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.

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
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 numerical 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

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

here, $\rho$ = density (kg/m$^3$), $\lambda$ = 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 ($^\circ$C). In Fig. 1, overall boundary condition for ambient temperature (e.g. fire) $T_\infty$ is

$$- \lambda(T) \frac{\partial T}{\partial n} = q_R + q_h = q_e$$  \hspace{1cm} (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:

$$T(x, 0) = f(x)$$  \hspace{1cm} (3)

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 $T^e_i$ ($i=1, 2, 3$) then, when simplified by the shape function $N$,

$$\{T^e\} = \begin{pmatrix} T^e_1 \\ T^e_2 \\ T^e_3 \end{pmatrix}$$  \hspace{1cm} (4)

$$T^e(x, y) = N_1 T^e_1 + N_2 T^e_2 + N_3 T^e_3 = \sum_{i=1}^{3} N_i T^e_i$$  \hspace{1cm} (5)
From Eq. (1), if we assume that $\rho(T)$, $\lambda(T)$, and $C(T)$ are constants for given temperature inside the element,

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

(6)

$$ R = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - \rho C \frac{\partial T}{\partial t} $$

(7)

When $N_1$ is used as a weight function, Eq. (5) is substituted into the equation,

$$ \int_{\Omega} N_1 R d\Omega = \int_{\Omega} N_1 \left[ \lambda \left( \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right) - \rho C \frac{\partial \theta}{\partial t} \right] d\Omega = 0 $$

(8)

$$ \sum_{i=1}^{3} \left[ \int_{\Omega} N_1 \frac{\partial^2 N_i}{\partial x^2} + N_1 \frac{\partial^2 N_i}{\partial y^2} \right] d\Omega T_i^e = - \sum_{i=1}^{3} \left[ h \int_{R} N_1 N_i d\Gamma T_i^e \right] + \sum_{i=1}^{3} \left[ \rho C \int_{\Omega} N_i d\Omega \frac{\partial T_i^e}{\partial t} \right] = 0 $$

(9)

In the first term of Eq. (9), integration that includes second order differentiation can be expanded using Green-Gauss theorem to yield

$$ \int_{\Omega} \left( N_1 \frac{\partial^2 N_i}{\partial x^2} + N_1 \frac{\partial^2 N_i}{\partial y^2} \right) d\Omega T_i^e = - \int_{\Omega} \left( \frac{\partial N_i}{\partial x} \frac{\partial N_i}{\partial x} \right) d\Omega T_i^e - \int_{R} N_1 \frac{\partial N_i}{\partial n} d\Gamma $$

(10)

Here, $\int_{R} N_1 \frac{\partial N_i}{\partial n} d\Gamma$ is line integral for element boundary. When this is substituted into Eq. (9)

$$ \sum_{i=1}^{3} \left[ h \int_{R} N_1 N_i d\Gamma T_i^e \right] + \sum_{i=1}^{3} \left[ \rho C \int_{\Omega} N_i d\Omega \frac{\partial T_i^e}{\partial t} \right] = 0 $$

(11)

Here, the second term is integration of heat flow at the element boundary. When transformed,

$$ \sum_{i=1}^{3} \left[ h \int_{R} N_1 \frac{\partial N_i}{\partial n} d\Gamma T_i^e \right] = \int_{R} N_1 \left( \frac{\partial T}{\partial n} \right) d\Gamma $$

(12)

When the element boundary is an external boundary, Eq. (2) for boundary condition can be included for the temperature gradient, producing

$$ \sum_{i=1}^{3} \left[ h \int_{R} N_1 \frac{\partial N_i}{\partial n} d\Gamma T_i^e \right] = \int_{R} N_1 \left( q_e T_{\infty} \right) d\Gamma + \int_{R} N_1 T_0 d\Gamma = \int_{R} N_1 \left( q_e T_{\infty} \right) d\Gamma + \sum_{i=3}^{3} \int_{R} N_1 N_i d\Gamma T_i $$

(13)

When substituted into Eq. (11)

$$ \sum_{i=1}^{3} \left[ h \int_{R} N_1 \frac{\partial N_i}{\partial n} d\Gamma T_i^e \right] + \sum_{i=1}^{3} \left[ \rho C \int_{\Omega} N_i d\Omega \frac{\partial T_i^e}{\partial t} \right] = \int_{R} N_1 \left( q_e T_{\infty} \right) d\Gamma $$

(14)

$N_2$ and $N_3$ can be similarly derived. Then for 1 element

$$ \left[ C^e \right] \left[ \frac{\partial T^e}{\partial t} \right] + \left[ B_1^e + B_2^e \right] \{T^e\} = \{f^e\} $$

