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Performance of fire damaged steel reinforced high strength concrete (SRHSC) columns

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Abstract. In this study, an experimental study is performed to understand the effect of spalling on the structural behavior of fire damaged steel reinforced high strength concrete (SRHSC) columns, and the test results of temperature distributions and the displacements at elevated temperature are analyzed. Toward this goal, three long columns are tested to investigate the effect of various test parameters on structural behavior during the fire, and twelve short columns are tested to investigate residual strength and stiffness after the fire. The test parameters are mixture ratios of polypropylene fiber (0 and 0.1 vol.%), magnitudes of applied loads (concentric loads and eccentric loads), and the time period of exposure to fire (0, 30, 60 and 90 minutes). The experimental results show that there is significant effect of loading on the structural behaviors of columns under fire. The loaded concrete columns result more explosive spalling than the unloaded columns under fire. In particular, eccentrically loaded columns are severely spalled. The temperature distributions of the concrete are not affected by the loading state if there is no spalling. However, the loading state affects the temperature distributions when there is spalling occurred. In addition, it is found that polypropylene fiber prevents spalling of both loaded and unloaded columns under fire. From these experimental findings, an equation of predicting residual load capacity of the fire damaged column is proposed.

Keywords: steel reinforced concrete; high strength concrete; concrete column; fire; spalling.

1. Introduction

These days, steel reinforced concrete (SRC) columns with high strength concrete (HSC) have been widely used in high rise buildings. Various studies about the fire resistance of steel-concrete composite structures have been published (Kim *et al.* 2005, Chung *et al.* 2009, Han 2001, Han *et al.* 2002, 2005, Yu *et al.* 2007, Kodur *et al.* 2003, Choi *et al.* 2010). Especially, Kim *et al.* (2005) reported experimental and analytical studies about fire resistance of concrete filled steel tube (CFST) and showed both Euro code 4 and AIJ code are satisfactory to predict temperatures of the CFST columns unless large axial loads are applied during fire tests. Relatively few studies have been reported on fire resistance of steel-concrete composite columns, and fire resistance of concrete columns reinforced with steel fiber or fire reinforced polymers (FRP) are studied by Kodur *et al.* (2003) and Chowdhurya *et al.* (2007). For mechanical behaviors of high strength concrete at high temperatures, experimental studies have been reported by many researchers such as Ahmed and Hurst 1999, Kodur *et al.* 2003, 2004, Cheng *et al.*

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2004, and Choi 2008. Also, post-fire full stress-strain response of fire damaged concrete was reported by Nassiff (2006), which helps understand the mechanical properties of fire damaged concrete in material level. Since spalling is critical to define damages of high strength concrete structures under fire and pore pressure is known to trigger spalling in high strength concrete, experiments have been performed to measure pore pressures of high performance concrete at high temperatures (Kalifa *et al.* 2000). Also, Ali *et al.* (2010) performed experiments on high strength concrete columns subjected to high temperatures and presented spalling degree by measuring weight loss. Based on the previous studies, Eurocode (1992, 1993) suggested fire safety design guide for concrete and steel structures. However, relatively few studies about SRC columns or fire damaged SRC member in real scale have been reported.

In this paper, three main issues of SRC columns under fire, such as spalling, temperature distribution, and residual load bearing capacity, are investigated. Toward this goal, an experimental study is performed to understand the effect of spalling on the structural behavior of fire damaged high strength concrete (HSC) columns, and the test results of temperature distributions and displacements at elevated temperature are analyzed. Also, an equation to predict residual strength of fire damaged HSC columns is proposed in this paper. The findings from this study allow understanding of fire damaged SRC columns and accurate and safe design guide for fire protection.

2. Experimental program

2.1 Test specimens

The test specimen sizes are 350 mm(width) × 350 mm(depth) × 4320 mm(length) for the long columns, and 350 mm(width) × 350 mm(depth) × 1,500 mm(height) for the short columns (Fig. 2). For main and tie rebars, D10 (deformed, diameter of 10 mm) are used. H-shape steel member with dimensions of 150×150×7×10 mm was used in the SRC columns (Fig. 3). Cross sectional area of the H-shape steel and the rebars are 4014 mm^2 and 285 mm^2, respectively. The total cross sectional area of steel members is 4299 mm^2 ($\rho_{st} = 3.51\%$) which satisfies the limit (3% of total cross sectional area) condition for composite structural members.

The H-shape steel, reinforcing bars, and thermocouples are assembled in a cast and fresh concrete is poured into a mold. The bolts used for applying uniaxial eccentric loading are installed at the bottom and top of the columns. The thermocouples to measure the temperature during the fire test are placed in the middle and upper part of the column as shown in Fig. 2(a). The specimens are then cured for six months (Harmaythy 1993) in the atmosphere prior to the fire test.

