Deformation Characteristics of Fire Damaged and Rehabilitated Normal Strength Concrete Beams

Yeo Kyeong Lee, Hae Won Min, Ji Yeon Kang, Hee Sun Kim, Yeong Soo Shin

International Science Index, Architectural and Environmental Engineering Vol:9, No:7, 2015 waset.org/Publication/10002085

***Abstract*—**In recent years, fire accidents have been steadily increased and the amount of property damage caused by the accidents has gradually raised. Damaging building structure, fire incidents bring about not only such property damage but also strength degradation and member deformation. As a result, the building structure undermines its structural ability. Examining the degradation and the deformation is very important because reusing the building is more economical than reconstruction. Therefore, engineers need to investigate the strength degradation and member deformation well, and make sure that they apply right rehabilitation methods. This study aims at evaluating deformation characteristics of fire damaged and rehabilitated normal strength concrete beams through both experiments and finite element analyses. For the experiments, control beams, fire damaged beams and rehabilitated beams are tested to examine deformation characteristics. Ten test beam specimens with compressive strength of 21MPa are fabricated and main test variables are selected as cover thickness of 40mm and 50mm and fire exposure time of 1 hour or 2 hours. After heating, fire damaged beams are air-recurred for 2 months and rehabilitated beams are repaired with polymeric cement mortar after being removed the fire damaged concrete cover. All beam specimens are tested under four points loading. FE analyses are executed to investigate the effects of main parameters applied to experimental study. Test results show that both maximum load and stiffness of the rehabilitated beams are higher than those of the fire damaged beams. In addition, predicted structural behaviors from the analyses also show good rehabilitation effect and the predicted load-deflection curves are similar to the experimental results. For the further, the proposed analytical method can be used to predict deformation characteristics of fire damaged and rehabilitated concrete beams without suffering from time and cost consuming of experimental process.

***Keywords*—**Fire, Normal strength concrete, Rehabilitation, Reinforced concrete beam

I. Introduction

FIRE accidents have been steadily increased for 10 years according to national emergency management agency of South Korea reported in 2014. As fire accidents in building structure induce strength degradation and member deformation, the structure can be lost structural ability. Therefore, investigation of the degradation and the deformation and selection of the rehabilitation methods are very important issue because reusing is more economical method than reconstruction.

Yeo Kyeong Lee, Hae Won Min, Ji Yeon Kang, and Hee Sun Kim are with Department of Architectural Engineering, Ewha Womans University, Seoul, 120-750, Korea (e-mail: 77771022@naver.com, mmr818@naver.com, everstella@naver.com, hskim3@ewha.ac.kr).

Yeong Soo Shin is with Department of Architectural Engineering, Ewha Womans University, Seoul, 120-750, Korea (corresponding author to provide phone: +82-2-3277-2596; fax: +82-2-3277-6875; e-mail:shinys@ewha.ac.kr).

Many experimental studies to examine structural behaviors of fire damaged concrete have been reported. Lee [1], Shin [2], and Choi et al. [3] perform experiments for thermal and structural behavior of RC beams at elevated temperatures. Lee [1] performs heating tests on normal strength concrete beams, while Shin [2] performs on high strength concrete beams. The effects according to various rehabilitation methods of fire damaged concrete have been reported for many years. Ahn [4] performs experiments of RC beams rehabilitated with polymeric mortar cement and Kang et al. [5] perform analyses of concrete beams rehabilitated with polymeric mortar or polymeric cement. Not only repairing with other materials but also recurring is good rehabilitation method. Poon et al. [6] and Lee et al. [7] perform experiments, and propose the restoration rates of concrete strength after air-recurring and water-recurring. Haddad et al. [8] report experimental results of one-way slab recurred or rehabilitated with advance composite material (FRP) to observe structural behavior. In order to define changes of material properties after high temperature heating, Harmathy [9], [10] performs fire experiments to report the temperature-dependent thermo-mechanical material properties such as effective specific heat (thermal capacity), thermal conductivity, mass change rate and thermal expansion of normal and lightweight concrete. ACI Committee 216 [11] and ENV [12] also report these material properties. In addition, Haj-Ali et al. [13] and Choi et al. [14] suggest a modeling technique including temperature-dependent thermo-mechanical material properties of concrete during transient heating for predicting temperature distributions.

