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Nominal moment capacity of box reinforced concrete beams exposed to fire

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Abstract

The performance of steel reinforced concrete (RC) beams with a box cross section exposed to fire is studied. The cross-section is divided into an appropriate number of segments so that non-uniform temperature profiles and variations of constitutive relationships across the section can be represented accurately. The temperature distribution in the cross-section is calculated by the finite difference method. The nominal moment capacity of RC beam is obtained using equilibrium of forces in the segments of beam. Advantage of circulating cold water and cover concrete on the nominal moment capacity under fire is examined. Results obtained by the prepared computer program were found to predict the fire resistance and performance of RC box beams well.

Key Words: Fire, reinforced concrete, nominal moment capacity, beam, box section, cover concrete.

Introduction

Reinforced concrete structures are widely used. They are built to safely carry loads. Furthermore, fire may also result in additional temperature loads. If these loads are not considered in their design, safety of these structures will be threatened. The fire safety of RC structures depends on their fire resistance, which in turn depends on the combustibility and fire resistance of beams and columns. Beams are subjected to flexural and shear forces. The residual bending moment and shear force of fire-damaged concrete beams are important factors in determining safety of the structure. The properties (e.g. strength and stiffness) of the constituent materials of RC beams, namely concrete and steel, are progressively reduced by the increasing temperature. Elasticity modulus and shear modulus decrease with the increase of temperature. Reduction coefficients of concrete and steel strengths with heating can be found in Eurocode2 (1992). Analyzing the bearing capabilities of RC beams after fire requires the knowledge of temperature distribution in cross sections. Two ways may be traced for determining temperature distribution in the cross sections; namely, numerical methods, such as finite element and finite difference methods, and semi empirical approaches. An increase in the ambient temperature changes not only the temperature distribution inside the beam's cross-section, but also the mechanical properties of reinforced steel and concrete, such as flexural and shear capacities. For places with high risk of fire, such as boiler rooms, destructive effects of fire can be minimized by reducing inside temperature of the beam. Reducing inside temperature of the beam may be ensured by increasing cover concrete, isolating or circulating cold water through the beam.

Hsu et al. (2006) combined thermal and structural analyses to study the effect of fire on the elastic modulus of reinforced concrete beams. Cai et al. (2003) presented a generalised beam-column element for 3 dimensional composite structures at ambient and high temperatures. The element can model reinforced concrete and steel sections. Zha (2003) investigated the behaviours of reinforced concrete members subjected to fire by 3 dimensional non-linear finite elements. Dwaikat and Kodur (2008) presented a model to predict the influence of fire induced restraints on the fire resistance of reinforced concrete (RC) beams. ACI Committee (1994) reported the guide for determining the fire resistance of concrete elements. It was a summary of practical information to be used by engineers and architects. Abbasi and Hogg (2005) developed a general method for predicting the properties of the constituent elements of a composite rebar reinforced concrete beam during a fire test. Nadjai et al. (2005) studied the structural behaviour of concrete beams reinforced with hybrid FRP and steel reinforcements at elevated temperatures. They used the slice approach model. Saafi (2002) examined the effect of fire on the behaviour of concrete reinforced with FRP rebars. He studied the effects of concrete covers and high temperatures on the FRP temperatures and on flexural and shear capacity of FRP reinforced concrete beams. Hsu and Lin (2006) combined thermal and structural analyses to assess the residual bearing capabilities, flexural and shear capacities of reinforced concrete beams after fire exposure. They used the finite difference method to model the temperature distribution of a reinforced concrete beam maintained at high temperature. Desai (1998) suggested that an approximate route to calculate the strength of a concrete section at elevated temperature is to produce a weighted average of the local strength of the concrete over the section. In his approach, the section is effectively considered as a series of equal slices with the average strength in each slice calculated by averaging the strength at the boundaries of the slice.

Although the advantage of circulating cold water through the beam is stated in the literature, a similar study has not been came accross and this study is presented to demonstrate the advantage of this application. Firstly, temperature distribution in the cross section is obtained with the finite difference method and it is used to examine the effects of heating in each segment of cross-section. Later, an equation for the residual nominal moment capacity of the RC box beam exposed to fire is obtained. Using the prepared computer program, examples are examined for different cases as exposed to fire surfaces, cover concrete, and circulating cold water through the beam. Results from case studies are presented to illustrate the influence of fire for different conditions on the fire resistance of the RC box cross section beams.

Strength Reduction in Concrete and Rebar

Effect of fire on the concrete

The compressive concrete strength reduces at high temperatures (Saafi, 2002). Therefore, this reduction has to be taken into consideration. The local concrete compressive strength σ_{cT} can be calculated knowing the temperature at each position and using the relationship given in Eurocode2 (1995) which requires the concrete compressive strength $\sigma_{c20^\circ C}$ at normal temperature and a specified concrete reduction factor k_c obtained from the following formulas:

$$\left.\begin{array}{lll}\frac{\sigma_{cT}}{\sigma_{c20^\circ C}} = k_c & & \\ k_c = 1 & \text{for} & T \leq 100 \\ k_c = (1.067 - 0.00067T) & \text{for} & 100 \leq T \leq 400 \\ k_c = (1.44 - 0.0016T) & \text{for} & 400 \leq T \leq 900 \\ k_c = 0 & \text{for} & 900 \leq T \end{array}\right\} \tag{1}$$

where T is °C.

As shown in Figure 1, after 100 °C, the compressive strength falls. At 400 °C, it reaches %80 of its initial value of the ambient temperature. With rising temperature, it continues to reduce and finally becomes zero at 900 °C.

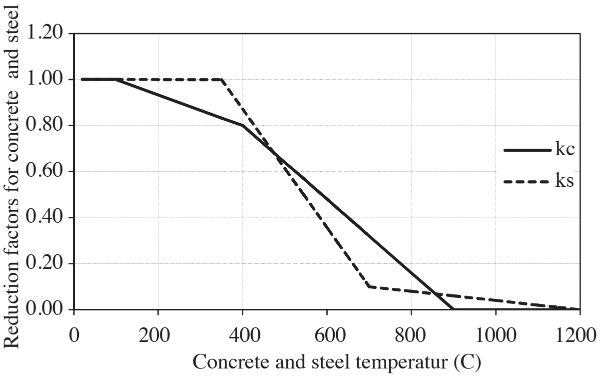


Figure 1. Reduction factors for concrete and steel strength.

Effect of fire on rebar

The values of reduced ultimate tensile strength of rebars due to the temperature can be obtained from the following equations (Eurocode2, 1995):

$$\left.\begin{array}{lll}\frac{f_{suT}}{f_{su20^\circ C}} = k_s & & \\ k_s = 1 & \text{for} & 0 \leq T \leq 350 \\ k_s = 1.899 - 0.00257T & \text{for} & 350 \leq T \leq 700 \\ k_s = 0.24 - 0.0002T & \text{for} & 700 \leq T \leq 1200 \\ k_s = 0 & \text{for} & 1200 \leq T \end{array}\right\} \tag{2}$$

where $f_{su20^\circ C}$ and f_{suT} are the ultimate tensile strength of rebars at 20 °C and temperature °C, respectively and k_s is the temperature reduction factor for the tensile strength. The yield stress remains constant till 350 °C and 700 °C, where it gets %10 of its initial value at the ambient temperature. The yield stress completely disappears at 1200 °C (Figure 1).

Temperature distribution inside beam cross-section under elevated temperature

In conduction analysis, determination of the temperature distribution is generally achieved by solving the appropriate form of the heat equation. For 2 dimensional, steady-state conditions with no generation and constant thermal conductivity, this form is (Incropera and Dewitt, 1996),

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \tag{3}$$

Analytical methods may be used, in certain cases, to affect exact mathematical solutions to steady, 2 dimensional conduction problems. These solutions have been generated for simple geometries and boundary conditions. However, generally, 2 dimensional problems involve geometries and/or boundary conditions that prevent such solutions. In these cases, a numerical technique is often used, such as finite difference, finite element, or boundary element methods.

In this study, we will consider the numerical solution of 2-dimensional steady heat conduction in rectangular coordinates using the finite difference method. In finite difference analysis, if a square mesh is used for simplicity, the finite difference formulation of an interior node is obtained by adding the temperatures of the 4 nearest neighbors of the node, substracting 4 times the temperature of the node itself, and adding the heat generation term. It can also be expressed in the following form, which is easy to remember (Çengel, 1998):

$$T_{left} + T_{right} + T_{top} + T_{bottom} - 4T_{node} = 0 \tag{4}$$

Residual ultimate moment capacity of reinforced concrete beams with box cross section at high temperatures

Present method

Once the temperature variations are known, the effects of temperature on the material properties and moment capacity of the beam can be examined. As can be understood from the reduction coefficients given in the previous section, rising temperature results in both the corruption of the material properties and decreases in the ultimate moment capacity of the beam. The harmful effects of high temperature due to fire can be prevented by cooling the structure. If the surface temperature can be lowered, then the materials used in the beam will be less affected. For that purpose, water with specified discharge and low temperature is assumed to be circulated through the inside of the beam. That's why, a box sectioned beam was chosen in this study.

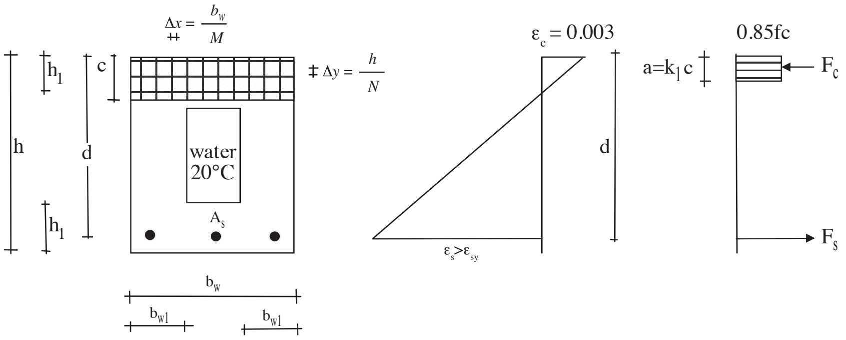


Figure 2. Variation of the strains and the internal forces in a box cross-section beam.

The flexural capacity of a beam is the ultimate bending moment that can be sustained by the beam in flexure before the failure occurs. Equilibrium between the compressive and tensile forces acting on the beam cross section at nominal strength should be satisfied. In order to ensure a ductile mode of failure, steel must be yielded before the crushing of concrete. The ultimate bending moments of RC beams after fire damage decrease, because of the reduced material properties after exposure to high temperature. Temperature distribution in the beam must be known to obtain the change of material properties inside the beam. The cross section of RC beam is divided into M×N segments and for each segment the material temperature, reduction factors, and mechanical characteristics are specified.

