World Academy of Science, Engineering and Technology
International Journal of Architectural and Environmental Engineering
Vol:9, No:7, 2015

Investigation of Rehabilitation Effects on Fire Damaged High Strength Concrete Beams

Eun Mi Ryu, Ah Young An, Ji Yeon Kang, Yeong Soo Shin, Hee Sun Kim

Abstract**—**When high strength reinforced concrete is exposed to high temperature due to a fire, deteriorations occur such as loss in strength and elastic modulus, cracking and spalling of the concrete. Therefore, it is important to understand risk of structural safety in building structures by studying structural behaviors and rehabilitation of fire damaged high strength concrete structures. This paper aims at investigating rehabilitation effect on fire damaged high strength concrete beams using experimental and analytical methods. In the experiments, flexural specimens with high strength concrete are exposed to high temperatures according to ISO 834 standard time temperature curve. From four-point loading test, results show that maximum loads of the rehabilitated beams are similar to or higher than those of the non-fire damaged RC beam. In addition, structural analyses are performed using ABAQUS 6.10-3 with same conditions as experiments to provide accurate predictions on structural and mechanical behaviors of rehabilitated RC beams. The parameters are the fire cover thickness and strengths of repairing mortar. Analytical results show good rehabilitation effects, when the results predicted from the rehabilitated models are compared to structural behaviors of the non-damaged RC beams.

In this study, fire damaged high strength concrete beams are rehabilitated using polymeric cement mortar. The predictions from the finite element (FE) models show good agreements with the experimental results and the modeling approaches can be used to investigate applicability of various rehabilitation methods for further study.

Keywords**—**Fire, High strength concrete, Rehabilitation, Reinforced concrete beam.

I. Introduction

It is important to evaluate strength of rehabilitated structures in order to reuse fire damaged building safely. For rehabilitating fire damaged structure, accurate estimation and studies on method of rehabilitation are needed. Especially, rehabilitation of fire damaged high strength concrete structure must be performed with extreme case, because high strength concrete shows severe damages such as spalling when exposed to high temperature.

In these days, the standard for fire resistance of Reinforced Concrete (RC) structural members in the thermal and mechanical material properties of concrete and steel is established in many countries. Choi [1] reported the rule about "The estimation for the fire resistance performance of high strength concrete column and beam" was most recently enacted in Korea. In this rule, the high strength concrete members have to satisfy the fire resistance in the fire test with the specimen manufacture and tested by [KSF 2257] code. This rule demands to conduct a fire test without loading in case of high strength concrete column and the average and maximum temperature of main steel bar has to be under 538℃ and 649℃, respectively during the time of requested fire resistance.

The thermomechanical material properties such as specific heat, thermal conductivity, mass change rate, and thermal expansion were tested under high temperatures by Harmathy [2]. For high strength concrete materials, thermal and mechanical material properties were reported by [3] and [4]. The former performed experiments for thermal material properties of high strength concrete at different temperature levels, and the later examined stress–strain curves of high strength concrete at different temperature levels. Shin [5] also reported structural behaviors of fire-damaged high strength concrete beam. In addition, [6] and [7] proposed a modeling technique for predicting temperature distributions and deformations of structural members. Choi et al. [8] performed parametric analyses, in order to examine effect of the wide ranges of material properties on thermal and structural behaviors of fire damaged concrete structures.

In this paper, high strength concrete beam is investigated experimentally and analytically. From the experiments, strength of rehabilitated high strength concrete beam is measured. The tendency of FE model's behavior is coincident with experimental specimen's behavior. Thus, findings from the study can be used for estimation of reuse of fire damaged structure members, and effect of the rehabilitation is estimated using FE.

II. Experimental and FE Modeling Approach

A. Experimental Approach

1) Fabrication of Specimen

Mixture ratios for concrete are listed in Table I. For 28day compressive strength of the concrete, compressive test is performed on cylindrical shaped specimens according to Korean standard for compressive test method [KSF 2403]. From the compressive test, averaged value is obtained as 54.39MPa. And, for tensile strength of the steel, tensile test is performed according to Korean standard for tensile test method [KS F 2403] (see Table II).

Width, depth and length of high strength concrete beams are equal to 250 mm, 400 mm and 4700 mm, respectively, as

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illustrated in Fig. 1. After 7 days of curing, formworks are stripped. Then, beams are cured for six months to prevent moisture effect during fire test.

TABLE I
MIXTURE RATIO FOR CONCRETE

28-day compressive strength	W/C (%)	s/a (%)	Weight per unit volume (kg/m^3)				
			W	C	S	G	AD
54.39MPa	31	41	168	542	666	974	1.6

TABLE II
MATERIAL PROPERTIES OF STEEL

	Normal tensile strength		Tensile strength	Elastic modulus
steel	392MPa	D10	382.2MPa	168.56GPa
		D22	430.2MPa	152.88GPa

TABLE III
LIST OF SPECIMENS

Specimen	Cover thickness	Fire exposed time period (sec)	Rehabilitation
Exp_H4BC	40mm	-	-
Exp_H4B1H	40mm	3600	-
Exp_H4B1HR	40mm	3600	○
Exp_H5BC	50mm	-	-
Exp_H5B1H	50mm	3600	-
Exp_H5B1HR	50mm	3600	○
Ana_H4BC	40mm	-	-
Ana_H4B1H	40mm	3600	-
Ana_H4B1HR	40mm	3600	○
Ana_H5BC	50mm	-	-
Ana_H5B1H	50mm	3600	-
Ana_H5B1HR	50mm	3600	○

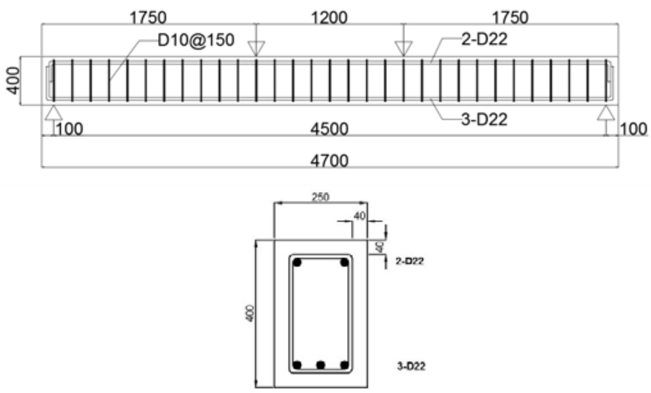


Fig. 1 Specimen details (units are in mm)

1) Fire Test and Rehabilitation

Fig. 2 describes the applied temperature curve, which represents a typical temperature load inside a building during fire condition developed by ISO 834 standard time temperature curve. The beams are loaded by four-point loading. Distance between the supports is 4500 mm, and distance between the loading points is 1200 mm as shown in Figs. 1 and 4.

After fire test, the specimens are damaged as shown in Fig. 6 and are left during one month. For comparing residual strength and strength of rehabilitated beam, rehabilitation is performed. Fire damaged U-shaped concrete cover is removed. And, removed part is filled with polymeric cement mortar.

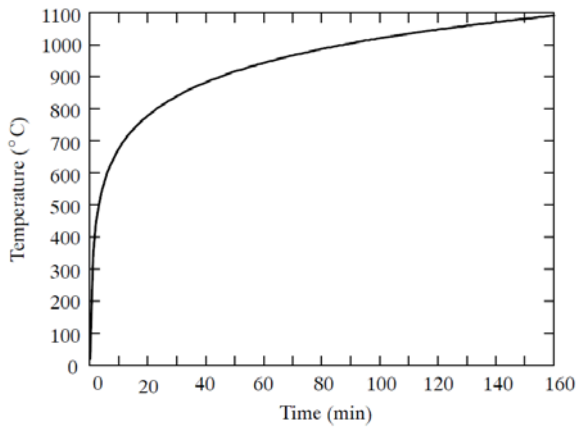


Fig. 2 ISO 834 time dependent heating curve

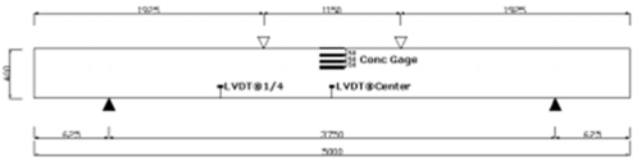


Fig. 3 Detail of gages and LVDT when loading

Fig. 4 The horizontal heating furnace for fire test

Fig. 5 Four-point loading test of rehabilitated beam

Fig. 6 Specimen on the horizontal heating furnace after fire test

2) Test Set-Up

Specimens are simply supported with an effective span of 3750mm and subject to four-point loading. The vertical deflection of the specimen is measured at midspan using a linear variable displacement transducer (LVDT). And the load increases with a gradual rate and is recorded though a data logger. Figs. 3 and 5 illustrate the instrumentation used for the test.

B. *FE Modeling Approach*

Structural analyses of RC beams are performed with same conditions as experiment to provide accurate prediction on structural and mechanical behaviors of rehabilitated RC beams. Commercial FE software, ABAQUS version 6.10-3, is used. Analyses consist of temperature analysis, integrated temperature-structure analysis and structural analysis of rehabilitated beams and damaged beams.

1) Step 1 Temperature Analysis

For temperature analysis, three-dimensional FE models with width, depth and length equal to experimental conditions are generated consisting of three parts of concrete beam, reinforcement and stirrup, as illustrated in Fig. 7. All parts are modeled using three-dimensional eight-node solid elements. The thermal energy from the remote heat sources is passed into the surface of concrete beams through convection heat transfer. Therefore, a convection heat flux is applied to as a boundary condition on the three exposed surfaces using FORTRAN language. Properties are used according to the previously reported paper [9].

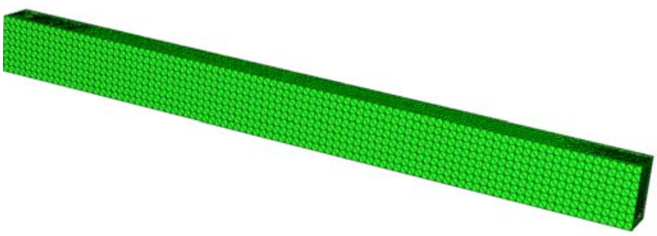
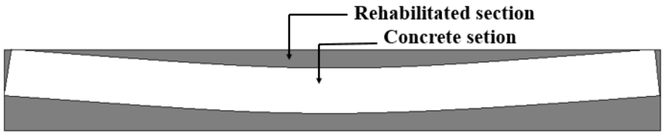
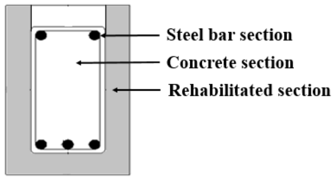


Fig. 7 FE model



(a) Side view



(b) Frontal view

Fig. 8 FE model of rehabilitated beam

2) Step 2 Integrated Temperature-Structure Analysis

The nodal temperatures obtained from the heat transfer analysis are used sequentially in the thermal stress analysis conducted while the beams are subject to four-point loading.

In thermal stress analysis, three-dimensional eight-node displacement brick elements are used with the same mesh refinement and time steps as the previous heat transfer analysis. The models having concrete, reinforcement and stirrup are generated using eight-node solid elements. Loading and boundary condition are modeled as same with experimental condition such that the RC beams are simply supported with roller support at onside and hinged support at the other side. In addition loads are prescribed in displacement control.

3) Step 3 Structural Analysis of Rehabilitated Beam and Damaged Beams

There are three types of beam models composed with control beams (H4BC, H5BC), damaged beams (H4B1H, H5B1H) and rehabilitated beams (H4B1HR, H5B1HR). From the integrated temperature-structural analyses, the models consist of concrete, steel bar and rehabilitated section. For the rehabilitated RC beam models, integrated temperature–structural analyses are performed in advance to obtain geometries of the fire damaged RC beams. After damaged parts are removed, rehabilitated part is added to the damaged model with material properties of polymeric cement mortar illustrated in Fig. 8. Properties are fabricated as same with experimental condition.

Rehabilitated part and the concrete part are modeled using three dimensional four-node solid tetrahedral elements and the reinforcement is modeled using three-dimensional eight-node solid elements. It is assumed that rehabilitated part and steel bars are perfectly bonded to concrete. The FE models of simply supported beams are subject to four-point bending.

It has been reported that concrete compressive strengths of damaged beams and repaired beams decrease to 90% of original strength when temperature of concrete after fire exposure is lower than 500°C [10]. For steel bar, 90% of original tensile strength is considered when temperature of steel bar after fire exposure is lower than 500°C [10].

III. Experimental and Analytical Results

A. Experimental Results

There are six experimental specimens of control beams (Exp_H4BC, Exp_H5BC), damaged beams (Exp_H4B1H, Exp_H5B1H) and rehabilitated beams (Exp_H4B1HR, Exp_H5B1HR) listed in Table III.

After fire test, the ultimate loads of damaged beams such as H4B1H and H5B1H are 13.4% and 28.6% lower than those of control beams respectively. But as shown in Figs. 9 and 10, the ultimate loads of rehabilitated beams are higher than those of control beams. The ultimate loads of H4B1HR and H5B1HR are 5.4% and 0.7% higher than those of H4BC and H5BC respectively. And structural behaviors are analogous between specimen having cover thickness 40mm and 50mm. The ultimate loads from experiments are listed in Table IV.

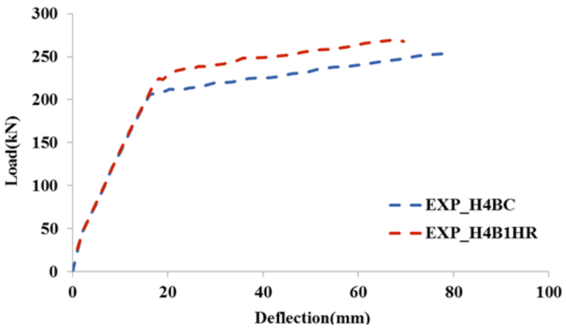


Fig. 9 Experimental load-deflection curves for specimen having cover thickness of 40 mm

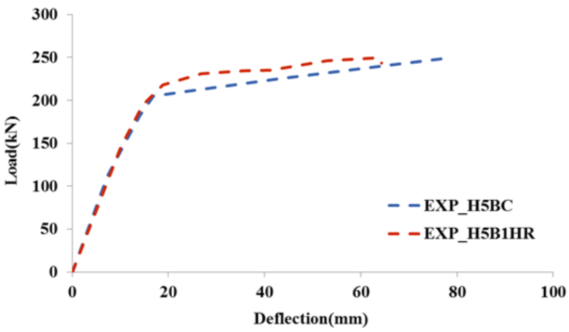


Fig. 10 Experimental load-deflection curves for specimen having cover thickness of 50 mm

TABLE IV
Ultimate Load and Slope from Experiments

Specimen	Ultimate load(kN)	Slope(kN/mm)
Exp_H4BC	254.1	13.3
Exp_H4B1H	220.1	9.4
Exp_H4B1HR	268.0	14.3
Exp_H5BC	248.0	13.2
Exp_H5B1H	177.0	6.6
Exp_H5B1HR	249.7	14.0

It can be seen that stiffness of rehabilitated beams are recovered similar to that of control beams. For beams having cover thickness of 40mm and 50mm, the slopes of H4B1HR and H5B1HR is 1.8% higher than H4BC and H5BC, respectively. And the slope ratios of control beam having cover thickness of 40mm are larger than those of beams having cover thickness of 50mm. Because the effective depth of beams having cover thickness of 40mm are larger than that of having cover thickness of 50mm.

TABLE V
Ultimate Load and Slope from FE Analysis

Name	Ultimate load(kN)	Slope(kN/mm)
Ana_H4BC	235.0	17.5
Ana_H4B1H	216.0	15.4
Ana_H4B1HR	252.6	21.2
Ana_H5BC	231.5	16.2
Ana_H5B1H	187.4	13.0
Ana_H5B1HR	238.3	20.6

B. Analytical Results

There are six analytical models of control beams (Ana_ H4BC, Ana_H5BC), damaged beams (Ana_ H4B1H, Ana_H5B1H) and rehabilitated beams (Ana_H4B1HR, Ana_H5B1HR) listed in Table III.

The results show that the ultimate loads of damaged beams such as Ana_ H4B1H and Ana_H5B1H are 8.1% and 19.0% lower than those of control beams, respectively. But the ultimate loads of rehabilitated beams such as Ana_H4B1HR and Ana_H5B1HR are 7.5% and 2.9% higher than those of control beams respectively. The ultimate loads obtained from experiments and analyses are listed in Table V.

The analytical results of load-deflection curves are shown in Figs. 11 and 12. The ultimate loads of rehabilitated beams are higher than those of control beams. And the ultimate loads of damaged beams are lower than those of control beams. Such tendencies between experimental and analytical results are in good agreements.

Analytical results of deformed shape and stress contours predicted from a FE model of rehabilitated beam are illustrated in Fig. 13. For the rehabilitated FE model, high stresses are distributed in rehabilitated part with polymeric cement mortar while low stresses are found in damaged concrete part.

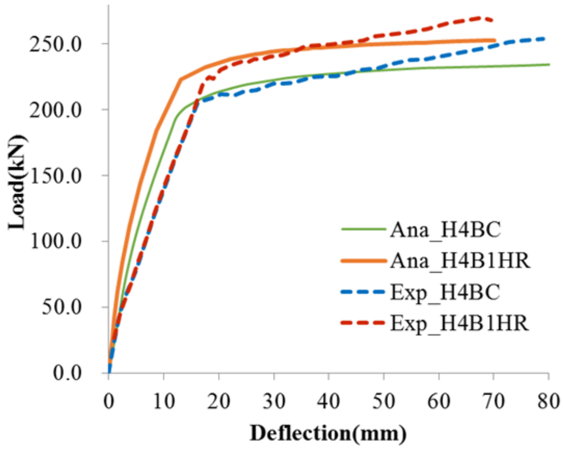


Fig. 11 Experimental and analytical load-deflection curves for beams having cover thickness of 40mm

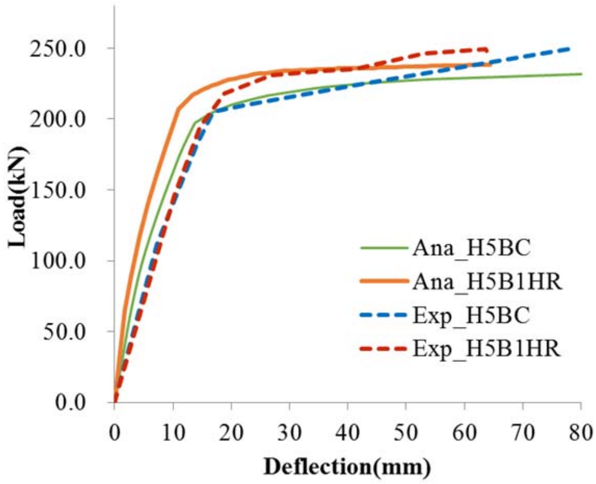


Fig. 12 Experimental and analytical load-deflection curves for beams having cover thickness of 50mm

TABLE VI
PROPERTIES OF POLYMERIC CEMENT MORTAR

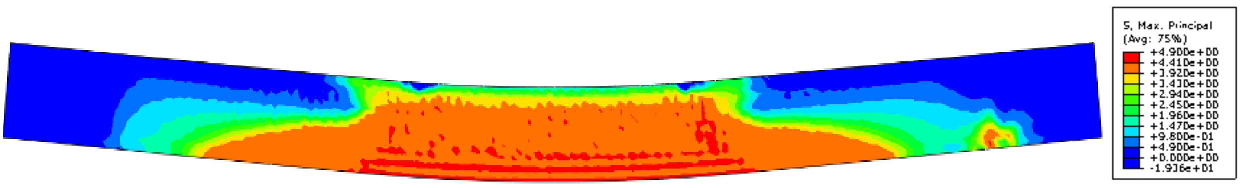
Description	Unit	Mortar type A	Mortar type B
Elastic modulus	MPa	29210	25540
Compressive strength	MPa	59.72	44.40
Poisson's ratio		0.2	0.2
Density	kg/m^3	20	20

