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Experimental study on the fire behaviour of reinforced concrete slabs under combined uni-axial in-plane and out-of-plane loads

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ABSTRACT

In this paper four large scale fire tests on the reinforced concrete slabs, under combined uni-axial in-plane and out-of-plane loading conditions with vertical restraint at four corners of the slabs, are presented. The research focuses on the quantitative relationship between horizontal restrained force and deformations, cracking patterns and spalling of the slabs in fire. Also the vertical restraint forces at the four corners of the slabs were measured in the tests. Comparisons of the results indicate that the compressive uni-axial in-plane loads have a considerable effect on the number and directions of cracks on the top of the concrete slabs in fire. The uni-axial in-plane restrained slabs have larger mid-span deflections and lower deflection recovery ratios than the slabs without in-plane loading. In addition, the test results indicate that increasing reinforcement ratio can effectively prevent the integrity failure of the restrained slabs. The research generates valuable test data which can be used to validate the numerical models developed by fellow researchers in the field of structural fire engineering.

1. Introduction

Previous researches indicate that reinforced concrete floor slabs play a key role in enhancing the fire resistance of composite steel-framed building. In recent years, a number of experimental studies for investigating the fire behaviour of reinforced concrete slabs have been conducted [1–6]. It is acknowledged that the behaviour of reinforced concrete slabs in fire is affected by the slabs' support conditions [6–8].

During the 1960s, the effects of restraint on the fire exposed concrete floor systems were studied at the Portland Cement Association (PCA) [9,10]. These studies reported that axial restraint of concrete slab increases the fire resistance of floor slabs. However, the tests were carried out mainly for a few types of floor systems, such as precast double tee slabs. In 1982, the analytical studies conducted by Anderberg and Forsen [11] indicated that the fire resistance of flat slabs does not always increase with increasing axial restraint. In 1989, Lin et al. [12] conducted one fire test on a restrained concrete slab with epoxy-coated bars according to the guidelines of ASTM E119. The restraining frames were used to apply in-plane axial forces on the slab during the fire test. It was observed that the applied restraining forces on the test slab resulted in larger deflection. In 1993, Cooke [13] conducted a series of fire tests on restrained concrete flat slabs. The test results show that compressive axial restraint is not always beneficial to the fire resistance of the slabs and the behaviour of the slabs strongly depends on the position of the restraint force applied at the supports. For instance, when the line of thrust at the supports is located at the position closest to the exposed face of the slab, the fire resistance of the slabs is significantly better than the slabs with their line of thrust located at mid-depth of the slab's thickness. The test results also shows that when an axial restraint load applied at mid-depth of the slab at the end supports the fire resistance of the slab is significant reduced compared to the slab without axial restraint. It is clear that there are some obvious controversies on the effect of the restraint on the fire behaviour of concrete slabs from previous fire tests.

In 2002, Lim et al. [3] conducted the fire tests on three reinforced concrete slabs. The slabs with the dimensions of 3.3 m by 4.3 m were simply supported on all four edges above the furnace. During the tests, the corners of one concrete flat slab were clamped. The test results show that the corner restraint has an important effect on the deformation of concrete slabs. In recent years, a series of small scale reinforced concrete slabs were tested at both ambient and elevated temperatures to investigate the influence of tensile membrane action on the structural behaviour of concrete slabs

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[2,14,15]. However, all slabs were tested under simply supported conditions. In 2009, Wang et al. [16,17] conducted two fire tests on the reinforced concrete slabs in which one slab was simply supported on four edges and another one was fixed on four edges. The experiments indicated that the failure pattern of the slab with four-edge simply supported is significantly different with the four-edge fixed slab. In 2012, Zhu et al. [18] conducted six full-scale fire tests on the two-way reinforced concrete slabs with different support conditions. The test results indicate that the boundary conditions have a considerable effect on the fire behaviour of the slabs, particularly the cracking patterns on the top surface of the slabs.

Previous researches [4,5,7,19–22] have confirmed that the deformations and cracking patterns of the floor slabs within the fire compartments are highly dependent on the locations of the fire compartments within the buildings. The restraints provided by the surrounding structures play a key role in influencing the fire behaviour of the floor slabs. From the literature review presented above it is clear that the majority of the fire tests on reinforced concrete slabs were subjected to simply supported conditions. Hence, further experimental research on the reinforced concrete slabs under fire conditions with well controlled axial restraint forces is needed.

