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The Effect of Cross Sectional Area on the Fire Performance of High Strength Concrete Columns

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Abstract

In this paper, the effect of cross sectional areas of high strength concrete (HSC) columns at elevated temperatures is investigated. Toward this goal, experimental and analytical studies are performed on short HSC columns subjected to fire. For the experimental studies, the HSC columns are fabricated having different cross sectional areas. The temperature in the chamber is controlled by following the ISO834 time-temperature curve for three hours. During the heating, temperature distributions on different locations inside the HSC columns are measured from the thermocouples. In order to verify the experimental results and to perform parametric studies, finite element (FE) models are generated using the commercial FE software, ABAQUS version 6.10-3. The analytical results of the temperature distributions show good agreement with the experimental results when considering spalled sections of the model.

Keywords: fire, high strength concrete, column, temperature distribution, spalling, cross sectional area, finite element analysis.

1 Introduction

High strength concrete (HSC) structures subject to fire show severe structural damage not only because of degradation of the mechanical material properties at high temperature but also because of spalling. The degradation of the mechanical material properties is temperature dependent, and temperature distributions are highly related to spalling. Also, it is known that spalling and temperature distributions are affected by many factors, such as concrete strength, cover thickness, reinforcing bar ratio and the spalling resistant technique [1, 2]. Especially for HSC, Kodur and Phan [3] examined the influencing factors on fire performance of HSC structural members such as fire intensity, fire size, heat output, and heating rate, concrete strength, fibre reinforcement, and aggregate type. Also, the effects of

tie spacing, confinement, tie configuration, load levels, and the size of the member on fire performance of the structural members are reported. Phan[4] reports studies about the effect of various factors on pore pressure build up and degradation of the mechanical material properties in normal and high strength concrete. These factors include water/cement ratios, curing conditions, heating rates, test methods, and polypropylene (pp) fibres. As a result of the experiments, HSC with additional pp fiber shows a significant reduction in pore pressure, thus preventing explosive spalling in specimens.
In this study, experimental studies were performed to investigate the effect of cross sectional areas of HSC columns at elevated temperatures on temperature distributions and spalling. Furthermore, analytical studies are performed to verify the experimental results. The FE model includes temperature dependent thermal properties and the spalling effect.

2 Experimental method

2.1 Tested specimens

Short HSC columns having a compressive strength of 50MPa were fabricated for the experiments. All columns are of length 1500mm, and the cross sections are varied from 350mm x 350mm, 450mm x 450mm, and 550mm x 550mm, as shown in Table 1. For the steel reinforcement, four reinforcing bars, D22 (diameter=22mm), D29 (diameter=29mm) and D32 (diameter=29mm) are placed with similar reinforcing ratios. Also, the D10 bars are used as stirrups with intervals of 250mm as transverse lateral steel with cover thickness of 40mm. The geometry and reinforced arrangements are illustrated in Figure 1. The columns are cured for more than six months to avoid moisture effects and then placed in a heating chamber for the heating tests.

Specimen	Concrete compressive strength (MPa)	Cross section (mm)	Reinforcing bar arrangement	Reinforcing ratio (%)
C11	50	350x350	4-D22	1.26
C21	50	450x450	4-D29	1.27
C31	50	550x550	4-D32	1.05

Table 1: Details of the test variables

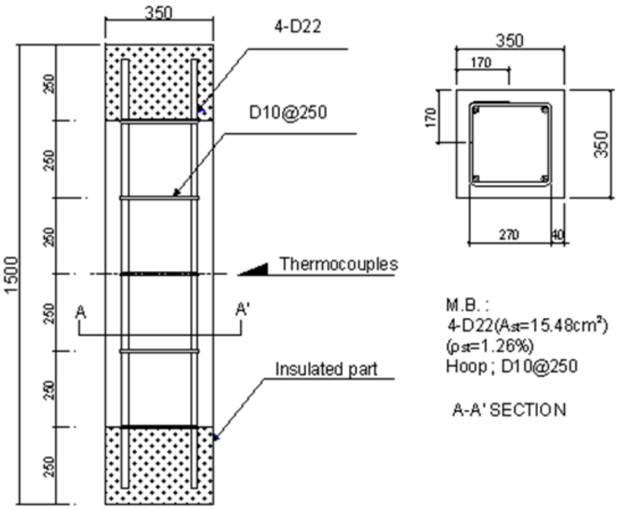

Figure 1: Details of columns

2.2 Test setup

The fire tests for the HSC columns are performed in a horizontal heating furnace sized 3mx1.2m for 3 hours. Five columns are placed in the furnace at one time as illustrated in Figure 2. Gas-fired burners are used to elevate the temperature inside the furnace. The temperatures of the furnace are monitored using ten thermocouples placed inside the furnace and are controlled to follow the ISO834 temperature-time curve as shown in Figure 3. Also, the temperatures are controlled to be constant throughout the furnace. During the heating, temperature distributions on different locations inside the HSC columns are measured using the thermocouples installed in the columns before the concrete is poured. Five thermocouples from C1 to C5 are placed at distances of 25, 100 and 175mm from a side surface of the concrete columns and the temperature of the steel bars are measured from the three thermocouples from S1 to S3 attached to the reinforcing bars. Detailed locations of the thermocouples are illustrated in Figure 4. To measure the amount of spalling, losses of cross sectional area are calculated by measuring spalling depth at every 50mm height from the side surfaces of the fire damaged columns. Also the weight of the columns before and after the fire tests are measured in order to calculate weight loss from the fire damaged columns.

