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Probabilistic Prediction and Field Measurement of Column Shortening for 41-storey Residential Building

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Abstract

Long-term axial shortening of the vertical elements of tall buildings results in differential movements between two vertical elements and may lead to the additional moments of connection beam and slab elements, and other secondary effects, such as cracks of partitions or curtain walls. Thus, accurate prediction of time-dependent column shortening is essential for tall buildings from both strength and serviceability aspects.

The uncertainty associated with assumed values for concrete properties such as strength, creep and shortening coefficients should be considered for the prediction of time-dependent column shortening of tall concrete buildings.

In this study, the probabilistic column shortenings of 41-story T building recently completed are predicted using Monte Carlo simulation. The probabilistic column shortenings considering confidence levels are compared with the actual column shortenings by field measurement.

Keywords: Column Shortening, Probability Analysis, Monte Carlo Simulation, Field Measurement

1. Introduction

Long-term axial shortening of the vertical elements of tall buildings results in differential movements between two vertical elements and may lead to the additional moments of connection beam and slab elements, and other secondary effects, such as cracks of partitions or curtain walls. Thus, accurate prediction of time-dependent column shortening is essential for tall buildings from both strength and serviceability aspects. But the material properties used in tall building construction can vary by natural or artificial causes even in the same material. According to the variability of material properties, the predicted values in column shortening may be different from the real values. In order to resolve this problem, the actual column shortening should be measured during construction and the differences between the predicted values and the real measured values have to be applied to compensation of column shortening.

In the deterministic analysis, the column shortening is predicted based on the fixed material property without considering its uncertainty. But the characteristics of the material property follow certain probabilistic and statistic distribution obtained by experimental results. All material properties do not have certain fixed values but have unique statistical characteristics. The probabilistic analysis considers these characteristics in predicting the column shortening. Considering the fact that the concrete properties such as strength, creep and shrinkage coefficients which influence on the column shortening have large variations, probabilistic analysis on the column shortening prediction is needed. Song et al(2002) has studied on the probabilistic analysis method using Monte Carlo Simulation.

A study on long-term field measurement of column shortening began on 3150 Lake Shore Drive, Chicago, USA, a 34-story reinforced-concrete building in 1962. Also, Water Tower Place, a 76-story building completed in 1979, gives an important measurement data(Russel et al, 1977). In Korea, results about field measurement of Petronas Twin Tower constructed in Malaysia were reported in 1999. Recently, field measurement results of Hyundai Hyperion, 69-story residential building and the Samsung Tower Palace, 59-story residential building are reported.

The previous studies have examined the deterministic shortening compared to field measurement data. In this case, it can not consider problem that the compensation values may be underestimated or overestimated in compensation stages for vertical elements of lower stories. Therefore, a study on comparisons of results from a probabilistic analysis and the actual column shortening by field

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measurement is needed.

In this study, the probabilistic column shortenings of 41-story T building recently completed are predicted using Monte Carlo simulation.

The probabilistic column shortenings considering confidence levels are compared with the actual column shortenings by field measurement.

2. Probabilistic column shortening analysis by Monte Carlo Simulation

2-1 Random Parameters and Member Properties

Strength, creep and shrinkage coefficient each of which has large variation in concrete properties has been selected as random parameters in this study.

ACI Committee 214(1997) specifies less than 10% of the coefficient of variation as 'excellent control'. Therefore, the coefficient of variation chosen in this study is 0.1(10%). Probabilistic and statistical characteristics of the creep coefficient and the shrinkage coefficient was proposed by Bazant and Baweja(1995). It was used by defining the coefficient of variation on the ACI model, where the coefficients of variation were 0.528 in creep and 0.553 in shortening (Bazant and Baweja, 1995). Different from elastic shortening, creep and shortening shrinkage are time-dependent. Therefore creep and shortening as probabilistic variables should be examined in relation to the lapse of time. The column shortening algorithm proposed by the PCA (Portland Cement Association) was adapted in this study. Creep and shrinkage equations are based on the ACI Committee 209(1992) model. Coefficients of variation applied to this study are summarized in Table 1.

Table 1. Random Parameters

	Concrete strength	Shrinkage coefficient	Creep Coefficient
Coefficient of variation	0.1	0.553	0.528

The perspective of T tall building is shown in Fig.1. This building is 41 stories reinforced concrete structure with 4 underground stories. The height of the structure is 131m. The PCSA (Probabilistic Column Shortening Analysis) program from reference (Song et al 2003) has been used as a probabilistic column shortening program in this study. The C1, C2, C3 columns and the interior core wall in Fig. 2 have been selected as elements for analysis. The elastic, creep and shrinkage shortenings of those elements were calculated by probabilistic method and the results were compared with those obtained by deterministic method.

