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Determining the Temperature Distributions of Fire Exposed Reinforced Concrete Cross-Sections with Different Methods

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Abstract: The main purpose of this study is to carry out the 2d nonlinear transient heat analysis of a chosen reinforced concrete cross-section, which is exposed to standard fire, by using simplified, finite difference and finite element method. In the finite element analyses, it is considered that the thermal properties of concrete and reinforcing steel vary as depending on temperatures in time domain. According to results drawn this study, it is put forward some conclusions and recommendations concerning the fire design of reinforced concrete structures.

Keywords: Cross-section, fire, reinforced concrete, temperature distributions

INTRODUCTION

It is known that all structures within economic lifetime must have a specific safety in response to collapse by becoming out of service under loading. It is also known that the structures have to maintain these characteristics during probable fires. In the circumstances, it is necessary to take into account the fire effects in design, construction and using stages of reinforced concrete structures like other structures.

The first step of fire design is to choose or evaluate the temperature-time curve which represents the fire. After determined the environment temperature change according to time, in the second step it is possible to determine the temperature distributions of structural element which used in structural analyses. For this reason there are many methods in technical literatures. These methods can be listed in order tabulated data methods which are developed based on tests and experiences, simplified methods and numerical methods which provide to be carried out thermal analyses by computers (Burnaz and Durmuş, 2007).

The results of the thermal analysis are compared to the experimental results in the literature and the analytically derived structural results are also compared with full-scale reinforced concrete beams in previous fire exposure experiments. The comparison results indicated that the calculation procedure in this study assessed the residual bearing capabilities of reinforced concrete beams exposed to fire with sufficient accuracy. As no two fires are the same, this novel scheme for predicting residual bearing capabilities of fire-exposed reinforced concrete beams is very promising in that is eliminates the extensive testing otherwise required when determining fire ratings for structural assemblies (Hsu *et al*., 2006).

Analyzing the bearing capability of RC beams after sustaining fire requires the knowledge of temperature distribution in the cross sections. This is determined by the thermal properties of the material, such as the heat capacity and thermal conductivity. A simple thermal model, which is generally to all beams with a rectangular cross section, has been assessed in a separate serious of studies which were also reported in a previous paper Hsu *et al*. (2006).

The modeling results achieved reasonable agreement with isothermal contours obtained by Lin (1985) who analyzed the temperature distribution of pure concrete according to the time-temperature curve of standard fire.

The analytical stage in the modeling process is to increment the time of the model such that the temperature experienced by the beam is increased. The increase in the ambient temperature changes the temperature distribution inside of beam's cross-sections. After sustaining high temperature, the mechanical properties of reinforced steel and concrete vary according to the fire-induced temperature. It makes the stress distribution in such beam structures a nontrivial problem. The structural analysis in this model follows American Concrete Institute (ACI) building code, which considers the influence of temperature on reinforced steel and concrete using a lumped system method to determine flexural and shear capacities. Modeling results for flexural capacities have been compared to the calculated results using the ACI code at room temperature and also compared with full-scale RC beam fire exposure experiments (Lin, 1985). The

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Table 1: Available design charts in (ENV 1992-1-2, 1996)

Member	Cross-section dimensions (mm)	Standard fire resistance
Slabs or walls expose to one side	Thickness = 200	R30-R240
Beams	Height × width = 300×160	R30-R90 and 500ºC isotherms
	Height × width = 600×300	R60-R120
	Height × width = 800×500	R60-R240
Square columns	Height × width = 300×300	R30-R120 and 500°C isotherms
Circular columns	Diameter = 300	R30-R120 and 500°C isotherms

analytically derived shear capacities have also been compared with experimental data (Lin, 1985; Moetaz *et al*., 1996; Lin *et al*., 1999; ACI 318R-02, 2002; Buchanan, 2000).

In order to determine the fire behaviour of reinforced concrete structures, there are many methods in technical literatures. These methods can be listed in order tabulated data methods which are developed based on tests and experiences, simplified methods and numerical methods which provide to be carried out thermal and structural analyses by computers. In this study it is used a developed computer code based on finite element method for both thermal and structural analyses.

Determining the temperature distributions of rc cross-sections: Heat transfer is the science to evaluate the energy transfer that takes place between material bodies as a result of temperature difference. The three modes of heat transfer are conduction, convection and radiation. The thermal analysis on structural fire problems can be divided into two parts:

- The heat transfer by convection and radiation across the boundary from the fire into structural members
- The heat transfer by conduction within structural members

The thermal analysis in structural members can be extremely complex, especially for materials that retain moisture and have a low thermal conductivity. The simplest method of defining the temperature profile through the cross-section is to use test data presented in tables or charts which are published in codes or design guides. These tabulated data are generally based on standard fire conditions.

