HBRC Journal (2012) 8, 36–46

Housing and Building National Research Center

HBRC Journal

http://ees.elsevier.com/hbrcj

Punching shear strength of reinforced concrete flat slabs subjected to fire on their tension sides

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Received 12 September 2011; accepted 30 October 2011

KEYWORDS
Punching;
Fire effect;
Flat slabs;
Sudden cooling;
Gradual cooling

Abstract The effect of fire on punching strength of flat slabs is experimentally investigated. An experimental program, consisting of fourteen one-third scale specimens pre-exposed to fire on their tension side and tested under concentric punching, is carried out. The main investigated parameters are the duration of exposure to fire, the concrete cover and the cooling method. Specimens are subjected to direct flame for 1.0, 2.0 and 3.0 h, respectively. Concrete covers of 25 mm and 10 mm are used for test specimens. Two cooling methods are employed; gradual cooling in air and sudden cooling with water applied directly to the heated surface of the slabs. It was found that exposure of slabs to fire resulted in a reduction of up to 18.3% and 43% in cracking loads and ultimate punching loads, respectively. Concrete cover was proven to have a significant effect on level of temperature in tension reinforcement. A reduction in punching strength of up to 14% was observed for specimens with 3 h exposure to fire compared to those with one hour exposure. Sudden cooling was found to reduce punching strength by 25% compared to specimens gradually cooled. A simplified mechanical model for calculating fire effect on punching capacity is proposed and found to be in good agreement with the experimental results.

Introduction

Punching shear strength in reinforced concrete slabs subjected to concentrated loads has received a lot of emphasis due to its importance in flat slab floor systems [1,2]. Due to its brittle nature, shear failure at slab-column connection may have disastrous consequences. It may result in progressive failures of adjacent connections of the same floor as the load is transferred to the surrounding columns causing the adjacent connections to be heavily loaded. Also, the lower floors may fail progressively as they become unable to support the impact of slabs dropping from above. A sample for such progressive collapse is shown in Fig. 1 for the Tropicana Casino parking garage in Atlantic City, N.J., October 2003 [3].

Punching failure may take place due to unconservative design of slab-column connections, slab overloading, and deterioration of strength of concrete and reinforcement. Being

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Peer review under responsibility of Housing and Building National Research Center

Production and hosting by Elsevier

1687-4048
http://dx.doi.org/10.1016/j.hbrcj.2011.10.001

Fig. 1 Progressive collapse of Tropicana Casino parking garage due to punching of flat slab [3].

exposed to fires represents one of the most sever causes of strength deterioration of reinforced concrete [4–7]. At high temperatures, both concrete and steel undergo considerable reduction in their strength, physical properties and stiffness. Some of these changes are not recoverable after subsequent cooling. It is therefore expected that punching capacities of flat slabs subjected to fire are significantly affected. The authors believe that the effect would be the highest when fire affects the tension side of the slab rather than the compression one, due to the formation of cracks and possible reduction of strength of main reinforcement. Up to the authors' knowledge, no experimental works have been carried out to study the effect of fire acting on the tension side of flat slabs. In this study, an experimental program consisting of fourteen concentric slab-column specimens was carried out where specimens were tested under concentric punching loads. Twelve specimens have been subjected to fire while two have not and are considered as control specimens. Study parameters were concrete cover, fire duration and cooling method.

Research objectives

The objective of the current research is to experimentally investigate the effect of elevated temperatures on punching strength of flat slabs. Main parameters of investigation are concrete cover, fire duration and cooling method.

Effect of high temperature on reinforced concrete

Effect of high temperature on concrete

There are a number of physical and chemical changes which occur in concrete subjected to heat [4–7]. Most of these changes are irreversible upon cooling and may significantly weaken the concrete structure after a fire. Concrete is a composite material consisting of aggregates and matrix as its basic components. The effect of heating on both of these components individually as well as their interactions affects the behavior of concrete at high temperature [4–7]. With the rise in temperature, the aggregates experience volume changes. For example quartz-based aggregates increase in volume, due

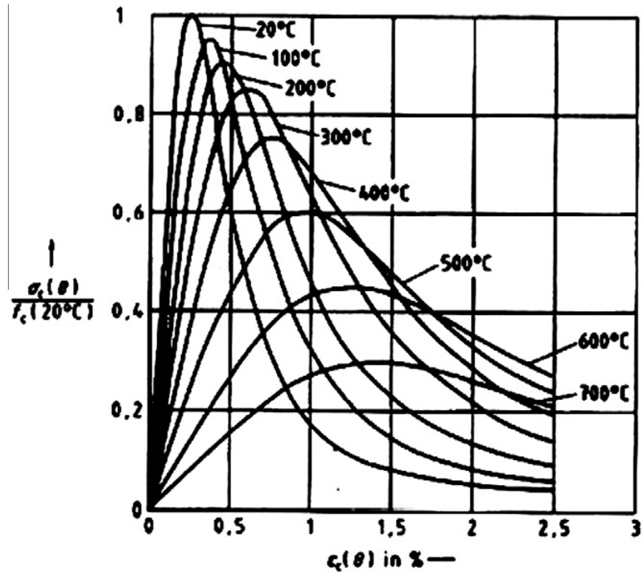

Fig. 2 Concrete stress–strain relationship at high temperature [9].

to a mineral transformation, whilst limestone aggregates will decompose. The expansion of the matrix, on the other hand, is completely negated by shrinkage due the evaporation of water. The resultant differential expansion causes internal cracking and reduces concrete strength and stiffness.

Concrete contains a certain amount of liquid water in its pores. This begins to vaporize if the temperature exceeds 100 °C, usually causing a build-up of pressure within the concrete. In practice, the boiling temperature range tends to extend from 100 to about 140 °C due to the pressure effects. Beyond the moisture plateau, when the temperature reaches about 400 °C, the calcium hydroxide in the cement will begin to dehydrate, generating more water vapor and also bringing about a significant reduction in the physical strength of the material.

Thermal gradient between inner and outer layers of concrete is also a cause of internal cracks in concrete especially for rapid heating. Kristensen and Hansen [8] showed theoretically and demonstrated experimentally that rapid heating of specimens of cement paste and concrete causes internal cracks due to stresses that develop when temperature differences between core and surface of specimens exceed 30 °C for cement paste and 50 °C for concrete.

After a fire, changes in the structural properties of concrete do not reverse themselves. This is due to the irreversible transformations in the physical and chemical properties of the cement itself. The behavior of concrete subjected to fire is well characterized by the compression model given by Euro code, EC2 [9] as shown in Fig. 2.

Effect of high temperature on steel

Similar to concrete, steel loses its strength with high temperatures [9]. Fig. 3 shows the stress–strain relations of reinforcing bars under different fire temperatures as given by Euro Code [9], where identical material behavior is assumed for both tension and compression. If reinforcing bars are heated up to 600 °C, they virtually recover their full normal temperature strength when cooled to room temperature again [10]. If, how-