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Development and Application of CFT without Fire Protection using High Performance Steel and Concrete

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Abstract

Concrete filled tube (CFT) columns, which consist of a steel tube filled with concrete, combine the benefits of the two materials. The steel tube provides a confining pressure to the concrete, while the local buckling of steel plate can be prevented by the concrete core. CFT columns also have a high fire resistance due to the heat storage effect of concrete under fire. For this reason, it is possible to develop CFT columns without fire protection measures. CFT columns without fire protection have many advantages, including quality control, cost reduction, better space efficiency and a shorter construction period. Due to these advantages, studies on the development of CFT columns without fire protection measures have been performed. However, CFT columns lose their bearing capacity under fire because the steel tube is exposed to the outside. As a result, the structure is collapsed, causing significant damage. In this research, we made a CFT column using high strength concrete (100 MPa) and high strength steel (800 MPa). We use steel fiber and nylon fiber with concrete to provide fire resistance. We perform the fresh concrete experiment and investigate the fire resistance of the CFT column (□ 400×400×15×3000 mm) under loading. To investigate the effect of steel fiber on increasing fire resistance, we compare the fire resistance time according to the steel fiber. Through the test, it was found that the CFT specimen with steel fiber had better fire resistance performance than other cases.

Keywords : high strength concrete, high strength steel, CFT, fire resistance

1. Introduction

1.1 Research objective

With the continuously growing demand for high-rise buildings, high-strength, high-performance materials have been the focus of a number of studies. Concrete filled steel tube (CFT) columns have been increasingly used in high-rise buildings. The CFT structure maximizes the material benefits of steel and concrete, and has such characteristics as good structural performance, seismic performance, constructability and economy. In particular, the CFT structure has good heat capacity, and the column itself has a certain level of fire resistance. CFT columns have been adopted for commercial use as fire-resistant structures in the US and Europe, as well as in Japan. However, in Korea the fire protection method is in wide use, similar with steel structure construction. For this reason, applications of CFT are rare in Korea compared with RC structures or SRC structures[1,2].

However, the clause requiring the fire resistance performance of a structure to be verified according to performance design approved by the president of the Korea Institute of Construction Technology (KICT) was additionally enacted in the Enforcement

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Table 1. Trend of research on CFT columns without fire protection

Year	Researcher	Concrete Strength	Load (kN)	Fire Resistance Time (min)	remark
2007	Samsung ENC	35 MPa	1250	60	Field application for Gumi Samsung Electronics factory
2009	Univ. of Seoul KICT, etc	24, 40 MPa	570 ~ 2580	30 ~ 180	Development of the Design technology about the fire resistance of CFT columns
2011	RIST	27 MPa	2800	60	Field application for Pohang/Gwangyang gym

Decree of Construction Law 'Regulations on the evacuation and fire resistant structure of a building structure.' Of the fire resistance evaluation methods for CFT columns, the heating test with loading are considered reliable. With the test, the capacity is evaluated by putting the load at a certain axial force ratio while heating the specimen according to the heating curve in ISO-834[3].

With the presentation of this fire protection plan, studies have been conducted on the CFT columns without fire protection in Korea. It is expected that when the CFT columns are used without fire protection, space can be utilized more efficiently, and the construction cost and duration can also be reduced. Table 1 indicates the domestic research findings and site applications of the CFT columns without fire protection[4,5,6].

The CFT column without fire protection, when heated, loses the capacity of the steel tube in the early stage and essentially becomes a plain concrete column, with the filled concrete supporting the load for a certain period of time. Likewise, at a high temperature, the final load-bearing capacity of the CFT column is determined by the concrete, and for this reason, the fire resistance of concrete is important[7]. The methods of securing the fire resistance performance of the CFT column include securing the vapor discharge passage, securing load-bearing capacity with the mixture of steel fiber or the arrangement of rebars, and the use of a double-skin CFT structure[8,9]. However, the research findings and the performance are from trials in which ordinary concrete was used, and the fire protection was reported to last only for an hour when it was applied to an actual site. In addition, the effects on a CFT column' s behaviors of spalling that could occur when high-strength concrete is applied to the CFT columns have not yet been studied.

