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An Analytic Method for the Residual Strength Evaluation of Fire-Damaged Reinforced Concrete Beam

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Abstract

This study is to get the proper evaluation of the residual property of reinforced concrete beam exposed to fire. This study focused on the strength resistance and analytical evaluation of RC members exposed high temperature. And this study is the basis analytical research to conduct the other studies. To analysis by the finite element method, the Total-RC program was used to analysis it and the Total-Temp program was also used to analysis the temperature distributions at the section. All of results were compared with the pre-existing experimental data of simple supported beam. Using it, the parameters influencing the structural capacity of the high temperature-damaged RC members and residual strength estimation are investigated. The temperature distribution and the structural capacity at the section are calculated in this step. An application of this method is compared with the heating test result and residual property test for simple supported beam which is subjected to ISO 834 test fire. The results of this study are as follows; 1) The loads-displacement relationship of RC beam, considering initial thermal stress of cross section and heat transfer analysis are estimated comparing analytical value with pre-existing experimental results. 2) by the heating time (0, 1, 2 hours), the results of analysis with parameters show that the load capacity exposing at fire is affected.

Keywords : Reinforced Concrete Beam, High Temperature (Fire), Residual Strengths, Finite Element Analysis(FEA), Section Repair

1. INTRODUCTION

Building structures must be able to protect human life, and have characteristics against disasters especially as fire. In fire statistical report in Korea (NEMA Report 2006), there are 30,000 fire occurrences annually, and most of these are the case of building fire. The modern architecture has pursued high-rising, large-sizing and modernization tendency for the high efficiency of land usage and urbanization. On this account, there is also dangerousness that large-sized fires and possibility are also able to be passed over. During fire, changes of material and thermal stress are occurred and the interior of concrete is damaged at each section. The dynamical characteristics of concrete are changed. Therefore, to grasp the degree of performance decrease of fire damaged reinforced concrete, we also have to predict and evaluate the internal temperature distribution of member section. To understand the thermal response of the building structures subjected to elevated temperatures, both information on the temperature distribution according to external heat and a full comprehension on the material behavior and model at the temperature condition are essential. But, most researches focused on the time when structural members were in during fire. And the material model to analysis of structural behavior is generally concerned about standard codes or others. Especially, there are hardly any researches for material model and evaluation of residual strength of structural members.

This study shows how to evaluate the residual property of reinforced concrete beam exposed to fire analytically, and is also the basis analytical research to find proper techniques of repair with fire damages, to define the structural behavior of reinforced concrete beam according to pre- or post-repair after fire-damages. Analytical condition is focused on UR(specimen heated Unstressed, tested at Room temperature). An analysis program using FEM (finite element method), the Total-RC program was used to analysis it and Total-Temp program was also used to analysis the temperature distributions in the section. All of results were compared with the existing experimental data under simple supported beam. Using the program, the parameters influencing the structural capacity of the high temperature-damaged, RC members and residual strength estimation are investigated. Both the temperature distribution and the structural capacity at the section are calculated in this step. An application of this method is performed, and compared with the heating test result and residual property test for simple supported beam which is subjected to ISO 834 fire test.

2. PROCESS AND SCOPE

In this study, non-linear finite element analysis(FEA) method was used to conduct analytical evaluation. According to the parameters with fire time, FEA program, Total-Temp and Total-RC were used to evaluate residual strength prediction during and after fire.

Reinforced concrete members exposed to high temperature like fire, have different temperature distribution according to heating temperature, continued heating time and section size. Thus, structural material, concrete and steel also have different properties. Then the residual capacity of RC beam was evaluated according to temperature distribution at the section during fire and after fire. Also, this research was focused on both structural behavior and evaluation residual load capacity of the fire damaged reinforced concrete beams repaired with polymer mortar and mortar using engineered cementitious composite. To this end, ISO 834 standard time/temperature curve is used for the temperature assumed fire condition.

The scope of this study is as follows.

1. Material models of concrete and steel according to during or after fire.
2. The evaluation of structural behavior of RC beam and residual strength according to fire time.
3. The evaluation of structural behavior of RC beam and residual strength at room temperature after fire.
4. An analytical evaluation on structural behaviors of fire-damaged RC beam retrofitted with repair materials after fire.
5. An analytical evaluation on structural behaviors of fire-damaged RC beam retrofitted with reinforcement materials after fire.

