The 2014 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM14)
Busan, Korea, August 24-28, 2014

Numerical Approach of RC Structural Members Exposed to Fire and After-Cooling Analysis

Ju-young Hwang[1)] and *Hyo-Gyoung Kwak[2)]

[1), 2)] *Department of Civil Engineering, KAIST, Daejeon 305-600, Korea*
[2)] *kwakhg @kaist.ac.kr*

ABSTRACT

This paper introduces a numerical analysis method for reinforced-concrete (RC) structures exposed to fire and compares the result with experimental results. The proposed analysis method for RC structure under the high temperature consists of two procedures. First step is to decide the temperature distribution across the section through the heat transfer analysis by using the time-temperature curve. After determination of the temperature distribution, the nonlinear analysis is followed. By considering material and geometrical nonlinearity with the temperature distribution, nonlinear analysis predicts the behavior of RC structure under the fire by the exposed time. The proposed method is validated by the comparison with the experimental results. Finally, prediction model to describe the status of after-cooling concrete can also be introduced based on the results of additional experiment.

1. INTRODUCTION

Concrete is one of the common material for structures that has a good resistance against high temperature. Despite its high resistance, RC structure gets damaged with loss of material strength or nonlinear deformation when exposed to high temperature. Especially, fire occurred in building structure, like high-rise building, apartment and department store, can lead to collapse the structure and also be the cause of human injuries and often even deaths. So it is essential to evaluate the ability against high temperature for RC structure to avoid the fire disaster.

There were several studies to evaluate the ability of RC structures at the high temperature. At the first, experimental approaches were the mainstream to investigate the behavior of RC members under fire. But there were so many limitations for doing experiment, so analytical approaches were needed. Researchers suggested the material model for RC members (Youssef 2007, Kodur 2012), and also the numerical model and method to evaluate RC structures (Terro 1998, Bratina 2008, Huang 2009).

The analysis program used in this paper is self-developed program which is

---

[1)] Graduate Student

[2)] Professor

programmed by using 「MATLAB®; Mathworks」 and 「Fortran 90」. Heat-transfer analysis procedure and nonlinear RC structure analysis procedure operates independently. Finite element procedure is applied to proposed analysis method and it is validated by performing the correlation study between experimental data and numerical results. Furthermore, the proposed model is modified and introduced to describe the status after-cooling concrete based on the results of experiments on fire-damaged concrete.

2. MATERIAL MODEL

2.1 Concrete

Compressive strength and material stiffness of concrete is reduced when it is exposed under high temperature as fire. Several researchers have been suggested material models to describe the fire-damaged concrete. The proposed stress-strain curve was based on the Lie & Lin model (Lin 1981), Hertz model, and Khennane & Baker model (Youssef 2007). Tension part is simplified to linear in this analysis method. Eq. (1) through Eq. (5) shows concrete material model.

$$\sigma_{c,T} = f'_{c,T}[1-(\frac{\varepsilon_{co,T}-\varepsilon_{c,T}}{\varepsilon_{co,T}})^2], \qquad \varepsilon_{c,T} \le \varepsilon_{co,T} \tag{1}$$

$$\sigma_{c,T} = f'_{c,T}[1-(\frac{\varepsilon_{co,T}-\varepsilon_{c,T}}{3\varepsilon_{co,T}})^2], \qquad \varepsilon_{co,T} \le \varepsilon_{c,T} \tag{2}$$

$$f'_{c,T} = f'_c \cdot [\frac{1}{1+\frac{T}{T_1}+(\frac{T}{T_2})^2+(\frac{T}{T_8})^8+(\frac{T}{T_{64}})^{64}}] \tag{3}$$

$$\varepsilon_{co,T} = 0.003, \qquad 20℃ \le T \le 200℃ \tag{4}$$

$$\varepsilon_{co,T} = 0.00001156 \cdot T + 0.000646 \le 0.0082, \qquad \mathrm{T} \ge 200℃ \tag{5}$$

where, ε_{co} : Strain at the maximum strength
f'_c : Maximum compressive strength
$f'_{c,T}$: Maximum compressive strength at T
ε_{co}, T : Strain at $f'_{c,T}$

2.2 Steel

Yield strength and stiffness of steel material is also reduced under high temperature, and enters the plastic zone after yielding. In this paper, EN1992-1-2 steel model (EN1992-1-2 2004) is adopted to explain temperature creep effect on steel well. More details about stress-strain relationship or reduction factor of the properties of steel at elevated temperature can be found in the referred design code (EN1992-1-2 2004).

