Fire Safety Journal 44 (2009) 691–703

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Assessing the flexural and axial behaviour of reinforced concrete members at elevated temperatures using sectional analysis

S.F. El-Fitiany, M.A. Youssef *

Department of Civil and Environmental Engineering, The University of Western Ontario, London, ON, Canada N6A 5B9

ARTICLE INFO

Article history:
Received 10 July 2008
Received in revised form
20 October 2008
Accepted 28 January 2009
Available online 4 March 2009

Keywords:
Reinforced concrete
Fire
Elevated temperature
Flexural capacity
Deformation
Sectional analysis
Curvature

ABSTRACT

Simplified, rational, and practical models that account for the effect of elevated temperature on concrete and steel properties are needed. These models will enable engineers to design and assess reinforced concrete (RC) structures to satisfy specific fire performance criteria. This paper introduces a simple method that predicts the flexural and axial behaviour of RC sections during exposure to elevated temperatures. The method is based on using finite difference analysis to estimate the temperature distribution within a concrete section and a modified version of the well-known sectional analysis approach to predict the axial and/or flexural behaviour. A rational approach is proposed to convert the two-dimensional temperature distribution to a one-dimensional distribution. This approach converts a complex problem to a simplified one and thus enables engineers to better understand the behaviour and have higher confidence in the results. The predictions of the proposed method are validated using experimental and analytical studies by others. Additional tests are needed to further validate and improve the proposed method.

1. Introduction

Fire impacts reinforced concrete (RC) members by raising the temperature of the concrete mass. This rise in temperature dramatically reduces the mechanical properties of concrete and steel [1]. Moreover, fire temperatures induce new strains, thermal, and transient creep [1]. They might also result in explosive spalling of surface pieces of concrete members [2].

Concrete structures are currently being designed for fire using prescribed methods that are based on experimental tests. These methods specify minimum cross-section dimensions and minimum clear cover to the reinforcing bars. As new codes are moving towards performance-based design and conducting experimental tests to satisfy different fire scenarios would be an expensive solution, engineers are in need of new design tools to achieve specific performance criteria for a defined fire scenario. The finite element method (FEM) has proven to be a powerful method to predict the behaviour of concrete structures during exposure to fire events [3,4]. Drawbacks of using the FEM, including the need to have a coupled thermal-stress analysis computer program and difficulty of comprehending its results and identifying potential modeling errors, make it impractical for design engineers.

In this paper, a methodology that relies on using both finite difference method (FDM) and a modified sectional analysis is proposed to estimate the behaviour of concrete sections during exposure to fire events. FDM is considered a simple method for evaluating the temperature variation within a concrete cross-section [5]. Sectional analysis allows evaluating the axial and/or flexural behaviour of a concrete section and is based on simple equilibrium and compatibility equations that can be easily applied by design engineers [6]. The modified sectional analysis is validated by comparing its predictions with the available experimental and analytical data.

The research conducted in this paper is limited to unprotected, siliceous, square concrete sections exposed to a standard ASTM-E119 fire on their four sides. This case is chosen since it represents the general case of an interior concrete column in a typical building. Simple modifications can be introduced to address other cases and fire scenarios. Normal strength concrete is assumed and thus spalling is not considered [7].

The column tested by Lie et al. [8] (Fig. 1a) is used in the following sections to provide example calculations for different components of the model. The column has dimensions of 305 mm × 305 mm and a height of 3810 mm. It is reinforced with 4–25 mm bars and has 10 mm ties spaced at 305 mm. The compressive and yield strength of the siliceous concrete and reinforcing bars are 36.1 and 443.7 MPa, respectively. The column is subjected to standard ASTM-E119 fire over a height of 3000 mm while being loaded axially.

* Corresponding author. Tel.: +1 519 661 2111x88661; fax: +1 519 661 3779.
E-mail address: youssef@uwo.ca (M.A. Youssef).

0379-7112/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.firesaf.2009.01.005