Fig. 1. T tall building

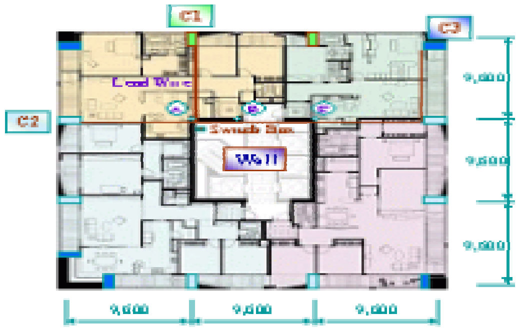

Fig. 2. Typical floor

Table 2. Material Properties

	Story	Concrete strength (Mpa)	Ultimate shortening (10^{-6} in/in)	Specific creep (10^{-6} in/in/psi)
Exterior Column , Interior Shear wall	1,7,9,26-28	49	750	0.422
	6,10-12,15, 24,25,29	47	750	0.439
	2,3,14,16-23	45	750	0.459
	4,5,8,13	43	750	0.479
	30-45	25	750	0.799

Table 3. Properties of C2 column

Story	Column area (㎠)	Steel area (㎠)	Volumn-to -surface Ratio (㎝)	Applied loads (KN)
1	16,000	627.3	28.57	582
2-3	16,000	627.3	28.57	500
4	16,000	579.1	27.69	588
5	14,400	579.1	27.69	784
6	14,400	514.7	27.69	627
7-8	12,600	514.7	25.20	500
9	12,600	514.7	25.20	598
10	12,600	514.7	25.20	520
11	11,700	386.1	23.88	539
12-15	10,530	386.1	23.19	510
16-19	10,530	257.4	23.19	510
20-23	10,530	193.0	23.19	510
24-26	10,530	160.8	23.19	510
27	10,530	160.8	23.19	794
28-29	10,530	160.8	23.19	510
30-42	12,600	98.2	23.19	510
43	4225	98.2	16.26	510
44	4225	98.2	16.26	47.3
45	4225	98.2	16.26	59.7

Relative Humidity: 65%

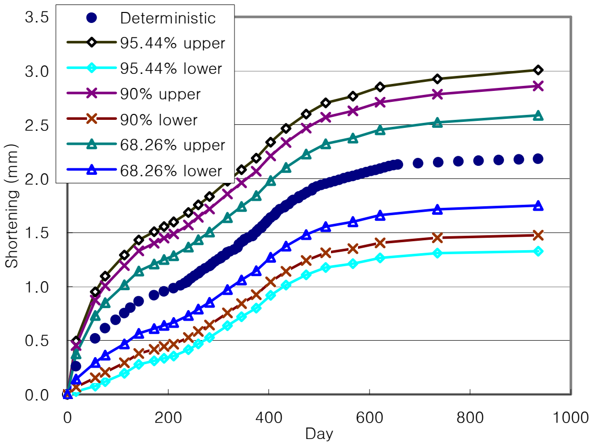

Fig. 3. Shortenings of C1 column at level B2 for three different confidence levels

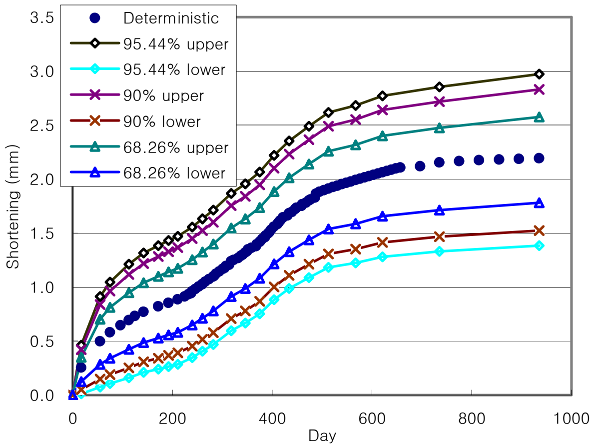

Fig. 4. Shortenings of C2 column at level B2 for three different confidence levels

