Alexandria Engineering Journal (2013) 52, 749–761

FACULTY OF ENGINEERING
ALEXANDRIA UNIVERSITY

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Behavior of one-way reinforced concrete slabs subjected to fire

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Received 21 August 2013; revised 16 September 2013; accepted 18 September 2013
Available online 17 October 2013

KEYWORDS

Cooling;
Fire resistance;
Finite difference;
Heat transfer;
Slabs

Abstract A finite difference analysis was performed to investigate the behavior of one-way reinforced concrete slabs exposed to fire. The objective of the study was to investigate the fire resistance and the fire risk after extinguishing the fire. Firstly, the fire resistance was obtained using the ISO834 standard fire without cooling phase. Secondly, the ISO834 parametric fire with cooling phase was applied to study the effect of cooling time. Accordingly, the critical time for cooling was identified and the corresponding failure time was calculated. Moreover, the maximum risk time which is the time between the fire extinguishing and the collapse of slab was obtained. Sixteen one-way reinforced concrete slabs were considered to study the effect of important parameters namely: the concrete cover thickness; the plaster; and the live load ratio. Equations for heat transfer through the slab thickness were used in the fire resistance calculations. Studying the cooling time revealed that the slabs are still prone to collapse although they were cooled before their fire resistance. Moreover, increasing the concrete cover thickness and the presence of plaster led to an increase in the maximum risk time. However, the variation in the live load ratio has almost no effect on such time.

1. Introduction

Structural fire performance engineering is a recent philosophy of design that has developed recently in structural engineering. Fire safety design can be achieved by active and passive fire protection systems. Active systems are generally self-activated once the fire is triggered. Such systems include fire detectors, smoke control systems, and sprinklers. However, passive systems are built into the structures such as building codes limitations, fire doors and windows and fire protection materials that prevent or delay the temperature rise in structural elements [1]. Many different fire exposures are used to study the reinforced concrete structure such as standard fire (without cooling phase), parametric and natural fires (with cooling phase) [1–4]. The parametric and natural fires usually represent actual fires better than the standard fire.

The behavior of reinforced concrete slabs under fire loading has been studied by researchers for many decades [5–9]. It is well known that when the temperature increases the slab fire resistance decreases. This is because when concrete is exposed to

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

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http://dx.doi.org/10.1016/j.aej.2013.09.004

heat, chemical and physical reactions occur such as loss of moisture, dehydration of cement paste and decomposition of the aggregate. Such changes lead to high pore pressures caused by the water evaporation, internal microcracks and damages appear in concrete [10]. Also, the increase in the temperature leads to a decrease in the yield strength of the steel reinforcement. Concrete spalling under high temperatures is a major factor of reducing its fire resistance [11,12]. The spalling is caused by the build-up of pore pressure during heating. High strength concrete is believed to be more susceptible to this pressure build-up because of its low permeability compared to the normal strength concrete. Thus, high strength concrete is known to have less fire resistance than normal strength concrete [13,14]. The behavior of concrete slabs under fire is very sensitive to the stiffness and ends restrain condition. The fire resistance of one-way restrained slabs is generally higher than those for unrestrained slabs because compressive restraint in the surrounding structure decreased the slabs thermal expansion [15–17]. It is well known that the bottom concrete cover has significant influence on the fire resistance of the flexural member, but the lateral concrete cover has a less beneficial effect on the member fire resistance compared to the bottom concrete cover [18]. Codes of practice state that the temperature rise leads to strength degradation in both concrete and steel reinforcement based on the aggregate type and the grade of the steel [19,20]. However, such codes believed that the steel reinforcement temperature played the important role in strength degradation. The Eurocode2-2004 [19] gives profiles for temperature distributions through the slab thickness in the case of slabs or through the cross section in the case of beams and columns based on fire resistance class for the load-bearing criterion for 30, or 60, . . . minutes in standard fire exposure. It gives simple calculation methods for calculating the mechanical behavior namely 500 °C isotherm and zone methods. The ACI committee 216 [20] gives fire resistance for the slab based on the relative slab bending capacity which is the ratio of the moment due to applied load to the moment capacity of the section where the cover thickness is based on the aggregate type. The ECP 203-2007 [21] gives the fire resistance for different structural elements, (slabs, beams, and columns) according to their dimensions and the concrete cover thickness.

Most of research work found in the literature studied the behavior of reinforced concrete slabs and their fire resistance during exposure to fire. However little research work dealt with the influence of cooling time on the fire resistance of concrete slabs. Such studies considered only the time of cooling start on the fire resistance [5,7,10]. However, up to the knowledge of the authors there is no research work studied the risk of cooling time before the fire resistance. There is a critical time between the time of cooling start and the fire resistance. This critical time leads to failure of the concrete slab if cooled before its fire resistance. This is because the fire starts to decrease (cooled) while the concrete slab core temperature still increasing [22].

This paper presents a finite difference approach [23–25] for tracing the fire response of RC slabs under the standard and parametric ISO834 fire. Several parameters were considered such as concrete cover thickness, presence of plaster at exposed surface, and live load ratio. The scope of this study covers the behavior of simply-supported one way reinforced concrete slabs under fire. The model is verified against experimental and numerical data by comparing the predicted temperatures to the measured ones from Lie and Leir [23]. The model is capable of predicting the fire resistance and the influence of cooling before the fire resistance (time).

2. The model

The Finite difference method is considered in the current research to study the behavior of reinforced concrete simply supported one-way slabs under fire loading. The model considers the heat transfer through the slab thickness and both concrete and steel reinforcement strength degradation due to exposure to fire. The ISO834 standard fire without and with cooling phase is considered. The model considers three parameters namely: concrete cover, live load ratio, and the plaster thickness at the exposed surface to identify fire resistance. Also, the effect of cooling time before the fire resistance on the possibility of such slabs to collapse is studied and the corresponding failure time could be estimated. Moreover, the maximum risk time is determined. To perform such model the following assumptions are considered:

- Plane sections before deformation remain plane after deformation (linear strain).
- The concrete tensile strength is neglected.
- The concrete slab is under static load.
- The effect of spalling, expansion and shrinkage are neglected.
- Slab edge restraint is neglected.

2.1. Heat transfer through concrete slab

There are generally three modes of heat transfer namely conduction, convection and radiation. The surface of the element exposed to fire is subjected to heat transfer by conduction, convection and radiation. For concrete members, the convection is usually ignored when calculating the exposed surface temperature because convection is responsible for less than 10% of the heat transfer at the exposed surface of the concrete members [8]. On the other hand, convection is usually accounted for when calculating the unexposed surface temperature. The internal heat transfer through concrete members is typically calculated by conduction only [9]. To study the performance of reinforced concrete slab under fire, the distribution of temperature inside the slab has to be known. The assessment of the slab behavior under fire should start by applying the standard fire temperature on the exposed surface, after that prediction of the temperature through the slab is obtained. This prediction is performed using a heat transfer analysis. The heat transfer analysis was performed using finite difference method. In such analysis, the temperature distribution mainly depends on the thermal properties of materials such as thermal conductivity, emissivity, specific heat and convection heat transfer coefficient.

2.1.1. Fire temperature

The fire temperature was calculated assuming that the slab was exposed to uniform fire from below (tension side). The fire temperature followed the ISO834 standard fire without cooling phase (phase 1) and the ISO834 parametric fire with cooling phase (phase 2). The time–temperature relationship for phase 1 and phase 2 could be described by the following expressions given by [11] and as shown in Fig. 1: