

Analytical correction of vertical shortening based on measured data in a RC high-rise building

Eun-seok Song^a and Jae-yo Kim*

Department of Architectural Engineering, KwangWoon University, 01897, Republic of Korea

(Received August 27, 2020, Revised October 10, 2020, Accepted November 6, 2020)

Abstract. In this study, a process is proposed to calculate analytical correction values for the vertical shortening of all columns on all floors in a high-rise building that minimizes the error between the structural analysis predictions and values measured during construction. The weight ratio and the most probable value were accordingly considered based on the properties of the shortening value analyzed at several points in each construction stage and the distance between these measured points and unmeasured points at which the shortening was predicted. The effective range and shortening value normalization were considered using the column grouping concept. These tools were applied to calculate the error ratio between the predicted and measured values on a floor where a measured point exists, and then determine the estimated error ratio and estimated error value for the unmeasured point using this error ratio. At points on a floor where no measured point exists, the estimated error ratio and the estimated error value were calculated by applying the most probable value considering the weight ratio for the nearest floor where measured points exist. In this manner, the error values and estimated error values can be determined at all points in a structure. Then, the analytical correction value, defined as this error or estimated error value, was applied by adding it to the predicted value. Finally, the adequacy of the proposed correction method was verified against measurements by applying the analytical corrections to all unmeasured points based on the points where the measurement exists.

Keywords: high-rise building; column shortening; construction sequence analysis; measurement; analytical correction

1. Introduction

With increasing worldwide demand, many new high-rise buildings are planned or under construction. Serviceability is important in the structural design of such high-rise buildings, as they must be designed to minimize any structural deformation or vibration that may interfere with use. As the height of a building increases, the shortening of its vertical members (such as walls and columns), which is negligible in low-rise buildings, becomes relatively large. Additionally, differential axial shortening between vertical members can degrade the structural and functional performance of a building; thus, shortening is an important consideration during the design of tall concrete or composite structures (Kim *et al.* 2019). Additionally, the shrinkage and creep of concrete are apparent in a high-rise building due to its extremely long construction period and the high stress level in its mass concrete. If these factors are not properly accounted for, critical problems such as excessive deformation, cracking, damage to the façade, and even inclination of the main structure could potentially occur over time (Moragasipitiya *et al.* 2010, Gao *et al.* 2019, Kim *et al.* 2020). Therefore, in order to assess the detrimental effects of vertical member shortening and the

excessive deflection of lateral members on the serviceability of high-rise buildings, it is necessary to predict the long-term column shortening behavior of such buildings considering typical properties including the long construction sequence required (Njomo and Ozay 2014, Lee *et al.* 2017). Furthermore, the differential column shortening should be appropriately predicted, appropriate measures should be taken to mitigate its adverse effects. Differential column shortening is affected by many factors such as the loading conditions, column properties, and construction sequence. In particular, the long-term behavior of concrete, such as creep and shrinkage, adds complexity to the prediction of column shortening in tall reinforced concrete buildings (Kim 2015, B-Jahromi *et al.* 2017). Therefore, in order to avoid problems related to the differential shortening of vertical members, their elastic and inelastic shortening must be accurately predicted and appropriately corrected for (Park 2003, Afshari *et al.* 2017).

Because it is difficult to accurately represent the actual construction process in the construction sequence analysis used to predict the amount of column shortening, there will inevitably be a difference between the results of the structural analysis and actual construction. This has been confirmed by the errors observed between values predicted by structural analysis and values measured during construction. Song and Kim (2019) determined that it is difficult to eliminate this error and accordingly applied an analytical correction to the construction sequence analysis in order to reduce it. However, they focused only on reducing errors between the predictions and measurements by assuming measurements that could occur; the analytical

*Corresponding author, Professor, Ph.D.

E-mail: kimjyo@kw.ac.kr

^aM.Eng. Student

E-mail: thddmstjr2@naver.com

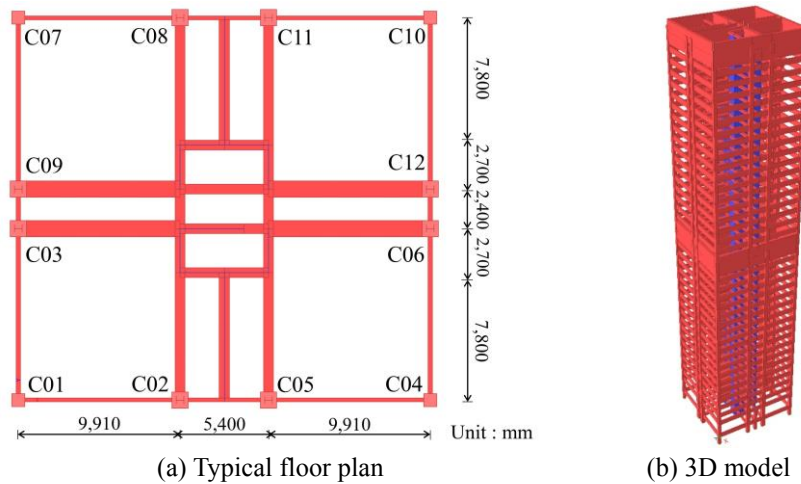


Fig. 1 Analysis model

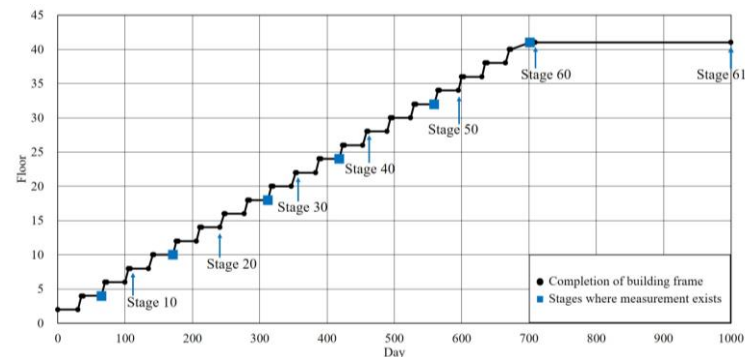


Fig. 2 Construction stages and measurement points by day

correction of the vertical shortening at the unmeasured points in a structure was not considered.

This study therefore proposed a method to calculate reasonable analytical correction values for the vertical shortening at all columns on all floors based on a limited number of measured points. For this, a process was proposed to calculate the correction value of the vertical shortening amount of the column and wall for all points and the adequacy of the proposed method was evaluated against measurements assumed during the construction of an actual high-rise building.

2. Calculation method of analytical correction amount

2.1 Analysis model

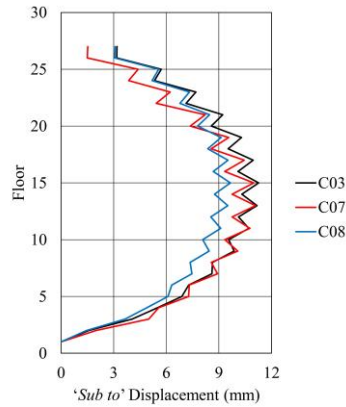
In this study, a 41-story RC structure consisting of RC core walls and RC or SRC columns was applied to develop an analytical correction method for vertical shortening. This high-rise building was 122 m tall with a 3 m high first story, 5 m high second story, and 3 m high remaining stories (Song and Kim 2019). A construction sequence analysis was performed on this building that consisted of 61 stages over 1,000 days. A typical floor plan of the building is shown in Fig. 1, in which columns C01, C04, C07, and C10 are RC columns with an 800 mm×800 mm cross section, and columns C02, C03, C05, C06, C08, C09, C11, and C12

are SRC columns with a 1,000 mm×1,000 mm concrete cross section containing an H 458×417×30×50 steel section. The compressive strength of concrete was 33 MPa, and the PCA material model was applied to model the time-dependent behaviors of concrete (Fintel *et al.* 1987). The amount of vertical column shortening (dz) was analyzed based on the shortening due to subsequent to slab installation shortening (*Sub to displacement*) in each stage of the construction sequence.

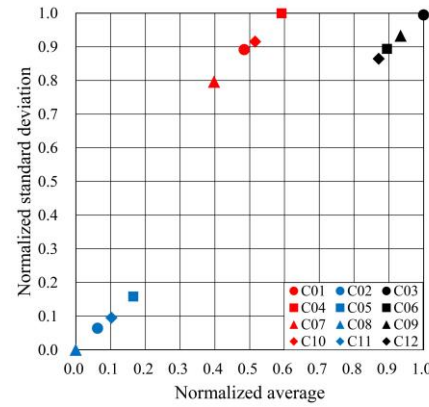
Fig. 2 shows the construction stages and measurement points according to the completion of the building frame. The total construction period of the analysis model was about 700 days, and was composed of a total of 60 stages. In addition, the 61st stage is the last construction stage, and about 300 days have elapsed after the completion of the construction. The analysis model stage has a process in which two floors are constructed per stage. When the frame is completed on the corresponding floor, the slab's self-weight and superimposed dead load are loaded, and live load is loaded when all frames are completed. At the stage of completion of the 4th, 10th, 18th, 24th, 32nd, and 40th floors, it was assumed that measurement exists.

2.2 Summary of calculation process

The purpose of this study was to reduce the error of the vertical shortening between predicted value and measured value using a construction sequence analysis through the



(a) Column shortening in Stage 40



(b) Normalized column shortening in Stage 40

Fig. 3 Normalization of the column shortening amount for a specific construction stage

application of an analytical correction. This analytical correction is calculated based on measured data by using the error between the measured and predicted values at a measured point during a specific stage as follows.

First, a construction sequence analysis is performed to calculate the predicted value of the vertical shortening at the selected points. In order to accommodate strain-based measurements of column shortening, a method of analyzing and correcting the analytically determined shortening value subsequent to slab installation (*Sub to* displacement) is used. Second, in order to apply the concept of column grouping, which shows a similar tendency of shortening, the effective range of the point (selected point) for analytical correction is set. The averages and standard deviations of the shortened values for all columns on all floors are normalized based on the predicted shortening values in the current construction sequence by applying the concept of grouping proposed by Kim (2011). Third, the error ratio at all points is determined through the process of calculating the error ratio of columns and walls at a specific construction sequences suggested in this study. At this stage, the analytical correction value is applied as the product of the error ratio and the predicted value of vertical shortening from the construction sequence analysis. Finally, the analytical correction values are added to the predicted values at all points in the construction sequence where analytical correction values are calculated, and the construction sequence analysis is performed again. The result of the re-performed construction sequence analysis then provides the corrected predicted value of vertical shortening at all points according to the difference between predicted and measured values at points where such data exist.

2.3 Normalization and effective range of vertical shortening

The concepts of normalization and grouping proposed by Kim (2011) were applied in this study to classify columns with a similar shortening tendency together in order to correct their predicted vertical shortening values during construction. A method for setting the effective range using the normalized averages and standard

deviations of the shortening values and calculating the error or estimated error ratios accordingly is therefore proposed.

In order to normalize the vertical shortening, the shortening value for each floor is first obtained through a construction sequence analysis, then the average and standard deviation of the calculated shortening values on each floor for each column line are calculated. The calculated average and standard deviation are then normalized according to

$$m_n = \frac{m - m_{min}}{m_{max} - m_{min}} \quad (1)$$

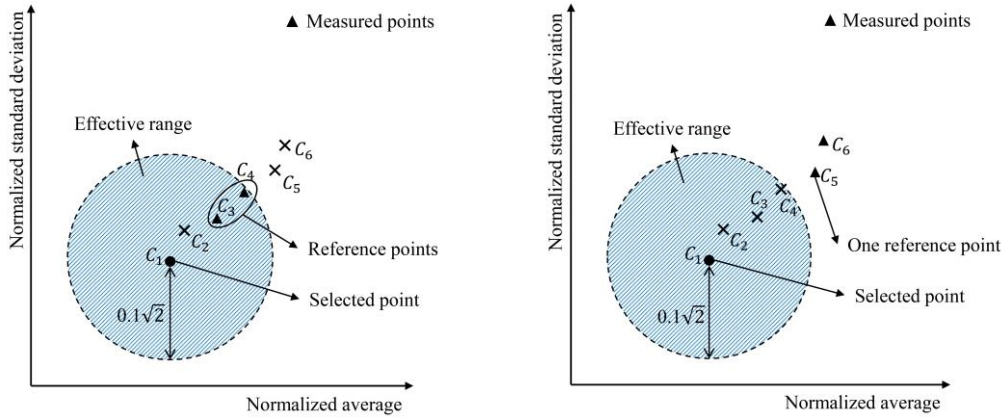
where m_n is the normalized vertical shortening value, m is the shortening value in question, m_{min} is the minimum shortening value, and m_{max} is the maximum shortening value.

The results of Eq. (1) can be represented on a normalization plane consisting of the normalized average on the horizontal axis and the normalized standard deviation on the vertical axis. For the specific construction sequence of the subject building, Fig. 3(a) shows the *Sub to* values of the vertical column shortening for C03, C07, and C08 among the 12 columns in the building plan, and Fig. 3(b) shows the normalization plane for the vertical shortening *Sub to* values of all 12 columns.

In order to calculate the analytical correction value for a selected point, the effective range of the selected point on the normalization plane was set by a circle with a radius of $0.1 \times \sqrt{2}$ (≈ 0.14) from that point. This distance is assumed to be a value corresponding to 10% of the distance between the minimum value (C08) and the maximum value (C03) on the normalization plane in Fig. 3(b). If the distance between the any two points on the normalization plane is small, it can be judged that the shortening values of the columns corresponding to those points are similar. Therefore, the effective range is the standard of the range set to calculate the error ratio or the estimated error ratio on the normalization plane, and it can be adjusted for precise calculation of the analytical correction value.

2.4 Calculation of error ratio using weight ratio and most probable value

In order to reduce the errors between predicted and



(a) When measured points are within the effective range

(b) When measured points are outside of the effective range

Fig. 4 Effective range and reference points in the normalization plane

measured values during the construction sequence analysis, it is necessary to calculate the estimated error ratio and the analytical correction value at selected points where no measurement exists. To calculate the estimated error ratio, the weight ratio and most probable value, commonly used in surveying (Punmia *et al.* 2016), were applied in this study. The weight ratio is an important factor when calculating the most probable value, and represents the relative reliability of each of the measured values. The weight ratio factor depends on the number of observations, distances, and errors. Among these various factors, the weight ratio is inversely proportional to the distance (d) as shown in

$$P_1:P_2:P_3 = \frac{1}{d_1}:\frac{1}{d_2}:\frac{1}{d_3} \text{ (horizontal element) or } \frac{1}{d_a}:\frac{1}{d_b}:\frac{1}{d_c} \text{ (vertical element)} \quad (2)$$

where $P_1:P_2:\dots:P_n$ is the weight ratio and $d_1, d_2 \dots d_a, d_b \dots d_n$ are the distances between the selected point and the measured points (or measured floors) on the same floor (horizontal element) or the same column line (vertical element), respectively.

If the selected point is close to the measured point, the probability that the shortening tendencies at these points will be similar is high, but if the selected point is far from the measured point, the probability that the shortening tendencies at these points will be similar is low. Therefore, the weight ratio was calculated as the inverse of the distance between the selected point and the measured points to calculate the estimated error ratio.

The error value (E) at the measured point is defined as the difference between the predicted value Δ_p and the measured value Δ_m at that point as follows

$$E_{i,j} = \Delta_{p,i,j} - \Delta_{m,i,j} \quad (3)$$

where i is the column number and j is floor number.

The error ratio (e) is the ratio of the error value determined in Eq. (3) to the predicted value at that point, and can be obtained by

$$e_{i,j} = \frac{E_{i,j}}{\Delta_{p,i,j}} \quad (4)$$

The most probable value concept is then applied to estimate the error at a selected point without a measured value. The most probable value is the value with the greatest probability of being closest to the true value. In other words, the most probable value can be said to be the most accurate in terms of probability. Therefore, the estimated error ratio (e_e) at the point without the measured value is calculated as the most probable value by using the error ratio at the point where the error ratio is determined and the weight ratio considering the distance as follows

$$e_{e,i,j} = \frac{\frac{1}{d_1}e_1 + \frac{1}{d_2}e_2 + \dots + \frac{1}{d_n}e_n}{\frac{1}{d_1} + \frac{1}{d_2} + \dots + \frac{1}{d_n}} \quad (5)$$

And the estimated error value (E_e) can then be obtained by applying the estimated error ratio based on the most probable value as follows

$$E_{e,i,j} = \Delta_{p,i,j} \times e_{e,i,j} \quad (6)$$

where e_e is the estimated error ratio (the most probable value) of the analytically determined vertical shortening at the selected point, and $e_1, e_2 \dots e_n$ are the error ratios at measured points.

The analytical correction value of each point is then defined as the error value or estimated error value calculated for that point, and the sign is transformed for application to the predicted value as follows

$$AC_{i,j} = -E_{i,j} \text{ or } -E_{e,i,j} \quad (7)$$

where AC is the analytical correction value of the previously predicted vertical shortening value.

This correction is then applied by adding AC to the value predicted using the construction sequence analysis as follows

$$\text{Corrected } \Delta_{p,i,j} = \Delta_{p,i,j} + AC_{i,j} \quad (8)$$

In summary, the analytical correction value can be determined by using either the measured error value or estimated error value. The error value at a measured point is the difference between the predicted and measured values at that measured point (see Eq. (3)), whereas the estimated error value at an unmeasured selected point can be obtained by multiplying the estimated error ratio based on the weight

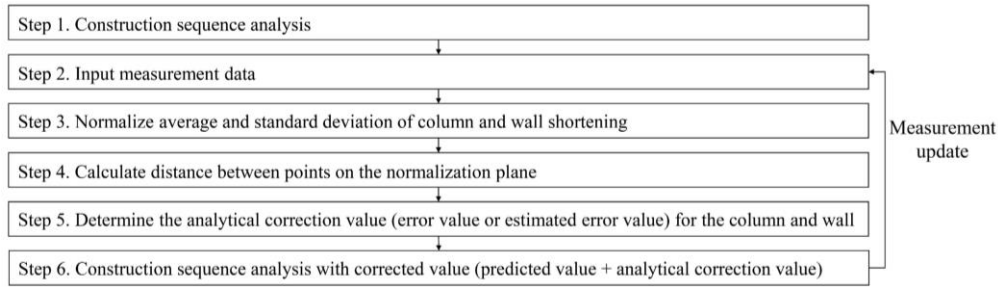


Fig. 5 Process for analytical correction

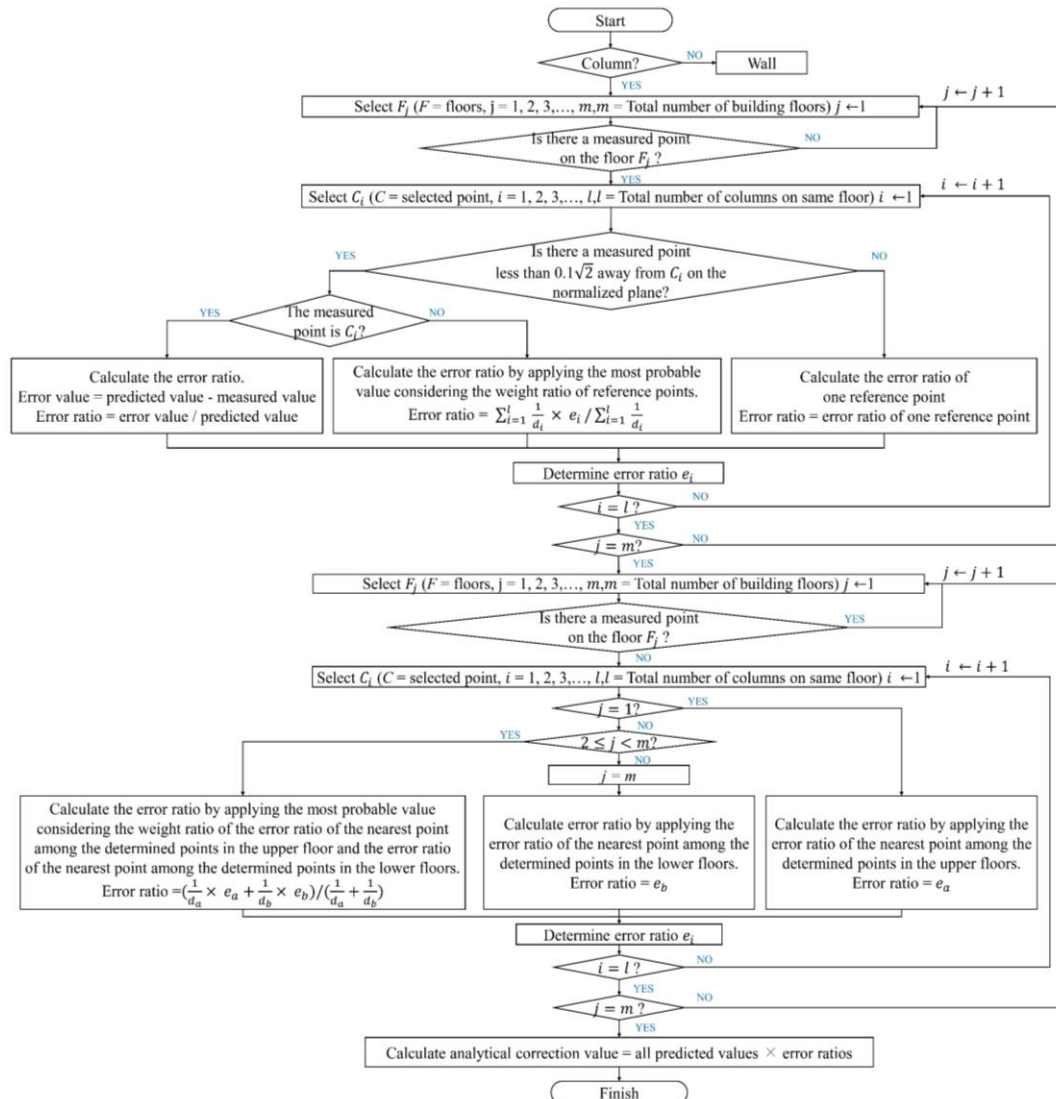


Fig. 6 Process for calculating the column shortening correction

Fig. 4 schematically shows the method used to obtain the estimated error ratio for a selected point when a measured reference point does or does not exist within the effective range. The closer the distance between the any two

points on the normalization plane, the more similar their shortening values. Accordingly, points located within the effective range can be regarded as belonging a group of columns having a similar shortening tendency. Therefore, in Fig. 4(a), all measured points within the effective range are considered reference points, and the estimated error ratio of the selected point is calculated using the error ratio of the most probable value considering the weight ratio of these reference points. However, as shown in Fig. 4(b), if the measured points are out of the effective range, none can be

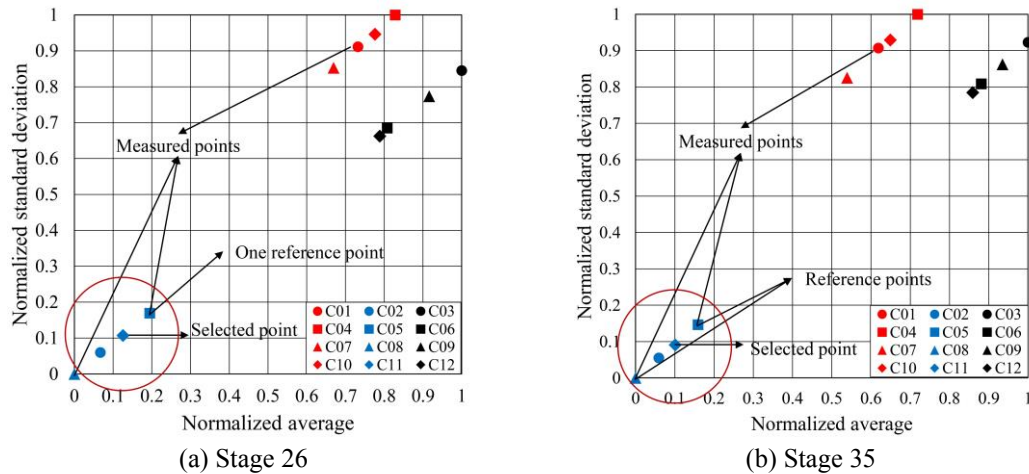


Fig. 7 Effective range and measured points for selection of reference points in two construction stages

classified into the same group as the selected point. Therefore, the measured point that is the least distance from the selected point on the normalization plane is chosen as the reference point, as it can be considered to have the most similar shortening to the selected point of all measured points. The error ratio of this single reference point is then applied as the estimated error ratio of the selected point.

3. Calculation process of analytical correction amount

3.1 Correction process of construction sequence analysis

Fig. 5 shows the process used to apply the analytical correction for the vertical shortening of columns and walls predicted using a construction sequence analysis. In Step 1, the amount of shortening is calculated by a construction sequence analysis. In Step 2, the measurement data is input. In Step 3, the averages and standard deviations of the shortening values in each column line in the construction sequence are obtained and normalized. In Step 4, the distances between the any two points on the normalization plane are calculated. In Step 5, the error ratio and estimated error ratio for the vertical shortening of the columns and walls are determined by following the process depicted in Fig. 6 for the same floor (horizontal element) and the same column line (vertical element). In Step 6, all error ratios have been determined, the analytical correction is performed, and the construction sequence analysis is conducted once again using the corrected values (calculated by multiplying the error ratio by the predicted value for each point then adding the results to the predicted value for that point).

3.2 Process for calculating the analytical correction amount of the column shortening

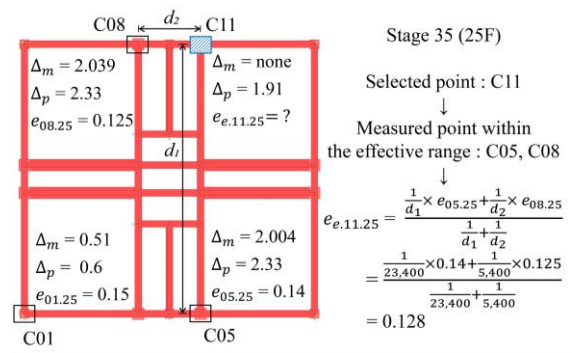
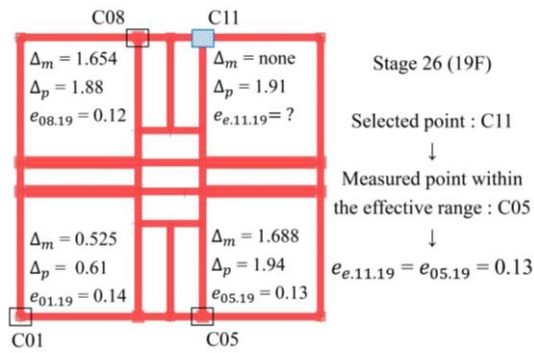
Fig. 6 presents the process for calculating the analytical correction of the column shortening. This is a detailed summary of Step 5 of the analytical correction process in

the construction sequence analysis in Fig. 5. First, one measured point on a column is selected to calculate the error ratio for each selected point on each floor where a measurement exists. Measured points less than or equal to $0.1\sqrt{2}$ from the selected point on the normalization plane are classified as being within the effective range, and measured points greater than $0.1\sqrt{2}$ from the selected point are classified as being out of the effective range. A reference point is defined as the measured point having the highest correlation with the shortening of the selected point. If multiple measured points are within the effective range, the error ratio is calculated according to one of two cases: when the selected point is a measured point, the error ratio is calculated using the difference between the predicted value and the measured value as the error value; when the selected point is not a measured point, the estimated error ratio is calculated by applying the most probable value considering the weight ratio of distance and the error ratios of the reference points within the effective range. If there is only one measured point within the effective range, the estimated error ratio of the selected point is equal to the error ratio of that reference point. If the nearest measured point is out of the effective range, the estimated error ratio of the selected point is the same value as the error ratio of the closest reference point.

After determining the error ratios and estimated error ratios for all measured points on all floors, the process used to determine the estimated error ratios for selected points in the same column lines on floors without measured points is divided into three cases. In the first case, when the selected point is on the first floor, its estimated error ratio is equal to the error ratio of the nearest point among measured floors on the floors above. In the second case, when the selected point is the top floor, its estimated error ratio is equal to the error ratio of the nearest point among the measured floors on the floors below. In the third case, if the selected point is between the second floor and the floor directly below the top floor, its estimated error ratio is equal to the most probable value considering the weight ratio of distance and the error ratios of the nearest two points among the measured floors on the floors above and on the floors below.

Table 1 Calculation of the estimated error value on the top floor in construction stages 26 & 35

Stage 26 - Construction of 19th floor							Stage 35 - Construction of 25th floor						
Column no.	Δ_p (mm)	Δ_m (mm)	E (mm)	e	e_e	E_e (mm)	Column no.	Δ_p (mm)	Δ_m (mm)	E (mm)	e	e_e	E_e (mm)
C01	0.61	0.525	0.085	0.140	-	-	C01	0.60	0.510	0.090	0.15	-	-
C02	1.90	-	-	-	0.120	0.228	C02	2.33	-	-	-	0.137	0.320
C03	2.23	-	-	-	0.140	0.312	C03	2.37	-	-	-	0.150	0.356
C04	0.62	-	-	-	0.140	0.087	C04	0.60	-	-	-	0.150	0.090
C05	1.94	1.688	0.252	0.13	-	-	C05	2.33	2.004	0.326	0.14	-	-
C06	2.17	-	-	-	0.140	0.304	C06	2.38	-	-	-	0.150	0.357
C07	0.60	-	-	-	0.140	0.084	C07	0.59	-	-	-	0.150	0.089
C08	1.88	1.654	0.226	0.12	-	-	C08	2.33	2.039	0.291	0.125	-	-
C09	2.20	-	-	-	0.140	0.308	C09	2.37	-	-	-	0.150	0.356
C10	0.61	-	-	-	0.140	0.085	C10	0.60	-	-	-	0.150	0.090
C11	1.91	-	-	-	0.130	0.248	C11	2.33	-	-	-	0.128	0.298
C12	2.16	-	-	-	0.140	0.302	C12	2.38	-	-	-	0.150	0.357



(a) When one measured point is within the effective range

(b) When two measured points are within the effective range

Fig. 8 Calculation of analytical correction for selected points on the same floor plane as a measured point

4. Application of analytical correction using measurements

The measurement assumed that the measured values exist on the 5th, 11th, 19th, 25th, 33th, and 41th floors of C01, C05, and C08 in consideration of possible situations. The measured values and measured points are assumed to confirm whether the analytical correction process is performed well. Analytical correction was performed for each floor and the results were compared with those of the initial construction sequence analysis.

Fig. 7 shows the effective range and measured points based on the column shortening values normalized for each stage in the construction sequence. Fig. 7(a) shows the effective range and corresponding reference point used to estimate the error ratio of C11 in Stage 26. Because C05 is the only measured point within the effective range of C11, C05 becomes the reference point for C11, and the estimated error ratio (e_e) of C11 is determined using the error ratio (e) of C05. However, in Fig. 7(b), there are two measured points, C05 and C08, within the effective range of C11 in Stage 35. In this case, both C05 and C08 are used as reference points to determine the estimated error ratio (e_e) of C11.

Table 1 shows the process of calculating the error value (E) and the estimated error value (E_e), used in the analytical correction on the top floors corresponding to stages 26 and 35, when the 19th and 25th floors, respectively, are

constructed. In Stage 26, the measured values of the shortening for some columns (C01, C05, and C08) can be checked on the 5th, 11th, and 19th floors. In Stage 35, the measured values of the shortening for the same columns (C01, C05, and C08) can be checked on the 5th, 11th, 19th, and 25th floors. The error ratio was determined at each measured point on these floors according to Eqs. (3) and (4). At points where no measured value exists, the estimated error ratio was determined using the error ratio of the measured points on the same floor according to Eq. (5). Fig. 8 presents the process of calculating the estimated error ratio (e_e) of column C11 on the top floors corresponding to stages 26 and 35. Because the only measured point existing within the effective range of C11 in Stage 26 is C05 (see Fig. 8(a)), this is the only reference point used to calculate the estimated error ratio. Thus, the error ratio of C05 (0.13) was applied to C11 (see Fig. 8(a)). However, in Stage 35, there are two measured points on C05 and C08 within the effective range of C11 (see Fig. 8(b)). Therefore, an estimated error ratio of 0.128 was calculated using the error ratios of C05 (0.14) and C08 (0.125) to determine the most probable value considering the weight ratio in Eq. (2) (see Fig. 8(b)). By repeating the process shown in Figs. 6-7 and Table 1, the error ratios for Stage 26 were determined for all columns on the 5th, 11th, and 19th floors, and the error ratios for Stage 35 were determined for all columns of the 5th, 11th, 19th, and 25th floors. The estimated error ratios were then calculated for the columns on floors where