It can be seen that the slopes of rehabilitated beams are higher than those of control beams. The slopes of H4B1HR and H5B1HR are 12.0% and 19.7% lower than those of H4BC and H5BC, respectively. But the slopes of H4B1HR and H5B1HR are 21.1% and 27.1% higher than those of H4BC and H5BC, respectively. Therefore cross sectional areas of the rehabilitated beams are increased when they are compared with control beams. However, it can be seen that the ultimate loads predicted from analyses are slightly different from experimentally obtained ultimate loads. The differences between experimental and analytical results are 7.5%, 1.9% and 4.7% from H4BC, H4B1H and H4B1HR, respectively. And the differences between experimental and analytical results of H5BC, H5B1H and H5B1HR are 6.7%, 5.9% and 4.6%, respectively. There are several effects that may cause this simulation, such that the interaction between damaged part, mortar and reinforcement are not considered in FE models. In addition, strength ratios obtained from experiments are lower than those obtain from FE model. This is because the capacities of mortar in the FE model may have more influence on stiffness and strength than those of tested polymeric mortar.

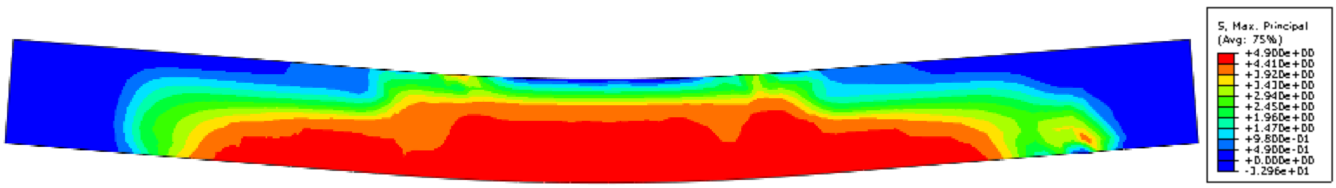
IV. PARAMETRIC STUDIES

Parametrical studies are performed in order to predict the structural behavior of high strength RC beam according to strength of polymeric cement mortar. There are four specimens that are listed in Table VI. Load-deflection curves predicted from the FE models according to strength of two different polymeric cement mortar types are illustrated in Figs. 14 and 15. Parameters are strength of two different polymeric cement mortar types such as 59.7MPa and 44.4MPa. Parameters are selected according to the previously reported paper [11] and listed in Table VI.

It is seen that ultimate loads of beams rehabilitated with polymeric cement mortar type A are higher than those of beams rehabilitated with polymeric mortar type B. As shown in Figs. 14 and 15, the ultimate loads of H4B1HRA and H5B1HRA are 281.5kN and 269.9kN while the ultimate loads of H4B1HRB and H5B1HRB are 252.6kN and 238.3kN. The ultimate loads of FE models are listed in Table VIII. The slopes of beams rehabilitated with mortar type A are stiffer than those of beams rehabilitated with polymeric mortar type B.



(a) Stress contour of concrete predicted from a FE model



(b) Stress contour of rehabilitated part predicted from a FE model

Fig. 13 Stress contour of a FE models for beam having cover thickness of 40mm

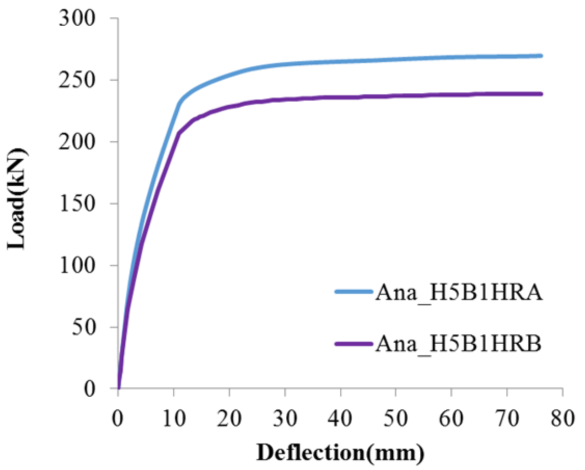


Fig. 14 Analytical load-deflection curves for beams having cover thickness of 40mm according to polymeric cement mortar