Therefore applicability and fire protection characteristics of the CFT column with steel fiber and nylon fiber were evaluated in order to apply high-strength concrete with 100MPa or higher to the CFT structure without fire resistance in a building, between 12m and 50m high, required of the 2-hour fire protection performance.

1.2 Research method and scope

In this research, to understand the applicability of 100Mpa high-strength concrete to the CFT column, the performance and the compressive strength of fresh concrete were examined in the indoor and BP tests, and the dynamic characteristics of the CFT column with increased steel fiber were evaluated through the load-heating test.

2. Experimental plan and method

2.1 Experimental plan

The fire protection performance of the CFT column was examined when steel fiber and organic fiber, which are usually employed to improve fire protection performance of the conventional high-strength concrete, were increased. To do this, the mix proportion was determined through an indoor experiment, and the fluidity and compressive strength were assessed. In addition, the temperature distribution of the concrete and changes in drooping in the vertical direction over time were measured through the load and heating test of the mock-up.

The target strength of the concrete was set at 100MPa, and different levels of the mix proportion of steel fiber were set to examine the fire protection. To reduce the spalling phenomenon, 1.5 kg/m^3 of nylon fiber was mixed into all of the specimens based on the previous research. The mix proportion of steel fiber was set at three different levels for the experiment: 0, 20, and 40 kg/m^3 [10].

2.2 Materials

2.2.1 Steel tube

The CFT for this study was manufactured using high-performance steel. The properties of the steel used in this experiment are shown in Table 2. 15mm-thick HSB 800 was welded with the K120TG welding rod.

Table 2. Steel properties

Type	Thickness	Tensile Strenght	Yield Strength	Fracture Elongation
HSB 800	15 mm	944 MPa	879 MPa	22%

Table 3. Concrete mix proportions

	W/B (%)	S/a (%)	Unit Weight (kg/m^3)					
			W	B	S	G	Steel Fiber	Nylon Fiber
SF0							0	
SF20	17.8	36.0	165	926	462	828	20	1.5
SF40							40	

2.2.2 Concrete

In this research, pre-mixed cement manufactured by domestic company H was used. It has strength of 60MPa or higher at 28 days, and fineness of about 7000 ㎠/g. The fine aggregate used in this research was dry sand from Incheon with density of 2.59, and fineness modulus of 2.87, and the coarse aggregate had the density of 2.57 and 13mm in the maximum length.

The organic fiber for spalling prevention was nylon fiber, which was 13mm long, and had density of 1.10 cm^3/g. The tensile strength was 800MPa and the melting point was between 220℃ and 270℃.

2.3 Performance evaluation of the concrete

For the performance evaluation of the 100MPa high-strength concrete for CFT, indoor and BP experiments were conducted. In the experiments, slump flow test (KS F 2594), air content test (KS F 2421), U-Box test (JSCE-F511), O-lot test (JSCE-F512), and L-flow test (JSCE-F514) were performed to understand the fluid characteristics of the fresh concrete.

In addition, simple insulation temperature and hydration heat of the actual members were measured considering the fact that the ultra-high-performance concrete is characterized as having high hydration heat. A thermocouple was embedded in the center and on the surface of the CFT to measure the temperature. In addition, to examine the compaction performance, which can have a great effect on the CFT structural performance, a compaction sensor was installed on the lower part of the diaphragm to proceed with the measurement. The compaction of the concrete was measured using the KZA-1C compaction sensor operated in the voltage measurement method[11].


Concrete filling sensor Hydration heat sensor

Figure 1. Concrete filling and hydration heat measurement

2.4 Fire resistance test method

The high-performance CFT mock-up was manufactured as shown in Figures 2 and 3.


Remicon Production Concrete test


Temperature Sensor Concrete Placing

Figure 2. CFT specimen for Fire resistance test

The dimension and thickness of the mock-up was 400 X 400 X 3000 mm and 15mm, respectively, and it was made with HSB800 steel plate with tensile strength of 800 MPa or higher. The effective heated length of the CFT column was 3,000mm, and the specimen was manufactured through four-sided welding using K120TG welding rod. The upper and lower ends were welded with endplate, and a total of 6 holes with a diameter of 20mm, 3 pairs, were drilled in the middle to release vapor and gas. The concrete temperature was measured at the center and a 1/4 point of the concrete section. The temperature distribution of the steel pipe was measured at a total of 6 points, on both sides at 900mm, 1500mm, and at 2100mm from the top of the column.