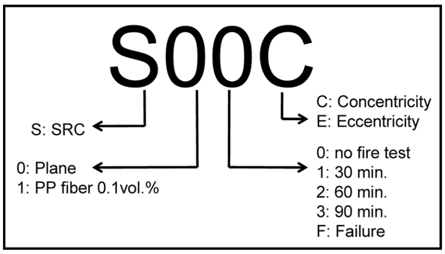
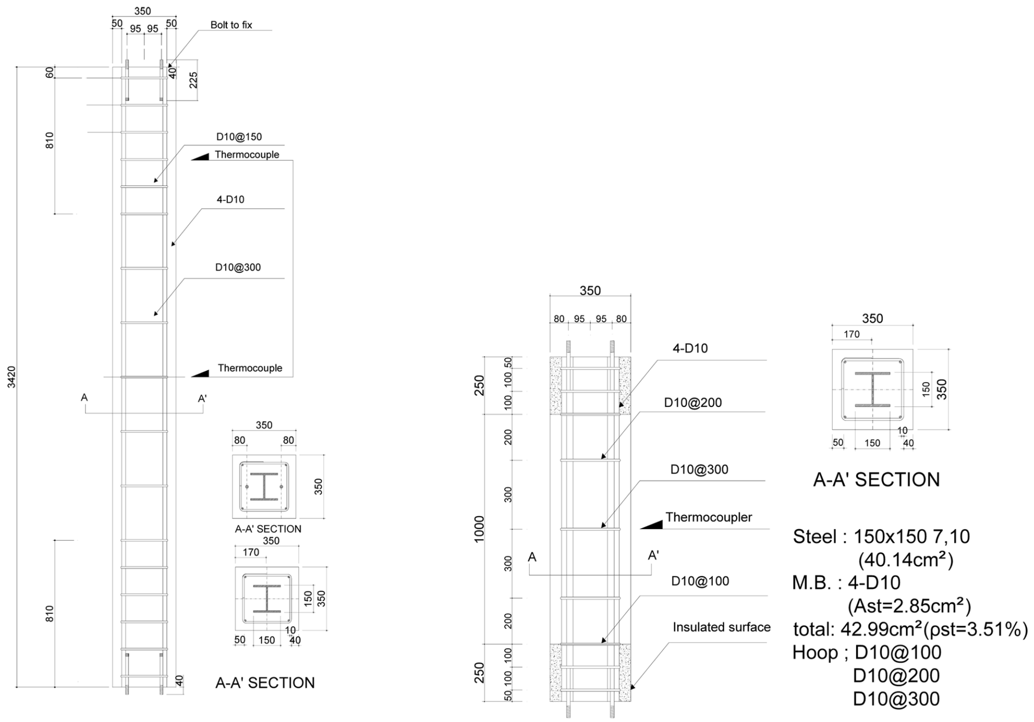


Fig. 1 Symbols of test specimen name



(a) Long column. **(b)** Short column.

Fig. 2 Details of column specimens

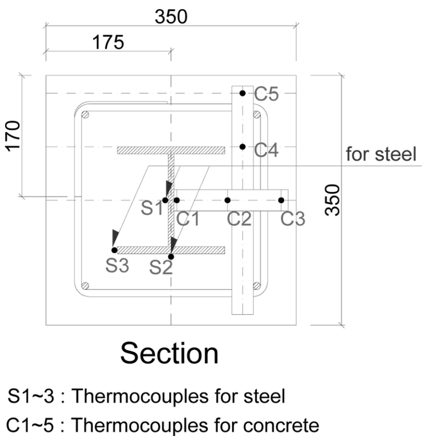


Fig. 3 Column section and location of thermocouples

The symbols for the specimen name are described in Fig. 1, and details of the columns are illustrated in Fig. 2. The temperatures in the column section are measured by thermocouples as shown in Fig. 3. In the case of explosive spalling, the temperature distributions show wide range of temperature distributions, so two sets of the thermocouples are placed along the height of the columns; first set of thermocouples is placed in the middle of column height and the second set is placed with the distance of

Table 1 Summary of test specimens

No.	Specimen	Type	Column height (mm)	PP fiber (vol.%)	Test time (min)	Initial axial load (kN)	Type of applied load	Eccentricity (mm)
1	S0FC	SRC	4320	0	to failure	694.4	Concentric	0
2	S1FC	SRC	4320	0.1	to failure	694.4	Concentric	0
3	S0FE	SRC	4320	0	to failure	694.4	Eccentric	35
4	S00C	SRC	1500	0	0	-	Concentric	0
5	S01C	SRC	1500	0	30	-	Concentric	0
6	S02C	SRC	1500	0	60	-	Concentric	0
7	S03C	SRC	1500	0	90	-	Concentric	0
8	S10C	SRC	1500	0.1	0	-	Concentric	0
9	S11C	SRC	1500	0.1	30	-	Concentric	0
10	S12C	SRC	1500	0.1	60	-	Concentric	0
11	S13C	SRC	1500	0.1	90	-	Concentric	0
12	S10E	SRC	1500	0.1	0	-	Eccentric	35
13	S11E	SRC	1500	0.1	30	-	Eccentric	35
14	S12E	SRC	1500	0.1	60	-	Eccentric	35
15	S13E	SRC	1500	0.1	90	-	Eccentric	35

1200 mm from the first set. The tested specimens are listed in Table 1.

2.2 Materials

2.2.1 Concrete

Ordinary Portland cement and pulverized fuel ash are used to make the concrete. The fine aggregate is medium zone quartz sand, commonly used in Korea. The coarse aggregate is siliceous gravel produced in Korea as well. The design strength of High Strength Concrete (HSC) is 50 MPa with a water-cement ratio of 30.5%. Here, the HSC is defined as a concrete which strength is over 40 MPa in Korea and 42 MPa in ACI committee 363. The slump flow is 700 mm and air container is 4.5%. A cylinder test specimen for the material properties test is fabricated with dimensions of 100 mm diameter and 200 mm height in accordance with KS F 2403(2010). The cylinder specimens are cured under the same condition as the columns.

The mix proportions and the material test results of HSC are listed in Table 2 and 3, respectively.