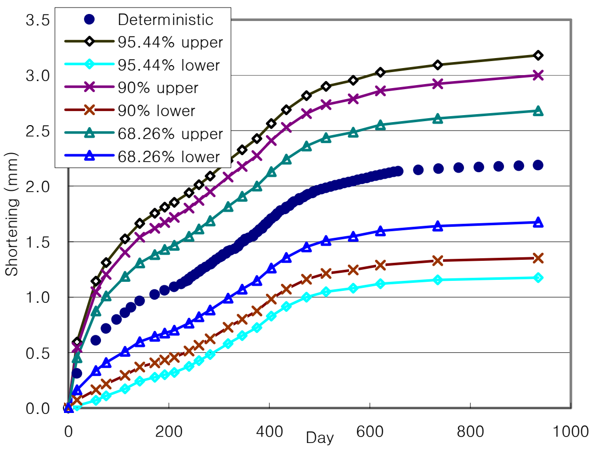

Fig. 5. Shortenings of C3 column at level B2 for three different confidence levels

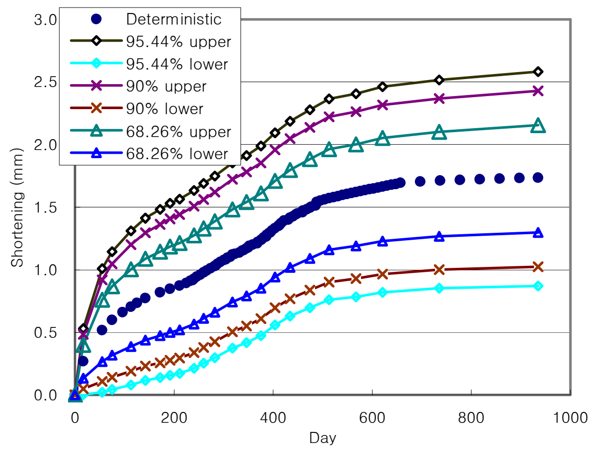

Fig. 6. Shortenings of Shear Wall at level B2 for three different confidence levels

Table 2 shows some properties of concrete materials used in T tall building, and properties of C2 column such as column area, steel area, volumn-to-surface ratio, and applied loads are summarized in Table 3. The another characteristics calculating column shortenings can be referred to in reference (Song et al, 2003).

2-2 Probabilistic analysis of column shortening

If a column shortening is calculated based on the probabilistic and statistical characteristics of material properties, it is possible to obtain both the expected value (average value) and the statistical characteristics which can be used to analyze the change of shortenings for each confidence level. The probabilistic analysis can take both the uncertainty of the deterministic analysis and the unexpected change of shortenings in real structures into account.

Fig. 3-6 show the time-dependent vertical shortenings by confidence level for three exterior columns and interior shear wall. Each shortening of exterior columns and interior shear wall increases gradually up to age of 500 days and after age of 500 days the shortenings occur slowly. This results present that the loading applied during frame construction does not act after finishing of frame construction, at age of 553days and inelastic shortenings proceed with increase in time asymptotically. The axial strains of exterior columns and interior shear wall were calculated to be 680 and 540 micro-strains, respectively. Table 4 describes shortening for confidence intervals of level B2.

In the probabilistic analysis, upper and lower values of the shortenings are different for different confidence intervals (σ, 1.645$\sigma$and 2σ). In the C1 shortening, the upper values of shortening which are 2.588mm, 2.858mm, 3.007mm, increase as the confidence interval gets larger. That means as the interval gets wider, the difference from the value of 2.182mm calculated by the deterministic analysis becomes larger.

Table 4. Shortening for confidence intervals of level B2

(unit : mm)

Shortenings \ Confidence intervals		$\mu-\sigma \le X \le \mu+\sigma$ (68.26%)	$\mu-1.645\sigma \le X \le \mu+1.645\sigma$ (90%)	$\mu-2\sigma \le X \le \mu+2\sigma$ (95.44%)
C1	upper	2.588	2.858	3.007
	lower	1.749	1.478	1.329
	mean		2.168	
C2	upper	2.574	2.830	2.971
	lower	1.781	1.525	1.384
	mean		2.178	
C3	upper	2.678	3.001	3.179
	lower	1.677	1.354	1.176
	mean		2.178	
Shear Wall	upper	2.154	2.430	2.581
	lower	1.300	1.024	0.872
	mean		1.727	
Shortening by deterministic analysis	C1		2.182	
	C2		2.191	
	C3		2.187	
	Shear Wall		1.735	

In case of C2 column, upper values are 2.574mm, 2.830mm, 2.971mm and lower values are 1.781mm, 1.525mm, 1.384mm, respectively, for three different confidence intervals. The change of axial shortenings for C2 column gives the same trend of shortening developments for C1 column.