Simplified method, the second method of determining of temperature distributions, is presented in codes and design guides.

It is possible to use simple heat transfer models based on one-dimensional heat flow. However, simple computer programs are needed to solve the heat transfer equations. Alternatively, advance finite-element heat transfer models can be used (The Concrete Center, 2004).

MATERIALS AND METHODS

Tabulated data: Annex A of ENV 1992-1-2 (1996) provides a series of calculated temperature profiles for slabs or walls, beams and columns. The available design charts are summarized as Table 1.

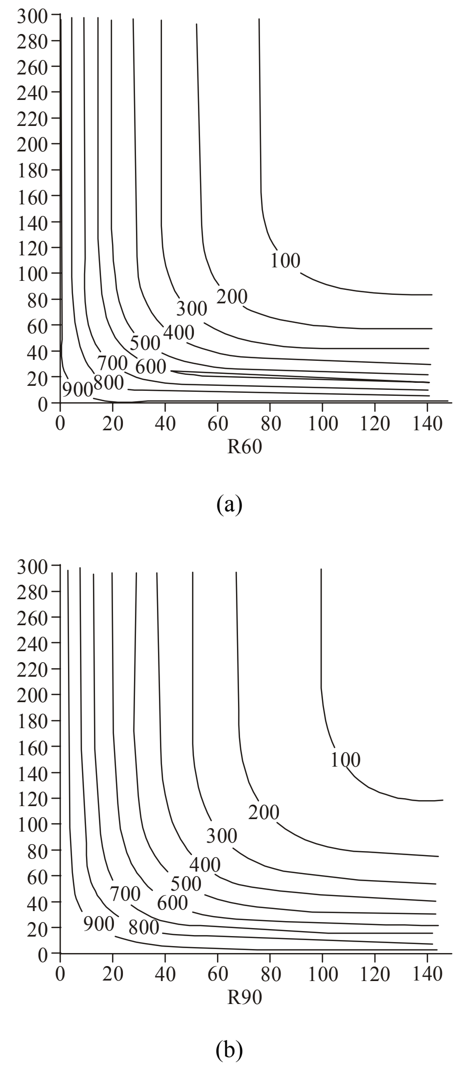

Fig. 1: Temperature profiles of a concrete beam for R60 and R90 (ENV 1992-1-2, 1996)

As an example of tabulated data, the temperature profiles of a concrete beam with 300 mm width for R60 and R90 (standart fire durations, min.) are given in Fig. 1.

Simplified method: In this study, the simple calculation method proposed by Wickström (1987) is used for calculating the temperatures in concrete members exposed to the standard fire. It should be noted that this method does not take into account of possible spalling of concrete.

The fire-exposed surface temperature T_s of a concrete member at a time *t* is first given by:

$$T_w = \eta_w T_f \tag{1}$$

with $\eta_w = 1- 0{,}0616\ t^{-0{,}88}$, where, η_w is the ratio between gas and surface temperatures of concrete member (°C) and T_f is the gas atmosphere temperatures (°C).

For uniaxial heat flow condition, the temperature rise T_c at any depth x (m) beneath the fire-exposed surface of the member is a factor η_x of the surface temperature T_w with n_x given by:

$$T_c = \eta_x T_f \tag{2}$$

where, $\eta_x = 0.18 \ln(t_h/x^2) – 0{,}81$.

The method can be applied to concrete members heated on parallel faces simultaneously, in which n_x is simply the superimposed total of the n_x values calculated with respect to each face.

The method can also be used for corners of beams where there is accommodated heat flow from two directions, through superimposition of the contributions from the orthogonal faces η_x and η_y as follows:

$$T_c = [\ \eta_w (\eta_x + \eta_y – 2\ \eta_x \eta_y) + \eta_x \eta_y\ ]\ T_f \tag{3}$$

Numerical methods: Two dimensional heat flows is governed by the following partial differential equation:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} k \frac{\partial T}{\partial x} + \frac{\partial}{\partial y} k \frac{\partial T}{\partial y} + Q \tag{4}$$

where, T(x, y, t), ρ, c, k and Q(x, y, t) are temperature distribution history, density, specific heat, isotropic conductivity and heat generation rate respectively. An integral part of above equation is in its boundary and initial conditions. The initial conditions consist of the temperature of every point in the structure when the analysis begins: $T(x, y, t_0) = T_0 (x, y)$ where the temperature distribution T_0 is specified. The boundary conditions must be defined at every point on the structures surface and can be a specified temperature history or a specified heat flow history.