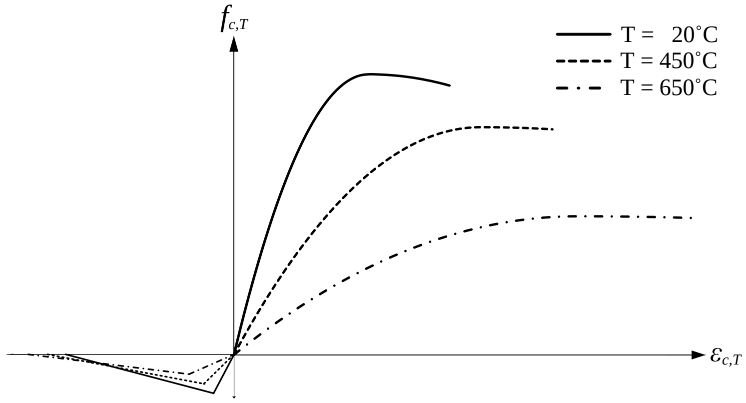

Fig. 1 Stress-strain relationship for concrete

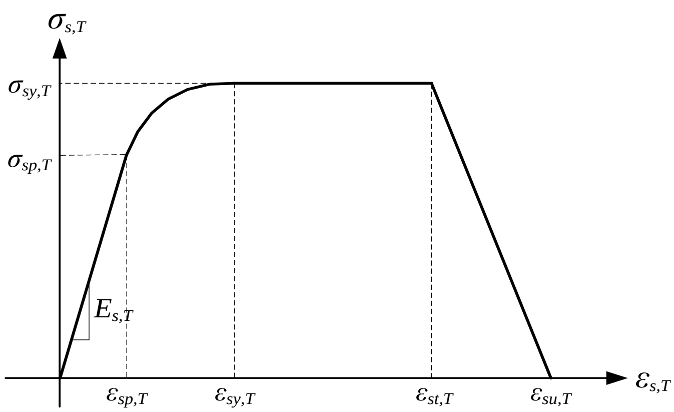

Fig. 2 Stress-strain relationship for steel

3. HEAT TRANSFER ANALYSIS

Among the previously proposed time-temperature equations, ASTM Designation E119 and ISO 834 fire curves are used for heat transfer analysis.

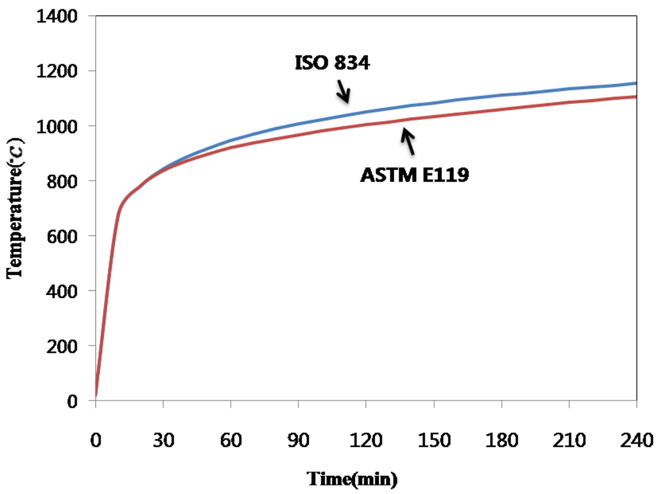

Fig. 3 Standard time-temperature curve

A section of member is divided into several fiber layers for the finite element analysis, and it is assumed that the hydration heat is not considered, and the temperature is uniformly distributed along the length of material. The governing equation and boundary condition is shown in Eq. (6) and Eq. (7). More details about the FE formulation procedures for the heat transfer analysis can be found in previous study (Kwak 2010).

$$k(T)\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)=r(T)c(T)\frac{\partial T}{\partial t} \tag{6}$$

$$k(T)\left(\frac{\partial T}{\partial x}+\frac{\partial T}{\partial y}\right)\cdot n_i=h_{eff}(T)\cdot(T_e-T_s) \tag{7}$$

4. NONLINEAR ANALYSIS

4.1 General

Nonlinear analysis is performed using the temperature distribution of the section obtained by the heat transfer analysis. In this study, the local coordinate system is consisted with the 2-D beam element with 5 DOF at each node. Section of the RC members is considered as fiber section which consists of steel and concrete grid. This fiber section is useful technique for nonlinear analysis to reflect the heat transfer on RC member. As a result, mechanical strain, non-mechanical strain, and stress are obtained via nonlinear analysis, and these parameters are used to determine the displacement of RC member.