The axial shortening of C3 column represents a maximum value among columns whereas upper values are 2.678mm, 3.001mm, 3.179mm and lower values are 1.677mm, 1.354mm, 1.176mm, respectively, for each confidence intervals.

The axial shortening of the interior shear wall is smaller than that of exterior columns, whereas for each confidence intervals upper values are 2.154mm, 2.430mm, 2.581mm compared with the value of 1.735mm calculated by deterministic analysis.

In the probabilistic analysis, the column shortening is predicted considering material uncertainty. Therefore, at the early design and construction stages, the variations of unexpected shortenings can be calculated for each confidence intervals and it is possible to apply to recalculation of shortenings and compensation values.

3. Experimental comparisons

3-1 Instrumentation for Field measurement

Vibrating wire strain gauge was used for strain monitoring of T tall concrete building. Strains are measured using the vibrating wire principle. A length of steel wire is tensioned between two end blocks that are embedded directly in concrete. This device has the advantages suitable for long term monitoring of column shortening: i.e. long term stability, maximum resistance to the effects of water, and a frequency output suitable for transmission over very long cables. Fig 7 shows a vibrating wire strain gauge installed between rebars.

Fig.7. Vibrating wire strain gauge installed between rebars

The measured strains considering temperature corrections are calculated by equation (1). Here, the coefficient of expansion of steel is 12.2 $\mu\varepsilon / {}^{o}C$ whereas the coefficient of expansion of concrete is approximately 10.4 $\mu\varepsilon / {}^{o}C$.

$$\mu\varepsilon_{LOAD} = (R_1 - R_0) + (T_1 - T_0) \times (CF_1 - CF_2) \quad (1)$$

Here

T_1, T_0 = the temperatures(℃)

CF_1 = the coefficient of expansion of steel

CF_2 = the coefficient of expansion of concrete

R_1, R_0 = the vibrating wire gauge readings

For reading out the guage values, is used GeoKon GK-403 ReadOut Box, that can apply calibration factors to convert readings to engineering units and also can read out the thermistor temperature directly in degrees. The data readings interval of the installed sensors is everyday until first 4 weeks, weekly until 6 months and monthly after 6 months. In this study, the measured data (Daewoo, 2002) from August 22, 2000 to August 10, 2001, 353 days, were used for comparisons with calculated shortenings at basement level B2.

3-2 Comparisons of the measured and predicted strains

The measured column shortenings and the deterministic predicted shortenings can be compared from Fig. 8 and Fig. 11. As can be seen, the results provide the trend of rapid shortening development at the early ages. The early axial shortenings increase rapidly by effect on the amounts of creep and shrinkage that will occur after slab installation. This is

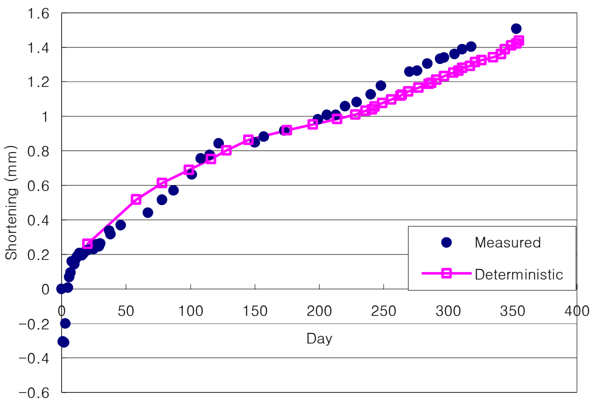

Fig. 8. Comparison of the measured and deterministic predicted shortenings of column C1 at level B2

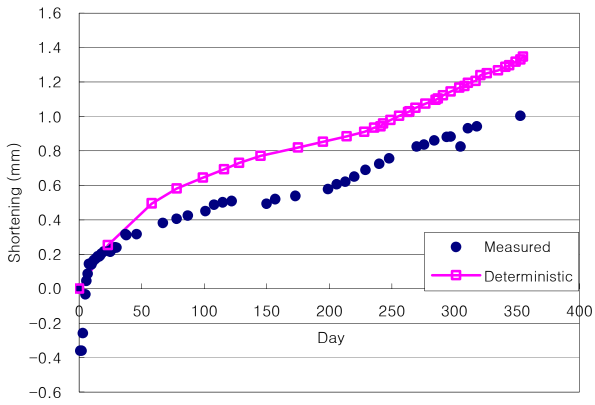

Fig. 9. Comparison of the measured and deterministic predicted shortenings of column C2 at level B2