Even though structural behavior of fire damaged or rehabilitated concrete has been examined in many studies, relatively few studies on comparison between fire damaged and rehabilitated concrete beams have been reported. This study aims at evaluating deformation characteristics of both fire damaged and rehabilitated normal strength concrete beams through experiments and finite element analyses. Comparing with residual strength and stiffness of fire damaged concrete beams, rehabilitation effects of rehabilitated beams can be investigated. In addition, this study proposes the analytical method which can be used to predict deformation characteristics of fire damaged and rehabilitated concrete beams. The analytical approach can save time and cost consuming of experimental process.

International Science Index, Architectural and Environmental Engineering Vol:9, No:7, 2015 waset.org/Publication/10002085

II. Experiment and FE Analysis Approach

A. Experiment Approach

1) Fabrication of Test Specimens

For experiments, reinforced concrete beams were fabricated with normal strength concrete having compressive strength of 21MPa and mix proportion for the concrete was listed in Table I. Sizes of the beams were 250mm×400mm×4700mm (width × depth × length) and the steel reinforcements were D22 (deformed bars with diameter 22mm) and D10 bars (deformed bars with diameter of 10mm) placed on 150mm interval. Reinforcement properties were shown in Table II and details of specimen was illustrated in Fig. 1. In order to investigate the effect of cover thickness on RC beams, cross-sectional areas were maintained and concrete cover thicknesses were varied between 40mm or 50mm.

After 1 week of curing, molds of the reinforced concrete beams were removed, and then the specimens were air-recurred for 3 months to perform fire test.

TABLE I
MIX PROPORTION FOR CONCRETE

W/C [%]	Weight per unit volume [kg/m^3]					
	Water	Cement	Fly ash	Fine aggregate	Coarse aggregate	AE agent
51.2	140	315	27	893	913	1.71

TABLE II
REINFORCEMENT PROPERTIES

Rebar	Tensile strength [MPa]	Elastic modulus [GPa]
D10	455.406	179.34
D22	416.500	176.40

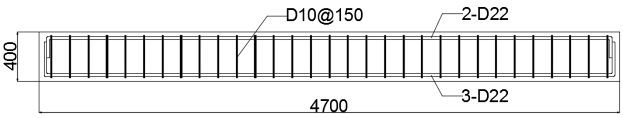


Fig. 1 Details of specimens (unit: mm)

2) Fire Test and Rehabilitation of Beams

After 3 months curing, the specimens were installed on the horizontal heating furnace for the fire tests as shown in Fig. 2. The surfaces exposed to heating were 3 faces except the upper face. The fire test was performed according to ISO-834 standard fire curve, Fig. 3, for 1 or 2 hours maintaining 87kN of the initial load corresponding to live load of general office building. Distance from hinge to roller was 4500mm and distance between 2 loading points for four points loading was 1200mm.

Four specimens were tested after 2 months air-recurring to investigate residual strength of fire damaged RC beams. Other four specimens were rehabilitated with polymeric cement mortar after being removed the fire damaged part of concrete cover as illustrated in Fig. 4. As shown in Fig. 5, these rehabilitated beams were cured for 1 month to get rehabilitation effects enough. The test specimens were tabulated in Table III.

3) Test Set-Up

Four points loading tests were performed in simple support condition for both fire damaged and rehabilitated beams as shown in Fig. 6. Test span was 4000mm and distance between 2 loading points was 1200mm as illustrated in Fig. 7.

