Parametric Analysis of High-Strength Reinforced Concrete Beams at High Temperature

Choi, Eun Gyu*　Kang, Ji Yeon*　Shin Mi Kyung　Shin Yeong Soo*****

ABSTRACT

An analytical method is proposed for the analysis of the reinforced concrete flexural beam subjected to high temperature. The analysis procedure for the material properties, in this study, is subdivided into two types; thermal properties for temperature distribution analysis and mechanical properties for structural analysis. Using F.D.M. and segmentation method, the program was made to predict the thermal behavior of RC beams during heating. In previous studies, the structural behavior of fire damaged RC beams was investigated though experiments. Comparing the result by program to the one by experiment, the comparison indicated that the proposed segmentation method for the thermal respose analysis present fairly a good agreement with experiment.

1. Introduction

As the reinforced concrete(RC) buildings become much higher, larger and more diverse, high-strength concrete is generally used. RC structures have been traditionally believed to have excellent fire resistance. However, previous studies show that mechanical properties of concrete such as elastic modulus and compressive strength are proved to change abruptly under fire as concrete strength becomes higher and higher. Moreover, high-strength concrete under high temperature is proved to be spalled out because of its low water cement ratio and high density of concrete and results in significant strength reduction by the decrease of cross-sectional dimensions of structural members. Through the fire tests of RC beams, the experimental results can show the structural behavior including the effects of changes of mechanical properties and spalling. However, structural analysis needs to be applied to consider the individual effects of them on structural behavior of RC beams under fire. For these purposes, material properties of concrete and several material model during heating and finite different method and the segmentation method is applied in developing the analysis program,

In this study, the analysis results by the developed program are compared with those of experimental results to verify the analysis program. Based on the program, parametric study is executed to evaluate the effect of several parameters such as cover thickness, the steel ratio, compressive effects of concrete, size of beam section, magnitude of load on the behavior of RC beams under fire.

2. Analysis of RC beams at high temperature

* KCI member, Graduate student, Dept. of Architecture, Ewha Womans Univ.

** KCI member, CS Structural Engineering Inc.

*** KCI member, Professor, Dept. of Architecture, Ewha Womans Univ.

2.1 Analytical flowchart

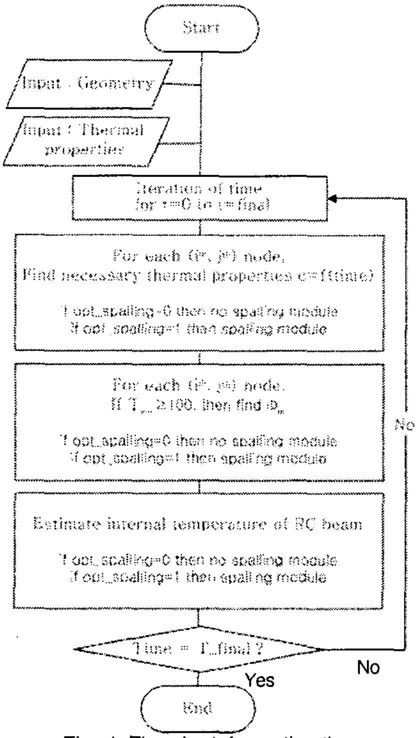

Fig. 1 Flowchart for estimation of internal temperature

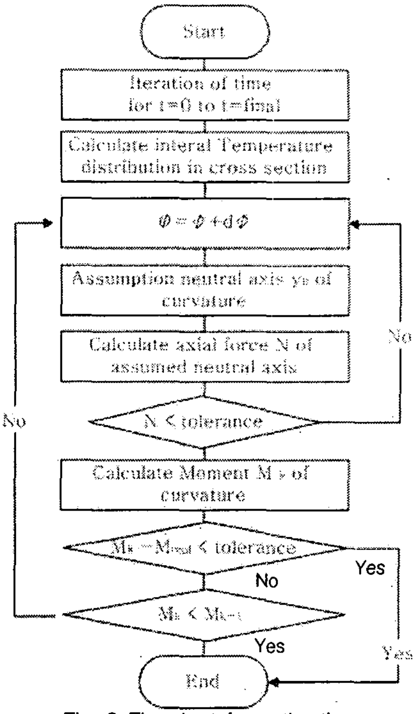

Fig. 2 Flowchart for estimation of deflection

2.2 Thermal analysis

Material properties of thermal conductivity of concrete(k), thermal capacity of concrete(ρc), thermal capacity of water($\rho_w c_w$), heat of vaporization(λ_w) must be found to estimate internal temperature of beams.