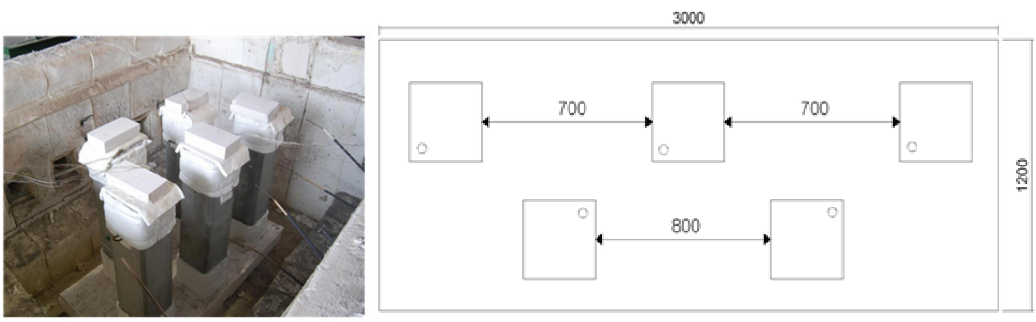

Figure 2: Fire test set-up

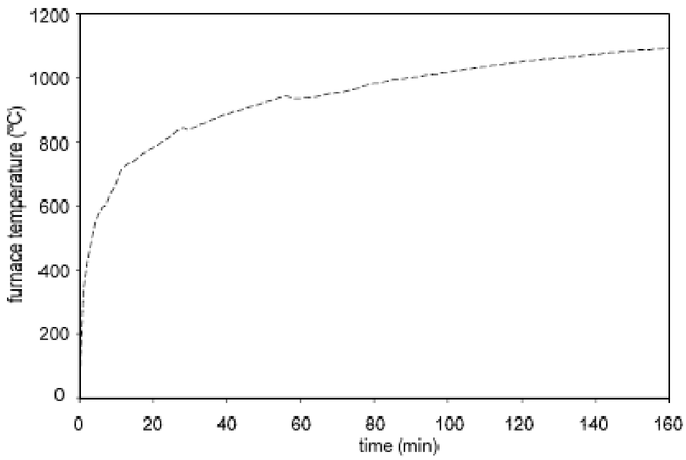

Figure 3: ISO 834 temperature-time curve

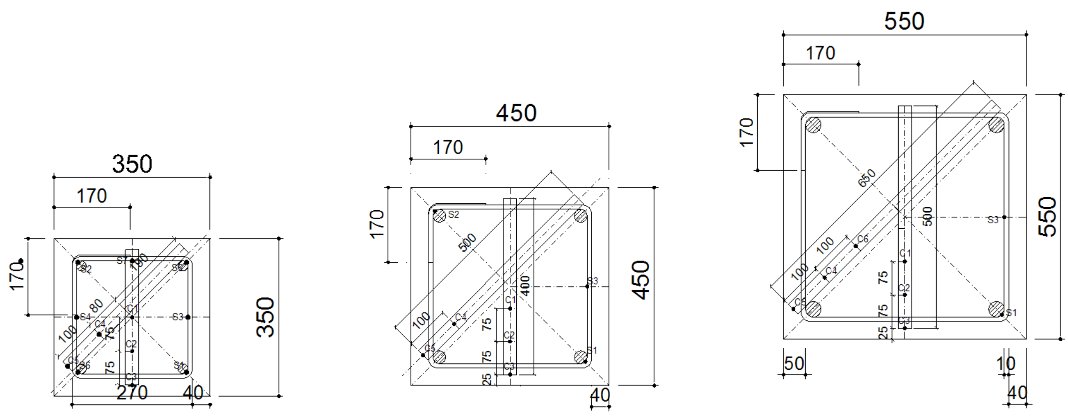

Figure 4: Locations of thermocouples

3 Experimental results

3.1 Temperature distribution

The temperatures are measured at eight points of the column section. The measured temperatures are shown in Figures 5-9. Each figure shows the temperature distribution of the C11, C21, and C31 specimens with respect to the distance from the surface exposed to fire. Regardless of the cross sectional area, increases of temperature distributions of all columns are similar to each other. From the figures, it can be seen that maximum temperatures of the fire damage columns are measured from thermocouple C3 or C5 and around 800ºC-900ºC, depending on the cross sectional area. At 20mins after the fire test, a delay in the temperature increase is observed due to moisture evaporation which occurs when the temperature of the concrete reaches 100ºC. Along with this moisture evaporation, a rapid temperature increase of the thermocouple located at the very surface of the column, which means that spalling has occurred. From the figures, it is also seen that the temperature at C3 and C5, which is located in the concrete cover, shows a rapid increase due to spalling, and therefore most sensitive to spalling effect, while temperatures at C3 and C5 are the more influenced by spalling compared to the temperature at C1..