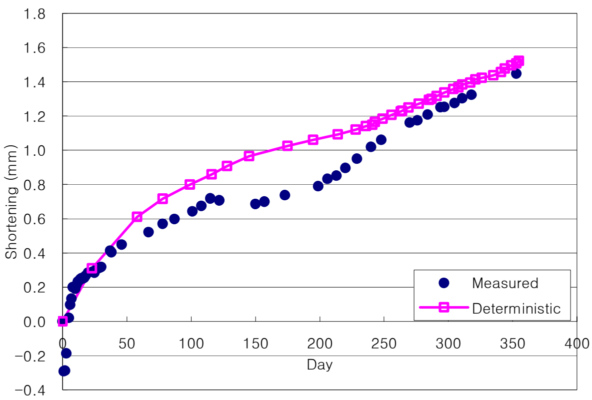

Fig. 10. Comparison of the measured and deterministic predicted shortenings of column C3 at level B2

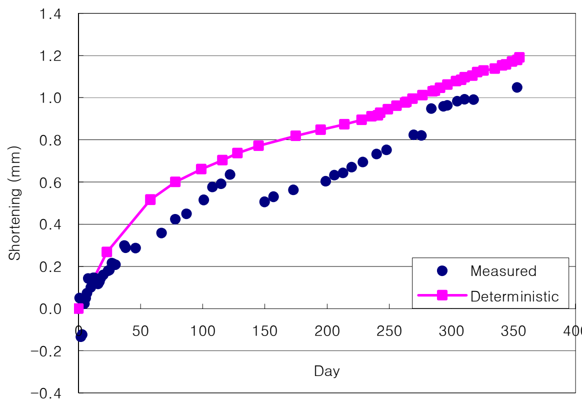

Fig. 11. Comparison of the measured and deterministic predicted shortenings of shear wall at level B2

because the concrete loaded at the early age creeps more and the rate of shrinkage is rapid at early stages.

The change of shortenings of the interior shear wall gives the same trend with comparison of the interior columns. The amount of shortening of the shear wall is smaller than that of columns.

In the case of column C1, Fig. 8 shows the good agreement between the deterministic predicted shortenings and the measured column shortenings. At age of 353 days, the predicted shortening is 1.421mm whereas the measured value of shortening is 1.507mm. The ratio of measured strain to calculated value is 1.05 as listed in Table 5. The good correlation between prediction and measurement was not obtained in the case of C2 column as shown in Fig. 9. The ratio of measured shortening to calculated value is 0.75 from Table 5. The predicted shortening is 1.330mm whereas the measured value of shortening is 1.003mm. If the predicted value is applied to the compensation value without considering measured values, the cambering for compensation is overestimated.

The predicted and measured values of C3 column are presented in Table 5 and the ratio of measured shortening to calculated value is 0.96. The difference value between predicted and measured shortenings is indicated greatly from age of 150 days to 200 days shown in Fig. 10.

In the case of interior shear wall, Fig. 11 shows the adequate agreement between the deterministic predicted and the measured shortenings, except those from age of 150 days and 200 days. The ratio of measured shortening to calculated value is 0.89.

Table 5. The measured and predicted shortenings at level B2

No	Predicted	Measured	Measured / Predicted
Column 1	1.421mm	1.507mm	1.05
Column 2	1.330mm	1.003mm	0.75
Column 3	1.506mm	1.446mm	0.96
Shear Wall	1.178mm	1.047mm	0.89

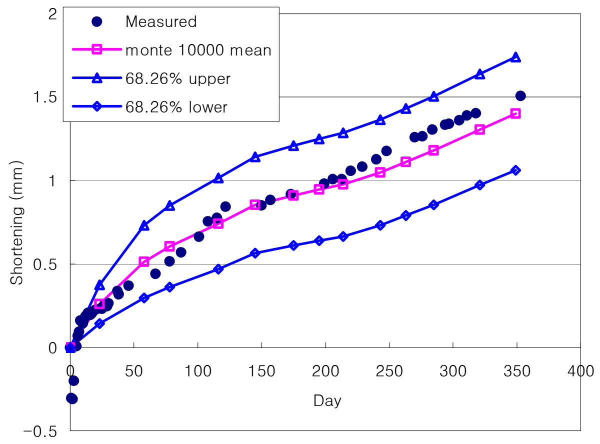

Fig. 12. Comparison of the measured and probabilistic predicted shortenings of column C1 at level