The tension force in the steel rebars can be derived by (Figure 2):

$$F_s = \sum_{i=1}^{M}\sum_{j=1}^{N} k_{s_{ij}} f_y A_{s_{ij}} \tag{5}$$

The compressive force in the concrete can be calculated by summing all the compressive forces on the compressive side of lumped units.

$$F_c = 0.85\sum_{i=1}^{M}\sum_{j=1}^{\frac{a}{\Delta y}} k_{c_{ij}} f_c \Delta x \Delta y \tag{6}$$

If the forces of the cross section are in static equilibrium, Eqs. (5) and (6) should be equal. If not, the value of c is increased progressively and the calculation is repeated. The process continues until Eqs. (5) and (6) are equal. When the beam is in equilibrium, the residual nominal moment of the beam M_n can be calculated as:

$$M_n = 0.85\sum_{i=1}^{M}\sum_{j=1}^{\frac{a}{\Delta y}} k_{c_{ij}} f_c \Delta x \Delta y \left(d - \frac{\Delta y}{2} - j\Delta y\right) \tag{7}$$

where f_c is the concrete compressive strength at a temperature of 20 °C, f_y is the steel yielding strength at temperature 20 °C, F_c and F_s are compressive and tensile forces in beam, respectively. M_n is the residual nominal moment capacity in beam. k_{cij} and k_{sij} are the reduction factors for each segment of the material temperature in beam.

Behaviour of the beam under the influence of bending can be observed using the moment-curvature diagram. Stress-strain behaviour of steel can be selected to be elasto-plastic for *M-Ø* diagram. In case stress-strain behaviour of concrete can be selected from one of different stress-strain formulas (Ersoy, 1987), the concrete strain on the compression face of the beam ε_{ci} is selected as a value for illustrating *M-Ø*, neutral axis c is assumed, and ε_{ci} and σ_{si} resulted in rebars are obtained. Elasticity modulus is assumed to be $E_s = 2 \times 10^5$ N/mm^2.

$$\begin{aligned} \sigma_{s1} &= 600\frac{c-d'}{c} \leq f_{yd} \\ \sigma_{s2} &= 600\frac{\frac{h}{2}-c}{c} \leq f_{yd} \\ \sigma_{s3} &= 600\frac{d-c}{c} \leq f_{yd} \end{aligned} \tag{8}$$

If the forces of the cross section are in equilibrium, Eqs. (9) and (10) should be equal. If not, the value of c is increased progressively, and the calculation is repeated. Forces are in negative sign for tension. When the beam is in equilibrium, the moment capacity of the beam M_i is calculated as taking moment according to center of gravity, and curvature is obtained using $\phi_i = \frac{\varepsilon_{ci}}{c}$. Similar treatments are repeated for different ε_{ci} and other M_i and ϕ_i values are calculated (Eq. 11). *M-Ø* diagram is illustrated using obtained M_i and ϕ_i values.

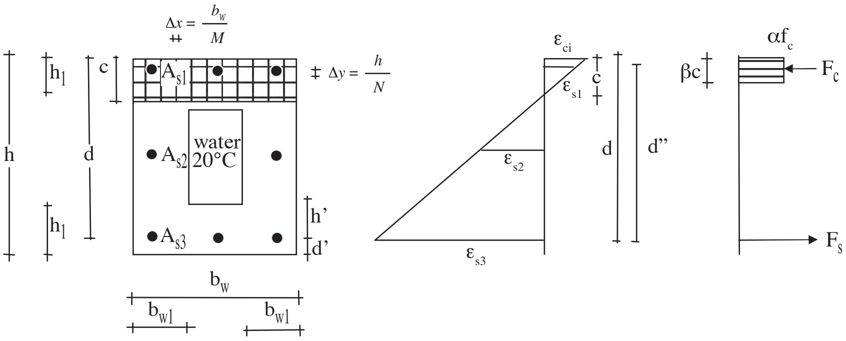


Figure 3. Variation of the strains and the internal forces in a box cross-section beam for different levels.

$$F_s = A_{s1}\sigma_{s1} + A_{s2}\sigma_{s2} + A_{s3}\sigma_{s3} \tag{9}$$

$$F_c = \sum_{i=1}^{M}\sum_{j=1}^{\frac{a}{\Delta y}} k_{c_{ij}}\alpha f_c \Delta x \beta \Delta y \tag{10}$$

$$\begin{aligned} M_n = & \sum_{i=1}^{M}\sum_{j=1}^{\frac{a}{\Delta y}} k_{c_{ij}}\alpha f_c \Delta x \beta \Delta y \left(\frac{h}{2} - \frac{\Delta y}{2} - j\Delta y\right) \\ & + A_{s1}\sigma_{s1}\left(\frac{d"}{2}\right) + A_{s2}\sigma_{s2}\left(\frac{d"}{2}\right) \end{aligned} \tag{11}$$

Approximate method

If surface in the compression region is isolated, effect of increasing temperature in beam compression region will be low. If this effect is ignored, it may be sufficient to use only the change in the tensile strength (ACI216, 1994). The residual nominal moment capacity of the beam M_n can be calculated as:

$$a = \frac{A_s f_y k_s}{0.85 f_c b_w} \tag{12}$$

$$M_n = A_s f_y k_s \left(d - \frac{a}{2}\right) \tag{13}$$

However, this equation is not appropriate for exposed fire to the beam compression region.

Advised method in ACI 216

If changing compression strength mentioned in the previous section is not ignored, the method given in ACI216 (1994) can be used. In this method, temperature is obtained for concrete and steel using d', b_w, and effective d ($0.35d$). k_c and k_s are obtained from given illustrations using the examined temperatures. As a result M_n can be obtained from the following formulas:

$$a = \frac{A_s f_y k_s}{0.85 f_c b_w k_c} \tag{14}$$

$$M_n = A_s f_y k_s \left(d - \frac{a}{2}\right) \tag{15}$$

For circulation of cold water through the inside of beam

Instead of using insulation material to prevent harmful effects of high heat, beams can be cooled by circulating cold water through the inside of them. This solution requires employing a beam that allows water to pass inside, such as a box cross-sectioned beam. With this solution, the temperature inside the beam decreases and temperature distribution also changes in a positive manner. Hence, the mechanical properties of the concrete and steel would be less affected and they would stay within acceptable limits.