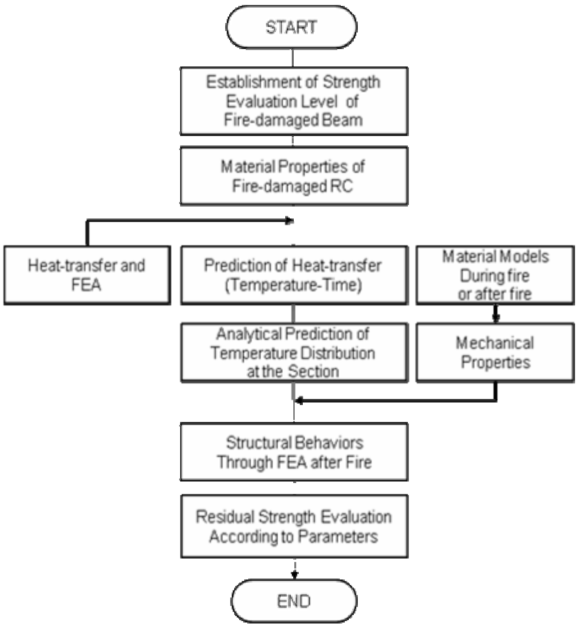


Figure 1. Flow of analysis evaluation of residual strength

3. TEMPERATURE DISTRIBUTION ANALYSIS

The temperature distribution of the member section with time is essential procedure for the successive solution of the analysis of structural behavior. In existing several methods for the prediction of temperature distribution, most common method involve either FEM(Finite Element Method) or FDM(Finite difference Method). Because FEM has more complicated and time consuming algorithm compared to FEM, most available computer programs for temperature analysis use FEM.

(1) Assume for Analysis

It is assumed that the heat flow relationship is presented in a 2-Demensional system for the convenience of the explanation as following Figure 2.

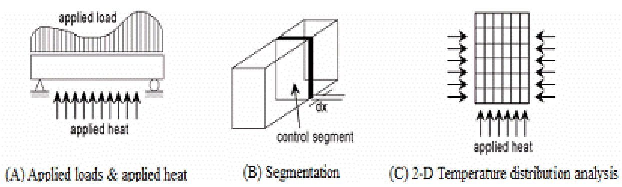


Figure 2. Assume for temperature distribution analysis

In the procedure of the evaluation on residual strength of fire-damaged RC beam, temperature distribution at the section can be obtained using geometry of the beam, type of bar arrangement and material properties. In this study, the geometry of the beam for experiment and analysis is as Figure 3. The solution program, Total-temp., was used for temperature distribution as analysis tool, and non-steady heat transfer equation was also used.

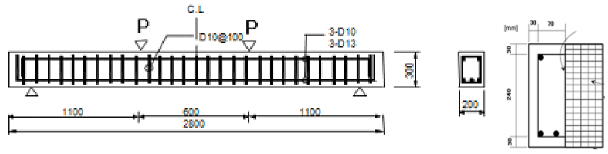


Figure 3. Geometry of the simply supported beam

(2) Standard Time-Temperature Curve

In order to simulate the fire performance of the structures, ISO 834(1999) standard time-temperature curve is used for the temperature assumed fire condition as Figure 4.

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

where, T = Heating Temperature [℃]
T_0 = Initial Temperature [℃]
t = Time [min]

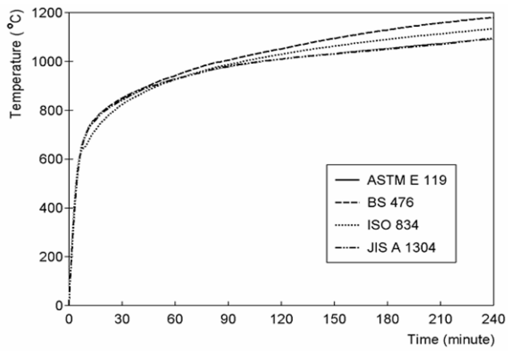


Figure 4. Furnace temperature of the standard fires; ASTM E 119, BS 476, ISO 834, JIA A 1304

(3) Temperature Distribution at the Section

In order to simulate the fire performance of the structures, ISO 834 standard time-temperature was used. Figure 5 shows temperature distribution at the segmented section with time and distance from the bottom surface.

