Experimental Study on the Temperature Distribution and Residual Strength of Fire-damaged RC Columns Depending on Heated Areas

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Abstract

Most of the columns in actual fire conditions are heated on partial faces rather than all four sides due to the floor plan, which results in asymmetric behaviors of columns. The asymmetric behaviors of fire-damaged columns may cause more vulnerability to the structural performance. In this study, temperature distribution and residual strength of reinforced concrete columns exposed to fire were investigated according to various heated areas. To achieve the objective, columns were heated for 2 h according to ISO-834 standard time-temperature curve and subsequently tested under the axial loading after a week. The test results show that the residual strength of the fire-damaged columns decreased as the heated area increased, and the residual strength reduced additionally due to asymmetric heating.

Key words : RC Column, Fire, Temperature, Residual Strength, Heated Area

요 지

실제 화재가 발생한 기둥은 평면 계획으로 인해 4면 전체에 가열되는 경우보다 일부 면에만 가열이 되는 경우가 대부분이다. 이는 부분 가열로 인해 기둥 부재에 편심이 발생할 수 있어 추가적으로 구조내력이 저하될 수 있다. 이에 본 연구에서는 기둥의 가열 면의 수가 다양한 경우를 반영하여 화재 피해를 입은 철근콘크리트 기둥의 온도분포 및 잔존강도를 분석하였다. 이를 위해 기둥은 ISO-834 표준화재곡선에 따라 2시간 동안 가열하였으며, 일주일 후 축력 실험을 수행하였다. 실험 결과, 화재 피해를 입은 기둥의 잔존 강도는 가열면이 증가할수록 감소하며, 국부 가열로 인하여 잔존 강도가 추가적으로 저감하는 것으로 나타났다.

핵심용어 : RC 기둥, 화재, 온도, 잔존강도, 가열면

1. Introduction

Since Reinforced Concrete (RC) is well-known thermal resistant materials, studies for the thermal and structural behaviors of fire-damaged concrete structures have been limitedly conducted. Moreover, most of the existing studies have performed fire tests on concrete columns by heating all four sides consistently. However, concrete column is commonly damaged partially and inconstantly due to fire condition and floor plan when a fire occurs, which may reduce

the residual strength of fire-damaged columns additionally.

Recently, the performances of fire-damaged concrete columns have been actively studied by many researchers (Kodur et al., 2004; Han et al., 2009; Yaqub and Bailey, 2011; Shah and Sharma, 2017). Jau and Huang (2008) investigated the behavior of corner columns under axial loading, biaxial bending and asymmetric fire loading. Chen et al. (2009) reported an experimental research into the effect of fire exposure time on the post-fire behavior of RC columns. After fire tests, the specimens were tested in axial load

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combined with uniaxial or biaxial bending. The test results indicated that the residual load-bearing capacity decreased with increase in fire exposure time. In addition, the reduction rate of stiffness was higher than that of ultimate load. In the research (Choe et al., 2015), material properties of Ultra-High-Strength Concrete (UHSC) and residual load of RC column at high temperature was evaluated. RC columns were fabricated with 200 MPa concrete and were heated by ISO-834 standard fire curve for 3 hours. From the results, the rate of compressive strength degradation of UHSC subjected to elevated temperature was higher than that of NSC. Li et al. (2017) tested to understand the cyclic behavior of damaged RC columns repaired with a high-performance fiber-reinforced cementitious composite with high-volume fly ash and to evaluate the effects of axial load and repair height. However, limited research has been conducted on the thermal and structural behaviors of the RC columns depending on heated area.

Therefore, this study aimed to investigate the effect of various heated areas on the thermal and structural behaviors of RC columns under and after the fire. Toward the goal, fire tests and loading tests were conducted to measure temperatures distributions and residual strengths of RC columns exposed to fire on different number of faces.

2. Experimental and Analytical Approaches

2.1 Test Specimens and Parameters

For the tests, five columns were fabricated with the dimensions of $350 \times 350 \times 1,500$ mm (width $\times$ depth $\times$ height), as shown in Fig. 1. Dimensions were determined with consideration of heating chamber sizes and to exclude the effect of buckling. For the longitudinal and transverse reinforcement, D22 and D10 (diameter = 22.2 and 9.53 mm, respectively) were used, respectively. Stirrups were arranged with intervals of 300 mm at center and 50 mm at the edge of column. The first tie was placed at a height of 50 mm from the column base.

The sheath temperatures inside the RC columns were measured by five thermocouples from measuring points of C1, C3, and C5 along the concrete cover, C4 at the middle of the cross section, and C2 in the mid of C1 and C4, as shown in Fig. 1. The reinforcing bars and thermocouples were placed inside the formworks, before fresh concrete was poured into the mold. All the specimens were cured for three months at ambient temperature to minimize moisture effect during the fire tests.

Fig. 1. Details of Specimens and Locations of Thermocouples

The variable of the experiment was heated area, which was varied from none to four side surfaces as listed in Table 1. The variable was determined to consider that columns can be partially exposed to fire depending on fire conditions and floor plans. In order to apply heat on the designated surface of the columns, insulations are attached on the surfaces to be unheated during the fire tests.

Table 1. List of Specimens

No.	Specimen	Heated Area	Location of Insulation (▨)
1	C0	None	None
2	H1	One side surface	
3	H2	Two side surfaces	
4	H3	Three side surfaces	
5	H4	Four side surfaces	

2.2 Materials

The the mix proportions of the tested concrete are designed as listed in Table 2 to satisfy design strength of concrete as 60 MPa. For the material strength tests, the cylindrical specimens were fabricated with 100 mm of diameter and 200 mm of height according to KS F 2403 and subjected to loading after 28 days of curing. The averaged compressive strength of concrete was obtained as 57.8 MPa. The average yield strength and elastic modulus of reinforcing bars were also obtained from the material strength tests as listed in Table 3.

