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Nonlinear Structural Analysis of Fire-exposed Reinforced Concrete Columns

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Abstract

A nonlinear structural analysis is presented for reinforced concrete (RC) columns exposed to fire. The analysis includes two steps: the first step is the calculation of the temperature distribution in concrete members, and the second the determination of the mechanical response due to elevated temperature and applied loading. In the thermal analysis, the effect of moisture is taken into account. The use of the computer program for evaluating the response of a RC column from the initial preloading stage to collapse, due to fire, is illustrated. The validity of the numerical model used in the program is verified by comparing the predictions from the computer program with measured results from full-scale fire resistance tests. The computer program can be used to predict the fire resistance of RC columns for any values of the significant parameters, such as load level, section dimensions, column length, concrete strength, concrete cover, aggregate type and reinforcement ratio.

Keywords: Fire resistance; Non-linear analysis; Moisture content; Load level; Size effect.

1. Introduction

It is well known that fire results in loss of life, homes, and livelihoods. A study (Scheuerman, 2002) of 16 industrialized countries (13 in Europe plus the USA, Canada and Japan) indicated that, in a typical year, the number of people killed by fires was 1 to 2 per 100,000 inhabitants and the total cost of fire damage amounted to 0.2 to 0.3% of GNP. Now, It has been well established that about 85% of the total fire loss was caused by building fire. These data and events show how fire safety is a formidable subject and one of the main concerns in the design of high-rise buildings and built infrastructure, where concrete members are often used due to the good fire resistance of concrete.

At present, many experimental investigations have been carried out to address the performance of RC columns under fire exposure (Sidibė, et al., 2000, Lie and Woollerton, 1988, Dotreppe,et al., 1997, Aldea, et al.,1997, Kodur and McGrath, 2003). These experiments are performed in special furnaces in which the surrounding air temperature follows the fire temperature curve described by the standards, such as the ISO 834 or ASTM Standard E119. However, fire testing, especially full scale, is expensive and time consuming, and the real fire scenario is different from the standard fire. The main differences between these tests and what happens in practical structures are due to boundary conditions (Sullivan, et al., 1993). A way to solve this problem is to perform tests of complete structures, but, in many cases, this can be impracticable.

As the world is moving toward performance-based fire codes, there is an increased focus on the use of numerical methods for evaluating the fire performance of structural members. Many researchers have been involved in numerical modeling of the fire response of RC exposed to fire (Lie and Irwin, 1993, Kodur and Lie, 1996, Huang and Platten, 1997, Terro, 1998, Daniel and Antonio, 2007). Most of them use finite element or finite difference methods to predict nonlinear transient heat transfer and mechanical analysis problems.

In this paper, a finite difference model, for evaluating the fire resistance of RC columns, is presented. The procedure includes two parts. The first part is the heat-transfer problem, which is to solve the heat-balance equation. The temperature distribution across the concrete section can be obtained. The second part is the calculation of mechanical properties of the concrete material and concrete structures problem based on the temperature distribution from part 1. The methods can predict the temperature distribution across the section, the fire endurance, the strength of the column under fire. The results of earlier experiments are used to check the structural behavior of RC columns at elevated temperatures. The validity of the numerical model used in the program is evaluated by comparing the computer analysis values with results from full-scale fire resistance tests.

2. NUMERICAL MODEL

A numerical model for predicting the behavior of RC columns, exposed to fire, has been developed as part of the present study. This finite difference model is similar to those developed by Lie and Irwin (1993), and Kodur and Lie (1996), but the moisture content effect on the model, and the material thermal and mechanical properties at elevated temperatures are different.

2.1 FIRE TEMPERATURE

The fire temperature is assumed to follow the ASTM E119 standard fire, which can be approximated by the following equation:

$$T_f = T_0 + 750(1-\exp(-0.49\sqrt{t})) + 22\sqrt{t} \tag{1}$$

where t=time (min); T0= initial temperature (°C); and Tf=fire temperature (°C).

2.2 HEAT TRANSFER

High temperature induces significant physical and chemical changes that alter the mechanical properties of concrete (Bazant, 1996). It is very complicated to consider all effects in a numerical model for concrete. Huang and Platten (1997) indicates that the temperature field has a significance effect on the strain field, while the effect of the latter on the former is insignificant. Therefore, this can be solved as an uncoupled system providing a dramatic simplification for solving the heat transfer problem.

In the current study, the following assumptions are made for the heat transfer analysis:

- The temperatures of the water and the concrete are the same at each location.
- Convection is ignored as a mechanism for heat flow from the fire surroundings into the column. Previous work in this area (Lie and Irwin, 1993) has led to the conclusion that convection is responsible for less than 10% of the heat transfer at the surface of the column in standard fire endurance tests, and can thus be neglected for the purposes of numerical fire modeling.
- Freedom water in concrete evaporates in the range of 100 to 140 ºC (Daniel and Antonio, 2007). The moisture content function in concrete by volume is defined as follows:

$$\phi(T) = \begin{cases} \phi_0 & T \le 100\,^oC \\ \phi_0\left[1-(T-100)/40\right] & 100\,^oC < T \le 140\,^oC \\ 0 & T \ge 140\,^oC \end{cases} \tag{2}$$

where ϕ_0 is the initial moisture content.

2.2.1 FINITE DIFFERENCE EQUATIONS

The cross-sectional area of the original column is modeled as a rectangular mesh with nodal points spaced Δx and Δy apart in x- and y-directions, respectively, as shown in Fig. 1.

INTERNAL NODES

Now consider a volume element of size, $\Delta x \times \Delta y \times 1$, identified as a general interior node (m, n) in a region in which no heat is generated, as shown in the Fig. 3 (a). Again assuming the direction of heat conduction to be toward the surface nodes, the energy balance on the volume element can be expressed as follows:

$$\Delta t \times \sum_{all\ sides} \dot{Q} = \Delta E_{element} \tag{3}$$

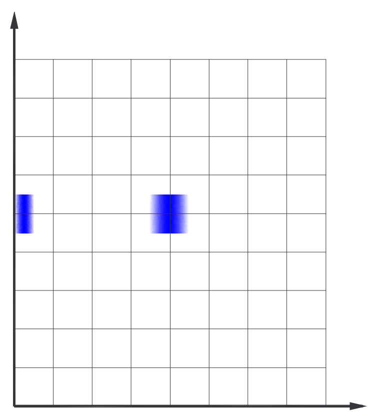
where $\dot{Q}$, is the rate of heat transfer, normally consisting of conduction terms for interior nodes, but may involve convection, heat flux, and radiation for boundary nodes, and $\Delta E_{element}$, the rate change of the energy content in the element, can be expressed as

$$\Delta E_{element} = mC\Delta T = (\rho_c C_c + \rho_w C_w \phi) V_{element} \Delta T \tag{4}$$

Dividing equation (2) by Δt, gives

$$\sum_{all\ sides} \dot{Q} = \rho_c C_c V_{element} \frac{T^{i+1} - T^i}{\Delta t} + \rho_w C_w \phi(i) V_{element} \frac{T^{i+1} - T^i}{\Delta t} \tag{5}$$

where ρ_c = the concrete density, C_c and C_w = the specific heat capacities of concrete and water, respectively, $V_{element}$ = the element volume, and $\phi(i)$ = the moisture content at time t=iΔt.



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OFFENDING COMMAND: .buildcmap

STACK:

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/WinCharSetFFFF-V2TT9BF4ACCAt
/CMap
-dictionary-
/WinCharSetFFFF-V2TT9BF4ACCAt