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Column Shortening of Concrete Cores and Composite Columns in a Tall Building

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Abstract

The effect of column shortening is a major consideration in the design and construction of tall buildings, especially in concrete and composite structural systems. The method presented in the PCA report by Fintel and Ghosh is the most widely used for the analysis of column shortening, but results can be very different depending on the time function of shrinkage suggested by ACI, CEB-FIP and PCA. Therefore it is necessary to compare the calculated column shortening with the field measurement for the more adequate shortening compensation.

This paper describes the predicted and measured column shortening of a reinforced concrete core wall and two steel embedded concrete columns in a 256m tall building. The properties of in-situ concrete are determined by laboratory tests, and strains had been measured for 21 months. The measured strains are compared with strains calculated depending on three time functions of shrinkage. The strain difference between steel and concrete in a composite column is also investigated.

Keywords: tall building, column shortening, measurement, shrinkage, creep

1. Introduction

Column shortening is a major consideration in the design and construction of tall buildings, especially in concrete and composite structural systems. The method presented in the PCA report by Fintel et al. (1987) is the most widely used for the analysis of concrete column shortening, but the amount of column shortening can be very different depending on the time function of shrinkage suggested by ACI, CEB-FIP, and PCA. Song et al. (1997) adopted the time function of shrinkage suggested by ACI, while Kim et al. (1999) compared measured concrete column shortening of the KLCC tower in Malaysia with the prediction adopting the time function of shrinkage of CEB-FIP 78.

Because of their efficiency and lower material and labor costs, composite columns are being increasingly used to construct tall buildings. The shortening behavior of concrete filled steel columns has been studied in other researches (Terry et al., 1994)(UY and DAS, 1997), while the steel embedded concrete column has merely been likened to a reinforced concrete column that has a steel ratio of rebar plus steel shape. This seems reasonable when the steel ratio of a column is relatively low, but the behavior has not been ascertained for composite columns with larger proportions of steel shape.

This paper presents the predicted and measured shortenings of a reinforced concrete core wall and two steel embedded composite columns in a 69-story tall building. The properties of the in-situ concrete are determined by laboratory tests, and strains had been measured for 21 months. The measured strains are compared with strains calculated by three different time functions of shrinkage, as suggested by ACI, CEB-FIP, and PCA. The strain difference between steel and concrete in a composite column is also investigated.

2. Description of the building and measurement

The building consists of a tower and podium with a total height of 256 m. It has 69 levels above ground (including 9 podium levels) and 6 underground levels. The vertical members of the building consist of two reinforced concrete cores and seventeen perimetric composite columns. Steel girders are used for connecting columns to cores and were designed as both-ends pin connections. The floor system comprises deck plates with 12 cm concrete topping. The building is shown in Fig. 1.

Three vertical members are investigated for column shortening: a core wall W1, and two composite columns C65 and C70. Dimensions of members are shown in Table 1. As the steel column in the composite column is not only for erection but also for structure,

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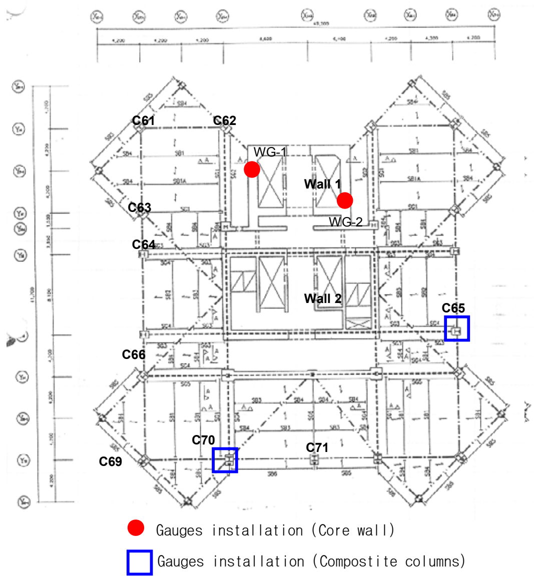

Fig. 1. The investigated building and its typical floor

the ratio of the steel section to the total cross section is much higher than in a general reinforced concrete column or steel embedded composite column. Table 2 shows that sectional ratios of the steel column to the entire section vary from 1.9 to 20.9%, and those of reinforcing bars comprise 1.2 to 1.3%. Design strengths of concrete for vertical elements are 49MPa (level B6 to 34), 39.2MPa (level 35 to 52), and 34.3MPa (level 53 to 69).