Table 2. Mix Proportions for Concrete

Compressive Strength (MPa)	W/C	Weight per Unit Volume (kg/m ³)				
		W	C	S	G	pp fiber
57.8	24.2	160	660	727	929	1.35

Table 3. Material Properties of Reinforcement

Type	Yield Strength f_y (MPa)	Elastic Modulus E_s (GPa)
D10	490	217
D22	473	195

2.3 Experimental Approach

2.3.1 Fire Test

The specimens were tested in the heating chamber as shown in Fig. 2. Top and bottom parts of the specimens were covered by insulations to protect those parts from being damaged during the heating so that the load and support can be applied easily during the loading tests. Specimens were heated for 2 hours according to ISO-834 standard time-temperature curve without axial loading. Nine thermocouples were placed inside the heating chamber to measure and control the temperature of the heating chamber to follow the ISO-834 standard time-temperature curve (ISO 1999) during the tests.

Fig. 2. Heating Chamber for Fire Test

2.3.2 Axial Loading Test

After cooled down in the air for a week, the fire-damaged columns were subjected to axial loading as shown in Fig. 3. A compressive force was applied to the top surface of specimen using a hydraulic jack. Linear Variable Differential Transformers (LVDTs) were installed at each side surface of the specimens to measure displacement of the columns during the loading.

Fig. 3. Setup of Axial Loading Test

3. Experimental Results

3.1 Experimental Results from Fire Test

3.1.1 Observation of the Fire-damaged Columns

As shown in Figs. 4(a) and 4(b), white and black stains were visible on the non-heated surfaces due to evaporation of moisture during heating. In addition, post-cooling spalling of specimens was observed from surfaces of the cooled down specimens. This was observed not during the heating, but cooling. The post-cooling spalling occurred mainly on the heated surfaces with depth less than 3 mm, and some of the columns show relatively large post-cooling spalling at corners with maximum depth of 15 mm. Since the post-cooling spalling occur during cooling, it is not possible to be explained by neither thermal stress spalling theory nor pore pressure spalling theory. Rather, it has been known that the spalling can occur from the concrete mixed with calcareous aggregate (Khouri, 2003, 2008), caused by over 40% of volume expansion resulting from rehydration of CaO to Ca (OH)₂ during cooling and then the expansion leads to make severe internal cracks (Annerel and Taerwe, 2007, 2009). In other studies (Xing et al., 2011; Klingsch, 2014), post-cooling spalling was reported from the heated specimens during cooling down in ambient temperature.

(a) Unheated Surface (b) Heated Surface

Fig. 4. Specimen H1 after Fire Test

3.1.2 Temperature Distribution

Figs. 5(a) and 5(b) show the time-temperature curves of columns measured at different depths along the thickness. The temperatures measured at 40 mm from the heated surface increased rapidly in the beginning of the fire test and then slowly increased in time. The temperatures at 100 and 175 mm from the heated surface reached 100 °C and stayed at this temperature longer than those at other locations because the moisture moved from the single face exposed to fire to the unexposed surface. Time-temperature curves of all tested specimens tended to be similar in other specimens. In case of H1, the temperatures at the C1 and C5 located in the concrete cover were similar and lower than other specimens because H1 was heated on one side. On the other hand, there was no significant difference of C2, C3, and C5 among heated specimens regardless of heated area.

(a) Specimen H1

(b) Specimen H2

(c) Specimen H3

(d) Specimen H4

Fig. 5. Time-temperature Curves of Columns

3.2 Experimental Results from Axial Loading Test

3.2.1 Failure Modes

Figs. 6(a)~6(d) show failure modes of the fire-damaged specimens after the loading tests. Severe damages such as concrete crushing and buckling of longitudinal bars were observed. In the loading tests, the specimen exposed to fire was observed to be more brittle than the control specimen. Moreover, increased concrete crushing was observed from the heated surface compared to the non-heated surface. This phenomenon became obvious in H3 and H4 due to the relatively large heated area.

Fig. 6. Failure Modes of Fire-damaged Columns after Loading Tests

3.2.2 Residual Strength

The experimental results of residual strength for the specimens were obtained from the axial loading test as listed in Table 4. It was obvious that the residual strength of the specimen decreased as the heated area increased. It was

interesting to note that the residual strengths of the partially heated specimens tended to decrease slightly larger than numerical results obtained by the 700 °C isotherm (Ryu, 2020). This was because the asymmetric cross sectional properties of the partially heated columns worked as if the column was subjected to eccentric loading. Therefore, it can be said that additional decrease of residual strengths can occur from the partially heated specimens because of the eccentric loading effect. This may become more obvious when the longer columns are used in real building.

Table 4. Residual Strength of RC Columns

Specimen	Experiment		Analysis (Ryu, 2020)	
	Residual Strength (kN)	Ratio	Residual Strength (kN)	Ratio
C0	5,931.4	1.000	6,096.7	1.000
H1	5,460.3	0.921	5,629.7	0.923
H2	4,810.8	0.811	5,168.1	0.848
H3	4,464.5	0.753	4,691.6	0.770
H4	3,991.9	0.673	4,128.4	0.677

4. Conclusions

In this paper, the thermal and structural behaviors of RC columns under and after fire were investigated according to heated area. The following conclusions can be drawn from the results.

- (1) Post-cooling spalling of specimens were observed on all parts exposed to high temperature not during the heating but after cooling down to ambient temperature. But there was no noticeable differences of crack patterns and temperature distributions among the heated specimens.
- (2) From axial loading test results, the residual strength of the columns decreased as the heated area increased. In addition, there was eccentric loading effect of the columns heated on one ~ three side surfaces, which causes additional decrease of residual strength.

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