Fig. 2 Specimen installed on the horizontal heating furnace

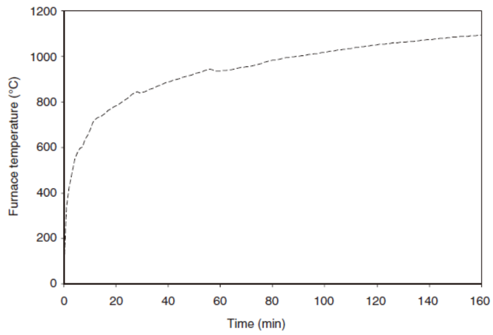


Fig. 3 ISO-834 standard fire curve

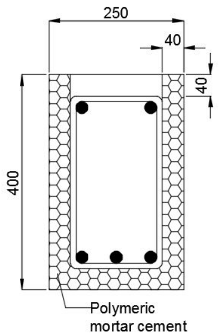


Fig. 4 Section of rehabilitated specimen (unit: mm)

Fig. 5 Curing of rehabilitated beams with polymeric cement mortar

International Science Index, Architectural and Environmental Engineering Vol:9, No:7, 2015 waset.org/Publication/10002085

Fig. 6 Four point loading test set up

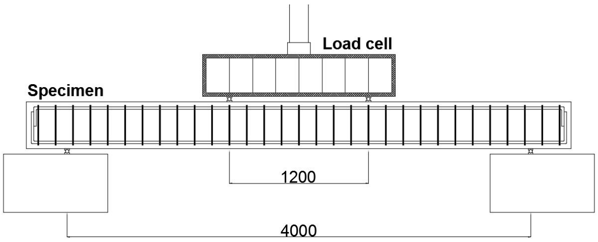


Fig. 7 Details of four points loading system (unit: mm)

TABLE III
LIST OF SPECIMENS

Specimen	Cover thickness	Heating time	Rehabilitation
40CV	40mm	-	-
40CV1H	40mm	1 hour	-
40CV2H	40mm	2 hour	-
40CV1HRH	40mm	1 hour	O
40CV2HRH	40mm	2 hour	O
50CV	50mm	-	-
50CV1H	50mm	1 hour	-
50CV2H	50mm	2 hour	-
50CV1HRH	50mm	1 hour	O
50CV2HRH	50mm	2 hour	O

TABLE IV
TEMPERATURE DEPENDENT MATERIAL PROPERTIES OF CONCRETE

Temperature [℃]	Conductivity [W/mm℃]	Specific heat [J/kg℃]
18	0.00139	780
100	0.00139	820
162	0.00139	1200
300	0.00139	1350
439	0.00139	1400
487	0.00135	1450
506	0.00130	1500
522	0.00130	1520
574	0.00130	1150
757	0.00130	1130
870	0.00130	1010
1000	0.00130	1030

B. FE Analysis Approach

Commercial software ABAQUS version 6.10-3 was used for finite element (FE) analyses. In order to analyze experimental results, main parameters applied to experimental study such as cover thickness and heating time were selected. Temperature analysis, integrated temperature-structural analysis and structural analysis for FE models were sequentially performed to investigate the effects of main parameters on structural behavior of the beam models.

1) Temperature Analysis

All of elements were three-dimensional continuum 8 nodded brick type for diffusive heat transfer analysis and these included temperature dependent material properties of conductivities and specific heat as listed in Table IV. Temperature analyses were performed using in-house written code with FORTRAN language and surfaces without upper face were subjected to heating for 3600 or 7200 seconds.

2) Integrated Temperature-Structural Analysis

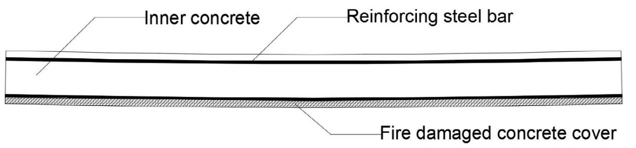
For structural analyses, temperature distributions obtained from the previous temperature analyses were implemented to predict the structural behavior of the beam models under fire. In addition, integrated temperature-structural analyses were considered geometrical and material nonlinearity to upgrade the accuracy of analytical results.