Table 2 Concrete mixture design

Max. size of aggregate (mm)	Compressive strength (MPa)	W/C(%)	s/a	Weight per unit vol. (kg/m^3)					
				W	C	FA	S	G	AD[a]
20	50	30.5	43	151	482	85	744	923	6.24

[a]Poly-carboxylate based high-range water reducing admixture

Table 3 Concrete compressive strength (MPa)

7 day	14 day	28 day	3 month	6 month	9 month
38.7	44.3	49.2	52.1	54.6	60.2

Table 4 Material properties of steel

	Nominal tensile strength (MPa)	Size (mm)	Type	Yield strength (MPa)	Ultimate strength (MPa)
Rebar	400	D10	SD400	440	577
H shape steel	400	150×150×7×10	SS400	215	400

Table 5 Material properties of polypropylene fiber

Diameter (μm)	Length (mm)	Tensile strength (MPa)	Specific gravity	Melting point (°C)
40	12	450	0.9	168

2.2.2 Steel

The tensile tests are performed to measure strength and elastic modulus of the D10 bars. Yield strength of D10 rebars and H shape steel are 440 MPa and 215 MPa, respectively, as listed in Table 4.

2.2.3 Polypropylene fiber

Polypropylene fiber of 0.1% in volume is added to concrete in order to prevent spalling of the HSC. The material properties of polypropylene fiber are listed in Table 5.

2.3 Test setup

2.3.1 Fire tests for unloaded columns

The unloaded eight short columns are placed in the horizontal furnace for the fire tests as shown in Fig. 5. The columns are heated for 30, 60, and 90 mins and temperatures of the furnace are controlled to follow ISO 834 standard curve (1999). Temperatures inside the short SRC column section are measured by eight thermocouples; five thermocouples are used to measure the temperature of concrete and three for the H-shape steel, as illustrated in Fig. 3.

2.3.2 Fire tests for loaded columns

The SRHSC long columns are heated in the vertical furnace as shown in Fig. 4. The specimens are placed in the furnace with pin supports at the bottom and top of the columns by bolts, and the targeted load is applied prior to heating. The magnitude of the applied load is 10% of the maximum load capacity of the column. The maximum load capacity is calculated using Eq. (1).

$$P_0 = 0.85 f_{ck}(A_g - A_{st}) + f_y A_{st} \tag{1}$$

where, f_{ck} is designed compressive strength of concrete and A_g is gross area of column cross section. Likewise, f_y is yield strength of steel and A_{st} is cross sectional area of steel bars. During the fire test, temperature of the furnace is monitored through ten thermocouples placed in the furnace and controlled to follow ISO 834 standard time-temperature curve (1999). To measure vertical displacement during the fire test, an LVDT is located at the bottom surface of the column, as shown in Fig. 4.

2.3.3 Structural tests of fire damaged columns

The loading tests are performed on the fire damaged columns one month after the fire tests. The loading is applied with displacement control system using a 10,000 kN UTM. As illustrated in Fig. 6,

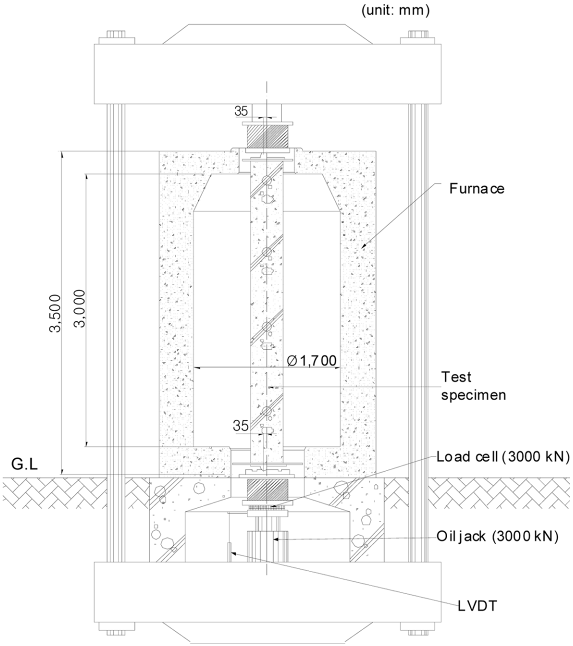
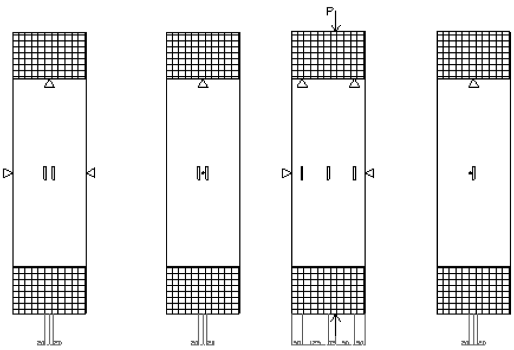


Fig. 4 Furnace for loaded fire test

Fig. 5 Photo of a fire testing furnace with short columns



(a) Concentric loading. (b) Eccentric loading.

Fig. 6 Location of LVDT and strain gauge two LVDTs are used to measure the vertical and horizontal displacements, and two concrete strain gauges are attached on surfaces of the column. For the eccentrically applied loading tests, two LVDTs and three concrete strain gauges are used.

3. Results

3.1 Spalling at elevated temperature

During the fire tests, explosive spalling is observed from the long columns between 15 min and 35 min of heating. Also, water leakage from inside the column is observed throughout the fire tests. The second explosive spalling is occurred from 65 min to 90 min of heating, which induces failure of the column. After the fire tests, spalling on the column surfaces are recorded as shown in Figs. 7~10.