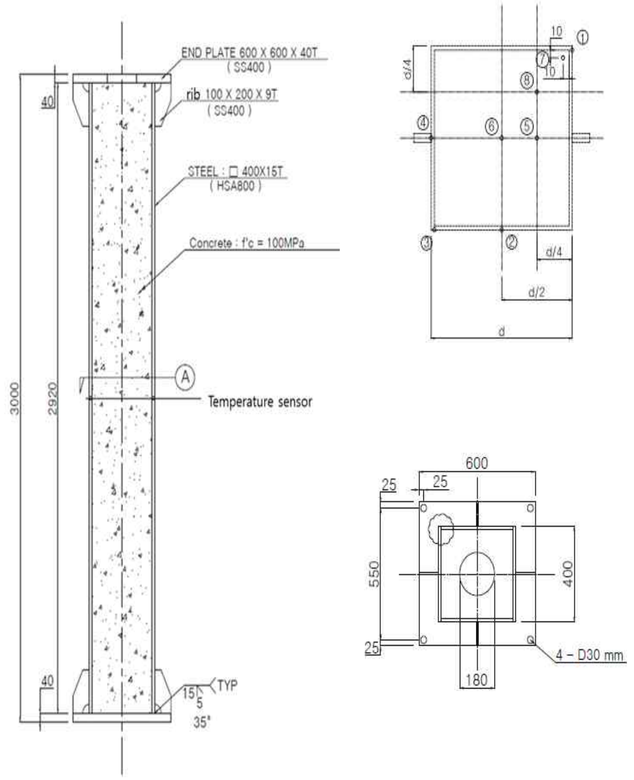


Figure 3. CFT Specimen design and Temperature Sensor

The fire resistance test was conducted based on KS F 2257. The load-heating test was implemented in KICT. Considering the load the CFT will bear in an actual site, 4000kN, which was equivalent to 0.3 of the concrete axial force ratio, was put on the CFT column, and it was heated according to the standard time-temperature curve. The test ended when the axial shrinkage reached 30mm, equivalent to 1/00 of 3000mm, the effective heated length, or when the deformation was found to be 0.003 mm/min, because it is believed that the CFT column loses the load bearing capacity at this point.

3. Test results and analysis

3.1 Concrete performance evaluation

The following are the BP test results of the fire-resistant specimen with the increase in steel fiber. Figure 4 shows the slump flow and air content with the increase of steel fiber. The slump flow was decreased by about 5–10% depending on the mix of steel fiber.

Figure 4. Fresh concrete depending on steel fiber

Figure 5 are the O-lot and L-flow test results to evaluate concrete pumpability. In general, O-lot passing time and L-flow reaching time are related with the viscosity of concrete. The higher the viscosity, the higher the resistance, and the reaching time was slowed as a result[12]. The pumpability tended to be higher, as the steel fiber was mixed more, which is believed to be because the concrete viscosity was increased with the increase in steel fiber. In the future, the relation between concrete viscosity and the concrete pumping for construction should be examined.

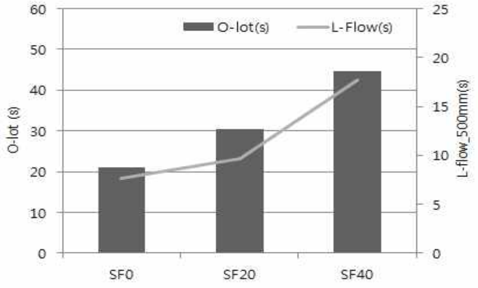


Figure 5. O-lot test and L-flow test

Figure 6 illustrates the compressive strength by age. At 28 days, the hardened concrete strength was higher than the target strength of 100MPa. A gradual increase in the strength at 28 days was found with the increase in steel fiber, but the differences were insignificant. In addition, 70% of the strength was developed before and after the 3rd day, and the initial setting is considered to be important to secure a certain level of compressive strength.