3) Structural Analysis

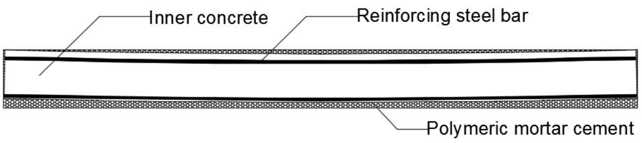
Control beams (40CV, 50CV), fire damaged beams (40CV1H, 40CV2H, 50CV1H, 50CV2H), and rehabilitated beams (40CV1HRH, 40CV2HRH, 50CV1HRH, 50CV2HRH) were structurally analyzed. Based on the deformed geometries from the integrated temperature-structural analyses, fire damaged beam models were generated. These models consisted of three parts; inner concrete, reinforcing steel bar, and fire damaged cover as shown in Fig. 8 (a). The parts were assumed as perfectly bonded each other. As illustrated in Fig. 8 (b), rehabilitated beams had also three parts; inner concrete, reinforcing bar, and rehabilitating part. These three parts were also assumed as perfectly bonded to each other. The rehabilitated beams were modeled in straight configuration by adding rehabilitation part to the location of removed concrete cover.

The element type of inner/fire damaged concrete part and the part for rehabilitation was 4-node tetrahedral element, while reinforcing steel bar part had 8-node linear brick element type. Inner concrete and reinforcing steel bars included 90% of the original elastic modulus and compressive/tensile strength as listed in Table V. Lee [1] and Ahn [4] had been reported that material properties decreased to 90% of the original properties when temperature of inner concrete after heating was lower than 500℃. Fire damaged concrete cover, which was air-recurred for 2 months after heating, had 31% of the original material properties since its temperature of inner concrete was higher than 800℃ as Poon et al. [6]. The material properties of polymeric cement mortar referred to available reports of existing material. Non-linear geometrical analyses were performed to investigate deformation characteristics of the beam models.

International Science Index, Architectural and Environmental Engineering Vol:9, No:7, 2015 waset.org/Publication/10002085



(a) Fire damaged beam model



(b) Rehabilitated beam model

Fig. 8 Details of beam model in analyses

TABLE V
MECHANICAL MATERIAL PROPERTIES (FROM THE COMPRESSIVE/TENSILE MATERIAL TEST)

Specimen	Elastic modulus [GPa]	Poisson's ratio	Compressive strength [N/mm²]	Tensile strength [N/mm²]	Density [kg/m³]
Concrete	22.442	0.2	21.40	2.57	2400
Steel	176.4	0.3	-	416.5	7850

III. EXPERIMENTAL AND ANALYTICAL RESULTS

A. Experimental results

1) Effect of Cover Thickness

Fig. 9 illustrates load-deflection curves of RC beam specimens having cover thickness with 40mm and 50mm heated for 1 hour. As shown, maximum load and slope of 40CV1H specimen are higher than those of 50CV1H specimen because 40CV1H has lower temperature distributions and larger beam depth compared to 50CV1H. The same tendencies are also shown in the load-deflection curves from results of RC beams heated for 2 hours as illustrated in Fig. 10.

2) Effect of Heating Time

Fig. 11 illustrates load-deflection curves of RC beams having 40mm of cover thickness heated for 0, 1 or 2 hours. As seen, the longer specimens are heated, the lower maximum loads and slopes of specimens are. The slopes of 40CV1H and 40CV2H decrease to around 74% and 66% of the slope of 40CV, respectively. All beams, however, show similar structural behaviors such as load beyond 40mm deflection.

3) Effect of Rehabilitation

Fig. 12 shows load-deflection curves of both fire damaged specimens (40CV1H, 40CV2H) and rehabilitated specimens (40CV1HRH, 40CV2HRH) compared with control specimen (40CV). As mentioned in Fig. 11, maximum loads and slopes of 40CV1H and 40CV2H specimens are lower than those of 40CV specimen. However, the load-deflection curves of rehabilitated beam; 40CV1HRH and 40CV2HRH show that the rehabilitation recovers load carrying capacity of the fire damaged concrete beams. Maximum loads of these two specimens reach that of control beam. Similar tendencies are shown in the load-deflection curves from results of RC beams having 50mm of cover thickness, as illustrated in Fig. 13.