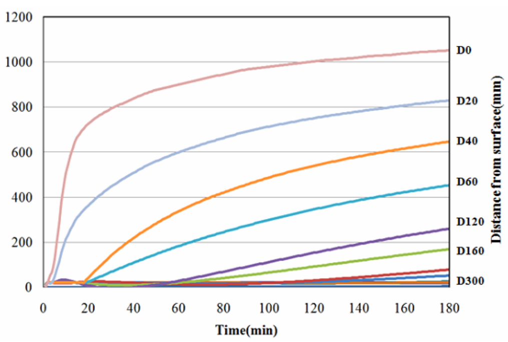


Figure 5. Temperature distribution at the segmented section with time and distance from the bottom surface

As a result of temperature distribution analysis, it was obtained that is similar to experimental result proposed by ACI 216R-89(2001). In KS F 2257, the maximum temperature of steel on RC structure is determined up to 500℃. The structural member exposed to fire about 2 hours is needed both evaluation of load capacity after fire and analytical investigation of distinction of repair or reinforcement. Figure 6 shows thermal distribution at the section, and Figure 7 also presents temperature distribution at the specimen section with time.

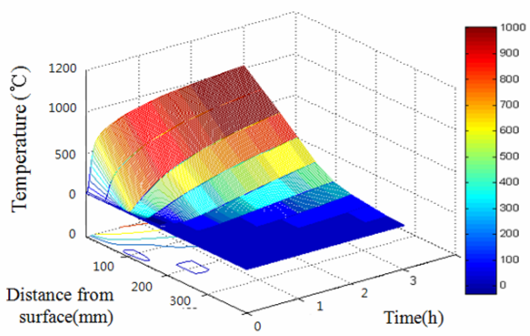


Figure 6. Temperature distribution at the section with time

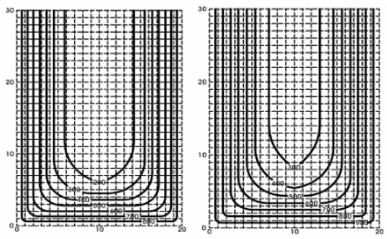


Figure 7. Temperature distribution at the section of specimen

4. EVALUATION OF RESIDUAL STRENGTH

(1) Outline of Finite Element Analysis (FEA)

Two-dimension non-linear FEA considering heterogeneous material to evaluate the structural behavior of RC beam exposed to fire was carried out. Analysis tool, Total-RC Program was used for FEA. Subject of modeling and meshing of elements is half-size of specimen as Figure 8. In Figure 8, boundary condition is divided into three types, concrete, steel and bonding between concrete and steel.

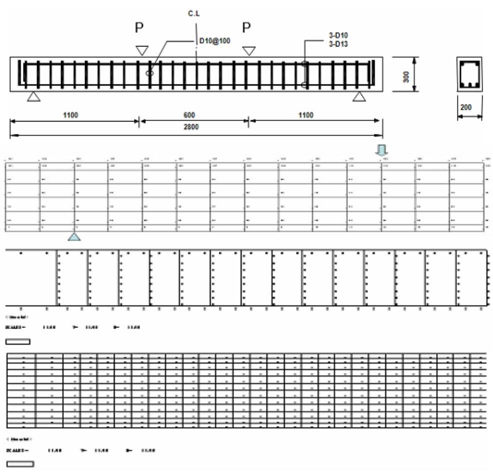


Figure 8. Finite element modeling

(2) Load Capacity Analysis of RC Beam

By displacement control(maximum capacity=25tonf) of Figure 9, the test of load capacity is carried out. Table 1 presents the material properties. The material properties were prepared at each element node. And Figure 10 shows the results that are both experimental results and FEA results.