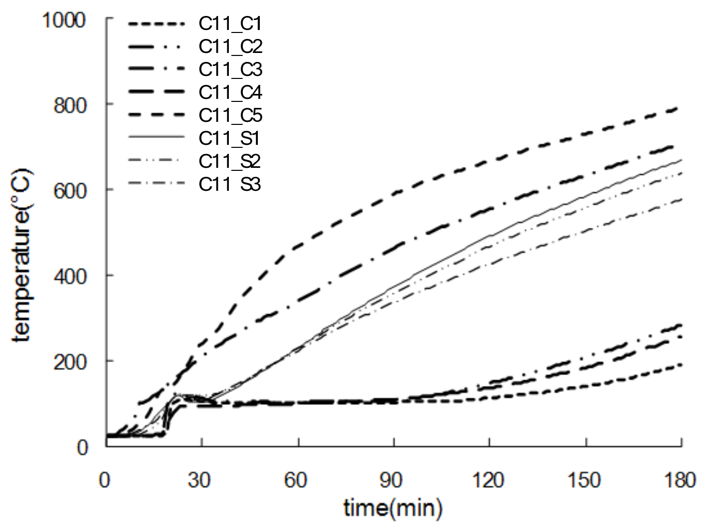

Figure 5: Temperature distributions of C11 column

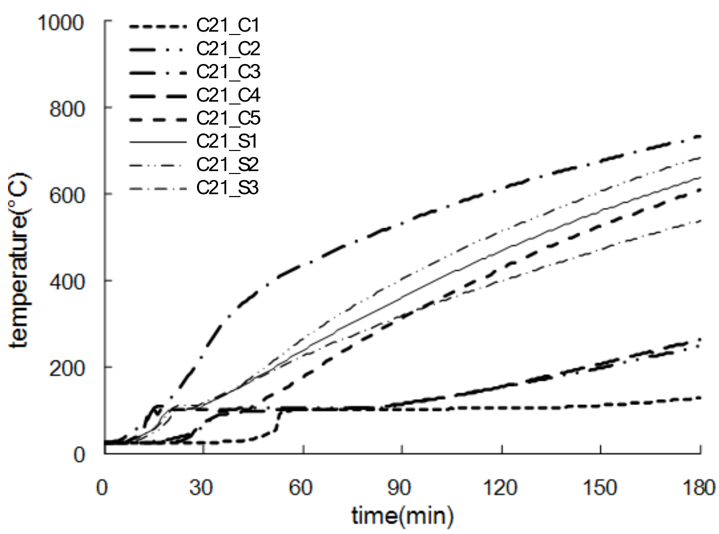

Figure 6: Temperature distributions of C21 column

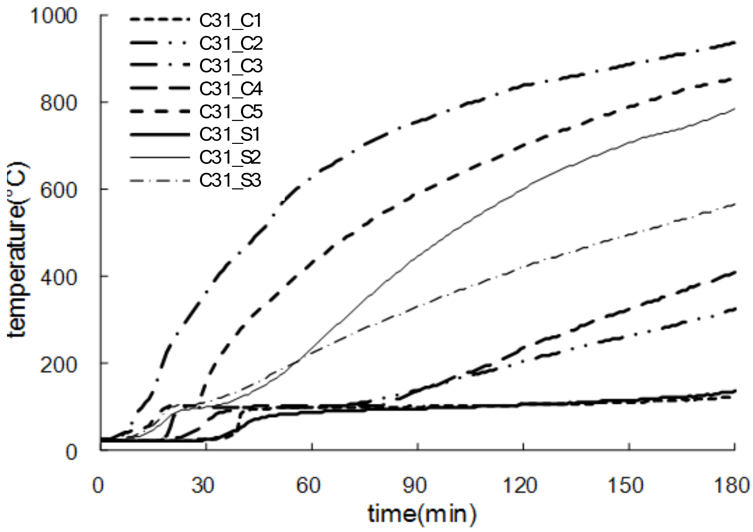

Figure 7: Temperature distributions of C31 column

Explosive spalling causes a reduction in the cross sectional area and exposure of reinforcing bars. The temperatures of reinforcing bars are presented in Figure 8. Also the temperature differences between the C11, C21, and C31 members can be found in Figure 9. The temperatures shown in Figure 9 are obtained at the end of fire tests (three hours of fire tests) and presented along the distances from the side surfaces.