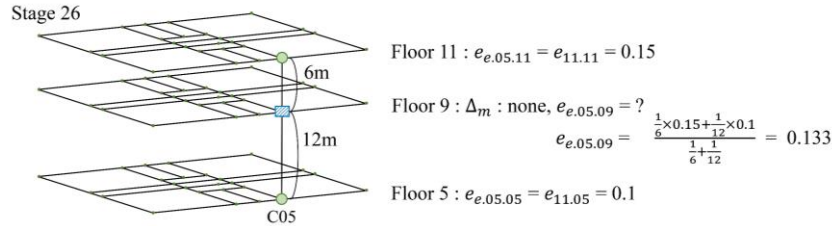


Fig. 9 Calculation process of analytical correction for unmeasured floors

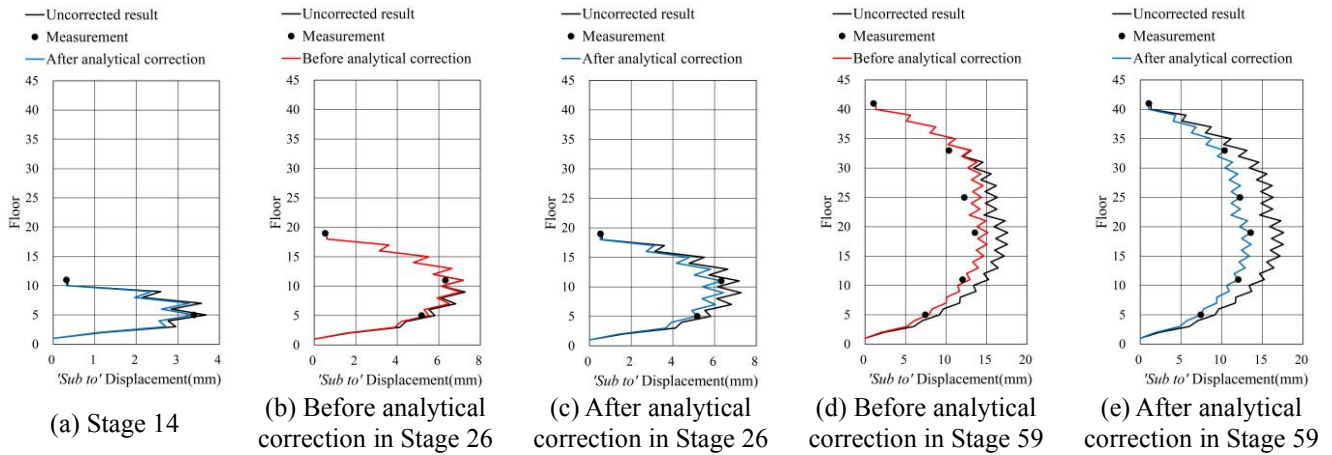


Fig. 10 Predicted column shortening for C01

Table 2 Calculation of error ratios for each floor

Error ratio (e) at Stage 26					Error ratio (e) at Stage 35				
Floor	C02	C05	C08	C11	Floor	C02	C05	C08	C11
11*	0.100	0.150	0.100	0.150	25*	0.137	0.140	0.125	0.128
10	0.098	0.142	0.098	0.142	24	0.138	0.141	0.126	0.129
9	0.097	0.133	0.097	0.133	23	0.139	0.142	0.127	0.129
8	0.095	0.125	0.095	0.125	22	0.140	0.143	0.128	0.130
7	0.093	0.117	0.093	0.117	21	0.141	0.143	0.128	0.131
6	0.092	0.108	0.092	0.108	20	0.141	0.144	0.129	0.132
5*	0.090	0.100	0.090	0.100	19*	0.142	0.145	0.130	0.133

* Measured values

no measured points exist using these error ratios.

Table 2 shows the calculated error ratios for columns C02, C05, C08, and C11 on several of the unmeasured floors in stages 26 and 35. Measured points exist on the 5th and 11th floors in Stage 26 and the 19th and 25th floors in Stage 35, and the error ratios at all points on these floors have already been determined. The estimated error ratios for the points on each floor without measured points were determined by applying the most probable values considering the weight ratio of distance and the error ratios for each column on the nearest measured floors. In Table 2, the estimated error ratios for each point on the 6th to 10th floors of Stage 26 were calculated as the most probable values based on the corresponding error ratios on the 5th and 11th floors. As the distance for the weight ratio is along the same column line in this case, it is defined as the difference in height between floors. As shown in Fig. 9, in Stage 26, the previously determined estimated error ratio for C05 on the 5th floor is 0.1 and on 11th floor is 0.15. Thus, for C05 on the 9th floor, the weight ratio representing

the difference in height between the 5th and 11th floors is applied, and a most probable value of 0.133 is determined as the estimated error ratio. Likewise, in Stage 35, the error ratios have been determined on the 19th and 25th floors; therefore, it is possible to calculate the estimated error ratios on the 20th to 24th floors using these values in a similar fashion (see Table 2).

5. Effects of analytical correction

Fig. 10 shows the analysis results for each construction sequence stage determined by applying the analytical correction based on Section 3 for the assumed construction and measurement situation. The error ratio of C01 was calculated to be 0.09 on the 11th floor and 0.08 on the 5th floor according to the measurement results at Stage 14, when the 11th floor is constructed (see Fig. 10(a)). Next, the error ratios on the floors at which measured points exist for columns were corrected by calculating the analytical correction values following the method shown in Table 1 and Fig. 8. The estimated error ratios for each floor without measured points were then calculated using the method shown in Table 2 and Fig. 9, and the analytical correction was applied accordingly. Fig. 10(b) shows the effect of applying the analytical correction in Stage 14. Without analytical correction, the measured values for the 12th to 19th floors are the same as the predicted values without analytical correction, but on the 1st to 11th floors only the values with the analytical correction applied are close to the measured values. As the building is still under construction at this stage but the analytical correction is applied only once, the effect of the analytical correction is not overt at

this stage, but becomes more pronounced as the upper floors are constructed, once the analytical correction has been performed several times. After the analytical correction was performed the first time at Stage 14, it was performed again at Stage 26, when the 19th floor was constructed. The error ratio of C01 was 0.14 on the 19th floor, 0.12 on the 11th floor, and 0.11 on the 5th floor, and analytical corrections were applied accordingly (see Fig. 10(c)). In this study, five analytical corrections were applied at stages 14, 26, 35, 47, and 59, and the effect of the first four corrections can be clearly observed by comparing the vertical shortening values obtained before the analytical correction was applied in Stage 59 (see Fig. 10(d)). Finally, the final analytical correction was applied in Stage 59, for which Fig. 10(e) indicates a good match between predicted and measured shortening values.