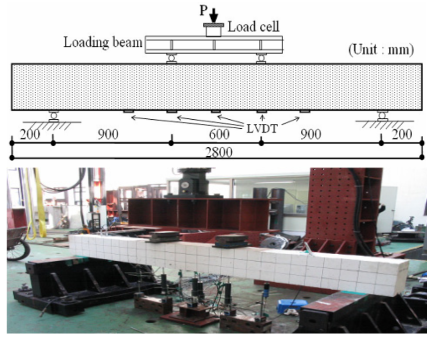


Figure 9. Elevation of the test specimen

Table 1. General properties of concrete and reinforcement

Classification	Age(days)	fc(MPa)	fy(MPa)	Ec or Es
concrete	28	21.8	-	$2.1*10^5$
reinforcement	-	-	400	$1.83*10^6$

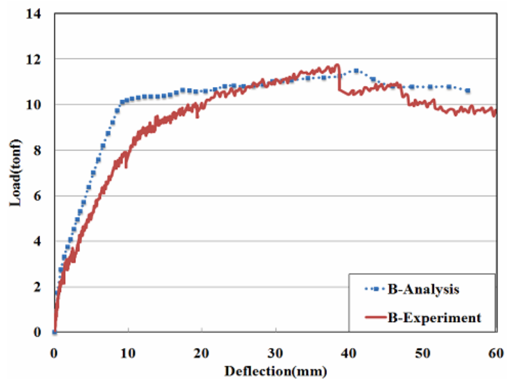
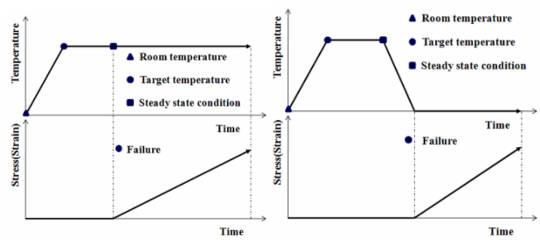


Figure 10. Comparison on analysis result and experiment

From the result of test at the normal temperature, it shows that the type of deflection in test coincidences of the result of analysis (Kang, S.W. and Han, S.H, 2004). Therefore, it is needed to propose the material models for analytical prediction and evaluation in case of unstressed residual strength test assumed at room temperature after fire like Figure 11-(b). Figure 11 shows two types of test methods, specimen heated unstressed test method at room temperature-UR test and specimen heated unstressed test at target temperature-UE test. Thus, in this study, UR test was used to evaluate the residual strength after fire.



(a)Specimen heated, Unstressed (b) Unstressed residual strength
Figure 11. General properties of concrete and reinforcement

5. PROPOSAL OF NUMERICAL MODELS

(1) Model of Steel

Throughout comparing existing experimental database with various standards(Eurocode 2004), the model of elastic modulus is proposed as following Figure 12.

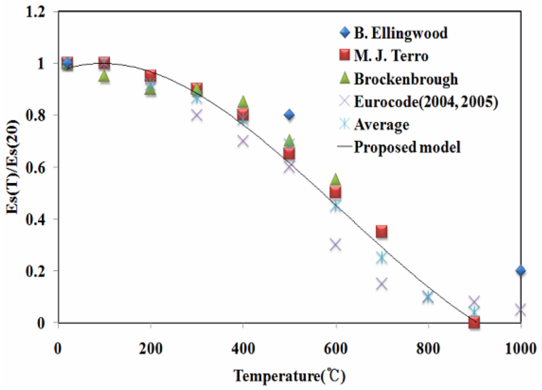


Figure 12. Residual ratio of elastic modulus of reinforcement

In the proposed model, the elastic modulus is recovered little. Otherwise it was presented that decrease ratio of stiffness of RC beam during fire was similar to result in case of it after fire. It is assumed that there is no elastic modulus recovery after fire. Therefore, in this study, it is also assumed that the elastic modulus recovers until yield point disappears at 200℃. And the arithmetic mean is used at range from 200℃ to 600℃ because the elastic modulus loses about 50% in the existing researches. Researches about reduction model of yield strength are insufficient. In existing research, the strength residual ratio is 1 on 350~400℃ after fire(Han, S.H.(2004)). On the other hand, cooled steel that heated range is 0~500℃ mostly recovers its strength in material characteristics of steel. Also, it is known that recrystallization of steel is occurred at 420℃ and the maximum temperature of steel is stipulated below on fireproof structure. Therefore, in this study, it is assumed that the strength residual ratio is 1 at 200℃.