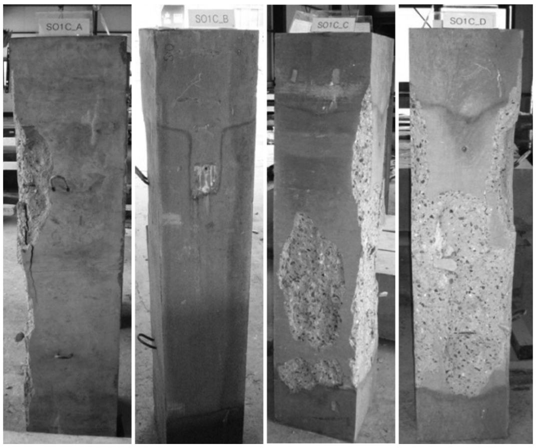


Fig. 7 Spalling of S01C after fire test

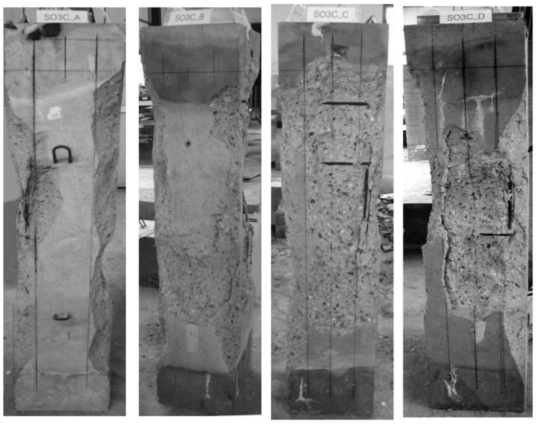


Fig. 8 Spalling of S03C after fire test

Fig. 9 Spalling of S11C after fire test

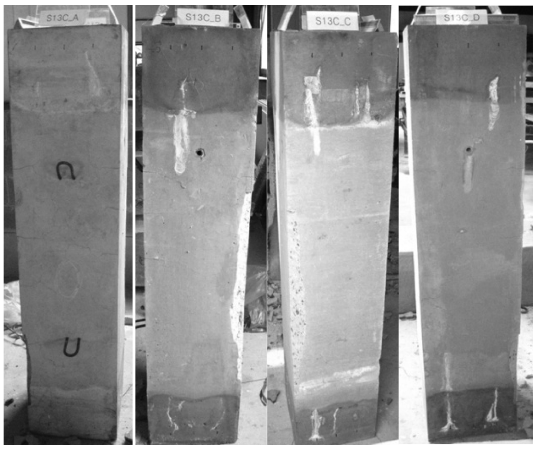


Fig. 10 Spalling of S13C after fire test

In the S01C column, severe spalling occurs on two faces and edges, thereby exposing a tie bar as shown in Fig. 7. The S03C column is tested for 90 min and spalling is more severe than S01C: all four faces are severely spalled as shown in Fig. 8, and a part of main steel is exposed in addition to tie bars. From the polypropylene fiber added specimens, spalling is not seen and only part of edge area is thinly broken off. So, the polypropylene fiber added specimens do not show significant loss of cross sectional area, but show moisture leakage as presented in Figs. 9 and 10.

After the fire tests, spalling depth, defined as a distance from the original surface of a specimen to the spalled surface, is measured from four side surfaces at every of 20 mm in column width and 50 mm in column height. The average residual and loss of cross sectional areas are calculated from the spalling depth as listed in Table 6. For specimen S12C with mixed polypropylene fiber, the averaged loss of the cross sectional area is 0.4%, which can be almost neglected. The weights of specimens before and after the fire test are also measured as listed in Table 7. The average weight of SRC columns before the fire test are 466.5 kg, and the average weights of the columns after the fire test when heated for 30 min and 60 min were 425 kg and 429 kg, respectively. The weight losses of the fire damaged SRC columns are about 8~9% after fire tests, which results from spalling and evaporation and moisture contents. Polypropylene fiber added SRC columns are also tested, where spalling does not occur, but the weight loss is about 0.4% which can be explained from the loss of moisture contents. Therefore, it can be said that measured weight loss is mainly due to spalling and the effect from moisture contents is almost ignorable. The existing literature has reported about weight loss of high strength concrete after fire test, which varies between 1% and 20%, when 20% of maximum load capacity is applied as an axial load. Considering that the specimens in the literature (Ali *et al.* 2010) use concrete with compressive strength of 90~100 MPa and are subjected to the axial load, 8.14~8.99% of weight loss reported in this study can be considered as reasonable results.

3.2 Time-temperature relationship

3.2.1 Effect of loaded state

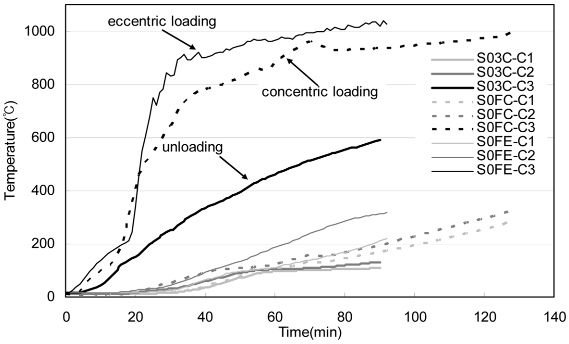
The temperature distributions of the unloaded specimen are compared with loaded specimens, as illustrated Figs. 11(a) and (b). The magnitude of concentrically or eccentrically applied load is 10% of maximum axial load capacity. In the comparison of the temperatures at C3 point, the temperatures of

Table 6 Loss of section area

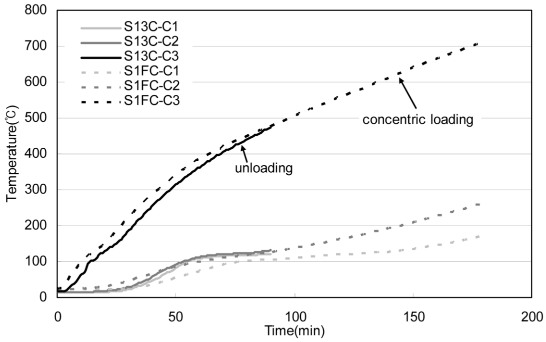
	S0-series		S1-series	
	Remain Section ratio (%)	Loss ratio (%)	Remain section ratio (%)	Loss ratio (%)
30 min	90.8	9.2	100	0
60 min	90.6	9.4	99.6	0.4
90 min	90.2	9.8	99.9	0.1

Table 7 Weight loss of the fire damaged columns after the fire (S0-series)

	Weight (kg)	Loss weight (kg)	Loss ratio (%)
0 min	467	-	-
30 min	425	42	8.99
60 min	429	38	8.14



(a) S0-series.