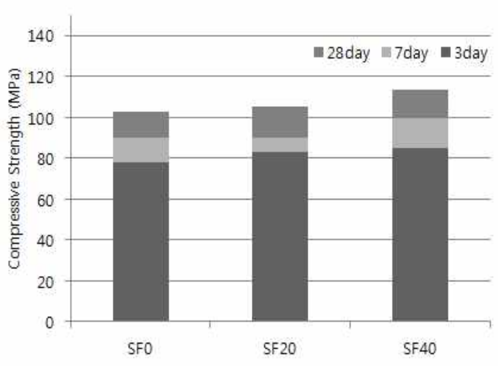


Figure 6. Compressive strength results

In addition, sensors were installed on the CFT mock-up to test the hydration heat and compactness within the CFT column filled with 100MPa ultra-high-performance concrete. There were no differences found in hydration heat and compactness according to the mix of steel fiber. The test results are shown in Figures 7 and 8, respectively. In terms of hydration heat, the highest temperature was measured as around 75℃, and the temperature difference from the center was identified to be within 20℃, based on which it is believed that there is no problem with the cracks caused by hydration heat.

In the results of the U-Box test conducted to examine compactness, the differential was shown to be less than 10mm in all specimens, and it is believed that there was no problem in the compactness of the specimens. In addition, considering the compactness measured in Figure 8, judging from the fact that voltage was measured by the compactness measuring sensor installed at the corner of the CFT diaphragm, the concrete is believed to have been compacted to the lower part of the diaphragm[11]. In addition, it was found that the measured voltage fell after 20 hours, and converged to 0 after 100 hours. This shows a similar tendency to the hydration heat graph, and it is possible to estimate the hardened level of concrete through the compactness sensor measurement in the future.

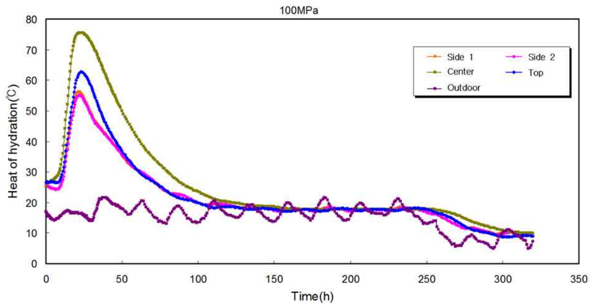


Figure 7. Hydration heat of concrete in CFT

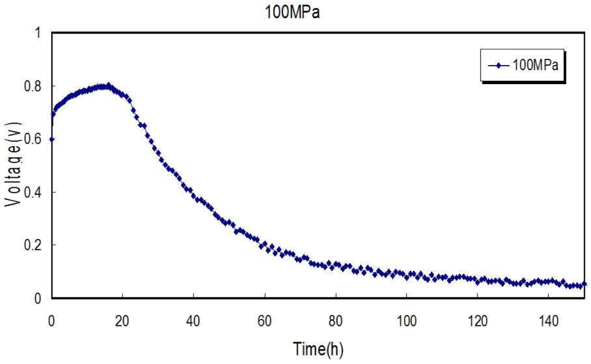


Figure 8. Filling ability of concrete in CFT

3.2. Fire resistance performance evaluation

3.2.1 Tests results

Figure 9 shows the mock-up before and after the fire resistance test with the increase in steel fiber. From the results of the fire resistance test of the high-strength CFT column, the brittle failure took place along with an explosive sound at 120 minutes in the CFT specimen in which 40kg/m^3 of steel fiber was added, and the test ended before the shrinkage reached 30mm, the fire resistance requirement, as it was considered that continuing the test would cause some damage to the test machine. The specimens in which 0 or 20kg/m^3 of steel fiber was added shrank greatly after 60 minutes, and the tests were terminated. Asymmetric local buckling took place in the steel tube with no steel fiber, based on which it is believed that the steel tube was deformed because the load bearing capacity was lost within the concrete by spalling or detachment of the concrete. In the CFT with 40kg/m^3 of steel fiber, spalling or detachment was found to have occurred due to heating. In the CFT with 20kg/m^3, a small opening was found on the welded part through which the heat was conveyed, and the temperature of the concrete rose dramatically. For this reason, it is impossible to make an accurate comparison with other specimens.

