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Fire behaviour of reinforced concrete slabs under combined biaxial in-plane and out-of-plane loads

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ABSTRACT

To better understand the fire behaviour of in-plane restrained reinforced concrete slabs, this paper presents the results of five fire tests on two-way spanning concrete slabs under compressive biaxial in-plane and flexural out-of-plane loads. The data presented include furnace temperatures, temperature distributions, vertical and horizontal deflections, restraint forces, crack patterns, and characterisation of spalling of the five slabs during both heating and cooling phases. Comparison of the results indicates that the fire behaviour of the restrained slabs is dependent on the restraint type, restraint level and the aspect ratio, and thus increasing the in-plane forces may result in an increase or a decrease of the mid-span deflections of the concrete slabs. Fire behaviour of the restrained slabs are considerably different from those of the simply supported slabs, and thus the effect of uniaxial or biaxial in-plane restraints on the failure mode should be considered to develop reasonable failure criteria for these slabs. In addition, it is suggested that the corners of the in-plane restrained slabs should be reinforced by arranging the whole span top steels along two directions since the corners fracture easily with large diagonal cracks during the fire tests.

1. Introduction

In recent years, a number of experimental studies have been conducted to investigate the fire behaviour of reinforced concrete simply supported slabs [1]. However, reinforced concrete or prestressed concrete slabs supported along all edges and subjected to combined uniaxial or biaxial in-plane compressive and lateral (out-of-plane) loads occur in many structural applications. Meanwhile, a review of the literature shows that there are some obvious controversies on the effect of the restraint on the fire behaviour of concrete slabs [2–6].

From the 1960s, the effects of restraint on concrete slabs at ambient and elevated temperatures have been investigated by many researchers. Issen et al. [2] proposed that any amount of restraint considerably enhanced the fire resistance of the concrete slabs. However, Anderberg and Forsen [3] proposed that the fire resistance of concrete slabs did not always increase with the restraint. In 1983, Lin et al. [4] showed that except near the 0% and 100% restraint conditions, the fire performance of the concrete slabs was not greatly influenced by the restraint. In addition, the high restraining forces lead to the compressive failure of the concrete slabs. In 1989, Lin et al. [5] presented the results of two fire tests on full-size concrete rectangular slabs under externally imposed restraint forces. The results showed that the restraining forces increased rapidly at the early stage of the fire and then the increase rate slowed considerably. In 1993, Cooke [6] conducted a series of fire tests on the restrained concrete slabs and proposed that the line of thrust at the supports had an important effect on the fire resistance of the restrained concrete slabs. In 1994, Ghoeim and Macgregor [7] reported the results of tests of 19 reinforced concrete squares or rectangular in-plane restrained slabs at ambient temperatures, with the results showing that the aspect ratio had an important effect on the load capacity of the concrete slabs. The results of these investigations, however, cannot be extended directly to the in-plane restrained rectangular slabs in fire, since different mechanical behaviour (thermal expansion and thermal strains) and failure mode (such as integrity failure and concrete spalling) can occur.

In 2002, Lim et al. [8] conducted the fire tests and numerical analysis on three reinforced concrete simply supported rectangular slabs. In 2004, Lim et al. [9] conducted computer modelling of axially and rotationally restrained, one-way concrete slabs in fire. The analyses found that the fire behaviour of one-way slab was very sensitive to the end support conditions and the axial restraint stiffness. Meanwhile, Lim et al. [9] pointed

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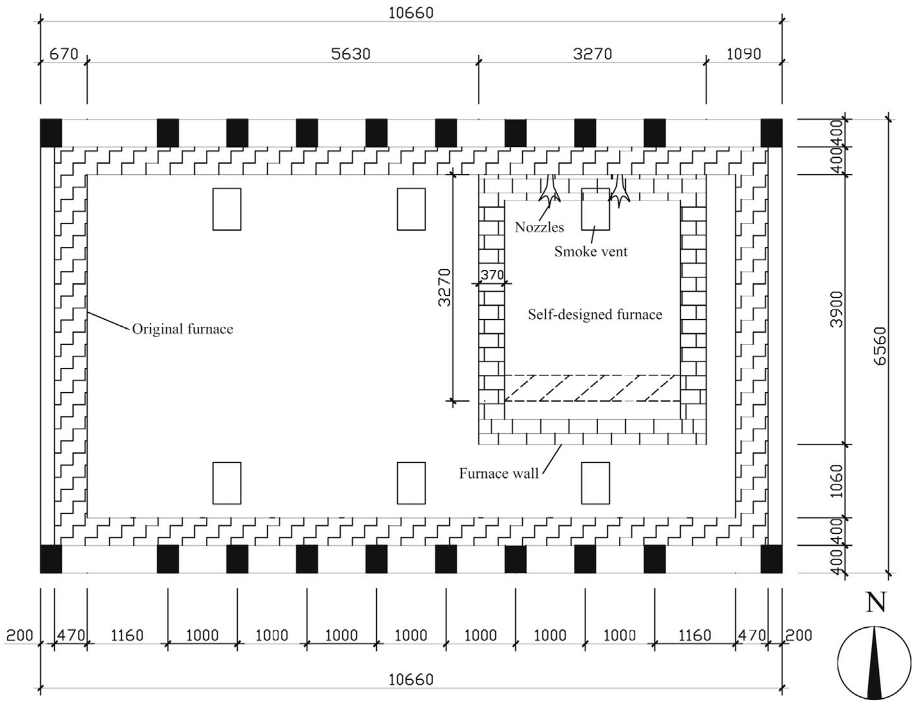
out that the effects of restraint on two-way square or rectangular slabs should be studied as it would better represent the support conditions of real construction.

In 2004, Foster et al. [10] presented the results from 15 small-scale tests (two aspect ratios of 2.09 and 1.55) conducted on horizontally unrestrained slabs at ambient temperature. The results showed that one tension crack formed across the shorter span of the slab (2.09), and two tension cracks occurred across the shorter span of the slab (1.55) at the intersection of the yield lines. Hence, the aspect ratio might have a certain influence on the failure mode of rectangular concrete slabs.

In 2007, Bailey and Toh [11,12] presented test results of forty-eight horizontally unrestrained two-way spanning reinforced square (1.1 m × 1.1 m) and rectangular (1.7 m × 1.1 m) concrete slabs at ambient and elevated temperatures. On one hand, the ambient temperature tests showed that the square slabs had a greater enhancement for a given displacement, but failed at a lower displacement compared to the rectangular slabs. On the other hand, at elevated temperatures, all square or rectangular slabs failed by fracture of reinforcement, and no compression failure was observed in any of the fire tests. However, there were unrealistic temperature distributions through the thickness of the small-scale slabs; therefore, the full-scale fire tests of the concrete slabs, especially the restraint slabs, should be further conducted.

In 2010, Wang and Dong [13] conducted fire tests on two reinforced concrete rectangular slabs with different boundaries: one simply supported slab and one four-edge fixed slab. For the simply supported slab, several cracks occurred parallel to the short span; for the four-edge fixed slab, plastic hinge lines of elliptic shape appeared on the top surface. In 2011, Dong and Zhu [14] reported the test results of a rectangular



(a) Plan view of the self-designed furnace

(b) Photograph of the self-designed furnace

Fig. 1. Self-designed furnace (all dimensions in mm).