(b) S1-series.

Fig. 11 Temperature distributions of the short columns

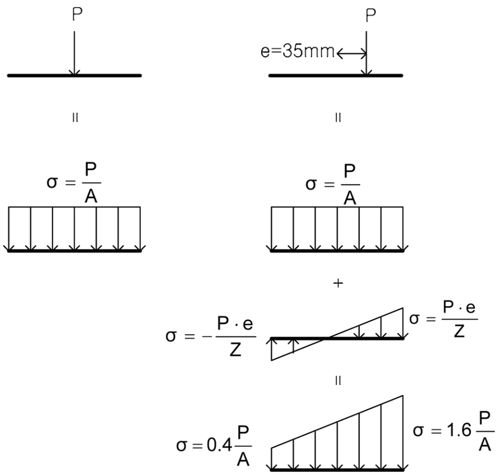


Fig. 12 Stress distributions of eccentrically loaded columns

S0FE and SOFC are rapidly increased, such that the temperatures at C3 are over 500°C at around 200 min. In the beginning of fire, temperatures of specimens loaded concentrically and eccentrically show similar increasing rates, but the temperature of S0FE is increased more rapidly than that of S0FC after 20 min of heating. The more severe spalling is observed from eccentrically loaded columns compared with concentrically loaded columns. This explains why the temperature is elevated more rapidly than concentrically loaded columns. Although there are many different causes for spalling, e.g., thermal and mechanical stress, pore pressure, moisture contents, thermal and mechanical loading rates, and etc., main difference between the eccentrically and concentrically loaded columns is stress distribution from the mechanical loading. Therefore, stress distributions of the two cases are approximated from the simple calculation as presented in Fig. 12. According to the calculation, the maximum stress of the eccentrically loaded column is 1.6 times larger than that of the concentrically loaded column, which plays a large role to cause severe spalling in the eccentrically loaded columns. The temperature distributions of S03C are under 500°C at 75 min of the fire test, which clearly shows that the temperature distribution is affected by loading.

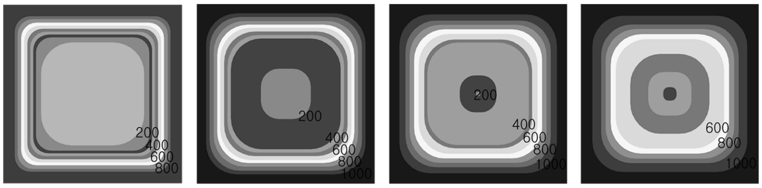
3.2.2 The effect of spalling

Temperature distributions of polypropylene added specimens are illustrated in Fig. 11(b). Explosive spalling is occurred in S0 specimen after 15 min of heating, and shows higher temperature distributions compared with S1 (polypropylene fiber added) specimen. By comparing Figs. 11(a) and (b), it is found that S1FC and S13C show the almost same temperature gradients, so there is almost no difference in temperature distributions between loaded and unloaded specimens when spalling does not occur. In other words, spalling governs temperature distributions regardless of loading condition.

3.3 Temperature profile

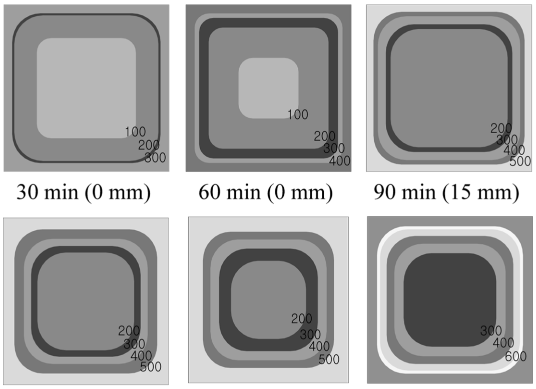
3.3.1 Temperature profiles of column

In this section, temperature profiles of the specimens at different time intervals are illustrated in Figs. 13~17. From thermocouples placed inside the cross section of the column, the temperature distributions can be obtained at different locations of the cross section of the columns during fire tests (Fig. 3). Then obtained temperature data is used to plot temperature profiles at different time intervals, by assuming circumferential identification of the temperature at a same distance from the column surface. In these figures, at each time frame, depths of the 500°C isotherm line from the column surface are indicated in mm unit. According to Cheng (2004), high strength concrete experiencing 500°C loses its strength by 40%. Therefore, defining 500°C isotherm line from the cross section of a structural member allows to find the cross sectional area of the structural member that can be reliable after the fire, and is important for fire resistant design.