This solution can be applied to columns and/or beams. For column applications, natural circulation, where the heated water rises and replaces the cold water, is adequate. However, for the applications of a whole carrying structure, columns and beams should be connected to each other using a kind of pipe network. In this case, leakage particularly at joints may occur. To prevent the leakage, water to the pipe network is given only in case of fire. This can be achieved using an automatic fire alarm. There is a need for a pump to circulate the water (Demirel and Özkan, 2003). In addition, inside of the box cross section of the beam may be covered with a resistant material to high temperatures to prevent loss of water in case of cracked concrete. Application of the system appears to be a complex process; however, it certainly is useful for fire safety.

The ISO834 temperature-time curve

There are some international temperature-time curves such as ISO834 (1975), BS476 (1987), ASTM119 (1998), NFPA251 (1999), the external (2002), the hydrocarbon (2002), and the Eurocode parametric curve (2002). In this study, ISO834 is used as shown in Figure 4. The equation for the ISO834 temperature-time curve is as follows:

$$T = 345 \log_{10}(8t + 1) + T_a \tag{16}$$

where t is the fire exposure time and T_a is the ambient temperature (°C).

Parametric Study

A rectangular RC beam exposed to fire

Firstly, temperature distribution inside the RC beam as given in Macgregor and Wight's book (2005) was obtained using the finite difference method with the prepared computer program (Figures 5 and 6). Afterwards, to show the usability of the method, the nominal moment capacity for the present method, the approximate method, and the method given in ACI216 were subjected to different fire time exposures (Figure 7). The results obtained from all 3 methods were found to be similar.

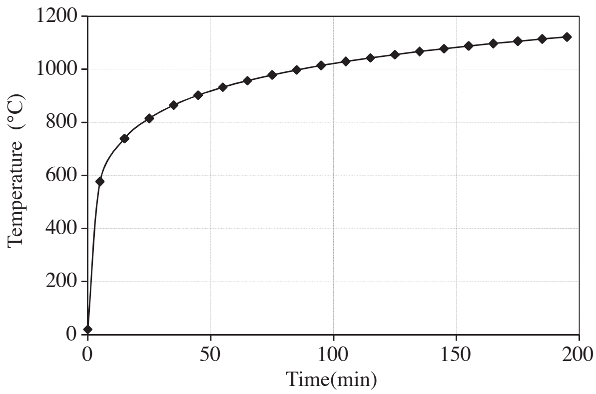


Figure 4. ISO834 temperature time curve.

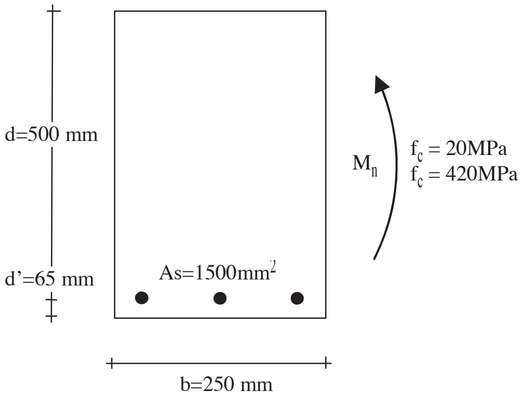


Figure 5. Cross-section and material properties of RC beam.

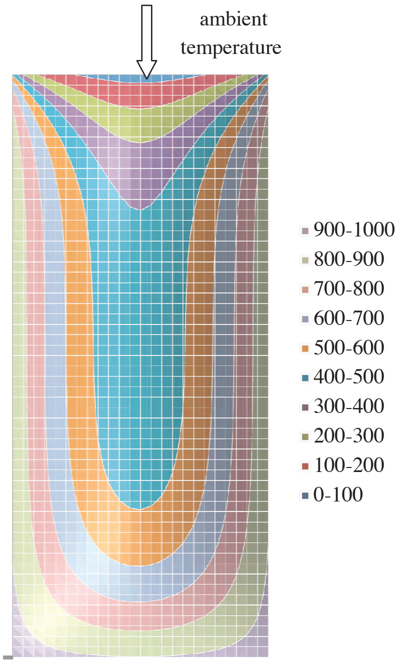


Figure 6. Temperature distribution in RC beam for t = 60 min (945 °C).

A box RC beam exposed to fire for different d' values

In this section, an RC box beam with given material and cross-section properties in Figure 8 is examined. Temperature distributions inside cross-section exposed to fire from different surfaces for t = 60 min are given in Figures 9, 10, 11, and 12. Temperature inside cross-section for unexposed and exposed fire in all surfaces is same in everywhere for uncirculating cold water. Average T_s and k_s in rebars and M_n are given in Table 1 for different exposure to fire condition. Table 1 shows that decreasing temperature in rebars has a positive effect. Thus, it can be said that circulating water to cool the beam exposed to fire may be favourable.

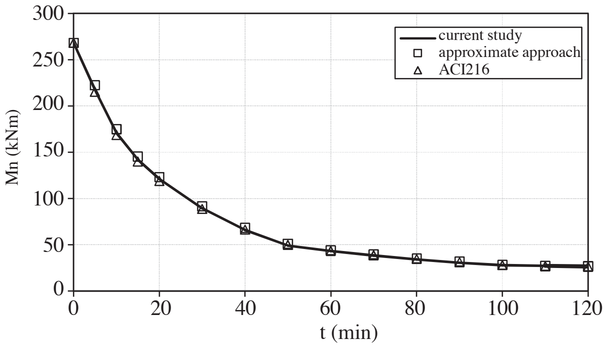


Figure 7. $M_n - t$ relationship for different methods.

