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Analytical model for predicting the load–deflection curve of post-fire reinforced-concrete slab

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ABSTRACT

This paper firstly presents the experimental results of two simply supported full-scale reinforced-concrete (RC) slabs (unheated and fire-damaged). Thereafter, an analytical model for predicting the load–deflection curves of post-fire RC slabs is described in detail. The model can predict ultimate loads and displacements in both post-fire RC slabs and those at ambient temperature. The developed model has been validated using test data generated in this research and previous research and compared with a few analytical models developed by other researchers; some of the proposed model's advantages are highlighted in this paper. Results indicate that the model can be employed to determine the residual strength of post-fire RC slabs with reasonable accuracy. It is evident that steel strain differences and vertical shear forces in the slab have considerable effects on the load-carrying capacities of unheated and fire-damaged RC slabs.

1. Introduction

The tensile membrane action of reinforced-concrete (RC) slabs with large displacements at ambient and elevated temperatures has been investigated by several researchers [1–9]. Recently, assessing the post-fire load carrying capacity of RC members has received considerable attention [11–18]. Predicting the residual strength of concrete slabs exposed to fire is a difficult task because of multiple uncertainties, influencing factors, and lack of data. Compared with numerical modelling, theoretical methods can be used with ease to determine the residual load capacities of fire-damaged RC slabs.

Since the 1960s, a number of experimental studies have been conducted to investigate the load–deflection behaviour and tensile membrane action of simply supported reinforced-concrete slabs at ambient temperature [1–3]. Recently, to appropriately investigate the tensile membrane action of RC slabs subject to large displacements, several tests on RC slabs at ambient or elevated temperatures were conducted by several researchers. In 2002, Lim and Wade [4] conducted fire tests and numerical analyses on three simply supported rectangular reinforced-concrete slabs. In 2004, Foster et al. [5] reported the results of 15 small-scale tests conducted on horizontally unrestrained slabs at ambient temperature. In 2007 and 2010, Bailey and Toh [6,7] presented the test results of 48 horizontally unrestrained two-way spanning RC slabs at ambient and elevated temperatures. In 2011, Cashell et al. [8] conducted a series of 18 tests on simply supported RC slabs at ambient temperatures to obtain the load–deflection behaviour of specimens and establish the appropriate failure criteria. In 2016, Wang et al. [9] conducted four large-scale fire tests on RC slabs, under combined uniaxial in-plane and out-of-plane loading conditions with vertical restraints at the four slab corners. In 2011, Chung et al. [10] investigated the residual strength of fire-damaged RC slabs by experimental tests and numerical simulations. However, the load capacity of fire-damaged RC slabs, which were not loaded during the fire, was investigated; this did not conform to the real condition of RC slabs in buildings. A review of literature shows that the residual strength of post-fire RC slabs should be investigated further to provide valuable test data that can be used to validate theoretical methods developed by various researchers [16–18].

In 2005, Cameron and Usmani [19] analysed the membrane action of restrained RC slabs based on differential equations that described slabs with large deflections. However, to be conservative, several researchers investigated the load carrying capacities of simply supported

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Table 1
Material properties of reinforced-concrete slabs.

Slab	$L \times l \times h$ (mm)	Steel		A_{sx} (mm^2/m)	A_{sy} (mm)	x/y spacing (mm)	c (mm)	m (MPa)	h_{cx} (mm)	h_{cy} (mm)	Φ (mm)
		E_s (GPa)	f_y (MPa)								
S0	2700 × 2700 × 100	200.0	414.0	503.0	503.0	100	15.00	25.0	73.00	81.00	8.00
S4-AF	2700 × 2700 × 100	167.0	364.0	503.0	503.0	100	15.00	16.8	73.00	81.00	8.00

two-way slabs at ambient and elevated temperatures. In 2007, Bailey and Toh [6,7,20] implemented a series of two tests on unrestrained, small-scale RC slabs and proposed two failure criteria to predict the ultimate loads of unrestrained RC slabs considering tensile membrane action. However, as discussed in Li et al. [21], the yield-line failure mode might not be appropriate for modelling the membrane action of RC slabs subjected to large deflections. In 2007, Li et al. [21] presented a new method to analyse the limit capacities of slabs based on a reinforcing steel failure criterion. At the limit state, the concrete slab is divided into five components: four rigid plates near the edges and an elliptic paraboloid at the centre. However, vertical shear forces along the yield line are not reasonably considered in their method, and thus, the limiting load-bearing capacities among the components are not equal. The concrete compressive failure mode was not considered in the method. Dong [22], Dong and Fang [23], and Wang et al. [24] considered the tensile membrane action provided by the vertical components of tensile steel forces along yield lines; failure modes of steel and concrete were proposed to determine the limit loads of RC slabs. Omer et al. [25,26] and Cashell et al. [27] proposed an energy-based bond strength-dependent method for determining the load capacities of slabs during the membrane-action stage. In 2016, Herraiz and Vogel [28] developed a new approach based on equilibrium and kinematics to determine the load–deflection curves of RC slabs. In 2017, Burgess [29] provided a systematic derivation of a new analytical approach to the tensile membrane action of lightly reinforced-concrete slabs at large deflections. However, in the above methods, after attaining the yield loads, the load–deflection relationships are linear, and the slope (structural stiffness) is maintained until failure conditions are reached. In 2017, Molkens et al. [30] proposed a compression-based methodology for the reliability-assessment of residual load carrying capacity of post-fire RC slabs. However, this method focuses on the ultimate capacity only.

