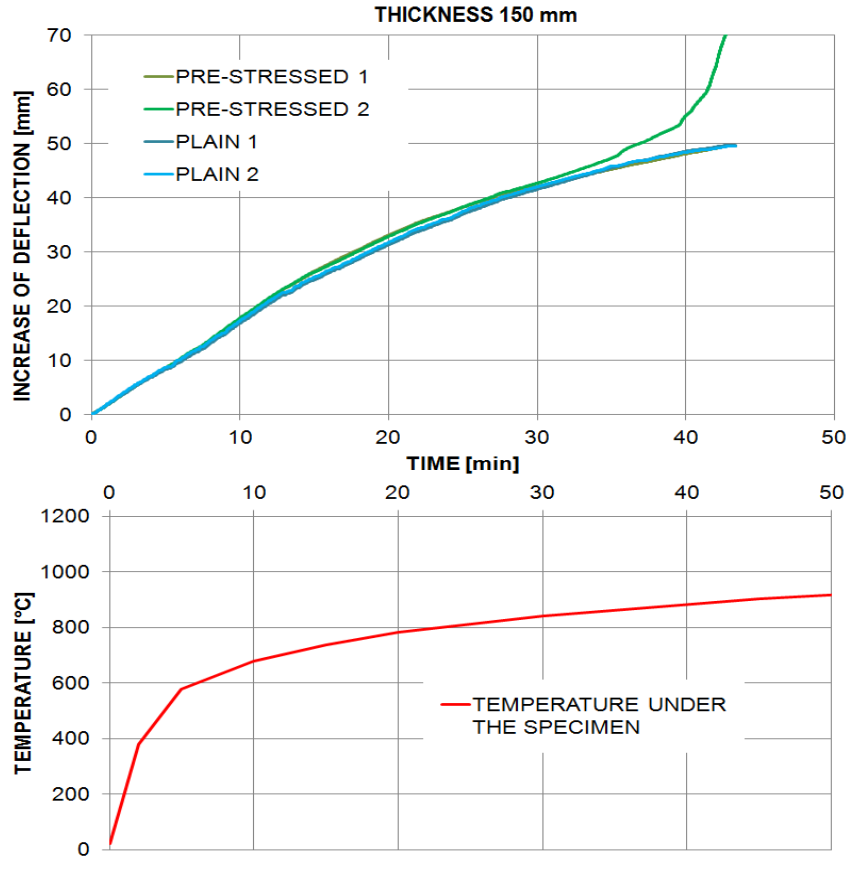
3.3 Fire experiments on the concrete ceiling panels

The fire resistant of the panels was estimated at 30 minutes while applying of standardised fire curve. End of the test was defined as failure of at least one of the test specimens (i.e. the grade of fire resistance R30). This time laps were estimated on the test results of used composite reinforcement (stated in Table 1).

In the end of the estimated life time under fire was exceeded by both panel types. Panels with thickness of 200 mm failed after 54 minutes of fire exposure (first failure was pre-stressed panel); panels with thickness of 150 mm collapsed after 44 minutes (again first failure was pre-stressed panel). Increment of deformation from the effect of fire is shown in Fig. 5 (separately for thickness 150 and 200 mm).



a)



b)

Fig. 5 *Increase of the deflection in the dependence on the temperature (constant load applied on the specimens); a) thickness 200 mm, b) thickness 150 mm*

4 Mathematical model of thermal transmittance in concrete

At present mathematical models are focused especially on the verification of thermal transmittance behaviour in concrete under fire load. These results will subsequently be used not only for a model of concrete panels reinforced by FRP, but also for another type of concrete construction subjected to fire effects in ATENA software.

The thermal transmittance speed in the concrete cross-section is of particular importance in the correct adjustment of the parameters of concrete under fire conditions. Thermal transmittance is especially dependent on moisture, the thermal conductivity factor, specific heat capacity and boundary conductance, which are also the basic parameters for mathematic model. For the purpose of measuring of thermal transmittance, thermocouples were embedded at exactly defined positions (Fig. 1) at depths of 30, 50 and 70 mm into the 150 mm–thick test panels during their manufacture. The results of the measurements were afterwards compared with the mathematical model in ATENA (Fig. 6).