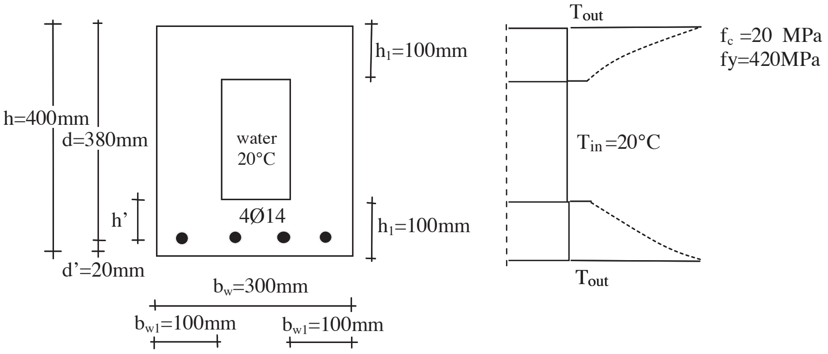
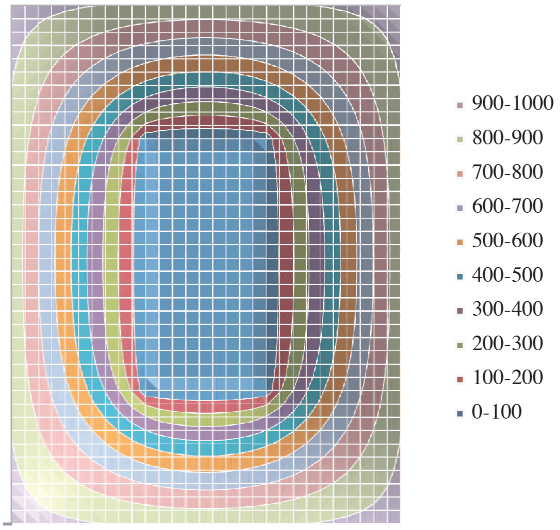


Figure 8. Details of the RC box beam used in case studies.



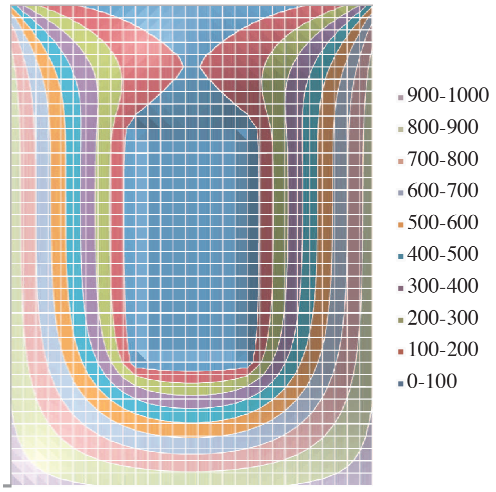


Figure 9. Temperature distribution in the box RC beam exposed to fire from all surfaces (t = 60 min).

Figure 10. Temperature distribution in the RC box beam exposed to fire for isolated top surface (t = 60 min).

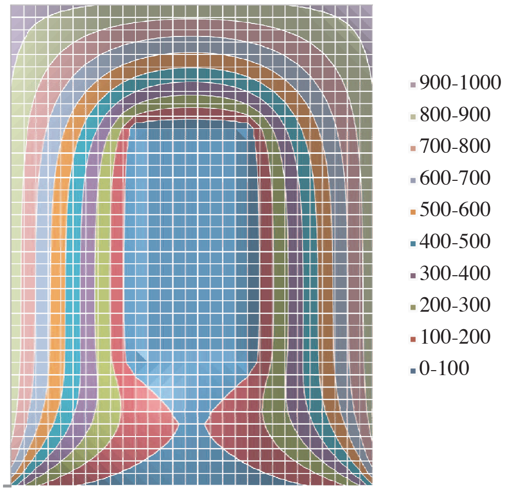


Figure 11. Temperature distribution in the RC box beam exposed to fire for isolated bottom surface ($t = 60$ min).

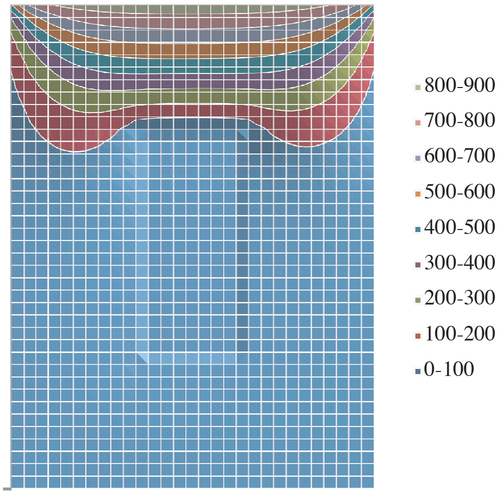
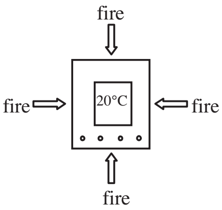
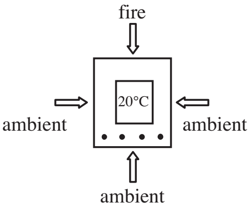
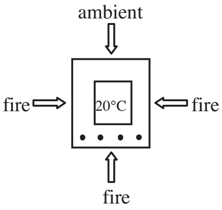
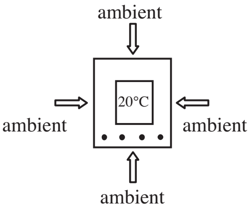
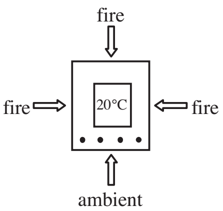
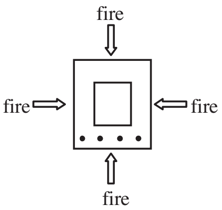


Figure 12. Temperature distribution in the RC box beam exposed to fire from top surface ($t = 60$min).