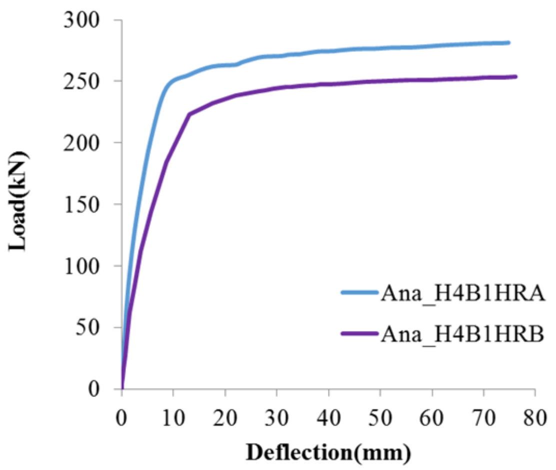


Fig. 15 Analytical load-deflection curves for beams having cover thickness of 50mm according to polymeric cement mortar

TABLE VII
LIST OF MODELS ACCORDING TO POLYMERIC CEMENT MORTAR

Model	Condition	Cover thickness
H4B1HRA	Rehabilitated with mortar type A	40mm
H4B1HRB	Rehabilitated with mortar type B	40mm
H5B1HRA	Rehabilitated with mortar type A	50mm
H5B1HRB	Rehabilitated with mortar type B	50mm

TABLE VIII
ULTIMATE LOAD AND SLOPE FROM EXPERIMENTS AND FE ANALYSIS

Name	Ultimate load(kN)	Slope(kN/mm)
H4B1HRA	281.5	23.5
H4B1HRB	252.6	21.2
H5B1HRA	269.9	21.6
H5B1HRB	238.3	20.6

The slopes of H4B1HRA and H5B1HRA are 10.8% and 4.9% higher than those of H4B1HRB and H5B1HRB.

It is found that the ultimate loads of beams having cover thickness of 40mm are higher than those of beams having cover thickness of 50mm. The ultimate loads of H4B1HRA and H4B1HRB is 4.3% and 6.0% higher than those of H5B1HRA and H5B1HRB.

The slopes of beams having cover thickness of 40mm are higher than those of beams having cover thickness of 50mm. The slopes of H4B1HRA and H4B1HRB are 8.8% and 4.8% higher than those of H5B1HRA and H5B1HRB. Because the effective depth of beams having cover thickness of 40mm is larger than that of beams having cover thickness of 50mm.

V. CONCLUSION

This study investigates the structural behavior of fire-damaged high strength RC beam retrofitted with polymeric cement mortar from experiments and FE analyses. The results obtained from experiments and FE analyses are summarized as:

1) In the experiments, the ultimate load of the rehabilitated beam is similar to that of the control beam. So, high strength concrete beam can be reused if a damaged beam due to fire is rehabilitated with polymeric cement mortars.
2) The load-deflection curves of the beams from the FE analyses are in good agreement with those of the experiments. So, parametrical studies are performed in order to predict the structural behavior of high strength RC beam according to strength of polymeric cement mortar.
3) The ultimate loads of the beams heated for 1hour are fully recovered regardless of strengths of polymeric cement mortar type.
4) It is found that the ultimate loads and slopes of beams having cover thickness of 40mm are higher than those of beams having cover thickness of 50mm. This is because the effective depths of beams having cover thickness of 40mm are larger than those of beams having cover thickness of 50mm.
5) Further studies are needed to see if the different beam size, reinforcing ratio, fire exposed time period and cover thickness have influence on effectiveness of rehabilitation.

ACKNOWLEDGMENT

The research was supported by NRF(National Research Foundation of Korea) -2013R1A2A2A04014772

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