(15)

$$ \{T^2\} = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} $$

(16)

$$ \left( \frac{\partial T_e}{\partial t} \right) = \begin{pmatrix} \frac{\partial T_1}{\partial t} \\ \frac{\partial T_2}{\partial t} \\ \frac{\partial T_3}{\partial t} \end{pmatrix} $$

(17)

$$ C^e = \rho C \int_{\Omega} N_i d\Omega $$

(18)
Using geometric condition of triangular element,

\[
\left[ C_{T_{ij}}^e \right] = \frac{\rho c A e}{12} \begin{bmatrix} 211 \\ 121 \\ 112 \end{bmatrix} \tag{22}
\]

\[
\left[ B_{T_{ij}}^e \right] = \frac{\lambda}{4A^e} \begin{bmatrix} b_1 b_1 + c_1 c_1 & b_1 b_2 + c_1 c_2 & b_1 b_1 + c_1 c_3 \\ b_2 b_1 + c_2 c_1 & b_2 b_2 + c_2 c_2 & b_2 b_1 + c_2 c_3 \\ b_3 b_1 + c_3 c_1 & b_3 b_2 + c_3 c_2 & b_3 b_1 + c_3 c_3 \end{bmatrix} \tag{23}
\]

\[
\left[ B_{T}^e \right] \text{ and } \{ f_e \} \text{ are transformed at the external boundary as shown below.}
\]

\[
\left[ B_{T}^e \right] = \frac{h}{6} \begin{bmatrix} 210 \\ 120 \\ 000 \end{bmatrix}, \{ f_T^e \} = \frac{q_e T_{\text{in}} L}{2} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ (1,2 node boundary)} \tag{24}
\]

\[
\left[ B_{T}^e \right] = \frac{h}{6} \begin{bmatrix} 000 \\ 021 \\ 012 \end{bmatrix}, \{ f_T^e \} = \frac{q_e T_{\text{in}} L}{2} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \text{ (2,3 node boundary)} \tag{25}
\]

\[
\left[ B_{T}^e \right] = \frac{h}{6} \begin{bmatrix} 201 \\ 000 \\ 102 \end{bmatrix}, \{ f_T^e \} = \frac{q_e T_{\text{in}} L}{2} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ (3,1 node boundary)} \tag{26}
\]

2.3. Establishing system equation and time differentiation

After obtaining element equation (15) for each element, system equation can be established as

\[
\left[ C \right] \frac{\partial T}{\partial t} + \left[ B + B' \right] \{ T \} = \{ f \} \tag{27}
\]

Difference method is used for differentiation for time \((t)\) in Eq. (27). That is,

\[
\frac{\partial T}{\partial t} = \frac{1}{\Delta t} \left[ \{ T^{n+1} \} - \{ T^n \} \right] \tag{28}
\]

\[
\{ T \}^n = \{ T_{(t=n\Delta t)} \}, \{ T \} = \{ T^{n+1} \} \tag{29}
\]

Here, \(n\) = time step. Therefore, Eq. (27) is

\[
\left[ \frac{\partial C}{\partial t} \right] + \left[ B + B' \right] \{ T^{n+1} \} = \left[ \frac{C}{\Delta t} \right] \{ T^n \} + \{ f \} \tag{30}
\]

This equation can be used to obtain temperature at each need.

2.4. Evaluation of boundary condition considering fire behavior

Fire of concrete structure usually accompanies smoke. Also, concrete may not be directly exposed to the heat source if it is protected by Tex or other shielding, and heat originated from one region may be prevented from reaching another region by a fireproof shutter. In the boundary condition Eq. (2), Equivalent heat flow \(q_e\) is,
Heat received from radiation (W/m²) $q_R$ is

$$q_R = \varepsilon \sigma (T_\infty^4 - T_0^4)$$

(32)

Here, $\sigma = $ Stefan-Boltzmann constant, $5.6697 \times 10^8$ (W/m² K), $\varepsilon = $ surface emissivity, $T_\infty = $ ambient temperature, and $T_0 = $ surface temperature. For surface emissivity $\varepsilon$, Lambert-Beer’s law was used. That is,

$$\varepsilon = \frac{i_0 - i_0}{i_0} = 1 - e^{-kL}$$

(33)