Table 1 Material properties according to temperature

ρc ($J/m^3 \cdot C$)	k (W/m^3)	λ_w (J/kg)
for 0℃ < T < 200℃ $\rho_c c_c = (0.005T + 1.7) \times 10^6$	for T > 800℃ $k = -0.000625T + 1.5$	$\lambda_w = 2.3 \times 10^6$
for 200℃ < T < 400℃ $\rho_c c_c = 2.7 \times 10^6$	for T < 800℃ $k = 1.0$	$\rho_w c_w$ ($J/m^3 \cdot C$)
for 400℃ < T < 500℃ $\rho_c c_c = (0.013T - 2.5) \times 10^6$		$\rho_w c_w = 4.2 \times 10^6$
for 500℃ < T < 600℃ $\rho_c c_c = (-0.013T + 10.5) \times 10^6$		

2.3 Spalling

The analysis of high strength concrete needs to consider spalling. It is currently impossible to evaluate the section loss and time at spalling because spalling may occur on account of a number of factors and the accurate mechanism has not been found out yet. Therefore the analytical models of spalling are made by the values obtained from the experiment. Spalling in experiment is as follows.

(1) Spalling occurs at first 10 minutes and is active at 30-40 minutes. No additional spalling after 60 minutes.

(2) Spalling occurs from upper section and moves gradually toward lower section.

(3) A shape which measured remains of section after spalling is made.

3. Verification of analysis program

3.1 Experiment

The fire resistance test are conducted for beams with rectangular cross section(250×400㎜). The specimens are tested in a beam furnace for heating on three sides and the imposed load is determined on basis of the service load in office. The fire performance of beam is evaluated from tests conducted according to ISO 834. The compressive strength of concrete at age 28 days is 53.8MPa.

Table 2 Experimental parameters of the beam specimens

specimens	heating time (minutes)	magnitude of load (tonf)	cover thickness (㎜)	specimens	heating time (minutes)	magnitude of load (tonf)	cover thickness (㎜)
H4-T	-	-		H5-T	-	-	
H4-1	60	9.82	40	H5-1	60	9.82	50
H4-2	90	9.82		H5-2	90	9.82	

3.2 Analytical models

The temperature in the furnace uses ISO 834 temperature distribution and the comparable experiment data used 250×400㎜ beams. The two-dimensional thermal model of cross section that the external temperature increased gradually regardless of longitudinal direction is made as [Fig 3]. The cross-section model shown in [Fig 4] and [Fig 5] are applied according to heating time and degrees of spalling.

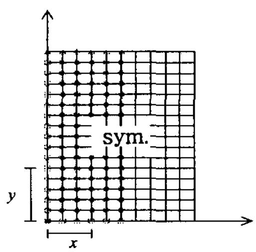

Fig. 3 The theoretical heat transfer analytical model

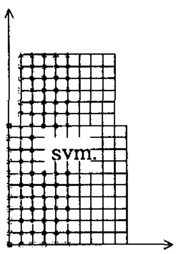

Fig. 4 after first spalling

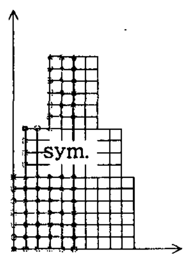

Fig. 5 after final spalling

(1) time < start time of spalling [Fig. 3] application

(2) start time of spalling ≤ time < active time of spalling [Fig. 4] application

(3) time ≥ active time of spalling [Fig. 5] application

3.3 Comparison of deflections obtained by analysis and experiment

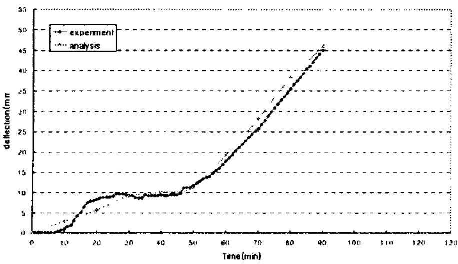

Fig. 6 H4-2

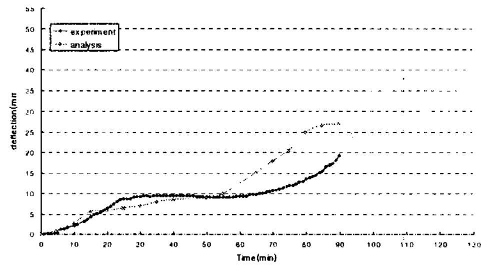

Fig. 7 H5-2

Comparing the result by analysis with the one by experiment, some difference in an early stage(20-50minutes) occurs. While the deflections in experiment almost tend to keep even at 20-50 minutes, the deflections in analysis tend to increase gradually. This phenomenon is why the temperature characteristics of the concrete cannot be duly accounted due to dehydration. So the analysis results don't have a horizontal period. The results of analysis show similar tendency to the results of experiment.