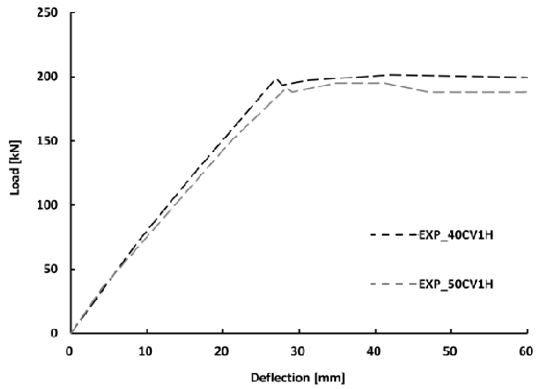


Fig. 9 Load-deflection curves of test specimens heated for 1 hour

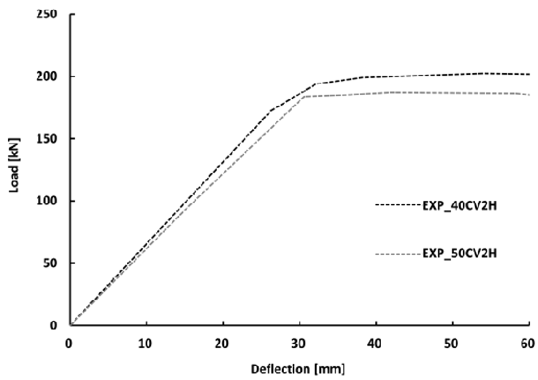


Fig. 10 Load-deflection curves of test specimens heated for 2 hours

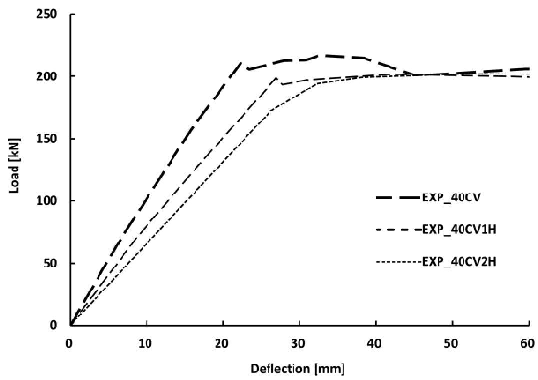


Fig. 11 Load-deflection curves according to heating time difference

International Science Index, Architectural and Environmental Engineering Vol:9, No:7, 2015 waset.org/Publication/10002085