Table 1. Dimensions of wall and columns (cm)

Level	W1	C65	C70
	Thickness	BxD	BxD
52-69	50	90x70	80x80
34-51	70		
10-33			
1-9	100		140x140
B3-B1		100x100	150x150
B6-B4		110x110	

Table 2. Steel Percentages in composite columns (%)

Level	C65		C70	
	Shape	Rebar	Shape	Rebar
52-69	1.9	1.2	1.9	1.2
34-51	8.3	1.3	12.3	1.2
10-33	13.1	1.2	20.9	1.2
B6-9	14.5	1.2	7.4	1.2

*All values are the averages in their levels

Strains occurred from column shortening were measured by vibrating wire gauges. To gain axial strains, two gauges were mounted on either side of the web center of a steel column and two gauges were embedded in a core wall. The reason for installing gauges to steel shape in the composite column is that the steel girder connected to the steel column determines the floor level. Fig. 2 shows the installed gauges at the core wall and the composite column. Strain gauges were installed at every tenth level (i.e. level 4, 16, 25, 36, 45, and 56) and the results of level 4 are presented in this paper.

The measurements were initiated just after pouring concrete. Measured data were all compensated considering temperature effects. Strain measurements were obtained once every day during the first month and once per week afterwards for a total of 21 months, from March 2001 to November 2002, when the construction of the structure was completed and interior works were under way.

(a) Core wall (b) Composite column

Fig. 2. Installed Strain Gauges

3. Calculation of column shortening

A computer program was developed to calculate column shortening. The program is based on the analysis procedure of the PCA report and enables users to select a function of shrinkage with time suggested by ACI, CEB-FIP, and PCA, which show considerable difference.

Material properties for analysis were determined by material tests of in-situ concrete. Specimens were taken from the concrete strength of 49 MPa (Type I) and 39.2 MPa (Type II), but samples of 34.3 MPa could not be obtained so assumed values are used for that strength.

3-1 Elastic strains

Elastic strains of concrete with time are determined from compressive strength, $f'_c(t)$, and elastic modulus, $E_c(t)$, in Eq. (1) and (2), respectively.

$$f'_c(t) = \frac{t}{4.0 + 0.85t} \cdot f_{28} \quad \text{(MPa)} \tag{1}$$

$$E_c(t) = 0.043 w^{1.5} \sqrt{f'_c(t)} \quad \text{(MPa)} \tag{2}$$

where t is the age of concrete (in days), f_{28} is the compressive strength of concrete at the age of 28 days (MPa), and w is the unit weight of concrete. For high-strength concrete above 41 MPa, ACI-363R (1992) suggests the elastic modulus in Eq. (3).

$$E_c(t) = 3{,}320\sqrt{f'_c(t)} + 6900 \quad \text{(MPa)}$$
$$\text{for } 21\text{MPa} < f'_c(t) < 83\text{MPa} \tag{3}$$

The test results show that the obtained compressive strengths are in good accordance with predictions of Eq. (1). The compressive strengths at the age of 28 days are 53.4 MPa (Type I) and 62.0 MPa (Type II). For the elastic modulus, Type I is more accordant with Eq. (3), while Type II is more accordant with Eq. (2). In this paper, Eq. (1) and (2) are used for calculating elastic strains.

3-2 Shrinkage strains

The PCA report suggested shrinkage strains with time in the form of Eq. (4). In the equation, shrinkage strains are taken from multiplying the ultimate shrinkage strain $(\varepsilon_{sh})_u$ with coefficients of the volume to surface of a member $SH_{v/s}$, relative humidity SH_H, shrinkage with time SH_t, and residual shrinkage of reinforced concrete SH_{rf}:

$$\varepsilon_{sh,t} = (\varepsilon_{sh})_u \times SH_{v/s} \times SH_H \times SH_t \times SH_{rf} \tag{4}$$

The ultimate shrinkage strain can be determined by regression fitting the data obtained from material tests with the time function of shrinkage. The time function of shrinkage differs according to codes, as shown in Eq. (5) to (7). ACI (1997) and CEB-FIP (1990) suggest a function like Eq. (5) and (6), while the PCA report prefers Eq. (7), which is based on the published work of Hansen and Mattock. In these equations, it is notable that CEB-FIP and PCA consider the influence of member size when shrinkage occurs with time.

$$SH_{t,ACI} = \frac{t - t_s}{35 + (t - t_s)} \tag{5}$$

$$SH_{t,CEB} = \sqrt{\frac{(t - t_s)}{3.5 \times h^2 + (t - t_s)}} \tag{6}$$

$$SH_{t,PCA} = \frac{(t - t_s)}{26.0 e^{0.36 \times v/s} + (t - t_s)} \tag{7}$$

where t is time in days after concrete pouring, t_s is time in days of initial wet curing, $h = 2A_c/u$ represents the nominal size of the member (cm), A_c is the cross-sectional area (cm^2), u is the perimeter of the cross section exposed to the atmosphere (cm), and v/s is the volume to surface ratio (in).