$0<T\leq 200℃;\quad \gamma_s=1$

$200<T\leq 600℃;\ \gamma_s=1.31-0.00145T$

$$f_{yT}=\gamma_s \cdot f_y$$

where, γ_s= Reidual ratio of yield strength
f_y= Yield strength of steel at the normal temperature
f_{yT} = After fire, Yield strength of steel arrived up to T℃

Table 2. Residual ratio of elastic modulus after fire

Temperature (℃)	Reinforcing rod			
	Residual Ratio (%)	Es ($*10^6$)	Residual Ratio (%)	fy (MPa)
20	100	1.83	100	400
100	100	1.83	100	400
200	92	1.68	100	400
300	87	1.59	87.5	350
400	78	1.43	73.0	292
500	69	1.26	58.5	234
600	45	0.82	44.0	220

(2) Model of Concrete

In normal strength concrete at high temperature, the residual ratio of material properties of concrete follows to CEB's recommendation. After fire, the elastic modulus model is proposed as following Figure 13 considering both CEB/Eurocode(2004) and existing experimental reports (Kim, H.Y., 2005). FEA is carried out using following numerical values in Table 3. In this model, it is configured 0.03~0.11 more bigger than CEB in range of 100~600℃ .

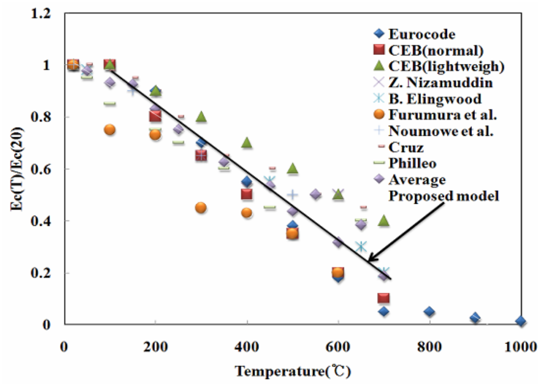


Figure 13. Residual ratio of elastic modulus of concrete

The compressive strength in Euro-code has a tendency of increase and decrease around 200℃. This is able to cause a overestimation of strain, and immoderation analysis result can be occurred. In this study, the numerical model is proposed through the generalization of the existing reports(normal strength concrete) as bellow Figure 14. It has similar tendency with CEB. Thus, the FEA is also carried out using following numerical values in Table 3.

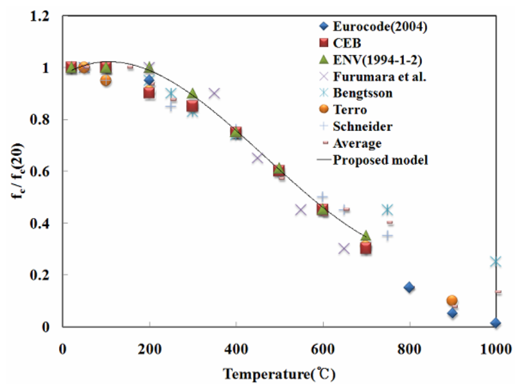


Figure 14. Residual ratio of compressive strength

Table 3. Mechanical property of concrete after fire

Temperature (℃)	Reinforcing rod			
	Residual Ratio (%)	Ec ($*10^5$)	Residual Ratio (%)	fc (MPa)
20	100	2.10	100	21.0
100	98	1.95	100	20.7
200	83	1.74	95.1	20.0
300	66	1.38	86.3	18.1
400	55	1.14	73.3	15.4
500	44	0.92	57.0	12.0
600	32	0.66	43.0	9.04

(3) Application of Numerical Model of Bond Strength

A calculating method for changes in bond strength of iron rods is proposed by C. Chiang(2003). Evaluation of bond strength of a fire-damaged RC structure for determining whether to reuse, reinforced, or abandon the structure is very important. The proposed equation is relating the residual ratio of bond strength. Figure 15 shows the result of both Chiang's and Sim's(2003). The residual ratio of bond strength accords Table 4.