In addition, a review of literature shows that several theoretical models were developed for predicting the ultimate bearing capacity or limit deflections of concrete slabs in fire. Bailey et al. [1,2] developed a theoretical method to determine the capacity of lightly reinforced concrete slabs with large displacements at elevated temperatures. Cameron and Usmani [23] proposed an energy method to calculate the membrane load capacity of a slab based on the failure criterion of steel strain. In addition, based on the fundamental structural mechanics (thermal strain and mechanical strain), Usmani et al. [24] conducted the theoretical analysis of the response of single structural members under a combination of thermal actions and boundary restraints (rotationally and laterally). Li et al. [25] presented a new model for analysing the behaviour of floor slabs involving membrane action. In this model, a slab at the limit state was divided into five parts, including four rigid plates and an elliptic paraboloid. Zhang and Li [26] proposed some new assumptions and modifications on the failure pattern and partial parameters of the '5-parameter model' proposed by Li et al. [25] for floor slabs. Dong and Fang [27] proposed a segment equilibrium method to determine the tensile membrane effects of concrete slabs at large displacements. This model considers the tensile membrane action that is provided by the vertical component of reinforcement tensile forces after the formation of the mechanism of the plastic hinge line. According to the model proposed by Dong and Fang [27], Wang et al. [28] presented a modified theoretical model for determining the load carrying capacity of reinforced concrete slabs.

This paper presents for the first time four large scale fire tests on the reinforced concrete slabs which were subjected to combined uni-axial in-plane and out-of-plane loading conditions with vertically restraint at the four corners of the slabs. The research focuses on the quantitative relationship between horizontal restrained force and deformation, cracking pattern and spalling of the slabs in fire. Also the vertical restraint forces at the four corners of the slabs were measured during the tests. The research generated valuable test data which can be used to validate the numerical models developed by fellow researchers in the field of structural fire engineering.

2. Test programme

2.1. Test furnace

As shown in Fig. 1, a furnace was specially designed and constructed to heat the four concrete slabs based on the original large furnace. The furnace walls were constructed from bricks (370 mm thick) and mineral wool (50 mm thick). The furnace was operated by two oil-fired burner nozzles located in the north furnace wall, and each nozzle was controlled independently. The dimensions of the furnace are 3270 mm × 3270 mm × 1500 mm.

2.2. Concrete slabs

In this research four full-scale reinforced concrete slabs were tested under fire conditions. The slabs were simply supported on four edges and subjected to various combinations of horizontal uni-axial in-plane and vertical out-of-plane loads. It is noted that one slab, named Slab S1, was tested under vertical out-of-plane load only for the purpose of comparison. The other three slabs (named Slab S2, Slab S3 and Slab S4) were tested under combined loading conditions. All four slabs were vertical restrained at four corners. The four slabs were identical in terms of concrete strength, dimensions, and the thickness of concrete cover.

The dimensions of the slabs were 3300 mm wide by 3300 mm long with a thickness of 100 mm. All four slabs were cast at the same time then they were stored in the laboratory to cure and dry. The ages of the concrete at the time of testing were: Slab S1 = 224 days; Slab S2 = 243 days; Slab S3 = 253 days; Slab S4 = 259 days. Commercial normal weight concrete (siliceous aggregates) with the specified cubic compressive strength of 30 MPa was used for the slabs. However, the actual compressive strength of concrete at the time of tests for all slabs was 28 MPa.

For the Slabs S1, S2 and S3, grade 3 hot-rolled reinforcing bars of 8 mm diameter were arranged at 200 mm spacing along the two directions. For the Slab S4, the space of the reinforcing steel bars for both directions was 100 mm. For each slab, the clear concrete cover was 15 mm from the steel reinforcing bars. In addition, the reinforcing steel bars were only placed at the bottom of the slabs. The tested yield strength and ultimate strength of the reinforcing steel were 414 and 475 MPa, respectively.

2.3. Instrumentations

The furnace temperatures were measured by two thermocouples (F-1 and F-2) during each fire test. In addition, for each slab, nine groups of thermocouple trees (T1 to T9) were used to measure the temperatures within the slab, as shown in Fig. 2(a). Each thermocouple tree consisted of 6 thermocouples (see Fig. 2(b) Points T-1 to T-6) distributed vertically to measure the concrete temperatures along the thickness of the slab. For measuring the temperatures of reinforcing steel, two thermocouples (Points R-1 and R-2) were placed at the mid-height of the steel bars, as shown in Fig. 2(b).

The vertical and horizontal deflections of each concrete slab were measured in the test. Fig. 3 shows the positions of vertical and horizontal displacement transducers which have limiting travel ranging from 10 to 500 mm. Eleven LVDT's (Points V1 to V11) were placed on the slab to measure the vertical deflections of the slab and the horizontal deflections of the slab were measured by two LVDT's called H1 and H2, respectively.

2.4. Test setup and procedure

The four edges of each slab were supported by steel balls and rollers on four furnace walls, according to the Standards of Concrete Testing Method of China [29]. A uniformly distributed load was applied on the top of each slab, to simulate live loads. Sandbags (each weighing 50 kg) were placed on the slab to simulate the uniformly distributed load of 2.0 kN/m^2.

As shown in Fig. 4(a), the horizontal uni-axial in-plane loads were applied by one independent loading frame. The uni-axial in-plane loads were applied to the slab by high-strength steel knife edges attached to the rams of the three 500 kN hydraulic jacks