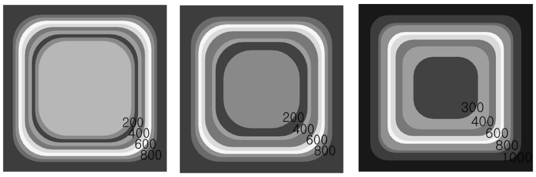
30 min (47 mm) 60 min (54 mm) 90 min (69 mm) 120 min (97 mm)

Fig. 13 Temperature profiles of S0FC



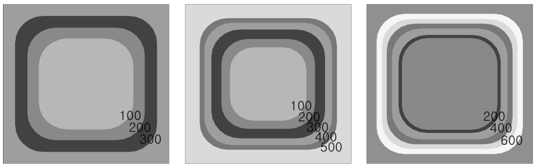
120 min (24 mm) 150 min (32 mm) 180 min (41 mm)

Fig. 14 Temperature profile of S1FC



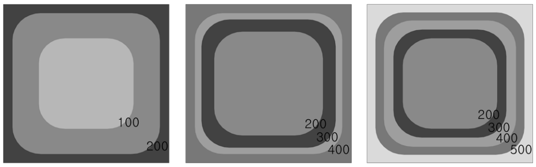
30 min (46mm) 60 min (53mm) 90 min (74mm)

Fig. 15 Temperature profile of S0FE



30 min (0 mm) 60 min (26 mm) 90 min (31 mm)

Fig. 16 Temperature profile of S03C



30 min (0 mm) 60 min (0 mm) 90 min (18 mm)

Fig. 17 Temperature profile of S13C

Temperature profiles of S0FC, where polypropylene fiber is not added, are illustrated as Fig. 13. The distance from the surface to the 500ºC isotherm is 97 mm at 120 min of heating. Spalling occurs before 30 min of heating, so the exterior temperature is very high and the distance from the surface and the 500ºC isotherm is 47 mm at 30 min of heating. The temperature of the steel is about 500ºC at this time frame. The maximum temperature is between 1000ºC and 1100ºC at outer section of the specimen, while the temperature of the inner section is about 200~300ºC. Temperature profiles of S1FC, where polypropylene fiber is added, are illustrated in Fig. 14. This specimen does not show spalling; therefore, the temperature of this specimen is not increased steeply. The distance from the surface and the 500ºC isotherm is 41 mm at 180 min of heating and the temperature of the steel is estimated to be lower than 500ºC. Compared with spalled specimen, larger cross sectional area can be used as a structural member when spalling does not occur. For the eccentrically loaded specimen without polypropylene fiber (S0FE), the column is severely spalled and the temperature is increase up to 1000ºC. Spalling begins at 15 min, so the depth of the 500ºC isotherm line at 30 min is 46 mm. Concrete and steel is severely damaged before 30 min of the fire test, and continued spalling causes the extreme elevation of temperature and failure. The depth of the 500ºC isotherm line is 74 mm at 92 min of heating, as illustrated in Fig. 15. In the spalled specimens, temperatures can be varied even at the same depth of one specimen depending on the amount of spalling occurred at each side surface.

Figs. 16 and 17 show the temperature profiles of unloaded specimens with and without polypropylene fiber (S13C and S03C), respectively. The temperature of S03C measured at the cover is over 300ºC at 30 min of heating and over 700ºC at 90 min of heating. The temperature of S13C at the cover is between 200ºC and 300ºC at 30 min and over 500ºC at 90 min. From these two specimens, it is found that the loss of structural capacity can be considered only in cover area.

3.3.2 Effect of loaded state

To compare the temperature profiles between loaded and unloaded specimens, the depth of the 500°C isotherm, the maximum temperature, and the minimum temperature measured at the same time frame are listed in Table 8.

The depths of the 500ºC isotherm at 90 min for S0FC, S0FE, and S03C are 69 mm, 100 mm, and

Table 8 Details of temperature profile

Specimen	Loading	Spalling	500°C isotherm depth (mm)			Maximum temperature (°C)			Minimum temperature (°C)		
			30min	60min	90min	30min	60min	90min	30min	60min	90min
S0FC	Concentric	Yes	47	54	69	900	1100	1100	100	200	300
S0FE	Eccentric	Yes	46	53	74	900	900	1100	200	200	300
		No	0	89	100	300	700	900	100	200	300
S1FC	Concentric	No	0	0	15	400	500	600	100	100	200
S03C	Unloaded	Yes	0	26	31	400	600	800	100	100	200
S13C	Unloaded	No	0	0	18	300	500	600	100	200	200

31 mm, respectively. The maximum temperatures of S0FC, S0FE, and S03C are 1100°C, 1100°C, and 800°C, respectively. In other words, the temperature distribution of the eccentrically loaded specimen is the highest, and that of the unloaded specimen is lowest. In the case of polypropylene added SRC structures, the depths of the 500°C isotherm at 90 min for S1FC and S13C are 15 mm and 18 mm, respectively. And the maximum temperatures of S1FC and S13C are about 600°C. Therefore, if spalling does not occur, the temperature is not affected by the loading state.

3.3.3 Effect of spalling

Temperature profiles of S03C and S13C are compared to investigate the effect of spalling. The depths of the 500°C isotherm at 90 min for S03C and S13C are 31 mm and 18 mm, respectively. The maximum temperatures of S03C and S13C are 800°C and 600°C, respectively. The spalled specimen shows the higher temperature distribution and the larger 500°C isotherm depth.

3.4 Structural performance

3.4.1 Effect of loading on failure of the structures

In this section, time to reach failure of the long columns and deformations at the failure are observed during fire tests. Failure of a column under fire is determined when maximum axial deformation reaches $h/100$, where h is the column height in mm. The time to failure of S0FC, S1FC, and S0FE are 129, 180, and 92 min, respectively. The eccentrically loaded specimen fails earlier than other columns, and the polypropylene added specimen (S1FC) reaches failure far after other two specimens fail.