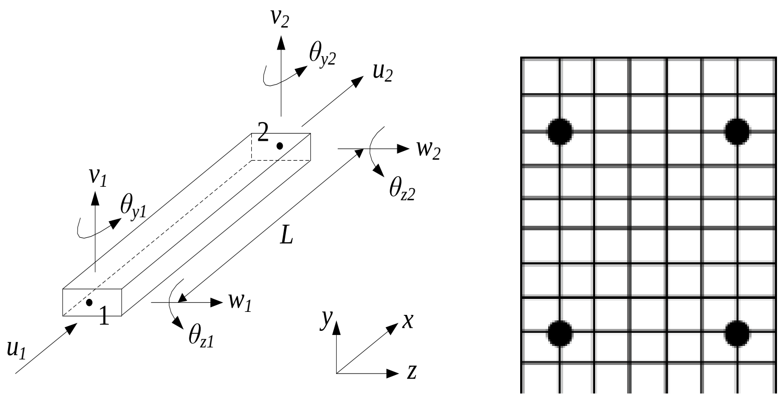

Fig. 4 Beam element and fiber section

4.2 Mechanical and non-mechanical strains of concrete

The total strain for concrete is expressed in terms of mechanical strain ($\varepsilon_{m,c}$) and non-mechanical strain. Non-mechanical strain does not induce additional stress but deformation. This study considered that thermal strain ($\varepsilon_{th,c}$, EN1992-1-2), creep strain ($\varepsilon_{cr,c}$, Harmathy 1967), and transient strain ($\varepsilon_{tr,c}$, Anderberg 1976) of concrete are non-mechanical strain. Therefore, the equation for the strain of concrete is as follows.

$$\varepsilon_{tot,c} = \varepsilon_{m,c}(\sigma,T) + \varepsilon_{th,c}(T) + \varepsilon_{cr,c}(\sigma,T,t) + \varepsilon_{tr,c}(\sigma,T) \quad (8)$$

4.3 Mechanical and non-mechanical strains of steel

Strain of the steel is also expressed with mechanical and non-mechanical strain. According to EN1992-1-2 and Harmathy creep model (Harmathy 1967), steel has thermal strain and creep strain as the non-mechanical strain. Total strain for steel can be expressed as the Eq. (9).

$$\varepsilon_{tot,c} = \varepsilon_{m,c}(\sigma,T) + \varepsilon_{th,c}(T) + \varepsilon_{cr,c}(\sigma,T,t) \quad (9)$$

4.4 Nonlinear analysis

Through the principle of virtual work, the equilibrium equations, at any time j, can be expressed as Eq. (10). Substituting equivalent forces due to non-mechanical strains into Eq. (10), finally, Eq. (11) can be obtained.

$$dR^j = (\int_V B^T EB\, dV + \int_V c^T \sigma c\, dV) \cdot dr - \int_V B^T E d\varepsilon^{nm} dV \quad (10)$$

$$dR = dR^j + dR^{nm} = K \cdot dr \quad (11)$$

After that, the residual force is compared with the external force for equilibrium between external and internal forces. Analysis program is performed until satisfying the suggested tolerance.

$$\sqrt{\frac{\sum_{i=1}^{n} (\text{Residual force})^2}{\sum_{i=1}^{n} (\text{External force})^2}} \leq (\text{Tolerance}) \quad (11)$$

5. NUMERICAL ANALYSIS

5.1 Validation

The validation of the numerical analysis results is confirmed through comparing them with experimental results of fire test on the RC beam performed by (Lin 1981).