Table 1. Average T_s and k_s in the rebars and M_n for different heating surfaces ($t = 60$ min).

Fire surface	T_s °C	k_s	M_n kNm	Fire surface	T_s °C	k_s	M_n kNm
	827	0.07	6.92		20	1.00	85.52
	827	0.07	7.23		20	1.00	91.76
	278	0.86	67.04		945	0.05	0

In addition, average T_s and k_s in rebars and M_n of the example are obtained for $t = 0$, 5, 60, and 120 min and different d' values and illustrated in Figures 13, 14, and 15. The figures show that temperature in rebars is decreased with increasing d' and k_s and M_n are less affected from fire. Hence, it is understood that choosing larger value of d' assists to save the M_n value. Figure 15 shows that durability of beam with a bigger d' for the same section and material can be increased. M_n value reduces fast in a short fire time as $d' = 20$mm. However, M_n value reduces slowly as increasing fire time at $d' = 80$ mm.

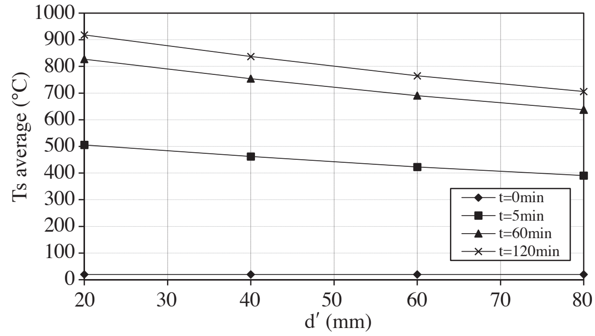


Figure 13. $T_s - d'$ relationship in the RC box beam for different d' and $t = 0$, 5, 60, and 120 min.

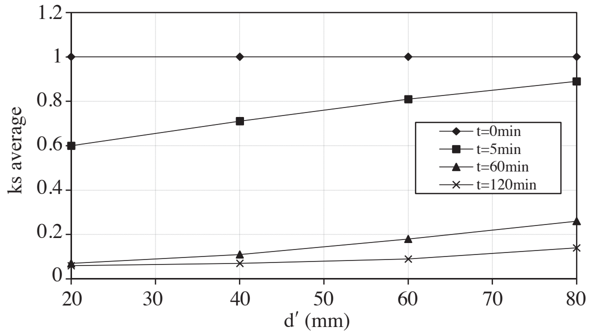


Figure 14. $k_s - d'$ relationship in the RC box beam for different d' and $t = 0$, 5, 60, and 120 min.

A box RC beam exposed to fire for different h' values

This time, the effect of water circulation through the inside of beam is examined. Hence, the box beam with properties presented in Figure 8 is used for $d' = 20$ mm. Temperature inside cross-section is 20 °C. Average T_s and k_s in rebars and M_n of the example are obtained for $t = 0$, 5, 60, and 120 min and different h' values, and illustrated in Figures 16, 17, and 18. The figures show that temperature in rebars is decreased with decreasing h' and especially for short exposure fire time k_s and M_n are less affected from fire. The reason is that temperature of rebars decrease as internal surfaces of rebars are approached.

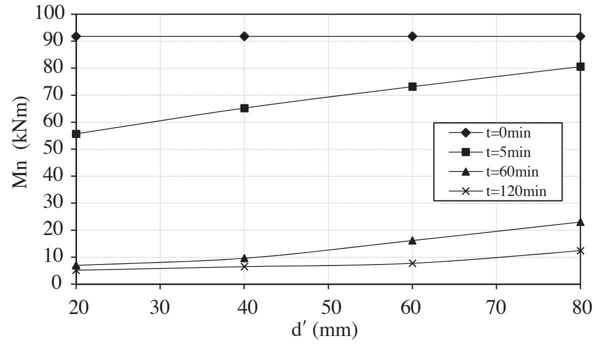


Figure 15. $M_n - d'$ relationship in the RC box beam for different d' and $t = 0$, 5, 60, and 120 min.

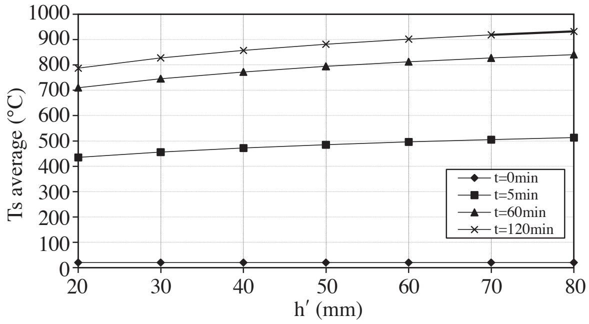


Figure 16. $T_s - h'$ relationship in the RC box beam for different h' and $t = 0$, 5, 60, and 120 min.

In the present instance, the effect of both d' and h' is investigated. Average T_s and k_s in rebars and M_n values for $t = 60$ min and different d' and h' values are obtained (Figures 19, 20, and 21). It is seen that temperature in rebars with increase of d' and decrease in h' decreases and it is not sufficient for only increasing d' for decreasing of temperature in rebars. Increasing d' as well as decreasing h' affect average T_s and k_s in rebars and M$_n$ values positively. For example, average k_s is 0.07 for $d' = 20$mm and $h' = 70$mm. However, if $d' = 80$mm and $h' = 10$mm are selected, average k_s is 0.899. Comparably, moment capacity is also 6.81 kNm for $d' = 20$mm and $h' = 70$mm. However, M_n is 69.83kNm for $d' = 80$mm and $h' = 10$mm.

