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Fire resistance performance analysis of reinforced concrete members using Galerkin finite element method

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Abstract

A research project is currently being conducted to develop and implement a 2D nonlinear Galerkin finite element analysis for reinforced concrete structures subjected to high temperature. Algorithms for calculating the closed-form element stiffness for a triangular element with a fully populated material conductance are developed. The validity of the numerical model used in the program is established by comparing the prediction from the computer program with results from full-scale fire resistance tests. Details of fire resistance experiments carried out on reinforced concrete slab, together with results, are presented. The results obtained from experimental test indicated that the proposed numerical model and the implemented codes are accurate and reliable. The changes in thermal parameters are discussed from the point of view of changes of structure and chemical composition due to the high temperature exposure. The proposed numerical model takes into account time-varying thermal loads, heat fluctuates due to the convection and radiation, and temperature-dependent material properties. Although, this study considers codes standard fire for reinforced concrete slab, any other time-temperature relationship can be easily incorporated.
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Keywords: Fire resistance; Nonlinear transient heat flow analysis; Galerkin finite element method; Reinforced concrete members

1. Introduction

For concrete structures, high-temperature environment in case of fire and the consequent high heated temperature are some of the extreme loads. Up to now, concrete has been seen as excellent fire resistance material due to significantly low thermal conductivity and diffusivity. Therefore, fire resistance has been confirmed only by simple analysis method or checking regulations for fire resistance time [1], and structures have been reused after fire by simple reinforcement. However, numerous cases of accidents and studies have reported that when reinforced concrete is exposed to high temperature for extended period of time, it undergoes severe performance degradation, decrease in effective cross-section of the material, direct exposure of steel by explosive fracture, and consequent possibility of collapse [2, 3]. On the other hand, most domestic studies have focused on empirical research of fire resistance performance for unit material and macroscopic analytical research [4, 5].

Internationally, Lie [6], Harada [7], and Kodur [8] have led active analytical research on fire resistance performance of concrete. However, analysis of fire resistance performance that includes heat transfer of concrete requires numerical analysis method for partial differential equation composing the governing equation and numerous assumptions and material

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test results for fire load, boundary conditions, thermal characteristics of the material, and time-temperature dependencies. For these reasons, each country is relying on internal fire resistance tests for verification of fire resistance [9].

This study attempts to contribute to analytical research on fire resistance performance of reinforced concrete structures that experience high-temperature environment such as fire, by proposing a nonlinear transient heat flow analysis method using Galerkin finite element method. Also, single-surface fire resistance test of full-scale slab has been performed to verify numeral analysis model and its validity. Through the test, effect of various fire scales and thermal properties on fire resistance performance of concrete has been analyzed. FORTRAN 90 was used for establishing analysis method. The results of this study provide fundamental data for establishing procedure for evaluation of fire resistance performance of concrete structures and evaluation of their fire safety.

2. Transient heat flow analysis

2.1. Governing equation

The 2-dimensional governing equation for heat conduction is

$$\rho(T)C(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T}{\partial y}\right) \tag{1}$$

here, ρ = density (kg/m^3), λ= thermal conductivity (W/m·K), and C = specific heat (J/kg K), which are temperature-dependent thermal characteristic values of the material to be analyzed. T is temperature (°C). In Fig. 1, overall boundary condition for ambient temperature (e.g. fire) T_∞ is

$$-\lambda(T)\frac{\partial T}{\partial n} = q_R + q_h = q_e \tag{2}$$

Here, q_R = heat received from radiation (W/m^2), q_h = heat received from convection, q_e = equivalent heat received. The initial condition is:

$$T(x,0) = f(x) \tag{3}$$

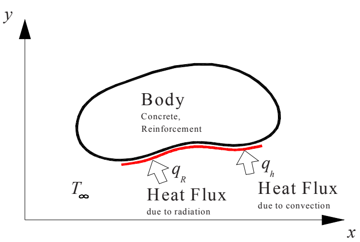

Fig. 1. 2-Dimensional conduction with surface convection (boundary condition).

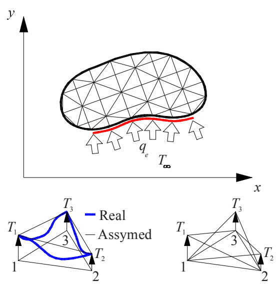

Fig. 2. Triangular element and real temperature *vs.* ideal temperature (shape function).

2.2. Formulation of element equation

As shown in Fig. 2, the target object was segmented by 3-node triangular elements and formulated by Galerkin finite element method. In the figure, if we let temperature of each node for single element as T_i^e (i=1, 2, 3) then, when simplified by the shape function N,

$$\{T^e\} = \begin{pmatrix} T_1^e \\ T_2^e \\ T_3^e \end{pmatrix} \tag{4}$$

$$T^e(x,y) = N_1N_1^e + N_2NT_2^e + N_3T_3^e = \sum_{i=1}^{3} N_iT_i^e \tag{5}$$

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