Figure 9. Appearance of the specimen before and after test

3.2.2 Shrinkage analysis

Axial deformation of the specimens caused by thermal expansion and shrinkage was measured using the linear variable differential transformer (LVDT) attached to the hydraulic cylinder. As in the test results, the more the steel fiber was mixed from 0 to 40kg/m^3 at the same level of nylon fiber, the higher the heat resistance became. In terms of overall shrinkage, the steel tube expanded by heat at the initial stage, but began to shrink after a certain period of time. For some time, the deformation slowed and then dramatically accelerated, and then the CFT was finally ruptured. It is believed that the steel tube bore the load caused by the expansion, and the inner concrete supported it after the load bearing capacity of the steel tube was lost, causing it to collapse in the end.

Figure 10 shows the changes in shrinkage of the CFT column with the increase in steel fiber. Thermal expansion of the steel tube was measured to be about 17mm, which was similar in all the specimens, but the more steel fiber was mixed, the more the deformation was slowed.

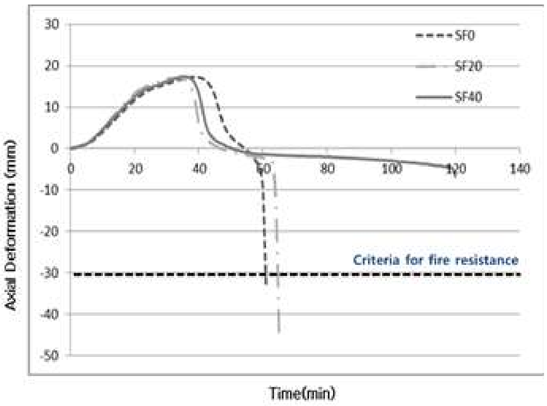


Figure 10. Axial deformation result by steel fiber

The fire resistance was shown to be improved by the mix of steel fiber. When only nylon fiber was mixed with no steel fiber, the fire resistance lasted for 61 minutes, while the fire resistance lasted for 120 minutes when 40 kg/m^3 of steel fiber was mixed, which doubled the fire resistance performance. This is believed to indicate that steel fiber improved the resistance of concrete in the CFT column to spalling and detachment[13].

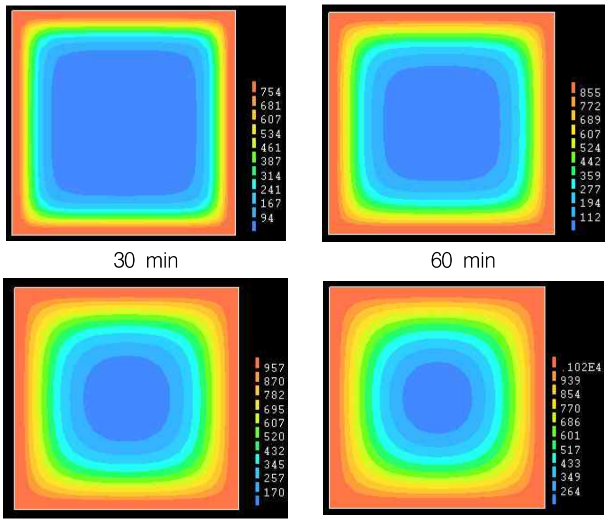
Table 4. Fire resistance test results

	SF 0	SF 20	SF 40
Fire resistance time (min)	61	65	120
Deformation (mm)	33.6	44.8	6.7
Deforamtion ratio (mm/min)	24.1	32.0	2.0

3.2.3 Temperature analysis results

Temperature was analyzed to make an accurate prediction of the temperature of the CFT column, and a comparison with the values obtained through the experiment. For fire resistance design of the CFT column, a design equation should be presented that considers stress-strain characteristics at high temperature, the predicted temperature distribution due to high irregularity of the fire resistance time of the load and heating test, and the complex behaviors of the column in a fire[14]. In addition, numerical studies need to be conducted to predict the load-bearing capacity of CFT columns at high temperature. Therefore, for the fire resistance design for the 100MPa high-strength CFT, the fundamental temperature data was predicted, measured through experiments, and compared to accumulate basic data of 100MPa high-strength concrete in the CFT at a high temperature.