Shrinkage tests were carried out in accordance with the requirements of KS F 2424 (2000). Regression analysis, as shown in Table 3, indicates that the predicted ultimate shrinkages of ACI and CEB-FIP are similar and that those of PCA are a little higher for both Type I and II. The ultimate shrinkage strains for the calculation are finally decided as 850x10^{-6} (Type I) and 570x10^{-6} (Type II), considering material tests and field conditions.

Table 3. The ultimate shrinkage strains by regression analysis

	ACI Eq. (5)	CEB-FIP Eq. (6)	PCA Eq. (7)	Applied Value
Type I	819x10^{-6}	817x10^{-6}	838x10^{-6}	850x10^{-6}
Type II	545x10^{-6}	545x10^{-6}	553x10^{-6}	570x10^{-6}

3-3 Creep Strains

Creep strains suggested by the PCA report can be determined by multiplying acting stress σ and specific creep $(\varepsilon_{cr})_u$ with coefficients of age of concrete at loading $CR_{t'}$, member size $CR_{v/s}$, relative humidity CR_H, creep with time CR_t, and residual creep of reinforced concrete CR_{rf}, as shown in Eq. (8). Specific creep refers to occurred creep strains per unit stress, which is taken from fitting data of material tests with time functions of creep. The time functions of creep are in Eq. (9) and (10), and the PCA report uses the equation of the ACI code, Eq. (9).

$$\varepsilon_{cr,t} = \sigma \times (\varepsilon_{cr})_u \times CR_{t'} \times CR_{v/s} \times CR_H \times CR_t \times CR_{rf} \tag{8}$$

$$CR_{t,ACI} = \frac{(t - t')^{0.6}}{10 + (t - t')^{0.6}} \tag{9}$$

$$CR_{t,CEB} = \left(\frac{(t - t')}{\beta_H + (t - t')} \right)^{0.3} \tag{10}$$

where t' is time in days to first loading after concrete pouring.

$$\beta_H = 150\left\{1 + \left(1.2\frac{RH}{100}\right)^{18}\right\}\frac{h}{10} + 250 \le 1500 \tag{11}$$

where RH is relative humidity (%)

Creep tests using $\phi 15 \times 30$ cm specimens were carried out in accordance with the requirements of KS F 2453 (2003). The results are shown in Table 4. In this paper, Eq. (9) is taken as the time function of creep and values of $83.5x10^{-6}$ /MPa (Type I) and $53.1x10^{-6}$ /MPa (Type II) are eventually applied as specific creeps, considering both material tests and field conditions. Table 5 presents a summary of material properties that were applied to calculate column shortening.

Table 4. The specific creep by regression analysis (1/MPa)

	ACI Eq. (9)	CEB-FIP Eq. (10)	Applied Value
Type I	$82.5x10^{-6}$	$79.2x10^{-6}$	$83.5x10^{-6}$
Type II	$51.1x10^{-6}$	$48.6x10^{-6}$	$53.1x10^{-6}$

Table 5. Summary of material properties of concrete

Level	Comp. Strength at 28 days (MPa)	Specific Creep (1/MPa)	Ultimate Shrinkage	Type
53-69	34.3*	$116.6x10^{-6}$*	$650x10^{-6}$*	-
35-52	62.0	$53.1x10^{-6}$	$570x10^{-6}$	II
B6-34	49.0	$83.5x10^{-6}$	$850x10^{-6}$	I

*Material properties of levels 53-69 were determined within ranges that the PCA report suggested.

3-4 Loads and Construction Schedule

The construction sequence of the structure starts from concrete core walls and then steel frames are erected 3 to 5 levels below the top of core walls. The concrete pouring of composite columns and slabs are also followed for about 10 to 12 levels below the top of core walls. The construction cycle of typical floors is about 4 to 5 days.

Loads are categorized into 6 types according to their construction sequence. The period for building core walls is 641 days and for building whole structures is 740 days. Live load by occupants is expected to go into effect after 971 days. Live load for the calculation of column shortening is reduced to 10% of design live load, considering that the real live load is much less than the design live load.