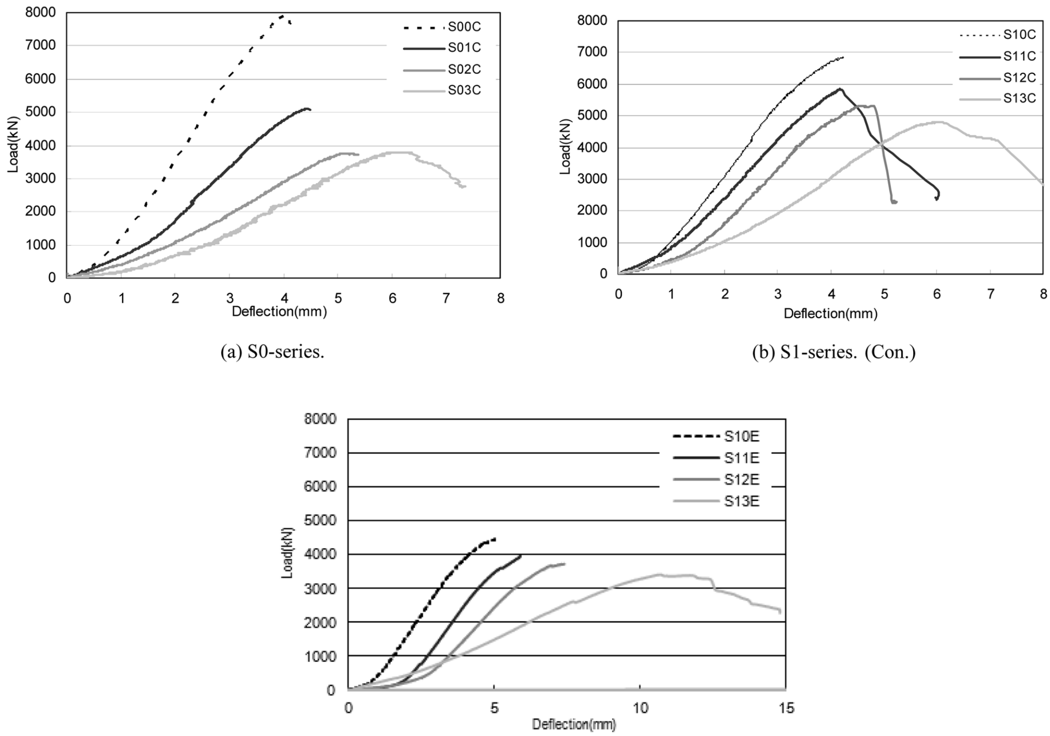
3.4.2 Load-deformation relationship and maximum load capacity

Axial loading tests are performed on the fire damaged columns cured in room temperature for one month. And the test results of maximum load capacity and the ratio of residual load capacity are listed in Table 9. From the axial loading test, maximum load capacity of the non-damaged specimen (S00C) is 7965 kN. The loading capacities of S01C, S02C, and S03C are 5093 kN, 3739 kN, and 3789 kN, respectively, so the ratios of residual load capacity of the fire damaged columns to the undamaged column are around 0.47~0.64. The ratios of residual stiffness of the fire damaged columns to the undamaged column are around 0.32~0.58, so the stiffness is reduced with larger ratio than the load capacity. S01C, S02C, and S03C specimens are spalled during the fire tests, so the cross sectional area and concrete strength are reduced, and the deeper damage depth is observed compared to the polypropylene fiber added specimens. The maximum load capacities of the polypropylene added specimens are 5838 kN, 5314 kN, and 4803 kN for S11C, S12C, and S13C, respectively; thus, the

Table 9 Maximum load and residual load capacity

No.	Specimen	Max. load (kN)	Moment (kN-m)	Axial deformation (mm)	Stiffness (kN/mm)	Ratio of residual load capacity	Ratio of residual stiffness
1	S00C	7965	-	4.06	1961.8	1.00	1.00
2	S01C	5093	-	4.46	1141.9	0.64	0.58
3	S02C	3739	-	5.18	721.8	0.47	0.37
4	S03C	3789	-	5.97	634.7	0.48	0.32
5	S10C	6842	-	4.25	1609.9	1.00	1.00
6	S11C	5838	-	4.18	1396.7	0.85	0.87
7	S12C	5314	-	4.62	1150.2	0.78	0.71
8	S13C	4803	-	6.04	795.2	0.70	0.49
9	S10E	4451	155.8	4.03	1104.5	1.00	1.00
10	S11E	3954	138.4	3.42	1156.1	0.89	1.05
11	S12E	3642	127.5	5.45	668.3	0.82	0.61
12	S13E	3392	118.7	4.79	708.1	0.76	0.64

ratios of residual load capacity of the fire damaged columns to the undamaged column are around 0.70~0.85. Also, the ratios of residual stiffness of the fire damaged columns to the undamaged column are around 0.49~0.87. From these, it is found that the smaller ratios of residual load capacity and stiffness



(a) S0-series. (b) S1-series. (Con.)

(c) S1-series. (Ecc.)

Fig. 18 Load-deformation relationships

are obtained from the spalled columns compared with the polypropylene added columns. The maximum load capacities of the eccentrically loaded specimens are 4451 kN, 3954 kN, 3642 kN, and 3392 kN for S00E, S01E, S02E, and S03E, respectively. The ratios of residual load capacity are around 0.76~0.89, and are higher than those of the concentrically loaded specimen.