By applying the process proposed in this study, it was possible to calculate a reasonable estimated error ratio for all points where no measured value existed by using the error ratio calculated for several nearby measured points. Additionally, by correcting the intermediate vertical shortening results in several construction sequence stages using the estimated error value, it was possible to improve the precision of the predictions in subsequent stages. In order to obtain a satisfactory correction for vertical shortening, it is recommended that the measurement and correction be made at all points. However, since all floors cannot be measured during actual construction, reasonable correction must be made at the stage corresponding to the point where the measurement exists. The results of this analysis indicate that, based on a limited number of measured points, the analytical correction proposed in this study can be successfully applied to provide vertical shortening predictions similar to the actual vertical shortening behavior of a building during construction.

6. Conclusions

In order to minimize the error between the vertical shortening of columns predicted by a construction sequence analysis and those measured, a process for calculating a reasonable analytical correction value for all points, measured or unmeasured, on all floors and columns (or walls) was proposed in this study. The effective range was defined to classify columns with similar shortening behaviors by analyzing their shortening tendencies. The weight ratio and most probable value concepts were then applied to estimate the error ratio between the analysis and construction results for the unmeasured points.

The error ratio of a measured point was determined as the difference between the predicted value and the measured value at that point, and this error ratio was used to determine the estimated error ratio for points where no measurement exists. In order to calculate the estimated error ratio for an unmeasured point, horizontal expansion was repeated across the same floor to other columns, then vertical expansion along the same columns to unmeasured floors was conducted. At this time, the horizontal or vertical distance between the measured points (or measured floors) and the unmeasured point was applied as weight ratio.

Finally, the error ratios and estimated error ratios were converted into analytical correction values and applied to the construction sequence analysis.

It was confirmed in this study that by performing the proposed analytical correction based on limited measurements during the intermediate stages of the construction sequence analysis, it is possible to improve the precision of the predicted vertical shortening values in subsequent construction sequence stages.

Based on these results, an applicability check and verification of the proposed method should be performed in future research by obtaining actual measured values in various types of buildings. Then, the proposed method can be expanded to study its application to the correction of lateral frame displacement analysis results and the analysis of the optimal interval between analytical corrections.

Acknowledgments

The research described in this paper was financially supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) funded by the Ministry of Land, Infrastructure and Transport (No. 20AUDP-B147683-06).

References

- Afshari, M.J., Kheyroddin, A. and Gholhaki, M. (2017), "Simplified sequential construction analysis of buildings with the new proposed method", *Struct. Eng. Mech.*, **63**(1), 77-88. <https://doi.org/10.12989/sem.2017.63.1.077>.
- B-Jahromi, A., Rotimi, A., Tovi, S., Goodchild, C. and Rizzuto, J. (2017), "Evaluation of the influence of creep and shrinkage determinants on column shortening in mid-rise buildings", *Adv. Concrete Constr.*, **5**(2), 155-171. <https://doi.org/10.12989/acc.2017.5.2.155>.
- Fintel, M., Ghosh, S.K., and Iyengar, H. (1987), *Column Shortening in Tall Structures: Prediction and Compensation*, Portland Cement Association, Skokie, Illinois, USA.
- Gao, F., Zhou, H., Liang, H., Weng, S. and Zhu, H. (2019), "Structural deformation monitoring and numerical simulation of a supertall building during construction stage", *Eng. Struct.*, **209**(15), 110033. <https://doi.org/10.1016/j.engstruct.2019.110033>.
- Kim, C.S., Gong, Y., Zhang, X. and Hwang, H.J. (2020), "Experimental study on long-term behavior of RC columns subjected to sustained eccentric load", *Adv. Concrete Constr.*, **9**(3), 289-299. <https://doi.org/10.12989/acc.2020.9.3.289>.
- Kim, H.S. (2015), "Optimum distribution of additional reinforcement to reduce differential column shortening", *Struct. Des. Tall Spec. Build.*, **24**(10), 724-738. <https://doi.org/10.1002/tal.1208>.
- Kim, H.S., Lee, H.L. and Lim, Y.J. (2019), "Multi-objective optimization of dual-purpose outriggers in tall buildings to reduce lateral displacement and differential axial shortening", *Eng. Struct.*, **189**, 296-308. <https://doi.org/10.1016/j.engstruct.2019.03.098>.
- Kim, Y.M. (2011), "The optimal column grouping technique for the compensation of column shortening", *J. Comput. Struct. Eng. Inst. Korea*, **24**(2), 141-148.
- Lee, Y., Kim, J.K., Seol, H.C., Yang, J.K. and Kim, K.J. (2017), "3D numerical analysis of column shortening and shore safety under construction of high-rise building", *Eng. Struct.*, **150**,

- 242-255. <https://doi.org/10.1016/j.engstruct.2017.07.049>.
- Moragaspiya, P., Thambiratnam, D., Perera, N. and Chan, T. (2010), "A numerical method to quantify differential axial shortening in concrete buildings", *Eng. Struct.*, **32**(8), 2310-2317. <https://doi.org/10.1016/j.engstruct.2010.04.006>.
- Njommo, W.W. and Ozay, G. (2014), "Minimization of differential column shortening and sequential analysis of RC 3D-frames using ANN", *Struct. Eng. Mech.*, **51**(6), 989-1003. <https://doi.org/10.12989/sem.2014.51.6.989>.
- Park, H.S. (2003), "Optimal compensation of differential column shortening in high-rise buildings", *Struct. Des. Tall Spec. Build.*, **12**(1), 49-66. <https://doi.org/10.1002/tal.212>.
- Punmia, B.C., Jain, A.K. and Jain, A.K. (2016), *Surveying Vol. II*, 16th Edition, Laxmi Publications, Daryaganj, Delhi, India.
- Song, E.S. and Kim, J.Y. (2019), "Analytical correction method by comparison of the column shortening measurement-prediction in tall buildings", *J. Comput. Struct. Eng. Inst. Korea*, **32**(6), 391-399. <https://doi.org/10.7734/COSEIK.2019.32.6.391>.