4. Calculated and measured strains

4-1 Core wall

Calculated and measured strains of W1 are presented in Fig. 3 and Table 6. In the graph, the legends of calculated strains indicate the time function of shrinkage used to calculate shrinkage. The strains are plotted with log-scale to 1,000 days, considering all loads up to when residents are expected to move into the building. The measured strains tended to fluctuate in early days; they sharply increased or decreased without any critical change in field conditions. This fluctuation was probably caused by temperature changes due to the hydration of concrete. The temperature of the concrete rose up to 65℃ at 2 days against an outside temperature of 1℃. Measured data and the temperature of concrete stabilized after 7 to 10 days.

The calculated strains show considerable difference according to the time functions of shrinkage. The rate of stains of ACI is much more rapid than that of either CEB-FIP or PCA, which have similar patterns. The calculated strain of ACI at 100 days is 36% of the strain at 1,000 days, whereas the strains of CEB-FIP and PCA are only 14% and 8.6%, respectively. In addition, the strain of ACI at 1,000 days is predicted to be $601x10^{-6}$, which is 30% and 55% greater than that of CEB-FIP and PCA, respectively. This difference comes from consideration of the effect of member size. The volume to surface ratio of W1 is 37.3 cm.

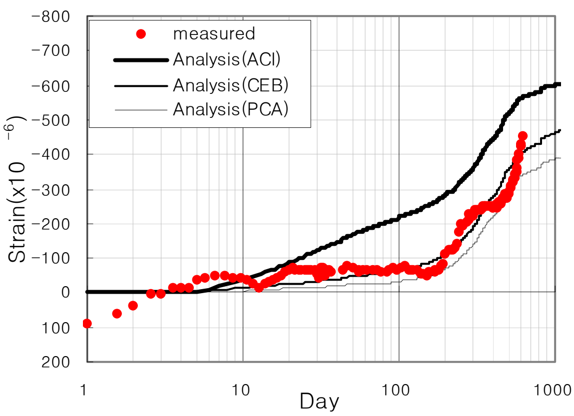

Fig. 3. Measured and calculated strains of W1 at level 4

Table 6. Axial strains with time of core walls at level 4

		Strain ($x10^{-6}$)				
		10 days	100 days	620* days	1,000 days	10,000 days
W1	Measurement	40.8	73.6	453.5	-	-
	Analysis (ACI)	35.3	219.0	564.7	600.9	632.4
	Analysis (CEB-FIP)	12.3	65.4	407.0	462.4	680.1
	Analysis (PCA)	4.5	33.3	340.9	386.2	541.6

* When the measurements stopped.

The measured strains of W1 had a pattern similar to CEB-FIP and PCA. The measurement of W1 had good accord with the two predictions and had a final strain of $453.5x10^{-6}$ at 620 days.

4-2 Composite columns

Under the calculation procedure presented in this paper, a steel column embedded in concrete is regarded like a rebar in a concrete column and the effect of steel on shrinkage and creep are considered using the factors of residual shrinkage and residual creep. This seems reasonable if the ratio of steel to gross section is low when the steel column is used for erecting the frame. However, when steel embedded composite columns used for tall buildings have a much higher steel ratio for structural purposes, it is not certain that the presented procedure can be also applied to. This section, therefore, focuses on the strains occurred in steel and concrete in the composite column. The investigated columns and percentages of steel shape and rebar are shown in Fig. 1 and Table 2. The volume to surface ratio is 19.6 cm for C65 and 32.5 cm for C70.