4. Analysis of fire-damaged beams

Parametric study is executed to evaluate the effect of several parameters as shown in Table 3

Table 3 Parameters

cover thickness (㎜)	b (㎜)	h (㎜)	the reinforced steel ratio	magnitude of load (tonf)	the compressive strength
40	25	35	ρ_{min}	D+0.4L	
50	26	45	0.5 ρ_{max}	D+0.5L	23.5MPa 53.8MPa
60	27	55	ρ_{max}	D+0.6L	

4.1 Analysis of cover thickness

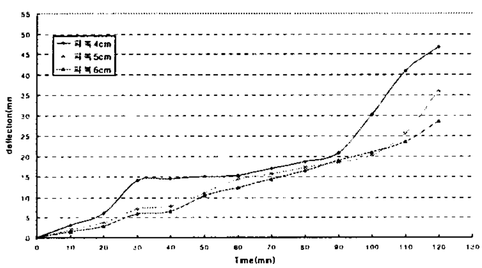

Fig. 8 Time-deflection relations according to cover thickness in normal strength concrete

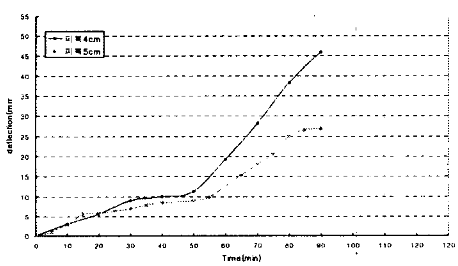

Fig. 9 Time-deflection relations according to cover thickness in high strength concrete

In case of the cover thickness, the analysis is executed about 40㎜, 50㎜ and 60㎜. In normal strength concrete, the thicker cover, the larger deflection. The value 40㎜ less than fire resistance standard (50㎜) has much larger than the others. So it seems that 50㎜ is appropriate minimum standard for the fire resistance. If spalling occurs violently in high strength concrete, the influence of the cover thickness is smaller than the normal strength concrete. As this program treats the more general occasion, there is the capacity difference of the cover thickness. While the deflection of the normal strength concrete increases rapidly heating during above 90 minutes, one of the high strength concrete increases rapidly heating during above 60 minutes.

4.2 Analysis of reinforcing steel ratio

With changes on the reinforced steel ratio that controls the deflections of RC beams, analysis by the cover thickness is executed. The deflection of minimum steel ratio increases faster than one of maximum and 50% of maximum steel ratio. The speed and magnitude of deflection at maximum and 50% of maximum steel ratio have a little difference. In case of the high steel ratio generally, However it has the smaller deflection. Because in the case of the high strength concrete steel that resists against tensile stress reinforced and analytical model is made for no loss in lower section zone where reinforced steel is considering spalling. The deflection in minimum steel ratio has 2.5-3 times than one of maximum and 50% of maximum steel ratio.

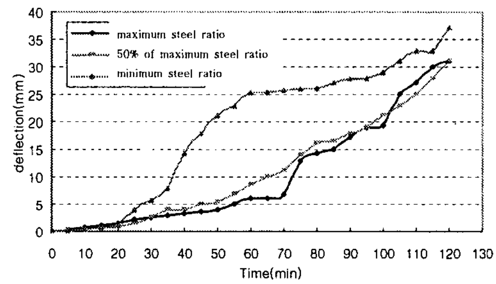

Fig. 10 The normal strength concrete according to the steel ratio

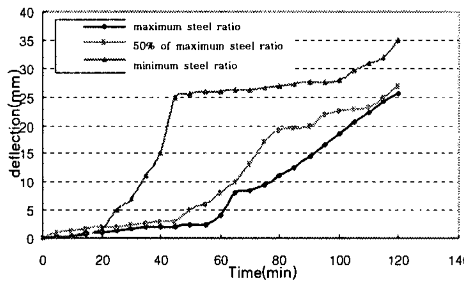

Fig. 11 The High strength concrete according to the steel ratio

4.3 Analysis of the compressive strength of concrete

The normal strength concrete without spalling in fire has a little deflection by the element force increase due to the compressive strength increase. But considering the section loss due to spalling, the deflection of high strength concrete had 1.5-2 times than one of normal strength concrete at first 60 min as shown in [Fig. 12], [Fig. 13]. It means that the elastic modulus drops in relation to normal strength concrete as the moment of second order drops due to the section loss. Therefore the element force of high strength concrete decreases, the rate of deflection increase.