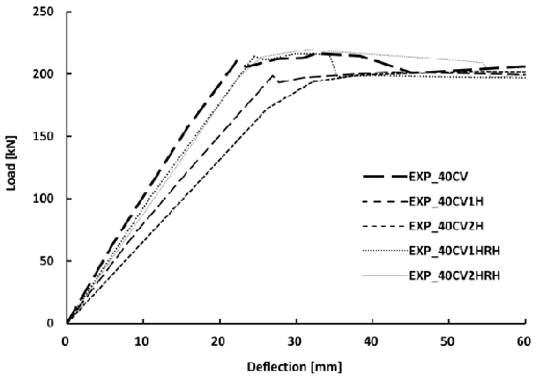


Fig. 12 Load-deflection curves of test specimens having cover thickness 40mm

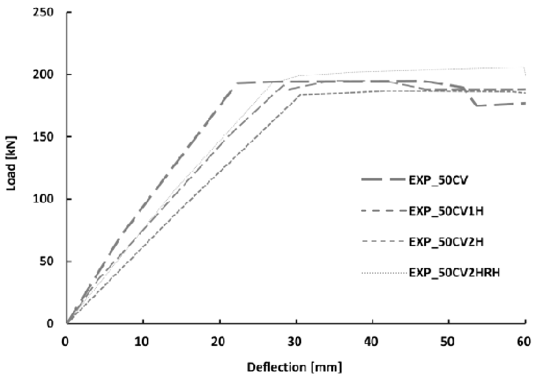


Fig. 13 Load-deflection curves of test specimens having cover thickness 50mm

B. Analytical Results

1) Effect of Cover Thickness

Fig. 14 illustrates load-deflection curves of RC beams having 40mm and 50mm of cover thickness heated for 1 hour and analytical results are compared with experimental results. As shown in the load-deflection curves, maximum predicted loads matches well with experimental results, but the slopes obtained from analyses are larger than experimental results. Two primary reasons would be able to explain the difference of slopes. First of all, inner concrete's inside cracks occurred by fire are not exactly reflected in analytical models although the decreased material properties are included. In addition, the RC beam models in analyses have larger heights than specimens of experiments, so polymeric cement mortar would affect to structural behaviors more. Between 40CV1H and 50CV1H, both analytical and experimental results show similar tendency. The specimens that have cover thickness of 40 mm have larger stiffness than the specimens that have cover thickness of 50mm because of the larger beam depth.

2) Effect of Rehabilitation

The rehabilitation effects can be illustrated in Figs. 15~17. Comparing Figs. 15 (a) and (b), rehabilitated beam model, 40CV1HRH, has larger maximum principal stress than fire damaged beam model, 40CV1H. As seen in Figs. 16 and 17, analytical and experimental results are in good agreements. Table VI shows that in analyses, the maximum loads of fire damaged models (40CV1H, 50CV1H) decrease to around 86% and 83% of the control models (40CV, 50CV), respectively. The stiffness also decreases to approximately 86% and 75% of the control models, respectively. These decreased rates between control and fire damaged beam models due to heating are higher than those obtained from experiments. In case of rehabilitated models in analyses (40CV1HRH, 50CV1HRH), both maximum loads and stiffness are much larger than those of fire damaged models. The increased rates are 5~6% and 10~14% for maximum loads and stiffness, respectively as listed in Table VI. These rates are very similar to increased rates of experimental results (about 7% and 20%). Therefore, both analyses and experiments confirm that rehabilitation with polymeric cement mortar of fire damaged RC beams has good effects for strength and stiffness recovery.

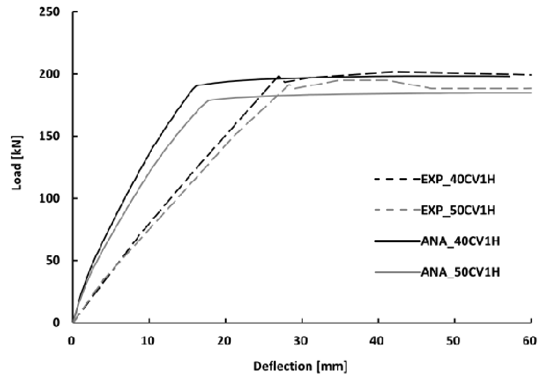
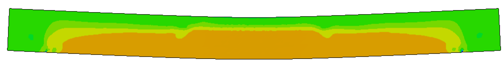
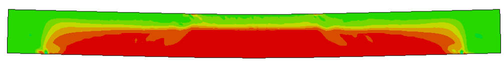


Fig. 14 Load-deflection curves from experiment and analysis of RC beams heated for 1 hour



(a) Contour for 40CV1H



(b) Contour for 40CV1HRH

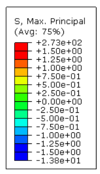


Fig. 15 Maximum principal stress contour predicted from FE models

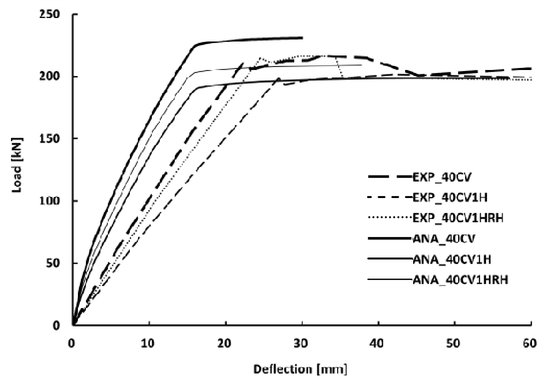


Fig. 16 Load-deflection curves from experiment and analysis of RC beams having cover thickness 40mm