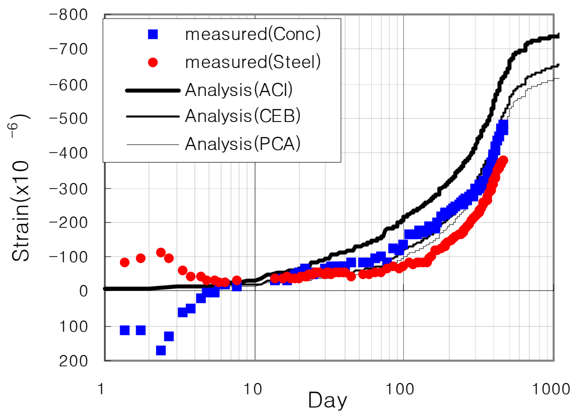

Fig. 4. Measured and calculated strains of C70 at level 4

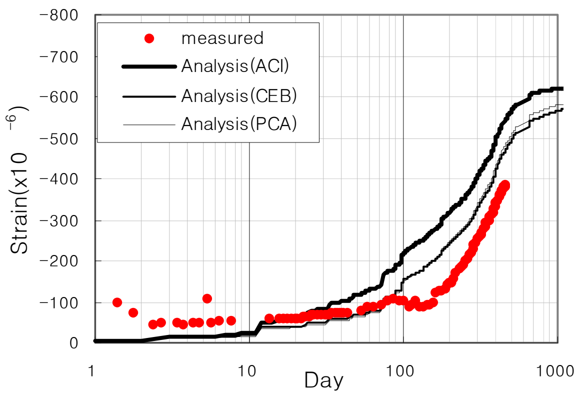

Fig. 5. Measured and calculated strains of C65 at level 4

The strains of steel and concrete due to shortening are measured at C70 and are shown in Fig. 4 and Table 7. In the graph, 'measured (Conc)' means the average strain gained at the four corners of the concrete, and 'measured (Steel)' means the average strain gained at both web centers of steel columns. Measurements began just after pouring concrete to the column. Measured strains of the steel and the concrete also fluctuated for 10 days, similar to core walls. The rate of strains of the concrete is more rapid than that of the steel up to 130 days, making the maximum difference 92x10-6. After 130 days, the gap is maintained to the end of measurement. The final strain of the concrete at 464 days is 483.8x10-6 while the steel is 380.5x10-6. This result seems to indicate that there is a little initial slip between steel and concrete until they are fully unified at 130 days. The strains gained at the concrete show better accordance with strains calculated from CEB-FIP and PCA, but the strains gained at the steel increased less than all calculations. The column C65 presents similar results. In Fig. 5, the measured strains, which were the strains of the steel shape, have lower values than calculated strains.

Table 7. Axial strains with time of composite columns

		Strain ($x10^{-6}$)				
		10 days	100 days	464* days	1,000 days	10,000 days
C65	Measurement	60.5	101.5	386.0	-	-
	Analysis (ACI)	24.6	220.2	546.6	619.1	642.6
	Analysis (CEB-FIP)	17.9	153.2	472.8	565.1	679.5
	Analysis (PCA)	15.0	150.6	485.8	579.1	636.8
C70	Measurement	32.0	72.5	380.5	-	-
	Analysis (ACI)	31.7	213.8	618.6	736.0	769.2
	Analysis (CEB-FIP)	20.7	120.6	512.3	648.6	806.8
	Analysis (PCA)	16.7	101.5	479.8	611.8	731.8

* When the measurements stopped.

The result of this investigation suggests that it is more appropriate to calculate column shortening with the time function of shrinkage of CEB-FIP or PCA than with that of ACI. It also implies that the procedure used in this paper might overestimate shortening of the composite column because the calculation does not completely consider the complicated behavior between concrete and steel such as initial slip and stress redistribution. The shortening compensation of composite columns should be determined in the earlier stages of construction, before steel columns are manufactured. Therefore, it is necessary to develop a more accurate method of calculating column shortening that considers the characteristics of steel embedded composite columns.

5. Conclusions

This paper presents the measured and calculated column shortenings of a 69-story building. The conclusions of the investigation are summarized as follows:

1) The material properties of the in-situ concrete are

verified by laboratory tests. A computer program that adopted the three time functions of shrinkage based on ACI, CEB-FIP, and PCA is developed for the calculation of column shortening.

2) From the investigation of the core wall W1, the calculated strains show some notable difference according to the time functions of shrinkage. The strain curve adopted in ACI shows the most rapid rate and the largest amount of strain. The measured strains are more compatible with the calculated strains by CEB-FIP and PCA. The core wall has a large volume to surface ratio 37.3 cm, but the ACI time function of shrinkage does not consider change of the volume to surface ratio effectively.
3) The strains of concrete and steel are both measured at the composite column C70. The strain rate of the concrete is more rapid than that of the steel, but the gap is maintained after 130 days. This implies that the concrete and steel are not fully unified during the initial period.
4) As steel beams and girders are connected with steel shape in the composite columns, strains obtained from the steel columns are considered as the shortening amount of the composite column. The measured steel strains from C65 and C70 also have patterns similar to the calculated strains by CEB-FIP and PCA, but their amounts are smaller than were calculated.
5) As the field compensation should be determined in the early stages of construction, it is important to properly predict shortening from the initial measurement. Therefore, it is necessary to develop a more accurate calculation method of column shortening considering the characteristics of steel embedded composite columns.

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