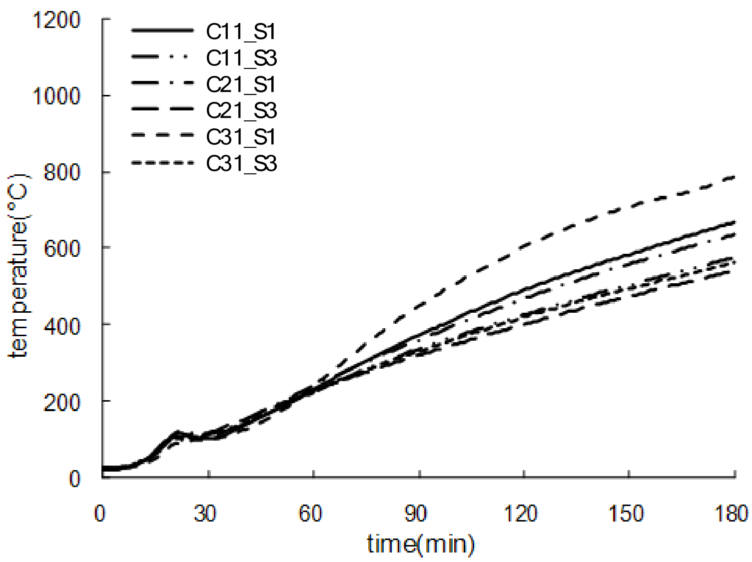

Figure 8: Comparison of temperature on reinforced bar

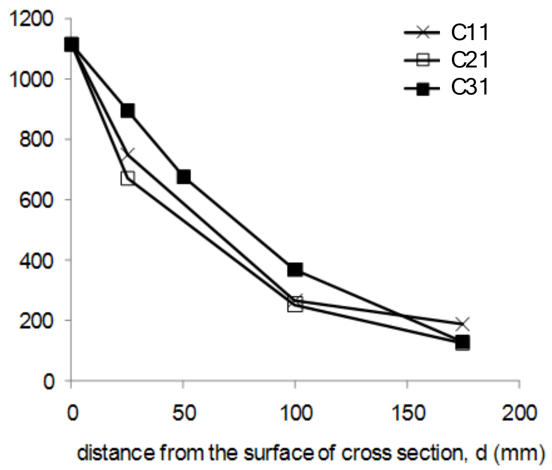

Figure 9: Effect of cross sectional area on temperature distributions

3.2 Spalling

The loss of cross sectional area and weight of the HSC columns on various cross sectional areas are shown in Figure 10. Even the ratio of weight loss and area loss are not identical, the tendencies between different cross sectional areas are the same. Therefore, the area and weight loss ratio increases with the cross sectional area loss. Especially, the ratios of area loss for the column with 350x350mm and 450x450mm are 7.64 and 7.67%, respectively. However, the ratio of area loss for the column with 550x550mm is 16.23%, which is much larger than other two cases. It also correlates with the temperature distributions presented in Figure 9, which confirm that the spalling and temperature distributions are fully coupled.

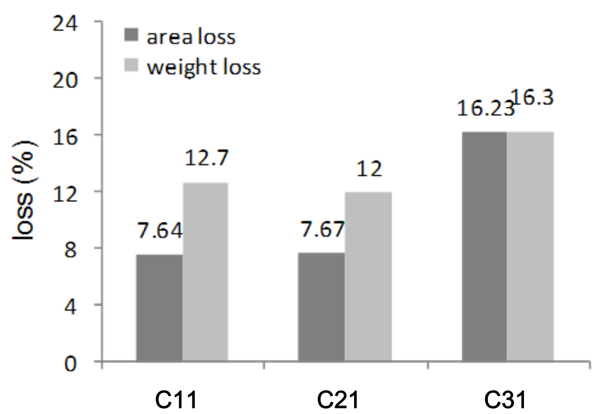

Figure 10: Area and weight loss of columns without pp fibers

4 Experimental results verification

4.1 Modelling method

In order to verify the experimental results, finite element models are generated to simulate the HSC columns with various cross sections and subjected to elevated temperatures. The program ABAQUS version 6.10-3 is used to perform thermal analyses. Three-dimensional models with different kinds of cross sectional area are generated. The models are composed of concrete and steel reinforcement. All two parts are modelled using eight node linear brick elements, also temperature dependent concrete, steel thermal material properties, and spalling effect are included. The columns are modelled with the same dimensions as the columns tested experimentally, as shown in Figure 11. To consider the loss of cross sectional area, three steps of analysis are performed. First, the model is heated to follow the ISO834 time-temperature curve and spalled elements are removed between10 to 20mins, and heated continuously, as shown in Figure 12.