For the temperature interpretation, a nonlinear transient heat analysis was conducted based on the assumption of an external heat source. For the interpretation, DIANA, a commercial finite element analysis program, was used. The target specimen was a CFT short column with the size of 400mm X 400mm. The column was divided into top and bottom in consideration of the symmetry of the 15mm-thick steel tube with 100MPa concrete. As the element, 3D Solid element(CHX60) was applied, and the boundary was modeled as the virtual element to take thermal load into account. The temperature history used in the interpretation was set to be identical to the load–heating test based on the ISO–834 standard fire curve. The initial temperature was set at 20℃. The convection coefficient was assumed as in consideration of the conditions in the heating furnace. The numbers assumed for the interpretation were the specific heat of 0.135J/min.·mm·℃, and heat capacity of 2.3×10^{-3}J/mm^{3}·℃. The physical properties of concrete utilized for concrete vary depending on aggregate type or density, but they have no impact on the interpretation, and the same aggregate and materials were used in the experiments, and the effects of the factors were not considered. Figure 11 shows the results of the analysis at 30, 60, 120, and 180 minutes.



30 min

60 min

120 min

180 min

Figure 11. Temperature of Concrete in CFT

Figure 12 is the comparison of the temperatures at the center of the steel tube and concrete of the CFT specimen with 40 kg/m^{3} of steel fiber with the predicted values. The temperature at the center of the concrete was lower than that of the steel tube, which means that the heat was not transferred to the center due to the insulation of the concrete. Based on this, it was found that the CFT in which spalling did not occur had a certain level of fire resistance. Based on this interpretation, it was found that the inner concrete temperatures were similar to the actual experimental values, and the validity of the interpretation results and the reliability of the method were verified. However, compared with the interpreted temperatures at the center of the concrete, the temperatures measured in the experiment were slightly higher, which may be due to the difference in temperature rise due to the rooms generated by heating and the changes in the pore structure.

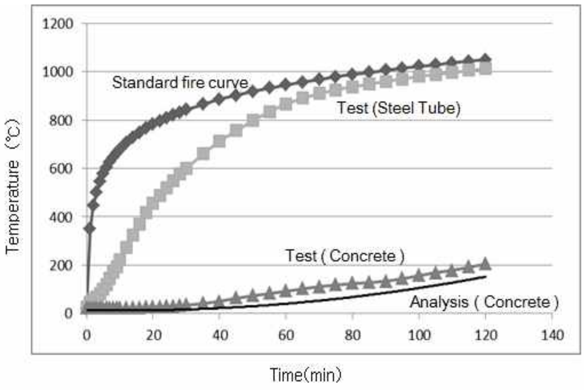


Figure 12. Temperature range of SF40 specimen

6. Conclusion

In this study, 80MPa and 100MPa high–strength concrete were adopted to develop a CFT column with better fire resistance. The performance of high–strength concrete mixed with steel and nylon fibers, and the applicability of the CFT, were examined. The fire resistant mock–up was also manufactured and tested to review the fire resistance performance of the CFT structure without fire protection through the load–heating test.

1) To improve fire resistance, nylon and steel fibers were mixed, and the mix proportion of

steel fiber was set as a variable to evaluate the performance and the mix proportion of 100MPa high-strength concrete for the CFT column. It was found that slump flow tended to be deteriorated when more steel fiber was mixed. In terms of the fluidity evaluated through O-lot and L-flow tests, when more steel fiber was mixed, the viscosity tended to increase.

2) The fire resistance tests showed that when 40 kg/m^3 of steel fiber was mixed, the fire resistance time was 120 minutes at axial force ratio of 0.3. When steel fiber was not mixed, the fire resistance time was 61 minutes. Based on these results, it is believed that steel fiber helped reduce detachment and spalling.
3) The steel surface was found to be coming off and detached in the specimen with 120-minute fire resistance, and brittle failure was observed along with an explosive sound.
4) When the interpreted temperatures were compared with the actually measured temperatures, the inner temperatures were similar, and thus the validity and reliability of temperature distribution interpretation can be verified.