All the methods mentioned above have several evident deficiencies, particularly at the membrane-action stage, as follows. (1) The enhancement factor tends to linearly increase with deflection during the membrane-action stage. In other words, the structural stiffness of concrete slabs do not decrease with increasing deflection, and undoubtedly, this does not coincide with experimental observations. (2) The conventional yield line pattern (such as four rigid plates) is often assumed during the membrane action. However, at larger deflections, a slab is deformed in double curvature. Hence, the assumed yield pattern is not reasonable. (3) According to previous research [31], the yield strain pattern of the bottom tensile steel has a square or rectangular shape. Hence, the assumption of an elliptical pattern at the bottom tensile steel [21] is not reasonable. (4) The descending stage of the load–deflection curve cannot be reasonably predicted by previous methods. For instance, the load–deflection curve calculated by Ref. [29] is concave (negative stiffness gradually increases with deflection); it does not coincide with most experimental results (convex trend) [8]. Therefore, one of the main objectives of this research is to develop an analytical model for predicting the load–deflection curve of post-fire reinforced-concrete slabs. The developed model can resolve all problems identified above.

In this paper, the tests on two full-scale slabs (fire-damaged slab and unheated slab) are first presented, and experimental results are discussed in detail. Subsequently, an analytical method, established to predict the load–deflection curve and residual strength of the fire-damaged slab is introduced. Finally, predictions of the present method, other existing methods, and numerical models compared with test data on full-scale and small-scale RC slabs conducted by different authors [1,3,6,31] are presented.

2. Tests on two full-scale slabs

2.1. Experimental programme

The tests consisted of two RC slabs—unheated (S0) and fire-damaged (S4-AF)—designed according to the Chinese code [32]. Both were 3300 mm × 3300 mm × 100 mm, tested under simply supported conditions, with a clear span of 2700 mm in each direction. Reinforcing steel bars were only placed at the bottom of each slab, with a 15-mm cover [32], and equal rebar spacing in both directions. The rebar positions were secured before concrete casting in order to ensure that the slab has a 15-mm concrete cover. Other slab properties are summarised in Table 1.

Prior to the residual strength test, slab S4-AF was exposed to fire. During the fire test, four edges of the slab were supported by steel balls and rollers on four furnace walls [9]. Based on the Chinese code recommendation [34], a uniformly distributed load (2.0 kN/m^2) was applied on top of the slab, to simulate live loads. Hence, the total vertical load on the slab was 4.35 kN/m^2 during the fire test. The uniaxial horizontal in-plane restraint stresses (approximately 2 MPa) were applied by one independent loading frame, and in-plane forces were kept constant during the fire test. The furnace temperature, concrete temperature, maximum steel temperatures, and midspan deflection during the heating and cooling phases are shown in Fig. 1(a)–(d). Note that the maximum temperatures of the rebar and concrete (top surface) were 650 and 240 °C, respectively. Thus, concrete residual properties were determined according to the maximum temperatures experienced [33], as listed in Table 1.

After the fire test, no spalling was observed at the bottom surface of the slab. However, diagonal cracks occurred at each corner of the slab. Several cracks parallel to the in-plane compression direction propagated from the centre to slab edges. Evidently, because of the lateral restraint, additional tensile strains in concrete were generated in a direction perpendicular to the restraining force resulting from the influence of Poisson ratio. Other details on this fire-exposed slab are found in Ref. [9].

Because of the of test condition limitation (laboratory space), the residual strength test on S4-AF was conducted one year after the fire test. Hence, it may be possible that the concrete exposed to high temperature regained some of its strength because of rehydration.

2.2. Measurement system

As shown in Fig. 2(a), the four edges of each slab were simply supported by steel rollers on the walls, and the load was applied to the slab using two jacks. Each corner was held down by a steel beam, as shown in Fig. 2(b). The restraining forces at the four corners were measured by pressure transducers (P-1–P-4). There were no horizontal restraints provided along the edges of the slab.

Fig. 3(a) shows the positions of vertical and horizontal displacement