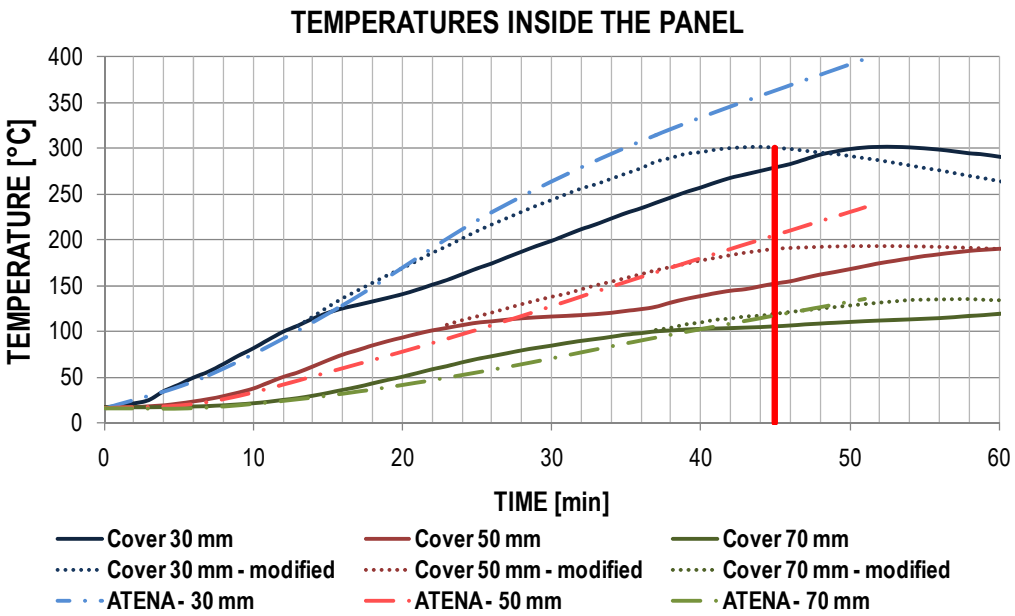


Fig. 6 *Comparison of thermal transmittance in concrete under fire conditions – experiment – ATENA (the end of the fire test was in the 45th minute)*
- experiment results (thermocouples) – continuous line,
- modified experiment results – dotted line,
- mathematical model in ATENA software – dash-dot line.

In contrast to the theoretical presumptions and the thermal transmittance results from the mathematical model in ATENA software, the thermocouple data from the experiment shows a delay in the temperature rise in the cross-section from approximately 100~150 °C (Fig. 6). This delay is incurred by significant changes in the material structure of concrete when a concrete element is exposed to the effects of fire. Changes occur not only in the chemical composition of the concrete, but also in its mechanical, deformation and material characteristics [4].

To determine the extent of these changes, it is important to understand the processes taking place at the high temperatures present inside the concrete element. It thus not only concerns time-dependent thermal conduction along the cross-section. Another important process for theoretical calculations is the transportation of water (or sometimes water

vapour), which is one of the basic components of concrete [5]. In this way, the conjugate problem of thermal and moisture conduction through porous material accompanied by chemical changes in this material is also solved. These transport processes are derived from the basic physical laws of the conservation of energy and matter, where heat represents the energetic component and water the matter component. The water quantity contained in the concrete element can be divided into two types: free water and bound water. Free water occurs in the structure of the concrete, either as water or as capillary water sealed in pores. Bound water is part of the solid phase of concrete until the dehydration of the concrete occurs. The temperature at which dehydration begins can vary in a range from 80 °C to 120 °C. During dehydration the quantity of free water in pores increases. The other water present in concrete is then water vapour, which originates during the vaporization of free water. The accurate determination of the quantity of water present during particular water phases thus has a significant influence on the calculation.

The equation for thermal conduction also includes several components as in the case of the equation for moisture conduction. The basic component is heat, which is used up during the warming of the solid phase of concrete, including chemically bound water. Another significant component of the equation is the warmth used up during sorptive processes involving free water. This covers latent heat and adsorption heat. Latent heat is heat necessary for the transformation of water from the liquid phase to the gaseous phase. Adsorption heat is then heat which is necessary for the adsorption of water on the surfaces of capillaries. The third component of the heat conduction equation can be considered to be heat transported by a flowing liquid.

The significance of the above-mentioned theoretical hypothesis is that the release of free and bound water from concrete under fire conditions causes a deceleration in thermal transmittance speed in concrete. Most software for the analysis of fire effects does not include this presumption, of course. The experiment results from the measurement of thermocouples were therefore modified so as to be able to compare them with the mathematical model (Fig. 6). The next part of the research work will deal with the formation of theoretical relations for the description of the behaviour of concrete elements reinforced by FRP reinforcement under fire conditions and the modification of the mathematical model to take account of the releasing of free and bound water.

5 Conclusions

Around the 15th minute of the fire test all pre-stressed panels suffered from spalling of concrete cover, which confirms generally known influence of compression on spalling. Almost the whole bottom surface exposed to fire was damaged by spalling to a depth of ca. 30 mm. It caused the revealing of reinforcement bars to the flames. The epoxy matrix burnt out released the fibres from the previously solid cross-section in the same way it was observed during the tensile strength tests. The fibres remained embedded in the ends of panels where they were supported above the furnace and partially protected against fire. Thanks to such situation the loosed fibres started acting as external cable that still contributed to the total bearing capacity of the panels. The complete failure of the specimens occurred after the rupture of the fibres. Assuming that there was no spalling and subsequent exposure of the bars into the flame longer life time of the specimens can be estimated (grade of fire resistance R60 for the panels with a thickness of 200 mm of concrete cover only 25 mm).

Acknowledgement

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