Here, $i = $ radiation intensity of radiation-permeable gas (media), $k = $ absorption coefficient, $L = $ average distance of radiation-permeable gas. When smoke is accompanied, $q_R$ in a single region is

$$q_R = \frac{\varepsilon_1 \varepsilon_0 A_G}{1 - (1-\varepsilon_1)(1-\varepsilon_0 A_G/A_1)} (T_\infty^4 - T_0^4)$$

(34)

Here, subscript 1 and $G$ denote absence and presence of smoke, respectively. If the region is completely filled with smoke ($A_G = A_1$)

$$q_R = \frac{\varepsilon_1 \varepsilon_0 A_G}{1 - (1-\varepsilon_1)(1-\varepsilon_0)} (T_\infty^4 - T_0^4)$$

(35)

When shielded by ceiling panel such as Tex, $q_{RL} + q_{RU}$ and

$$q_R = \frac{q_{RL} + q_{RU}}{2} = \frac{q_{RL}}{2}$$

(36)

Here, subscripts $L$ and $U$ each denote below and above the ceiling. By Newton’s law of cooling, the amount of heat received by convection $q_h$ is

$$q_h = h(T_\infty - T_0)$$

(37)

Here, $h = $ convection coefficient (W/m² °C). Because fire is forced-convection heat transfer and turbulent, average Nusselt number $N_u$ is used. That is,

$$h = \frac{\varepsilon}{L} N_u$$

(38)

$$N_u = 0.037 Pr^{1/3} Re_s^{3/5} \ (turbulence)$$

(39)

and coefficients for air are specific heat ($c_v = 1.0$ (kJ/kg K)), viscosity coefficient $\mu = 2.5 \times 10^{-7} T^{3/4}$ (Pa s), dynamic viscosity coefficient $\nu = \mu / \rho = 7.2 \times 10^{-10} T^{3/4}$ (m² s), thermal conductivity $\lambda = 3.7 \times 10^{-7} T^{3/4}$ (kW/mK), thermal diffusivity $\alpha = 1.0 \times 10^{-9} T^{7/4}$ (m²/s), Prandtl number $Pr = \nu / \alpha = 0.72$, $Re_s = qL / \nu$, $q = $ heat flow of air. As a trivial case, $q_h = 0$ when shield such as Tex Present. Therefore, Eq. (2) is

$$q_e = \varepsilon \sigma (T_\infty^4 - T_0^4) + h(T_\infty - T_0) = (h + \alpha_R)(T_\infty - T_0)$$

(40)

Here, $\alpha_R = \varepsilon \sigma (T_\infty^2 + T_0^2)(T_\infty + T_0)$ and $T_0$ is surface temperature calculated at time $t_n$.  

2.5. Evaluation of temperature-dependent thermal characteristic values

Values from references [10] and standards [11] were used for temperature-dependent thermal characteristic values of concrete and reinforcing steel. The program was made to allow users to directly enter thermal characteristic values obtained from tests instead of default values above (user subroutine).
2.6. Analysis algorithm

The Galerkin finite element analysis method mentioned above was programmed using FORTRAN 90, using the algorithm shown in Fig. 3. Explicit scheme was used for analysis, as it does not change the stiffness matrix.

![Fig. 3. Program algorithm (flowchart).](image)

3. Experimental verification of numerical analysis result

Experiments were performed to verify validity of transient heat flow analysis using Galerkin finite element method and to examine thermal behavior of reinforced concrete.

3.1. Test overview and specimen

Three specimens were created, with thermal load and heating time as main parameters (Table 1). Specimens had dimensions of $600 \times 180 \times 4000$ mm and were formed as a unidirectional slab reinforced with four SD40-class HD13 Steel bars in the upper and lower parts. From material test, compressive strength of concrete was 31 MPa, tensile strength of reinforcing steel was 410 MPa, and water content was 4.9%. Heating test was performed at Fire Insurers Laboratories of Korea, with test set-up as in Fig. 5.

![Fig. 4. Basic details for specimen and thermocouple.](image)

![Fig. 5. Experimental test set-up and measurements.](image)
Specimen was simply supported on a horizontal heating furnace for single-surface heating test. Actual heated surface was \(600 \times 180 \times 3700\) mm. For heating methods, the standard fire-resistance test standard ISO834 was used, with fire load increment as a parameter. Heating time was set to 60 and 120 minutes.

\[
T_\infty = 345 \log(8t + 1) + 20 \quad (41)
\]

\[
T_\infty = 510t^{1/6} + 20 \quad (42)
\]

Here, \(t\) = time in minutes.