International Science Index, Architectural and Environmental Engineering Vol:9, No:7, 2015 waset.org/Publication/10002085

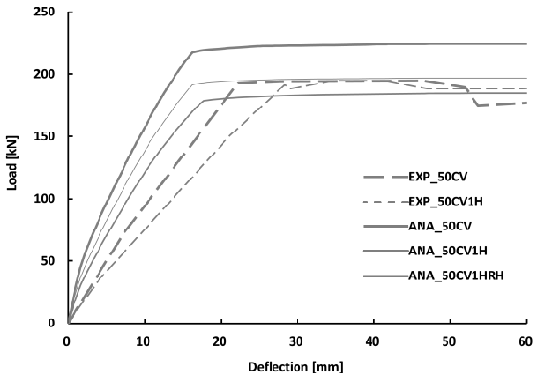


Fig. 17 Load-deflection curves from experiment and analysis of RC beams having cover thickness 50mm

TABLE VI
RESULTS OF LOAD-DEFLECTION CURVES

	Specimen	Max. load [kN]	Slope [kN/mm]
EXPERIMENTAL RESULT	EXP_40CV	213.03	9.95
	EXP_40CV1H	201.58	7.37
	EXP_40CV1HRH	216.23	8.89
	EXP_50CV	194.95	9.96
	EXP_50CV1H	194.94	7.12
ANALYTICAL RESULT	ANA_40CV	231.03	13.97
	ANA_40CV1H	198.39	12.00
	ANA_40CV1HRH	208.96	13.25
	ANA_50CV	223.25	13.54
	ANA_50CV1H	184.77	10.06
	ANA_50CV1HRH	196.99	11.51

IV. CONCLUSION

This study reports the deformation characteristics of fire damaged and rehabilitated normal strength concrete beams. RC beam specimens are prepared to have 40mm and 50mm of cover thickness, and exposed to fire for 1 or 2 hours. After fire tests, some specimens are air-recurred for 2 months and other specimens are rehabilitated with polymeric cement mortar after being removed damaged part of concrete cover. From four points loading tests on control, fire damaged and rehabilitated beam specimens, maximum loads and stiffness are measured to investigate deformation characteristics. In addition, FE analyses under the same conditions as the experiments are performed through three sequentially integrated stages. In final stage, fire damaged beam models are generated based on deformed shape from temperature analysis. Rehabilitated beams are modeled in straight configuration by adding rehabilitation part to the removed cover part. The results are compared to the experimental results. Based on this study, the following conclusions can be drawn:

1) Difference of beam depth causes different maximum load and stiffness. The higher maximum load and stiffness are observed from the beams with cover thickness of 40mm compared to the beams with cover thickness of 50mm regardless of fire exposure time.
2) Experimental results show that stiffness of the fire damaged beam decreases as fire exposure time period increases. As the beams are heated for 1 hour or 2 hours, comparing control beams, the reduction rates of stiffness are 74% and 66%, respectively.
3) From load-deflection curves of rehabilitated beams with polymeric cement mortar, good rehabilitation effects can be seen. In both experimental and analytical results, the rehabilitated beams' increase rates of maximum load and stiffness are around 5~7% and 10~20%, respectively.
4) The experimental and analytical results are in good agreements although stiffness obtained from analyses is a little higher than stiffness from experiments. Therefore, the proposed analytical method can be used to predict deformation characteristics of fire damaged and rehabilitated concrete beams without suffering from time and cost consuming of experimental process.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. NRF-2013R1A2A2A01015603).