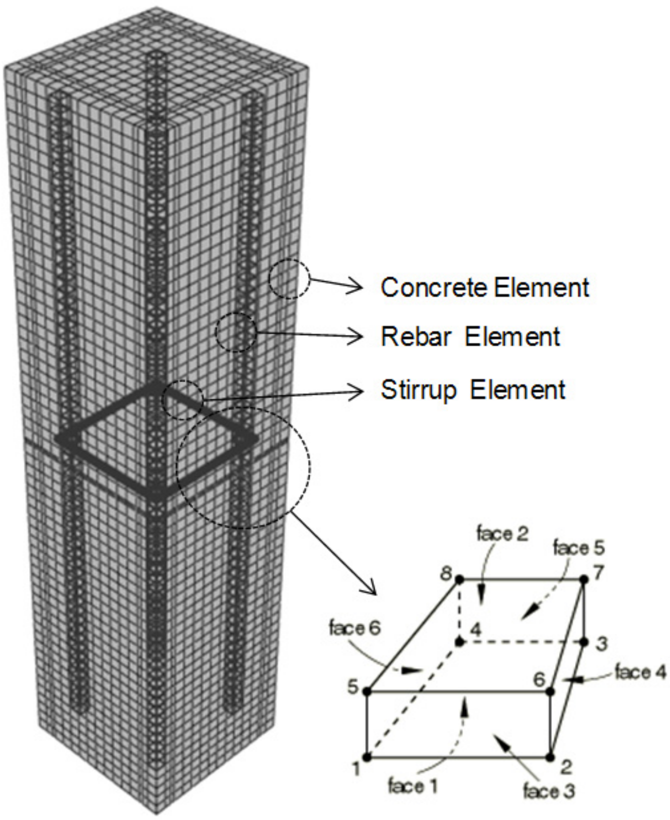

Figure 11: FE model

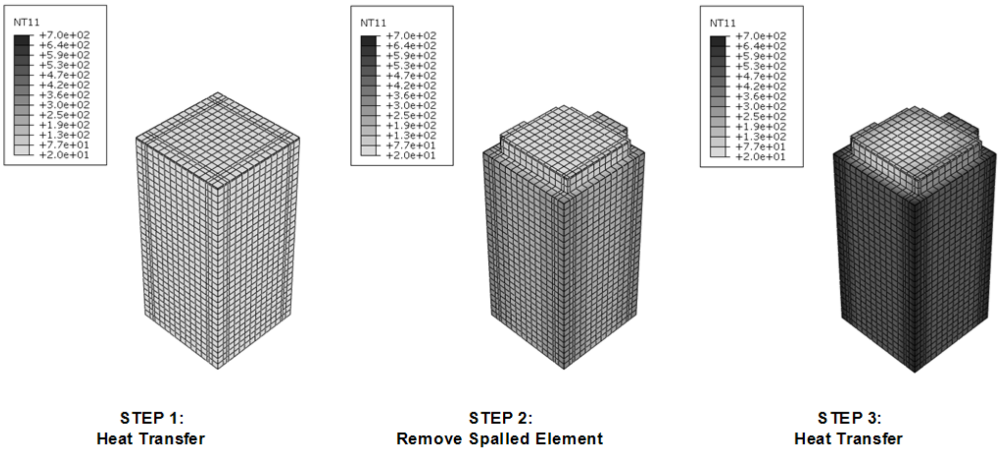

Figure 12: Steps of analysis

4.2 Modelling results

The comparison of the temperature distributions for specimens with dimension of 350x350mm are shown as in Figure 13. Figures 14 and 15 are temperature distributions for specimens with dimension of 450x450mm and 550x550mm, respectively. Analytical results of temperature distributions over heating time predicted from the finite element model are compared with the experimental results and show good agreements overall. In this analytical result, the delay of temperature increase caused by moisture evaporation, which occurs when temperature of concrete reaches 100C, does not appear, because the moisture movement is not considered in the model. So the difference between the experimental and the analytical results arises from the moisture evaporation which not included in the model. Even if the moisture evaporation is not modelled, dramatic increases of temperatures caused by spalling result by the analysis, as spalling is modelled by removing elements where the spalling occurs.