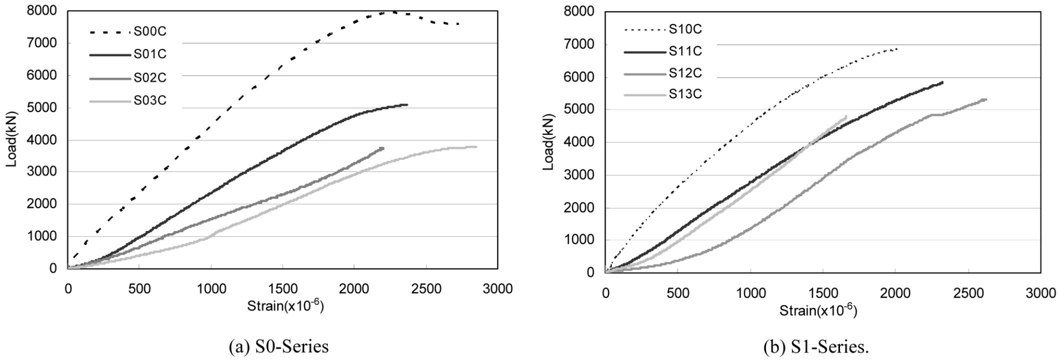
The residual strength of a fire damaged column can be related to the heating time. Only 64% of the load capacity is remained in the spalled column when the column is exposed to fire for 30 min, and about 50% is remained when the columns are exposed to fire for 60 and 90 minutes. Therefore, the load capacity of the SRC column under fire is rapidly degraded in short period of time. In the polypropylene added specimens, about 80% of the original load capacity is remained after 30 min of heating. In case of S12C specimen, over 78% of the original load capacity is remained after 60 min of heating. This finding shows that polypropylene fiber is able to not only prevent spalling, but improve the load capacity of the fire damaged structures.

3.4.3 Load-strain relationship

From the loading tests, load-strain relationships of fire damaged columns are obtained as illustrated in Fig. 19. Load-strain relationships of the tested specimens show similar tendency with the load-displacement relationships, and the tangent ratio and the initial strength are reduced in proportion to the heating time, which may be caused by stiffness reduction of the fire damaged HSC as high temperature changes the material characteristics.

4. Discussion

Using the experimental findings, regression analysis is performed and an equation is proposed to estimate residual load capacity and stiffness of fire damaged SRC columns as a function of heating time. The proposed equation is in an exponential form as shown in Eq. (2), where A is a constant. For better prediction, different values for A are suggested depending on spalling and the applied load of the columns under fire as listed in Table 10. The ratios of residual load capacity and stiffness are predicted using Eq. (2) and compared with tests results as illustrated in Figs. 20 and 21. The regression analyses for predicting residual load capacity of a spalled column and the stiffness of a non-spalled eccentrically loaded column are excluded from this study, because the aspects of reduction are irregular; therefore, more test results are needed in those cases.



(a) S0-Series (b) S1-Series.

Fig. 19 Load-strain relationships

Table 10 A values for Eq. (2)

	Spalling	No spalling	
	Concentric loading	Concentric loading	Eccentric loading
For max. load capacity reduction	-	-0.0041	-0.0032
For stiffness reduction	-0.0142	-0.0071	-

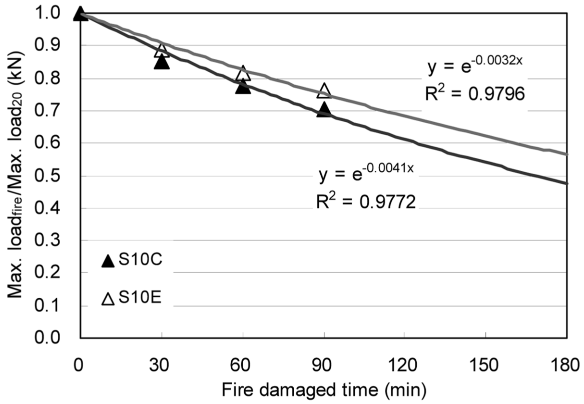


Fig. 20 Prediction of residual load capacity from the proposed equation

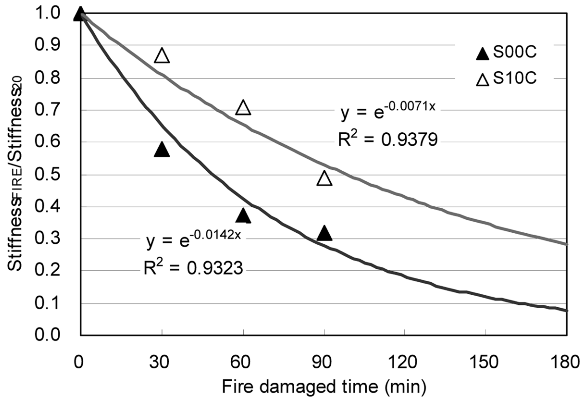


Fig. 21 Prediction of residual stiffness from the proposed equation

$$R = \exp^{At} \tag{2}$$

Where, A is a constant and t is heating time in min.

5. Conclusions

In this study, fire tests are performed on three long columns to investigate the effect of various parameters on the thermal and structural behaviors of SRC columns using HSC during a fire, and twelve short columns are tested to investigate residual strength and stiffness of HSC columns after a fire. The tested parameters are polypropylene fiber, the axial load, and the time period of fire tests.

The loaded concrete columns are more explosively spalled than an unloaded column when subjected to fire. In particular, the eccentrically loaded columns show severe spalling. The polypropylene fiber added columns are not spalled under both loaded and unloaded states. The temperature distributions of concrete are not affected by the loading if the columns are not spalled. However, when the column is spalled, loading affects the temperature distributions. In addition, as closer to the loading points, the larger spalling is observed from the side surfaces in case of the eccentrically loaded specimens. Also, this study proposes an equation in an exponential form to predict residual load capacity and stiffness of the fire damaged column as a function of heating time. The load capacity of the fire damaged columns is reduced about 50~70% of their original load capacity. The experimental findings from this study would allow estimating temperature distribution and of fire safety design of the SRC columns in HSC.

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