REFERENCES

[1] S. J. Lee, "A Study on Structural Behaviors of Fire-Damaged Reinforced Concrete Beams with Normal Strength Concrete," *M.S. thesis, Ewha womans university*, Seoul, 2003.
[2] M. K. Shin, "Structural behaviors of fire-damaged reinforced concrete beams with high strength," *M.S. thesis, Ewha womans university*, 2004.
[3] E. G. Choi, Y. S. Shin and H. S. Kim, "Structural damage evaluation of reinforced concrete beams exposed to high temperatures," *Journal of Fire Protection Engineering*, vol. 23, no. 2, pp 135-151, Apr. 2013.
[4] J. H. Ahn, "Structural behaviors of Fire-damaged normal strength concrete beams retrofitted with Polymer mortar," *M.S. thesis, Ewha womans university*, Seoul, 2003.
[5] J. Y. Kang, H. W. Jung and Y. S. Shin, "An Parametric study on structural behaviors of Fire-damaged concrete beams retrofitted with Polymer mortar," in *Proceeding of Architectural Institute of Korea*, Seoul, Korea, Oct. 2005, pp. 227-230.
[6] C. S. Poon, S. Azhar, M. Anson, and Y. L. Wong, "Strength and durability recovery of Fire-damaged concrete after post-fire-curing," *Cement and Concrete Research*, vol. 31, pp. 1307-1318, Sep. 2001.
[7] J. W. Lee, K. H. Choi, and K. P. Hong, "Strength recovery of Fire-damaged concrete after Post-fire-curing," in *Proceeding of Korea Concrete institute*, Muju, Korea, Mar. 2006, pp. 170-173.
[8] R. H. Haddad, N. AL-Mekhlafy, and A. M. Ashteyat, "Repair of Heat-damaged reinforced concrete slabs using Fibrous composite materials," *Construction and Building Materials*, vol. 25, pp. 1213-1221, Mar. 2011.
[9] T. Z. Harmathy, Properties of building materials at elevated temperatures, DRP Paper No. 1080 of the Division of Building Research, Ottawa: National Research Council of Canada, 1983.
[10] T. Z. Harmathy, Properties of building materials, Bethesda, MD: Society of Fire Protection Engineers and National Fire Protection Association, 1988, pp. 378-391.
[11] ACI Committed 216, *Guide for determining the fire endurance of concrete elements*, American Concrete Institute Committee Report, ACI 216R1-48, Farmington Hills, MI, USA 1994
[12] Eurocode 2, *Design of concrete structures-part 1-2: general rules-structural fire design*, ENV 1992-1-2, European Committee for Standardization, 1995.
[13] RM. Haj-Ali, J. Choi, and H. S. Kim, "Integrated fire dynamics and thermomechanical modeling framework for steel-concrete composite structures," *Steel and Composite Structure*, vol. 10, pp. 129-149, Oct. 2010.
[14] J. Choi, RM. Haj-Ali, and H. S. Kim, "Integrated fire dynamic and thermomechanical modeling of a bridge under fire," *Structural Engineering and Mechanics*, vol. 42, no. 5, pp 815-829, May. 2012.

International Science Index, Architectural and Environmental Engineering Vol:9, No:7, 2015 waset.org/Publication/10002085

Yeo Kyeong Lee was born in Suwon, South Korea, October 22, 1990. She is with the Architectural Engineering Department, Ewha Womans University, Seoul, South Korea.

Hae Won Min was born in Seoul, South Korea, August 18, 1988. She is with the Architectural Engineering Department, Ewha Womans University, Seoul, South Korea.

Ji Yeon Kang was born in Busan, South Korea, March 23, 1978. She is with SH (Seoul Housing) Corporation, Seoul, South Korea.

Hee Sun Kim was born in Seoul, South Korea, December 26, 1979. She is professor in Ewha Womans University, Seoul, South Korea. Prof. Kim is with the Architectural Engineering Department, Ewha Womans University, Seoul, South Korea.

Yeong Soo Shin was born in Busan, South Korea, May 10, 1956. He is professor in Ewha Womans University, Seoul, South Korea. Prof. Shin is with the Architectural Engineering Department, Ewha Womans University, Seoul, South Korea.