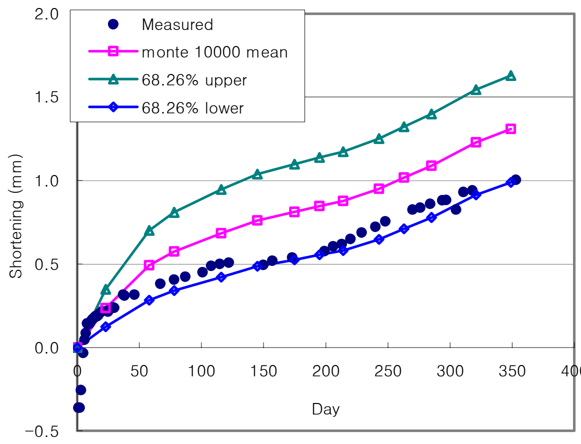

Fig. 13. Comparison of the measured and probabilistic predicted shortenings of column C2 at level

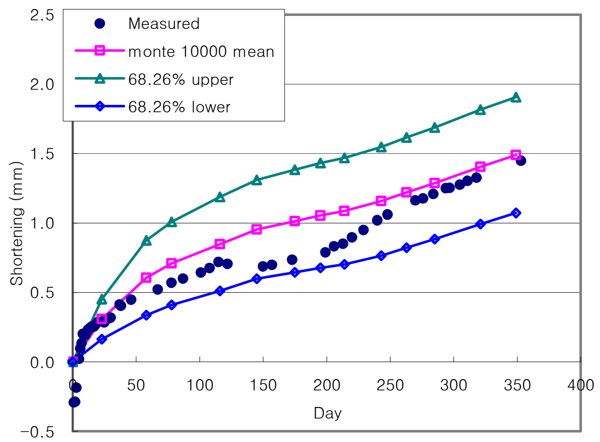

Fig. 14. Comparison of the measured and probabilistic predicted shortenings of column C3 at level

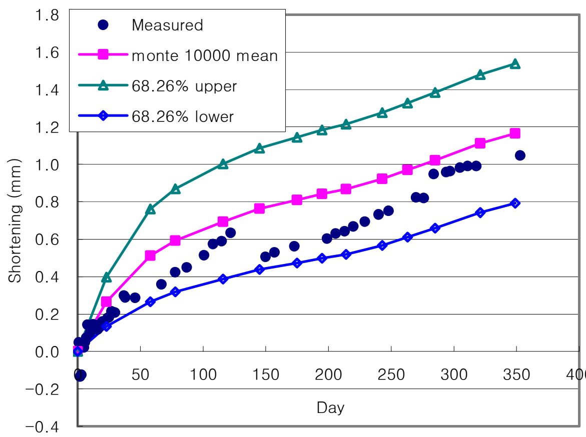

Fig. 15. Comparison of the measured and probabilistic predicted shortenings of shear wall at level

The measured column shortenings and the probabilistic predicted shortenings can be compared from Fig. 12 and Fig. 15.

As shown in Fig. 12, C1 column shows the good agreement between the mean values of probabilistic predicted shortenings and the measured column until age of 200 days. After age of 200 days, the measured values are fell within a range $\mu + \sigma$, the upper values of confidence level 68.26%.

In the case of C2 column, the good agreement between measured values and the lower values of confidence level 68.26% is obtained as shown in Fig. 13. The measured value is 1.003mm whereas the lower value of confidence level 68.26% is 0.988mm at age of 353 days. Hence the difference value between two shortenings yields 1% error.

The measured values of column C3 and interior shear wall are fell within a range $\mu - \sigma$, the lower values of confidence level 68.26% calculated by probabilistic analysis.

4. Conclusions

In this study, the probabilistic column shortenings of 41-story T building recently completed are predicted using Monte Carlo simulation. The probabilistic column shortenings considering confidence levels are compared with the actual column shortenings by field measurement. The results in this research are as follows:

1. The actual column shortenings of tall concrete building are predicted of probabilistic using Monte Carlo simulation and the predicted values of time-dependent column shortenings can be presented with confidence level.

2. The time-dependent shortenings measured at T building are generally agreed with the predicted shortenings, and the measured value of C2 column of T building is lower than the predicted shortenings, 29%. In the case of compensation for vertical elements of lower stories, the compensation values can be overestimated or underestimated.

3. The time-dependent shortenings measured at T building were generally lower than the predicted shortenings, and the measured values fell within a range μ - σ, confidence level 68.26%. These probabilistic column shortening values can be applied to predict of compensation values of upper stories.

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