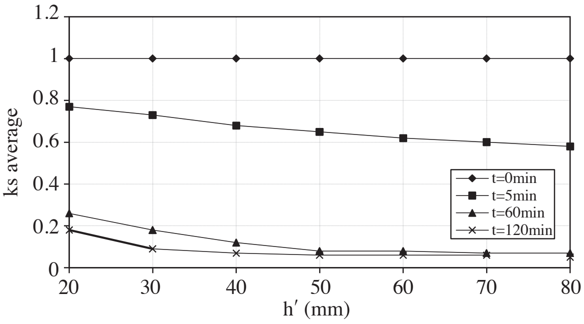


Figure 17. $k_s - h'$ relationship in the RC box beam for different h' and t = 0, 5, 60, and 120 min.

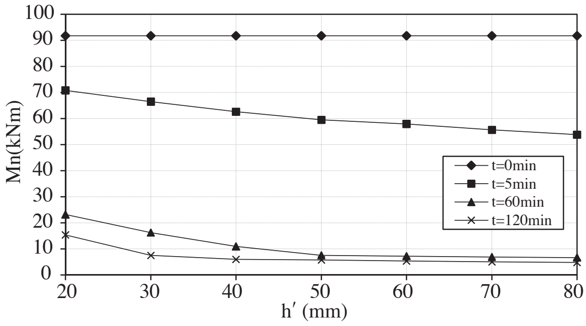


Figure 18. $M_n - h'$ relationship in the box RC beam for different h' and t = 0, 5, 60, and 120 min.

Moment-curvature diagram of a RC box beam having reinforcements in different levels exposed to fire

In this section, moment-curvature relation of a RC box beam having reinforcements in different levels exposed to fire is investigated (Figure 22). Equivalent stres-strain diagram of Hognestad model is used for concrete (Ersoy, 1987). Elasto-plastic model is used for steel. *M-Ø* diagrams are obtained for different exposure times (t = 0, 5, 60, and 120 min.) and are given in Figure 23. It is seen from figure that plastic-moment capacity value decreases while the fire exposure time increases.

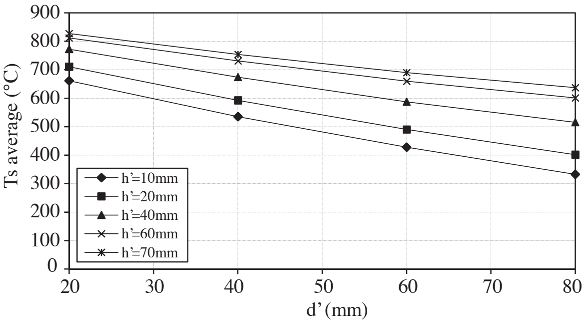


Figure 19. $T_s - d'$ relationship in the RC box beam for different d' and h’ (t = 60 min).

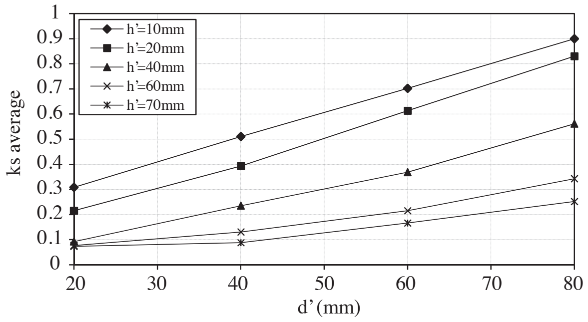


Figure 20. $k_s - d'$ relationship in the RC box beam for different d' and h’ (t = 60 min).

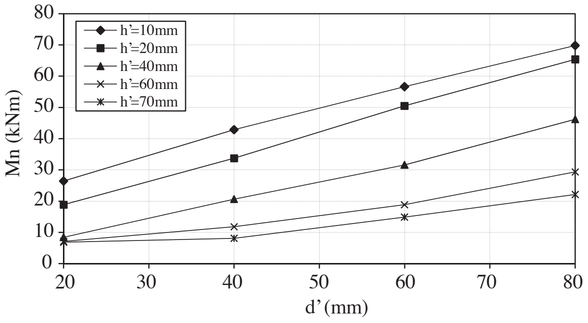


Figure 21. $M_n - d'$ relationship in the RC box beam for different d' and h’ (t = 60 min).

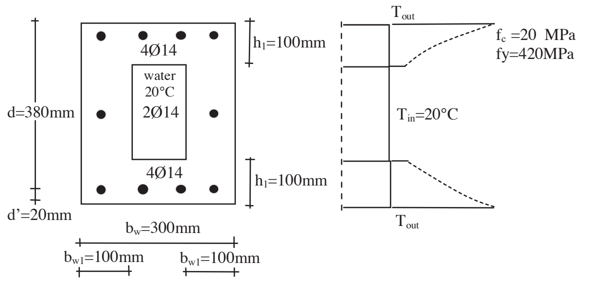


Figure 22. Details of the RC box beam having reinforcements in different levels for moment-curvature relationship.

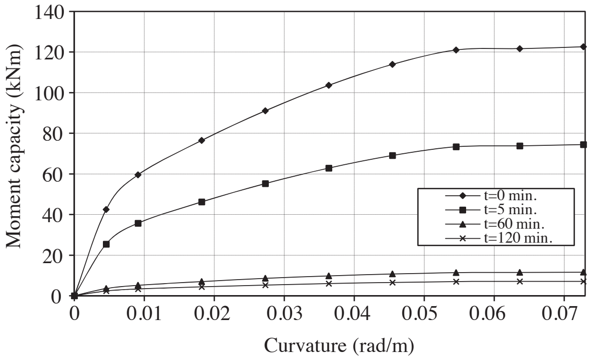


Figure 23. Moment-curvature relationship for RC **box** beam having reinforcements in different levels.