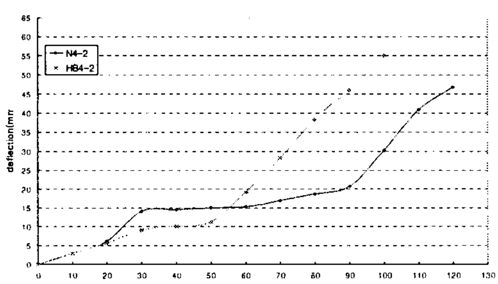

Fig. 12 Time-deflection relations according to the compressive strength (cover:40mm)

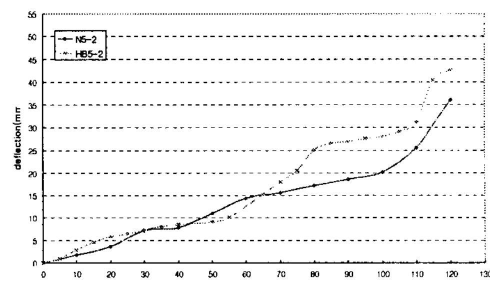

Fig. 13 Time-deflection relations according to the compressive strength (cover:50mm)

[Fig. 14], [Fig. 15] show the difference in analysis of high strength concrete beam whether to consider for spalling. After spalling causes to the section loss, the difference of deflection shows

10-30㎜. Therefore spalling seems to affect noticeably in fire.

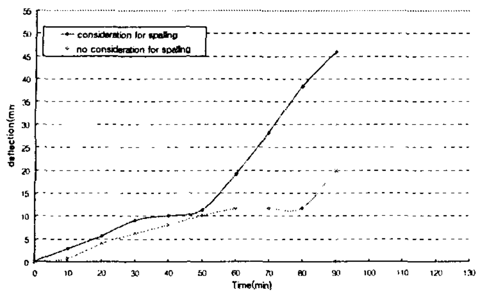

Fig. 14 Time-deflection relations of H4-2 whether to consider spalling

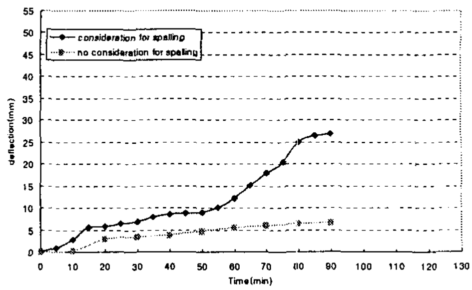

Fig. 15 Time-deflection relations of H5-2 whether to consider spalling

4.4 Analysis of the load during heating

The first stage of heating is shown little difference of the deflection but then as the load increase, the deflection increase. High strength concrete has a clear difference than normal strength concrete about the load parameter. Because spalling causes to the section loss and the internal temperature rise makes the effect of the load strong.

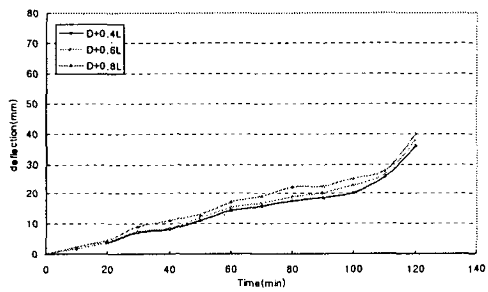

Fig. 16 The normal strength concrete of 50㎜ cover thickness

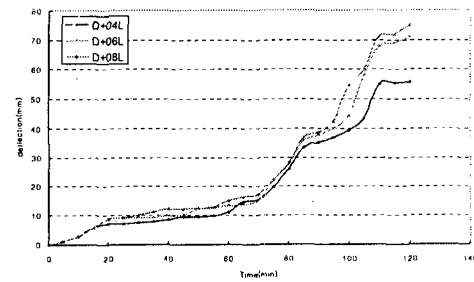

Fig. 17 The high strength concrete of 50㎜ cover thickness

5. Conclusion

The objective of this research is to evaluate the behavior of fire-damaged high strength concrete beams by thermal analysis considering spalling. A study comparing results from analysis and experiment is observed the tendency to be almost a similar shape. Using it, parameters that influence the behavior of heated RC beam is investigated by analysis.

Reference

1. T.Z. Harmathy, Fire Safety Design & concrete ,Longman Scientific & Technical.
2. Shin Mi-Kyung "Structural Behaviors of Fire-Damaged Reinforced Concrete Beams with High Strength", The dissertation for the master's degree, Ewha university 2004.
3. Kim Jin-Keun, Moisture diffusion of concrete considering self-desiccation at early ages.
4. Kang Suk-Won, "Numerical Analysis of Reinforced Concrete Column and Beam at High Temperature", The dissertation for the doctor's degree, Seoul national university 2001.