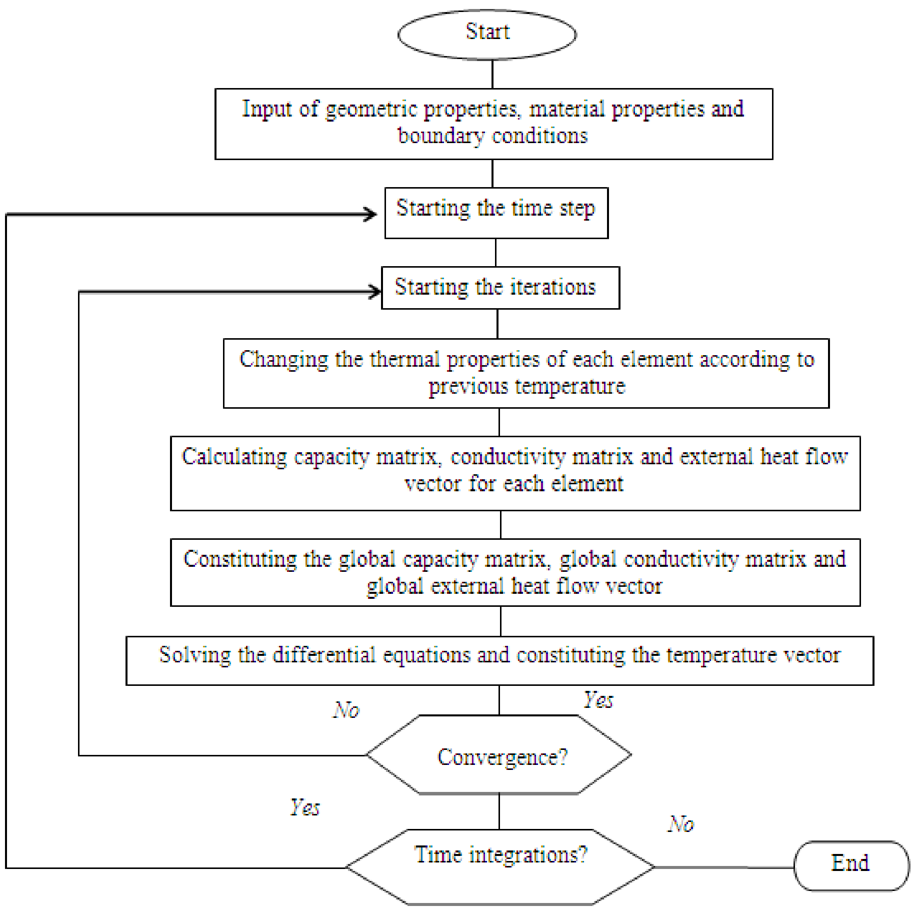

Fig. 2: Flow diagram of the nonlinear thermal analysis

The heat flow equations for two dimensional bodies are very complex and have nearly no closed-form solution. An approximate numerical method must be used in order to obtain a solution. In this study finite difference and finite element method has been used. The thermal analysis of RC cross-sections with finite difference method can be seen exhaustive in Burnaz (2003).

The finite element equations can be visualized physically in matrix form. That is, at each node in the discretization:

$$(C)\left\{\dot{T}(t_i)\right\} + (K)\left\{T(t_i)\right\} = \left\{Q(t_i)\right\} \tag{5}$$

where, (C), (K), {Q}, {T} and $\{\dot{T}\}$ are capacity matrix, conductivity matrix, external heat flow vector, temperature vector and temperature time rate of change vector respectively. The temperature rate of change vector $\{\dot{T}\}$ at any t_i can be approximated in terms of nodal temperatures:

$$\left\{\dot{T}(t_i)\right\} = \left\{T(t_i) - T(t_{i-1})\right\} / \Delta t_i \tag{6}$$

where, Δt_i is the time step between t_{i-1} and t_i. So the Eq. (5) can be written as:

$$(K + \frac{C}{\Delta t_i})\{T(t_i)\} = \{Q(t_i)\} + \frac{(C)}{\Delta t_i}\{T(t_{i-1})\} \tag{7}$$

The step-by-step assembly and solution of Eq. (4) gradually traces out the temperature history in the structure (Iding *et al*., 1977). These steps are presented in some detail in the flow diagram of Fig. 2.