Nomenclature

A_s	the area of reinforcement steel
b_w	the width of the beam
d	the distance from the extreme fiber in compression to the centroid of the steel on the tension side of the beam
d'	the distance from the extreme fiber in tension to the centroid of the steel on the tension side of the beam
h	the overall height of beam cross section
f_c	the compressive strength of the concrete
f_y	the yield strength of the reinforcement
k_c	the temperature reduction factor for the compression strength
k_s	the temperature reduction factor for the tensile strength
M_n	the nominal moment capacity
σ_s	the current stress in steel
ε_{ci}	the assumed concrete strain on the compression face of the beam
ε_{si}	the strain in the reinforcements

Conclusions

With this study, the relationships between the use of circulating water to cool the beam exposed to fire and the nominal moment capacity of the beam are investigated. To do this, unlike the literature, a box cross-section beam is selected. Several formulas describing different heat conditions in a fire are first developed and then used in examples. Temperature distribution inside cross-section is obtained by the prepared computer program using the finite difference method. Comparisions are made between the nominal moment capacities obtained from different heat conditions, d' and h' values. It is concluded that both the material mechanical properties and the nominal moment capacities of the beam reduces with rising temperature, which also increases with time. It is shown that concrete cover is important for fire resistance. In addition, application of the circulation of cold water is found to be very effective and improve the material mechanical properties and so the nominal moment capacities of the beam exposed to fire. It may be suggested that its use particularly in tall buildings would be very beneficial in terms of the structure safety.

References

Abbasi, A. and Hogg, P.J., "A Model for Predicting the Properties of the Constituents of a Glass Fibre Rebar Reinforced Concrete Beam at Elevated Temperatures Simulating a Fire Test", Composites part B, 36, 384-393, 2005.

ACI216 R-89, "Guide for Determining the Fire Endurance of Concrete Elements", ACI Committee 216, 1994.

ASTM 119-98, "Standard Test Methods for Fire Testing of Building Construction and Materials", American Society for Testing and Materials, Philadelphia, 1998.

BS 476-20, "Method of Determination of Fire Resistance of Elements of Constructions", Fire Tests on Building Materials and Structures, British Standard Institution, 1987.

Cai, J., Burgess, I. and Plank, R., "A Generalised Steel/Reinforced Concrete Beam-Column Element Model for Fire Conditions", Engineering Structures, 25, 817-833, 2003.

Çengel, Y.H., "Heat Transfer: A Practical Approach (International Edition)", McGraw-Hill, 57-111, 1998.

Demirel, F. and Özkan, E., "Steel Structures Components and Fire Safety Protections", J. Fac. Eng. Arch. Gazi University, 18(4), 89-107, 2003 (in Turkish).

Desai, S.B., "Design of Reinforced Concrete Beams under Fire Exposure Conditions". Mag. Concrete Res. 1998;1:75-83.

Dwaikat MB, Kodur VKR. "A Numerical Approach for Modeling the Fire Induced Restraint Effects in Reinforced Concrete Beams", Fire Safety Journal, 43-4, 291-307, 2008.

Ersoy, U., Reinforced Concrete, Evrim, 95-139, 1987.

Eurocode 1, "Actions on Structures, ENV1991 Part 1-2: External Fire Curve Section 3.2.2.", European Committee for Standardization Brussels, 2002.

Eurocode 1, "Actions on structures, ENV1991 Part 1-2: Hydrocarbon curve Section 3.2.3.", European Committee for Standardization Brussels, 2002.

Eurocode 1, "Actions on Structures, ENV1991 Part 1-2: Parametric Temperature-Time Curve Appendix A.", European Committee for Standardization Brussels, 2002.

Eurocode 2, "Design of Concrete Structures, ENV 1992 Part 1-2: General Rules-Structural Fire Design", European Committee for Standardization, Brussels, 1995.

Hsu, J.H., Lin, C.S. and Huang, C.B., "Modeling the Effective Elastic Modulus of RC Beams Exposed to Fire", Journal of Marine Science and Technology,14(2), 102-108, 2006.

Hsu, J.H. and Lin, C.S., "Residual Bearing Capabilities of Fire-Exposed Reinforced Concrete Beams", International Journal of Applied Science and Engineering, 4(2),151-163, 2006.

Incropera, F.P. and Dewitt, D.P., "Fundamentals of Heat and Mass Transfer", John Wiley&Sons, 161-209, 1996.

ISO-834, "Fire Resistance Tests-Elements of Building Construction Part 1-9", International Standards Organisation, Geneva, 1975.

Macgregor, J.G. and Wight, J.K., "Reinforced Concrete Mechanics and Design", Pearson Prentice Hall, 100-162, 2005.

Nadjai, A., Talamona, D. and Ali, F., "Fire Performance of Concrete Beams Reinforced with FRP Bars", Proceeding of the Int. Sympsium on Bond Behaviour of FRP in Structures, 401-410, 2005.

NFPA 251, "Standart Methods of Test of Fire Endurance of Building Construction and Materials", National Fire Protection Association, Quincy, 1999.

Saafi, M., "Effect of Fire on FRP Reinforced Concrete Members", Composite Structures, 58, 1-20, 2002.

Zha, X.X., "Three-Dimensional Non-Linear Analysis of Reinforced Concrete Members in Fire". Building and Environment, 38, 297-307, 2003.