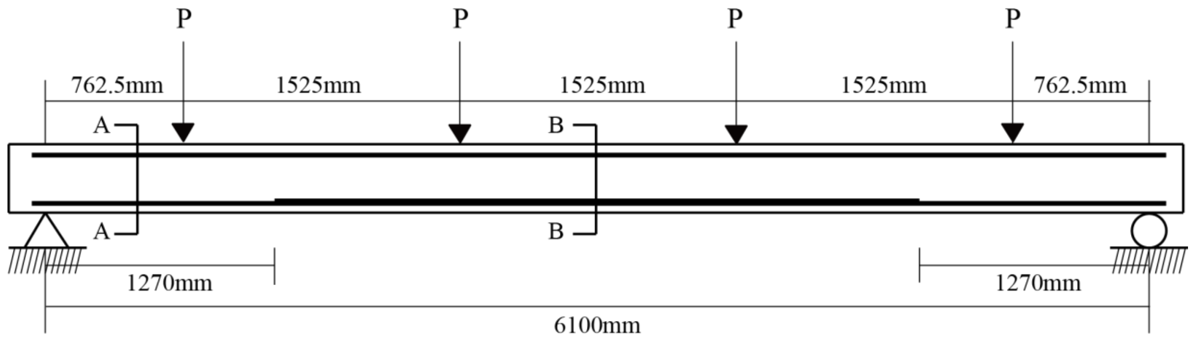

Fig. 5 RC BEAM (Lin 1981)

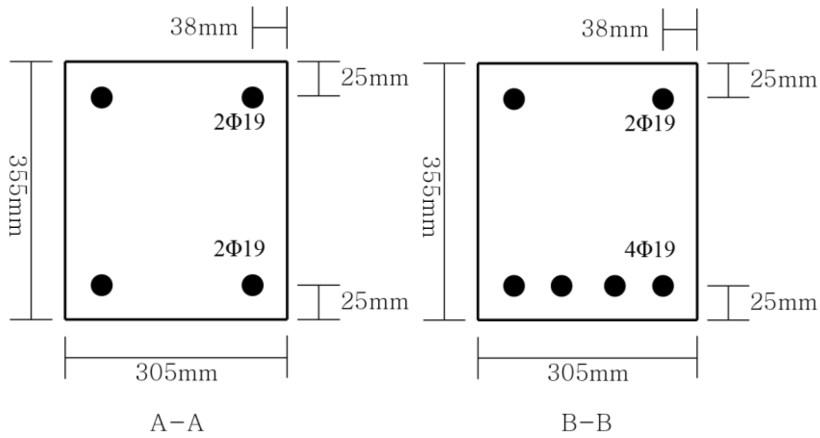

Fig. 6 Cross section

The geometries are given in Fig. 5 and Fig. 6. The compressive strength of concrete was 30 MPa and the yield stress of steel was 435 MPa with the value of 2×10^5 MPa for the modulus of elasticity at normal temperature. The beam was exposed to high temperature from bottom and two sides of section according to ASTM E119 time-temperature relationship. Emissivity and the convection coefficient are assumed to be 0.2~0.3 and 30 W/mK, respectively. Fig. 7 shows the average temperature of steel in B-B section, which results were used for nonlinear analysis. The result of numerical analysis is mostly same with the experimental result. The displacements from numerical analysis are well compatible with the experiment as can be seen in Fig. 8.