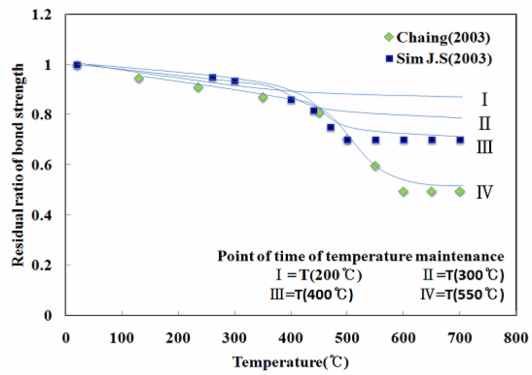


Figure 15. Residual ratio of bond strength

Table 4. Residual ratio of bond strength

Temperature(℃)	200℃	300℃	400℃	500℃
Residual ratio(%)	95	90	75	50

6. RESULTS AND ANALYSIS

(1) Load Capacity at High Temperature

The analytical result of load-deflection was evaluated from standards concerned allowable deflection. Generally, limitation of deflection is prescribed on L/240(beam L/240=10.00mm). When deflection exceeds more than 10.00mm, though there is not structural collapse, the structure has a problem to use. Due to ductility of steel, it has no structural performance in case of over-deflection. Table 5 presents the classification of analysis factors in this study.

Table 5. Residual ratio of bond strength

Classification	Analysis factors(*B: Basic specimen)	
Specimen indication	B – HOO – ROO ① ②	
	Heating time	Repair materials
Value	1, 2 (hour)	Polymer-mortar High ductility mortar
	H1,H2	RP, RH

The load-displacement curve with heating time is presented in Figure 16. This is resulted from FEA using material models in chapter 2. Also, it is the results assumed unstressed test. According to heating time, the reduction of resistance force is presented as Table 6. The load-deflection curves show both similar type and structural behavior. In case of 1 hour, the maximum load decreased about 18.5%. On the other hand, when the deflection was 10mm, the reduction ratio was about 10.2%. Thus, the ductility was decreased according to heating time.

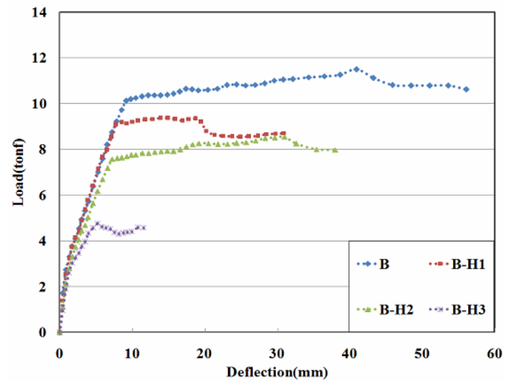


Figure 16. Load-displacement curve with heating time

Table 6. Load reduction ratio at L/240 with time(UE test)

Specimen	Load (max) (tonf)	Reduction ratio (%)	Load (δ=L/240) (tonf)	Reduction ratio (%)
B	11.49	-	10.25	-
B-H1	9.36	18.5	9.21	10.2
B-H2	8.54	25.7	7.76	24.3

(2) Residual Strength after fire

In case of residual strength after fire, the load-displacement curve is presented as Figure 17 at normal temperature. This is resulted from FEA using material models in chapter 5. The results are based on unstressed residual strength test. According to heating time, the reduction of strength is presented as Table 7. In case of 2 hours, the maximum load decreased about 10%. On the other hand, seeing with the deflection 10mm, the reduction ratio was about 28.5%. It means that the ductility reduction was decreased.