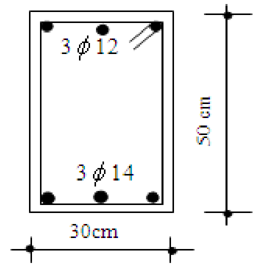

Fig. 3: The cross-section of R.C. beam

In this study ISO-834 standard fire curve which is accepted to represent the fire around the beam is used. The curve is calculated as:

$$T_f = 345 \log_{10}(8t + 1) + T_0 \tag{8}$$

where, T_f, T_0 and t are fire environment temperature, ambient temperature and time, respectively. Heat exchange at the boundaries of the fire exposed member depends on the heat transfer coefficients of both emissivity and convection. These factors and thermal properties of concrete (thermal conductivity, specific heat and density) which are function of temperature were adopted in Burnaz and Durmus (2007).

Numerical examples: The cross-section of R.C. beam is shown in Fig. 3. The diameter and longitudinal bars were ignored in the thermal analysis because of not effecting results too much. Figure 4 shows thermal cross-section finite element model of the beam which was subjected to ISO-834 standard fire (T_f (t)) from three sides and the thermal boundary conditions

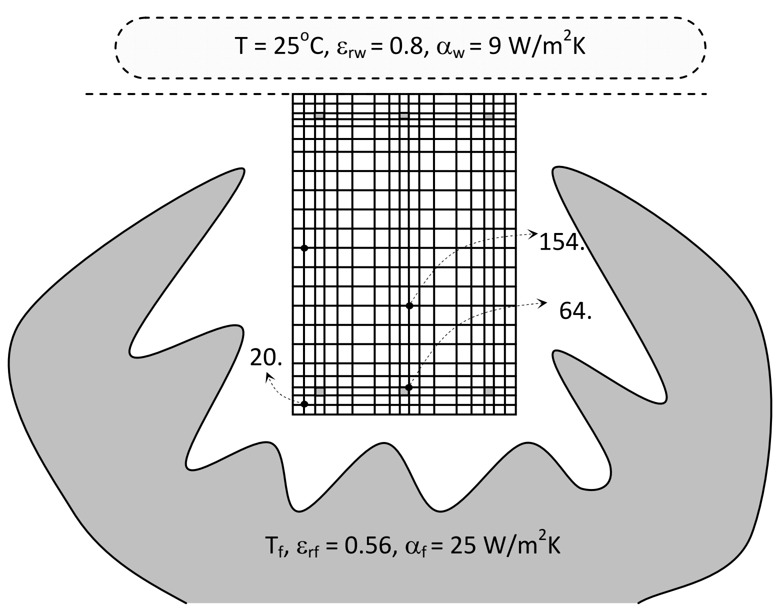

Fig. 4: Thermal finite element model of beam and boundary conditions

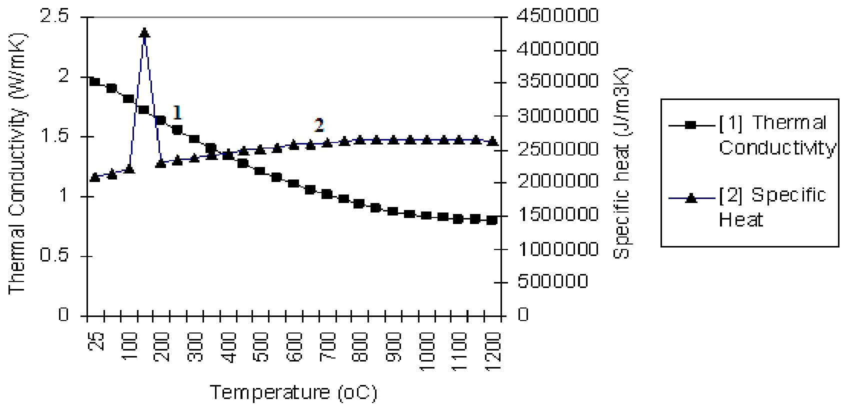

Fig. 5: The changing of thermal properties of concrete according to temperatures

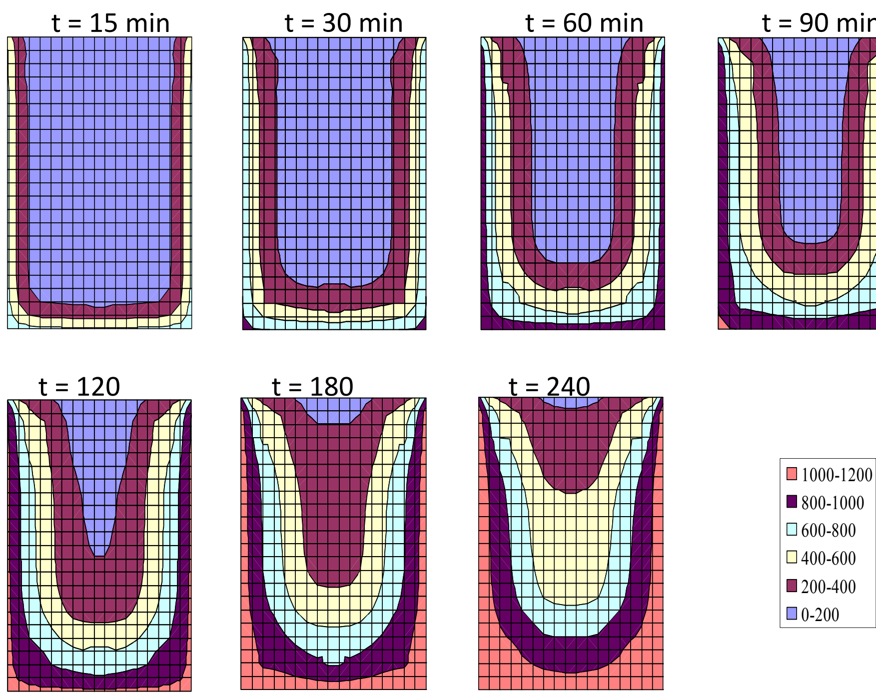

Fig. 6: The changing of temperature distributions of R.C. beam cross-section according to fire durations

(environment temperature, resultant emissivity ε_r and convection factor h_c) for fire exposed and unexposed surfaces. On the other hand, the changing of thermal properties of concrete according to temperature is given in Fig. 5.

The thermal analysis with finite element method was carried out in order to obtain temperature distribution history of beam cross-section. This was determined by using a developed computer code (Burnaz and Durmus, 2007) based on nonlinear finite element method. During thermal analysis 0.005 h was used as a time step. Finally the temperatures of all elements of beam cross-section were calculated according to each time steps.

Same numerical example was also solved with finite difference method. In this method, the thermal properties of concrete (thermal conductivity 1, 2 W/m°C, specific heat 1100 J/kg°C ve density 2200 kg/m^3) were accepted to take into constant.

RESULTS AND DISCUSSION

After running the aforementioned finite element thermal analyzing program, the temperatures of all elements of R.C. beam cross-section were determined according to each time steps. Some temperature distributions obtained from the analysis were given in Fig. 6 for 15, 30, 60, 90, 120, 180 and 240 min by using