By mixing steel and nylon fibers in the concrete for the CFT columns, the fire resistance time can be doubled, and 2-hour fire resistance performance applicable to the buildings with less than 12 stories or less than 50m can be secured. In future research, 3-hour fire resistant CFT columns without fire protection will be developed and tested.

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References

1. Kim WJ, Lee YD, Park HG, Lee JS, Jung SJ. Research on the mock-up fo CFT using 100 MPa high strength concrete and 800 MPa strength steel. Proceedings of the Korea Institute of Building Construction; 2011 May 20; Dong-eui University, Busan. Seoul(Korea): The Korea Institute of Building Construction; 2011. p. 35-7.
2. Kim KY, Kim YS, Lee TG, Kang SJ, Kim MH. An experimental study on the evaluation of fire-resist performance of high-strength concrete filled steel tube column. Journal of the Architectural Institute of Korea. 2008 Aug;24(8):147-54.
3. Park SH, Ryoo JY, Chung KS, Choi SM. An evaluation for the fire resistance of concrete-filled steel square tube columns under constant axial loads. Journal of Korean society of steel construction. 2007 Dec;19(6):703-14.
4. Han HC, Kim YG, Kang SJ, Choi, SM. The 1st site application of non-fire-protection CFT columns. Journal of Korean society of steel construction. 2007 Jun;19(2):77-83.
5. Cho KS, Kim HY, Kim HJ, Kwon IK. The study on the fire resistance performance of the CFT column according to the concrete compressive strength and load ratio. The 1st site application of non-fire-protection CFT columns. Journal of the Korean Institute of Fire Sci. & Eng. 2010 Apr;24(2):44-51.
6. Kim JH, Kim TW, Chung KS, Kim DH, Choi IR. Application of unprotected CFT columns for Pohang/Gwangyang sports complex projects. Journal of Korean society of steel construction. 2011 Oct;23(5):49-53.
7. Kim KY, Lee TG, Kim YS, Min CS, Kang YW. Evaluation of mechanical properties of CFT stub column at elevated temperature. Journal of the Architectural Institute of Korea. 2011 Jul:27(7):159-66.
8. Venkatesh Kodur. Guidelines for fire resistant design of concrete-filled steel HSS columns-state-of-the-art and research needs. International Journal of Steel Structures. 2009 Sep;7(3):173-82.
9. Song KC, Bang JS, Park SH, Chung KS, Choi, SM. An experimental study on fire resistance of concrete filled double

skin tubular columns. Proceedings of the Architectural Institute of Korea.; 2009 Oct 23–24; Kangwon University. Seoul (Korea): The Architectural Institute of Korea; 2009. p. 433–6.

10. Kim WJ, Kim HB, Kim KY, Kim YS. An experimental study on the fire resistant performance of the high strength concrete with loading and unloading test. Proceedings of the Korea Institute of Building Construction; 2009 Nov 14; ChungJu University. Seoul (Korea): The Korea Institute of Building Construction; 2009. p. 61–4.
11. Seo I, Jun WC, Hong SB, Park HG, Kim WJ, Lee JS. An experimental study to evaluate compaction of high performance concrete for concrete filled tube. Proceedings of the Korea Concrete Institute; 2011 May 11–13; Jeju. Seoul (Korea): The Korea Concrete Institute; 2011. p. 553–4.
12. Ko JW, Kim JJ, Lee SH, Moon HJ, Park SJ. An experimental study on the physical property change of high strength concrete for high-rise building before and after concrete pumping transfer. Journal of the Architectural Institute of Korea. 2010 Sep;26(9):71–8.
13. Won JP, Jang CI, Lee SW, Kim HY, Kim WY. Fire reistance performance for hybrid fiber reinforced high strength concrete column member. Journal of the Korea Concrete Institute. 2008 Dec;20(6):827–32.
14. Kim KY, Lee HJ, Lee TG, Kim YS, Kang SJ. A study on the prediction of residual strength of concrete filled steel tube column without fire protective coating by unstressed heating. Journal of the Korean Institute of Fire Sci. & Eng. 2009 Jun;23(3):31–9.