Table 1. List of specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>(f_{\text{c}}) [Mpa]</th>
<th>(f_y) [Mpa]</th>
<th>Cover Depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC-1</td>
<td>31</td>
<td>410</td>
<td>20</td>
</tr>
<tr>
<td>RC-2</td>
<td>31</td>
<td>410</td>
<td>20</td>
</tr>
<tr>
<td>RC-3</td>
<td>31</td>
<td>410</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Water content [Wt.%]</th>
<th>Heating Rate*</th>
<th>Heating time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC-2</td>
<td>3.5</td>
<td>I</td>
<td>60</td>
</tr>
<tr>
<td>RC-3</td>
<td>3.5</td>
<td>II</td>
<td>120</td>
</tr>
</tbody>
</table>

* I = Eq. (41), II = Eq. (42)

Table 2. Test results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ambient Temp.</th>
<th>Temperature distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>0</td>
</tr>
<tr>
<td>RC-1</td>
<td>II 60 min</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>RC-2</td>
<td>I 120 min</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>RC-3</td>
<td>II 120 min</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
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<tr>
<td></td>
<td></td>
<td>40</td>
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<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

3.2. Experimental results

The pictures of heated surface of the specimen after the experiment are shown in Fig. 6. The RC-1 and RC-3 specimens which had larger heating scale experienced more explosive fracture than the RC-2 specimen. The maximum temperature at the location of reinforcing steel for RC-1, RC-2, and RC-3 specimens was 555.9 °C, 730.5 °C, and 785.2 °C, respectively.
4. Experimental verification of numerical analysis result

4.1. Modeling for verification of analysis method

As in Fig. 8, modeling and analysis were performed for only 190 × 180 mm due to symmetry, using 3-node triangular element derived in Section 2. Elements were segmented into 20 × 20 mm, except at the interface where they were segmented finer at 10 × 10 mm to account for rapid temperature gradient at the interface.

Boundary condition $q_e$ of fire resistance test was evaluated. First for $q_e$, heating furnace had dimensions of $4 \times 3 \times 1.6$ m (ignoring lower vent), volume of $V = 19.2$ m$^3$, surface area of $A = 46.4$ m$^2$, and average radiation length of $L = 3.6(V/A) = 1.49$ m, and diesel fuel was used ($k = 0.43$ m$^{-1}$). Then from the Eq. (33)

$$
\epsilon = 1 - e^{-kL} = 0.4731
$$

Next for $q_h$, assume forced convection, turbulence in which heat flow acts parallel to the heating surface, and flow velocity of $u_0 = 8$ m/s. Then from Eqs. (38) and (39), $3 \times 10^5 < Re_\infty < 3 \times 10^6$ and $13.4 < h < 33.3$. Therefore, the mean value of $h = 23$ was used. From Eq. (40), the boundary conditions are
\[ q_e = (23 + \alpha_R)(T_w - T_0), \quad \alpha_R = 0.4731(5.6667 \times 10^{-8})(T_w^2 + T_0^2)(T_w + T_0) \]  

(44)

4.1.2. Thermal characteristic values of material

Values for thermal characteristics of the material were obtained by converting temperature- and time-dependent thermal characteristics \[ (\chi_c, \rho_c C_c(t)) \] and reinforcing steel \[ (\chi_s, \rho_s C_s(t)) \] into functions of temperature:

\[ \chi_c(t) = \begin{cases} \xi [1.5 - (0.5/800)T] & (\chi > 1.0) \\ \xi & (\chi < 1.0) \end{cases} \]  

\[ \chi_s = 40 \]  

(45)

(46)

\[ \rho_c C_c(t) = \begin{cases} \rho_c(930) & (T < 90) \\ \rho_c(930) + \rho_c w_t \frac{590 \times 4.190}{20} & (90 \leq T < 100) \\ \rho_c(930) & (T \geq 110) \end{cases} \]  

\[ \rho_s C_s = 7,850 (482) \]  

(47)

(48)

Here, \[ \xi = 0.8 \] and \[ w_t \] = water content (4.9%, assumed to be uniform within cross-section).

4.2. Analysis results and verification

Figure 9 shows comparisons of analysis and experimental results. From the temperature history curve and the analytic curve, it can be seen that the analytical method very closely estimates the temperature history. Especially, analysis result for each heating time (30, 60, 90, and 120 minutes) in Table 2 show that the ratio of experimental and analytical results was within 0.96~1.03 excluding RC-1 for 30 minute condition (0.84), corresponding to error within 10%.