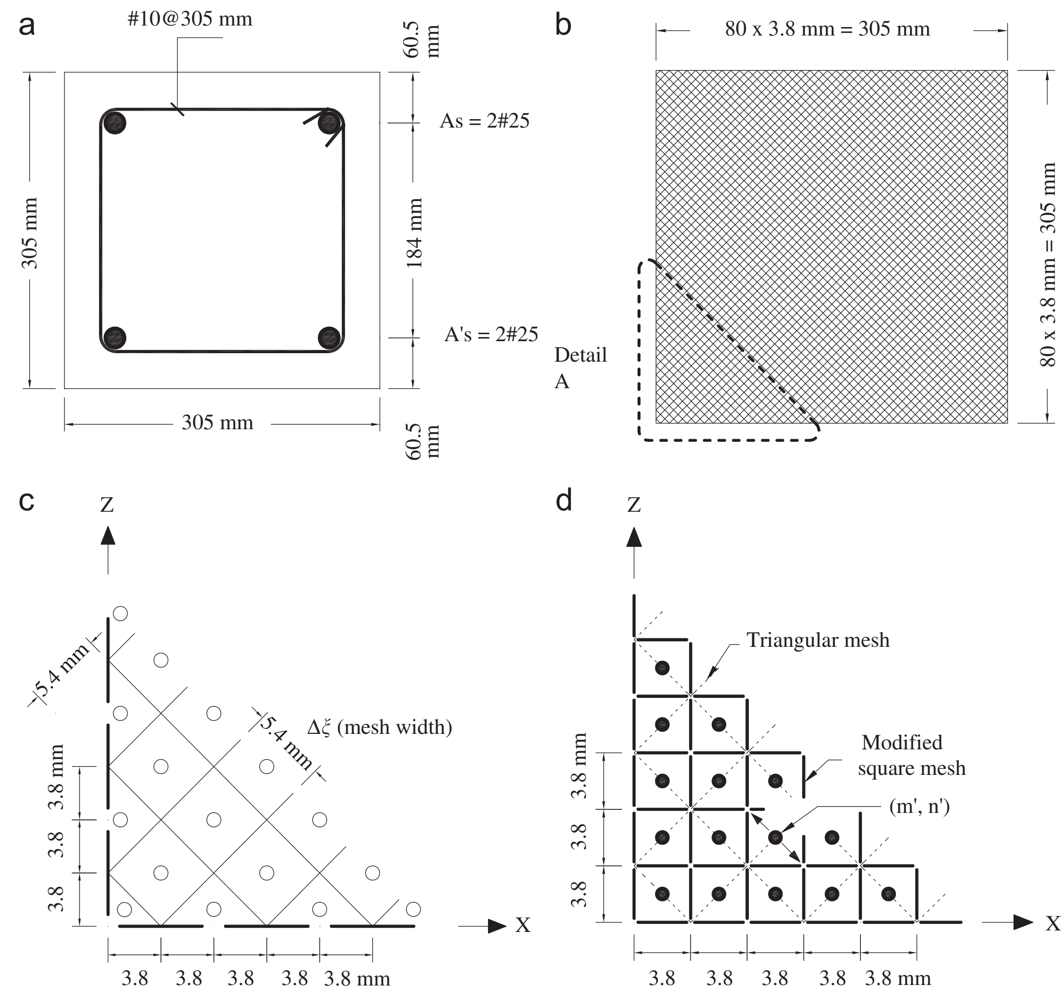

Fig. 1. Heat transfer modeling: (a) RC cross-section, (b) heat transfer mesh, (c) detail A—45° mesh, and (d) detail A—equivalent square mesh.

2. Heat transfer model

Several methods are available to predict the temperature distribution in a concrete section due to exposure to fire temperatures. Simplified methods predict the temperature distribution using pre-assumed temperature variation [9,10]. Such methods might produce accurate predictions for specific cases but might also result in significant errors for other cases. The FEM [11] is considered to be the most accurate tool to predict the thermal distribution as it accounts for irregular cross-sections subjected to any pre-specified fire condition. The FDM [5] is a simplified version of the FEM. It has the advantage of accounting for irregular shapes with good accuracy in addition to the ease of implementation in any programming code.

The following sub-sections briefly describe the required steps to predict the temperature gradient for a square, normal strength, siliceous concrete cross-section exposed to fire temperature from its four sides. A detailed description of the FDM is given by Lie [5]. The effect of steel reinforcement on the heat transfer calculations is neglected because of its small area relative to concrete area [5].

2.1. Concrete thermal properties

The amount of the heat transferred through the concrete mass is governed by its thermal conductivity (k_c) and specific heat capacity (C_c). For normal strength concrete, models representing k_c and C_c are reported by Lie [5].

2.2. Heat transfer mesh

The studied concrete section is divided into a number of 45° mesh elements as shown in Fig. 1b. The temperature at the center of each element represents the temperature of the entire element. The location of any element inside the mesh can be determined from its coordinates and the mesh width ($\Delta\xi$) (Fig. 1c).

2.3. Heat transfer calculations

Lie [5] proposed a set of equations that are based on the FDM to conduct heat transfer calculations. These equations are implemented into a C# programming code. Fig. 2 shows a flowchart for the developed program. The boundary conditions including dimensions, number of exposed faces, and the fire duration are first identified. The incremental temperature increase at the surface of the column is determined at each time step based on the relationship between the fire temperature and its duration. Part of the heat energy conveyed to the boundary elements is used to increase their temperatures while the remaining energy is transferred to the inner elements. The effect of the moisture content is included based on the fact that water