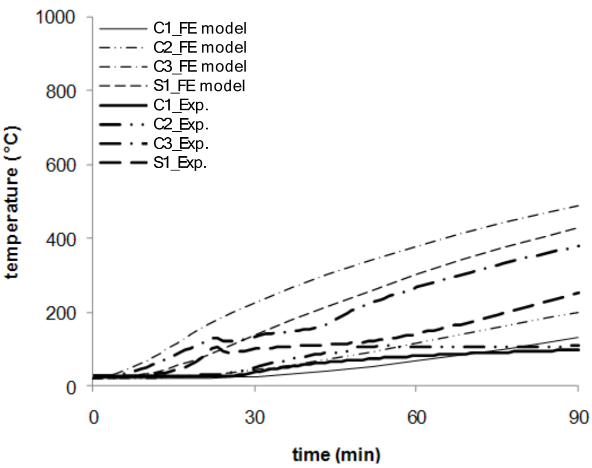

Figure 13: Comparison of experimental and analytical temperature distributions for specimen C11

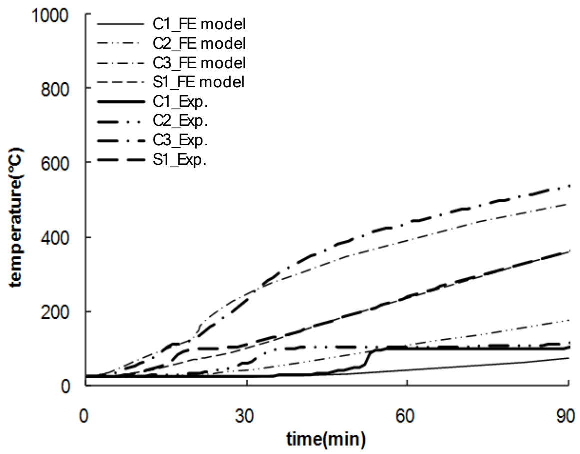

Figure 14: Comparison of experimental and analytical temperature distributions for specimen C21

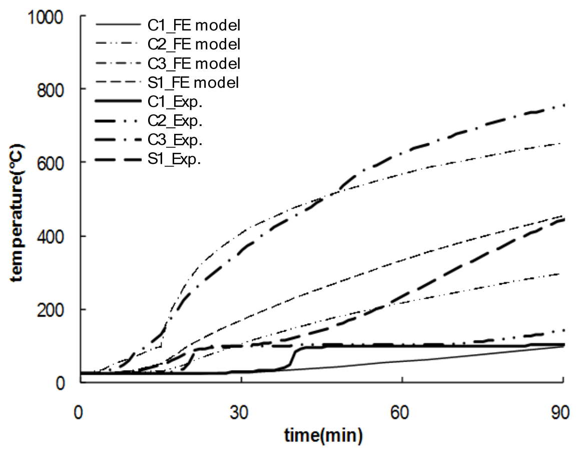

Figure 15: Comparison of experimental and analytical temperature distributions for specimen C31

5 Conclusion

In this paper, experimental and analytical studies have been performed to investigate effect of cross sectional areas of HSC columns at elevated temperatures. Based on the results, following conclusions can be drawn:

1) Cross sectional areas have significant effects on the thermal behaviour of high strength concrete columns under elevated temperature.
2) The column with the largest cross sectional area shows the highest temperature distribution and spalling.

3) Temperature distributions of the HSC columns can be predicted using the proposed analytical methods considering temperature dependent thermal material properties and spalling.
4) The proposed analytical methods are validated by comparing with the experimental results and show good agreement.

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