However, as measurement location was further from the heating surface, error of analysis result tended to be larger. For example, ratio of experimental and analytical results at 100 mm from the heating surface for different heating times was 2.33 at maximum. The cause for this error is thought to be due to lack of consideration for water transport or relaxation of temperature gradient by latent heat as well as by experimental error and relative increase in error for small temperature values. Nevertheless, trend line closely estimated actual experimental values, especially the temperature distribution near the reinforced steel, and thereby verified the validity of the analysis method.

5. Parameter analysis

Using the nonlinear transient heat flow analysis method established in this study, parameter analysis for fire scale, thermal characteristics of concrete, and water content was performed. Analysis model shown in Fig. 8 was used for analysis of heated temperature of reinforcing steel at slab (20 mm) and pillar (40 mm).
5.1. Modeling for verification of analysis method

Analysis results of temperature distribution for different times (1, 2, 3, and 4 hours) for given standard fire heating curve (ISO 834) are shown in Fig. 10 (water content = 3%, values for thermal characteristics of concrete = Eqs. (45)–(48), and \( q_v = \text{Eq } (44) \) constant). In the figure, cooling after heating is

\[
T_x = [345 \log(8t + 1) + 20] - \eta[(345\log(8(t - t_{\text{max}})) + 1) + 20] \tag{49}
\]

Here, \( t_{\text{max}} \) = reference heating time and \( t = 4.5/3.2 \) were used. As a result of analysis, temperature by scale of fire (2 hours ISO 834) at the slab (reinforcing steel location = 20 mm) was 729 °C and the pillar (3 hours ISO 834, reinforcing steel location = 40 mm) was 641 °C, which did not satisfy the regulation standard of 547 °C for fire-resistance performance. Although lower heated temperature is expected in real structures due to flow of smoke (radiation absorption of gas) or effect of convection coefficient, measures against fire (e.g. increase in shielding thickness) will be required when there is a need to satisfy existing fire-resistance standards.

5.2. Effect of thermal characteristic values of concrete

Figure 11 shows effect of thermal conductivity of concrete (water content =3%, 2 hours ISO 834, \( q_v = \text{Eq. } (44) \) constant). Analysis showed that using thermal characteristic values of the standard (EC13) yielded results 9~10% lower than the suggested equation(12). Thermal characteristic values in the suggested equation are generally large, causing the observed discrepancy. This in turn is probably because of insufficient experimental result or difference in composition ratios of concrete used in Korea. Therefore, accumulation of test data for thermal characteristics of concrete is needed in the future.

5.3. Effect of water content inside concrete

Figure 12 shows effect of water content inside concrete (2 hours ISO 834, \( q_v = \text{Eq. } (44) \) constant, thermal conductivity Eq. (45) constant). Analysis result showed that as the water content increased, internal heated temperature decreased.
Especially, the result demonstrated decrease in gradient of heated temperature at 90–110 °C range as an effect of latent heat, which was generated by phase change (liquid to gas) of excess water. Although this study does not account for water transport into concrete and consequent increase in evaporation speed and therefore has results that differ from actual experimental data, this study is useful as analysis reflecting thermal/water transport is currently only possible in small, single-material analysis.

6. Conclusions

This study was performed as a part of analytical research on fire-resistance performance of reinforced concrete structures that may undergo high-temperature environment such as fire. Nonlinear transient heat flow analysis technique was established using Galerkin finite element method, and analysis results obtained using this technique led to the following conclusions.

(1) Verification of the nonlinear transient heat flow analysis, which uses Galerkin finite element method, of reinforced concrete structures exposed to high-temperature environment showed that time history trend line closely estimated actual experimental values. Especially, estimation of temperature distribution near the reinforcing steel was very close to the actual data. These results confirmed validity of the analysis method.

(2) Boundary conditions in this study that account for thermal convection, radiative properties, and temperature dependencies will help simulation of heat transfer that is closer to actual data. Verification test showed that for equivalent convection coefficient of specifications and fuel of heating furnace at Fire Insurers Laboratories of Korea, convection coefficient was $h = 0.23$ and internal absorptivity of heating furnace was $\epsilon = 0.4731$.

(3) The nonlinear, transient heat flow analysis method for concrete established in this study does not account for water transport and additional evaporation speed caused thereby. The following studies are required in the future.
- Analysis of explosive fracture caused by water transport and pore pressure
- When crack is formed by stress of heated temperature, explanation of material transport and stress distribution
- Introduction of shape function for time increment ($\Delta t$) and Gaussian integration
- Accumulation of sufficient experimental data on thermal characteristic values of concrete

Acknowledgements

I would like to thanks, the funders of this research, MLTM, R&D of the Slab Systems in Large Basement Floors Using Ductile Cement Composite.

References