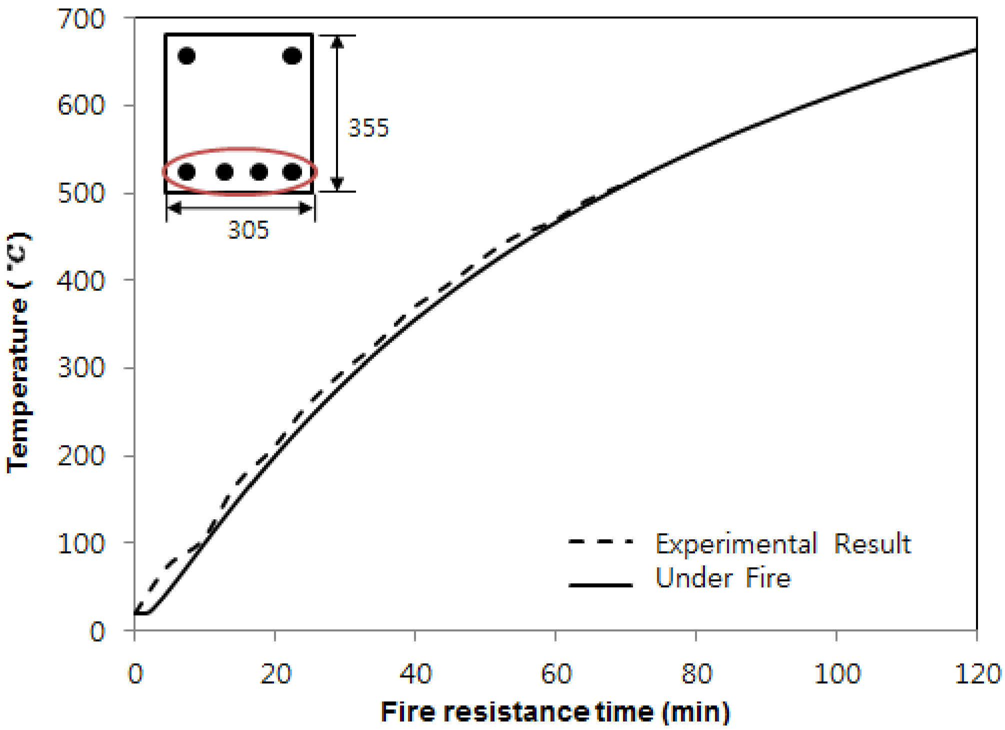

Fig. 7 Average temperature of steel in B-B section

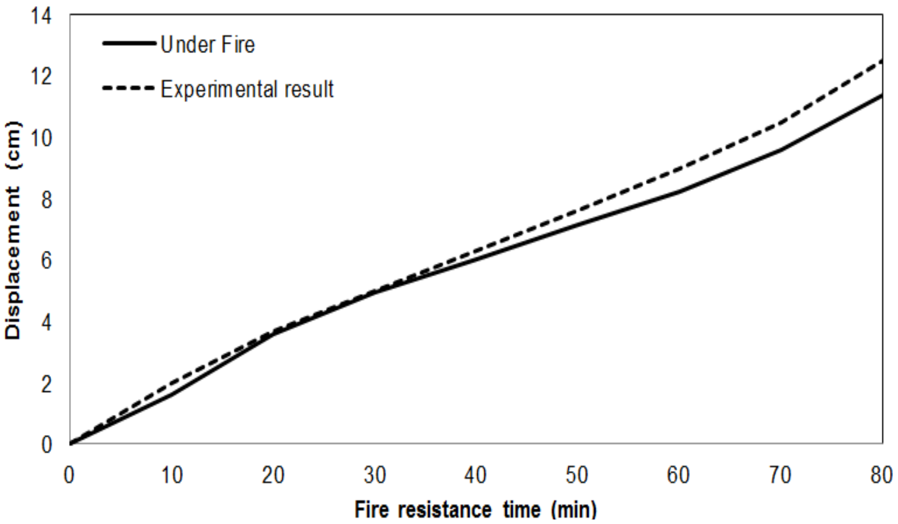

Fig. 8 Predicted and measured displacements at center of beam

Beginning of the fire, strain of analysis shows almost same with the experimental result. Time between 30 min. to 60 min., slope of the graph is slightly decreased because rate of increase for the fire temperature is smaller than the early time. After the 70 min. creep of steel caused from high temperature makes rate of strain higher again. Other minor differences between two curves seem to be due to the experimental limitation of several environmental and material variables such as mixing ratio, water content and kinds of aggregates.

6. AFTER-COOLING ANALYSIS

Several studies reported that the strength of concrete decreases during the cool-down phase because of micro defects caused by high temperature, which were supported from the some experiments data (Nassif 2006, Chang 2006). Fig. 9 from the ACI Committee report shows that the residual compressive strength of after-cooling status is lower than under-fire status.

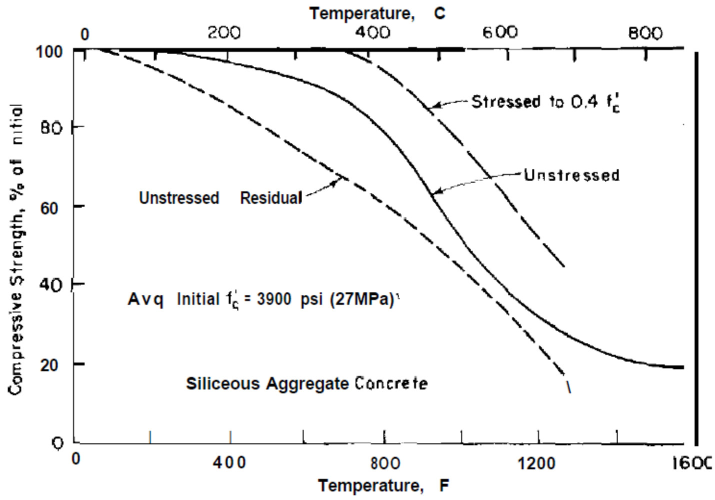

Fig. 9 Compressive strength of concrete at high temperature and after cooling (ACI)

This study therefore attempted the after-cooling analysis of fire-damaged concrete based on the comparison with proposed concrete models and experimental results at high temperature. This study expects to show that the safety side design of RC structures against fire. From the experimental data, the concrete model for after-cooling status can be suggested. In all temperature range, the maximum strength is lower than the strength of concrete in high temperature, and strain is also smaller.