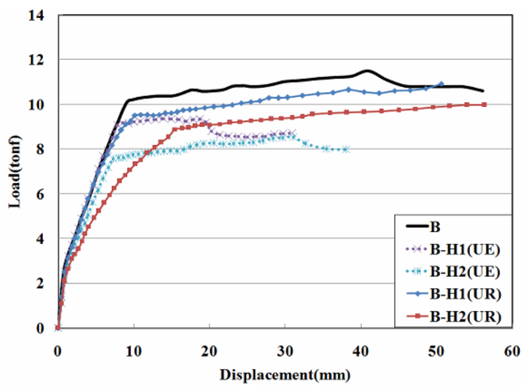


Figure 17. Load-displacement curve with heating time

Table 7. Load reduction ratio at L/240 with time(UR test)

Specimen	Load (max) (tonf)	Reduction ratio (%)	Load (δ=L/240) (tonf)	Reduction ratio (%)
B	11.49	-	10.25	-
B-H1	10.91	5.0	9.5	7.4
B-H2	9.98	13.14	7.33	28.5

(3) Residual Strength after Section Repair

For structural behavior of fire-damaged RC beam repaired with section recovery material, FEA was carried out according to both heating time and kinds of materials. The result is presented as Figure 18, 19 and Table 8, 9.

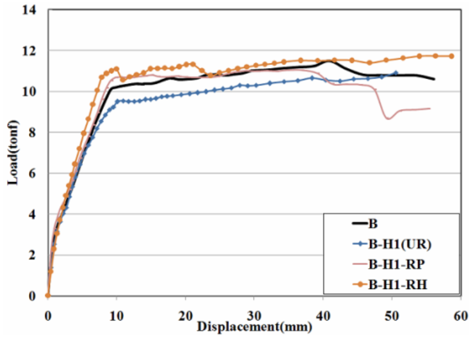


Figure 18. Load-displacement with heating time(1hour) and repair

Table 8. Load reduction ratio at L/240 with time(UR test)

Specimen	Load (max) (tonf)	Reduction ratio (%)	Load (δ=L/240) (tonf)	Reduction ratio (%)
B-H1-RP	11.18	2.6	10.7	-4.3
B-H2-RH	11.72	-2	11.08	-8.1

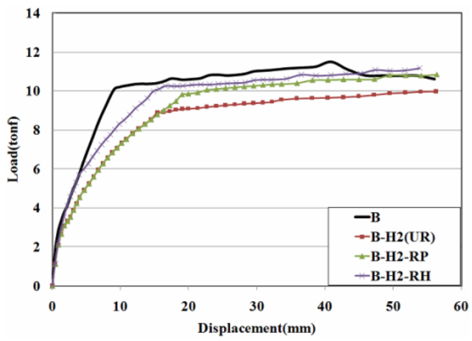


Figure 19. Load-displacement with heating time(2hour) and repair

Table 9. Load reduction ratio at L/240 with time(UR test)

Specimen	Load (max) (tonf)	Reduction ratio (%)	Load (δ=L/240) (tonf)	Reduction ratio (%)
B-H1-RP	10.85	5.6	7.33	28.5
B-H2-RH	11.17	2.8	8.37	18.3

As results of residual strength of repaired RC beam, load-deflection curve is similar to that of the original specimen in case of 1 hour. The change of the tensile strength of repair materials was observed for the reparative effect of residual strength of fire-damaged RC beam. The maximum load value of the repaired beam is increased about 4~8%. Otherwise, in case of 2 hours, RC beam has less than unheated specimen although section was repair. It shows that it has to be not repaired but reinforced.

7. CONCLUSION

Based on this study summarized as above, the followings could be drawn as the conclusions:

1) Throughout the nonlinear finite element analysis, temperature distribution was obtained reliably comparing with the experimental result proposed by ACI 216. Also, evaluation about load capacity of RC beam was able to be carried out using FEA.
2) To carry the analytical evaluation out assumed fire-damaged RC beam at normal temperature, the numerical models of material properties was proposed throughout existing standards and reports.
3) The analysis of load-deflection could be evaluated from not only standards concerned allowable deflection throughout the limitation of deflection is prescribed on L/240(beam L/240=10.00mm) but also fireproof standards. Therefore, it is concluded that the maximum residual strength loss of fire-damaged beam below 1 hour is little and the member stiffness loss is 28.5% in case of 2 hours.
4) In case of the damaged RC beam repaired, the repaired RC beam recovered the initial member stiffness of over 90% in case of fire-damaged time 1 hour. The change of the tensile strength of repair materials was observed for the reparative effect of residual strength of fire-damaged RC beam. As the tensile strength of repair material is larger, the effect is noticeable finely. The maximum load value of the repaired beam is increased about 4~8%.

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