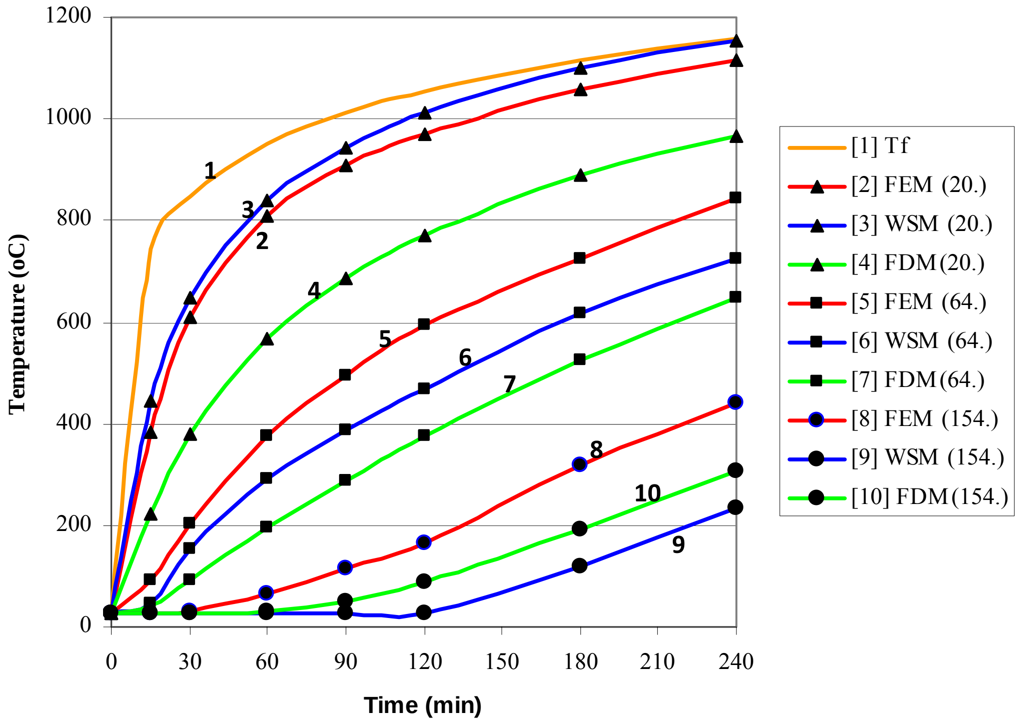

Fig. 7: The comparison of different methods for determining of temperature distributions of R.C. cross-sections

isotherm curves. As it is seen, the temperatures increase with time increment through inside the cross-section. At the end of the two hours, the temperature of some area of cross-section exceeds 1000ºC. The results are very similar to the tabulated data in EN1992-1-2 for 60 and 90 min.

The results obtained from nonlinear Finite Element Method (FEM) are compared with the Finite Difference Method (FDM) and Wickström's Simplified Method (WSM) in Fig. 7. T_f curve in this figure shows the standard temperature-time curve. If the temperature-time curves of 20th node at the bottom corner of the cross-section were compared, it is seen that the curve of WSM is very similar to FEM, but these curves are different from FDM. In the other nodes (64 and 154), differences between these methods are more than 20th node. The temperatures obtained from FEM in 64 and 154th nodes are higher than the other methods.

CONCLUSION

The comparison which has been made between nonlinear finite element, finite difference and Wickström simplified method shows that these method's results are different from each other, but the FEM's results are very similar to graphics in EN1992-1-2. Consequently, the computer codes which were developed by using nonlinear finite element method can be used for determining the temperature distributions of the R.C. cross-sections exposed to fires. However, the other methods can also be used for practical purposes.

It is obvious that these conclusions are valid for this example and its conditions. Therefore there is benefit to take into account different cross-sections, real fires and spalling of concrete in the thermal analyses of R.C. structures according to fire. The studies about this subject have been continued.

REFERENCES

ACI 318R-02, 2002. Building Code Requirements for Structural Concrete and Commentary. American Concrete Institute, Michigan.

Buchanan, A.H., 2000. Structure De-sign for Fire Safety. John Wiley and Sons, LTD, UK.

Burnaz, O., 2003. Fire in Reinforced Concrete Structures and Investigation of Fire Design on a Model. MsD, K.T.Ü., Trabzon.

Burnaz, O. and A. Durmuş, 2007. Nonlinear thermal analysis of reinforced concrete beams exposed to fire. Proceeding of ULIBTK07 16th National Thermal Science and Technology Congress, Kayseri, Turkey, (In Turkish).

ENV 1992-1-2, 1996. Eurocode 2: Design of Concrete Structures- Part 1-2: General Rules-Structural Fire Design. CEN, Brussels.

Hsu, J.H., C.S. Lin and C.B. Hung, 2006. Modeling the effective elastic modulus of RC beams exposed to fire. J. Mar. Sci. Technol., 14: 102-108.

Iding, R., B. Breslerand and Z. Nizamuddin, 1977. FIRES-T3: A computer program for the Fire response of structures-thermal. Report UCB FRG 77-15, University of California, Berkeley.

Lin, T.D., 1985. Measured temperature in concrete beams exposed to astme 119 standard fire. Research and De-velopment Report, Portland Cement Association, Skokie.

Lin, I.J., S.T. Chen and C.J. Lin, 1999. The Shear Strength of Reinforcing Concrete Beam after Fire Damage. Structure Safety Evaluation after Fire Dam-Age, Scientific and Technical Publishing Co. Ltd., Taiwan, pp: 117-136.

Moetaz, M.E., M.R. Ahmed and E. Shadia, 1996. Effect of fire on flexural behaviour of rc beams. Constr. Build. Mater, 10(2): 147-150.

The Concrete Center, 2004. Concrete and Fire, Using Concrete to Achieve Safe, Efficient Buıldings and Structures Ref. TCC/05/01, ISBN 1-904818-11-0.

Wickström, U., 1987. A very Simple Method for Estimating Temperature in Fire Exposed Concrete Structures. Swedish National Testing Institute, SP Report, Boras, Sweden.