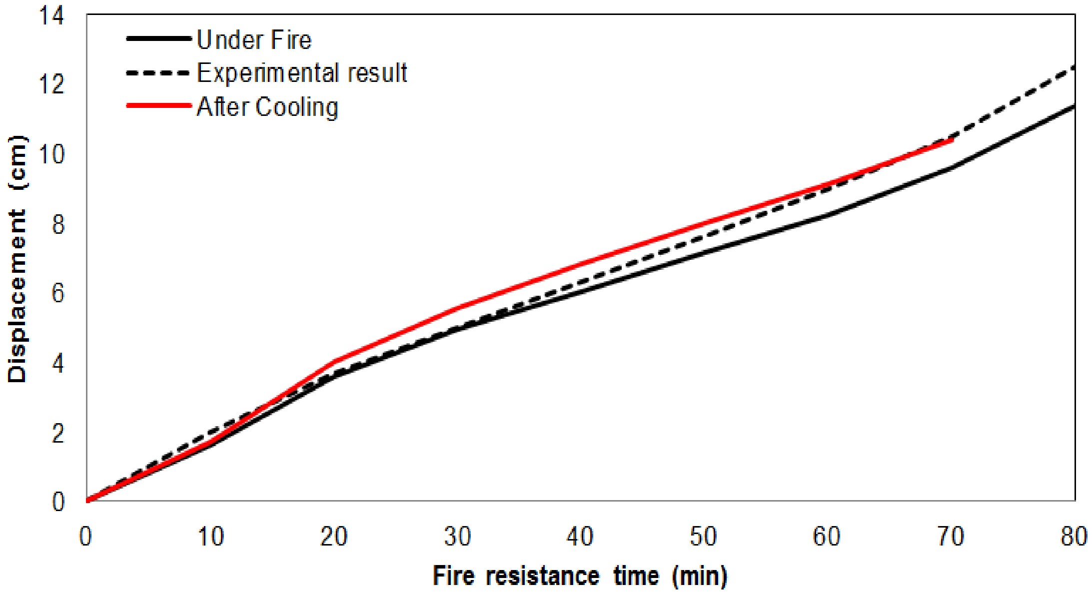

Fig. 10 Displacement by after-cooling analysis

Fig. 10 is the result of after cooling analysis applying to the example above mentioned. Beam from under-fire collapse at 80 min of fire resistance time, but after-cooling beam collapse earlier than that, at 70 min of fire resistance time.

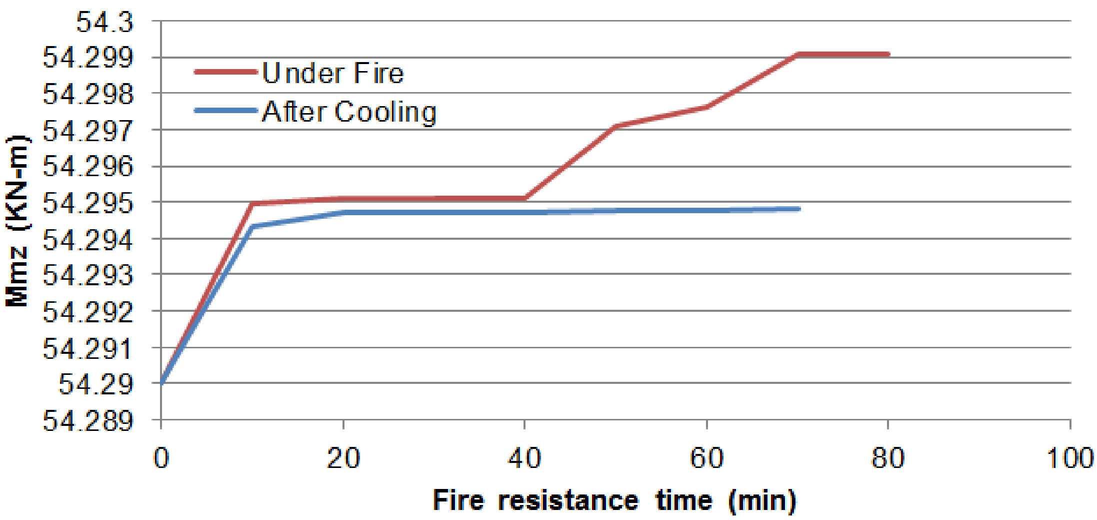

Fig. 11 Moment at the mid-span

But moment at the mid-span is not that different as shown in Fig. 11. Failure caused from moment is controlled by the steel failure but after-cooling analysis is applied to concrete only. So the difference of maximum moment between under-fire and after-cooling is small.

The model still needs to verify under the different load conditions because it has low strength to collapse. The advanced study will be reported in further study.

7. CONCLUSIONS

This paper introduced a numerical approach for the RC structures exposed to high temperature and suggested new material model, which is after-cooling analysis. The proposed numerical approach was validated by comparing its analysis results with the data from fire test on beam, the after-cooling analysis was proposed with comparison of experiment data. For the future study, nonlinear analysis needs to verify comparison with design codes, and after-cooling analysis needs to be verified under the several load condition such as moment load combined with axial force. Also, new model for steel is needed to be applied to after-cooling analysis.

ACKNOWLEDGEMENT

This research was supported by a grant from a Construction Technology Research Project (Development of impact/blast resistant HPFRCC and evaluation technique thereof, 13SCIPS02) funded by the Ministry of Land, Infrastructure, and Transport and a grant (13SCIPA01) from Smart Civil Infrastructure Research Program funded by Ministry of Land, Infrastructure and Transport (MOLIT) of Korea government and Korea Agency for Infrastructure Technology Advancement (KAIA).

REFERENCES

Anderberg.Y., Thelandersson.S., “Stress and deformation characteristics of concrete, 2-experimental investigation and material behavior model”, Bulletin 54, University of Lund, Sweden, 83pages, 1976.

ASTM Designation: E119, “Standard Methods of Fire Tests of Building Construction and Materials”, American Society for Testing and Materials, Philadelphia.

Bratina, S., Saje, M., Planinc, I., “The effect of different strain contributions on the response of RC beams in fire”, Engineering Structures, 29(3), pp. 418-430, 2008.

Chang,Y.F., Chen, Y.H., Sheu, M.S., Yao, G.C., “Residual stress-strain relationship for concrete exposure to high temperatures”, Cement and Concrete Research, 36(10), pp. 1999-2005, 2006.

EN1992-1-2. EUROCODE2: Design of concrete structures Part 1.2: General rules-Structural fire. CEN, Brussels, 2004.

Harmathy. T. Z., “A Comprehensive Creep model”, Journal of Basic Engineering, 89(D-3), pp. 496-502, 1967.

Huang, Z., Burgess, Ian W, Plank, Roger J., “Three-Dimensional Analysis of Reinforced concrete Beam-Column Structures in Fire", Journal of Structural Engineering, 135(10), pp. 1201-1212, 2009

ISO 834: 1975 Fire Resistance Test – Elements of Building Construction, International Organization for Standardization, Switzerland.

Kodur, V.K.R, Raut, N., "A simplified approach for predicting fire resistance of reinforced concrete columns under biaxial bending", Engineering Structures, 41, pp. 428-443, 2012.

Kwak, H.G. and Kwak, J.H., "An Improved Design Formula for a Biaxially Loaded Slender RC Column", Engineering Structures, 32(1), 2010.

Lin, T.D., Gustaferro, A.H., Abrams, M.S., "Fire Endurance of Continuous Reinforced Concrete Beams(RD072.01B)", Portland Cement Association, 1981.

Nassif, Ayman, "Postfire full stress-strain response of fire-damaged concrete", Fire and Materials, 30(5), pp. 323-332, 2006.

Terro, M.J., "Numerical Modeling of the behavior of concrete structures in fire", ACI Structural Journal, 95(2), pp. 183-193, 1998.

Youssef, M.A., Moftah, M., "General stress-strain relationship for concrete at elevated temperatures", Engineering Structures, 29(10), pp. 2618-2634, 2007.