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Prediction of Time-dependent Lateral Movement Induced by Differential Shortening in Tall Buildings Using Construction Stage Analysis

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Abstract

High-rise buildings move during construction due to time-dependent material properties of concrete (creep and shrinkage), construction sequences, and structural shapes. The building movements, including vertical and horizontal displacements, result from the sum of axial and lateral deformation of vertical members at each level. In addition to the vertical shortenings, the lateral movement induced by differential shortening can have adverse effects on the construction tolerance and serviceability of non-structural elements such as elevators and curtain walls. In this study a construction stage analysis method is developed to predict lateral movement induced by shortening, including the effect of creep and shrinkage. The algorithm of construction stage analysis is combined with the FE analysis program. It is then applied to predict lateral movement of a 58-story reinforced concrete building that was constructed in Kuala Lumpur, Malaysia. Gravity induced lateral movement of this building is predicted by the construction stage analysis. A field three-dimensional laser scanning survey is carried out to verify the prediction results, and satisfactory agreement is obtained.

Keywords: Column shortening, Lateral movement, Creep, Shrinkage, High-rise building

1. Introduction

Today's high-rise buildings usually exhibit some extraordinary features such as super-tall height, elevation set-backs, overhangs, or free-form exterior surface, all of which makes the construction difficult, complex, and even unsafe at some construction stages. In addition to the elaborately planned construction sequence, prediction and monitoring of the building's movement during construction and after completion are required for precise and safe construction. The building movement means vertical and horizontal displacement of building which result from the sum of axial and lateral deformation of vertical members at each level. The major factors affecting building movement include loads, geometry, properties of structural members, and sequence of construction.

The building movement mainly affects the building with serviceability problems. The shortened vertical structural elements inevitably transfer some forces to neighboring non-structural elements such as partitions, cladding, piping, and elevator rails, which are not designed to carry vertical load. The effects of differential shortening between adjacent vertical members are pronounced particularly in tall buildings with central core and perimeter columns. As the central core is generally less stressed than the perimeter columns and may be constructed in advance using climbing form, the amount of shortening is much less than that of the perimeter columns. Accumulated differential shortenings cause curvature, which is integrated along the height of the building, and result in a lateral movement (Baker et al., 2008). Lateral displacement induced by lateral loads under service states transiently remain in the structures. However, the differential shortening induced lateral movement permanently remains in the building. This lateral movement is gradually developed during construction and constantly increases after the completion of construction due to time-dependent creep and shrinkage of concrete. These can have adverse effects on the workability and serviceability of non-structural elements such as lift elevators and curtain walls. Therefore, a lateral movement induced by differential shortening as well as vertical shortening should be accurately predicted in high rise building projects.

Most of previous research was focused on the prediction of vertical shortenings. In an earlier study such as PCA Report (Fintel et al., 1986), individual vertical members were analyzed without the restraining actions of horizontal members and lateral movement could not be

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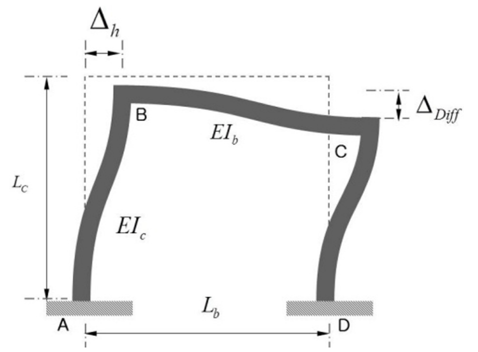


Figure 1. Rigid frame with differential shortening between columns.

considered. Although 2-dimensional frame analysis including time dependent properties of concrete was developed in recent researches (Kim, 2008; Maru et al. 2001; Chiorino et al., 2011), the prediction and monitoring on lateral movement induced by differential shortenings have not been researched.

This research describes a theoretical study of the behavior of the lateral movement induced by differential shortenings and construction stage analysis method including the time dependent effects of creep and shrinkage. The developed analysis method is used to predict the lateral movement of 58 story reinforced concrete building. The time dependent properties of the horizontal deviation of this building are discussed. Finally, the analysis results are verified by field survey results.

2. Time Dependent Lateral Movement Induced by the Differential Shortening

In the rigid frame, the differential shortening between vertical members causes the horizontal members such as slabs and beams to tilt causing additional moment and shear forces due to differential displacement. To find the relations between differential shortening and lateral movement, consider a simple rigid frame, where differential shortening (Δ_{Diff}) is developed as shown in Fig. 1. The differential shortening between vertical members causes an additional moment at horizontal member as shown in Eq. (1).

$$M_B = -\frac{6EI_b}{L_b^2}\Delta_{Diff} \tag{1}$$

According to the condition of the end rotation at vertical member and the principle of moment area theorem (Alexander, 1990), the lateral movement caused by the differential shortening can be written as:

$$\begin{aligned}\Delta_h &= \left(\frac{M_B}{EI_c}\times L_c\times\frac{1}{2}\right)\times\frac{L_c}{3} - \left(\frac{M_A}{EI_c}\times L_c\times\frac{1}{2}\right)\times\frac{2L_c}{3} \\ &= \frac{M_B L_c^2}{6EI_c} = \frac{I_b/L_b^2}{I_c/L_c^2}\Delta_{Diff}\end{aligned} \tag{2}$$

From Eq. 2, it is noted that the differential shortening is the major factor affecting the lateral movement of high-rise building. The differential shortening in tall buildings results from the differences between axial shortenings of adjacent columns and walls. Time-dependent effects such as creep and shrinkage influence axial shortening and differential shortening of column and wall. Therefore, to predict the horizontal deviation precisely, the time-dependent effects should be considered by the construction stage analysis.

3. Analysis Method

3.1 Construction Stage Analysis

The construction stage analysis is a series of nonlinear static analysis where new construction steps are applied to a stressed and deformed structure of the previous step. The proposed analysis method consists of a deformation analysis of individual structural members to evaluate

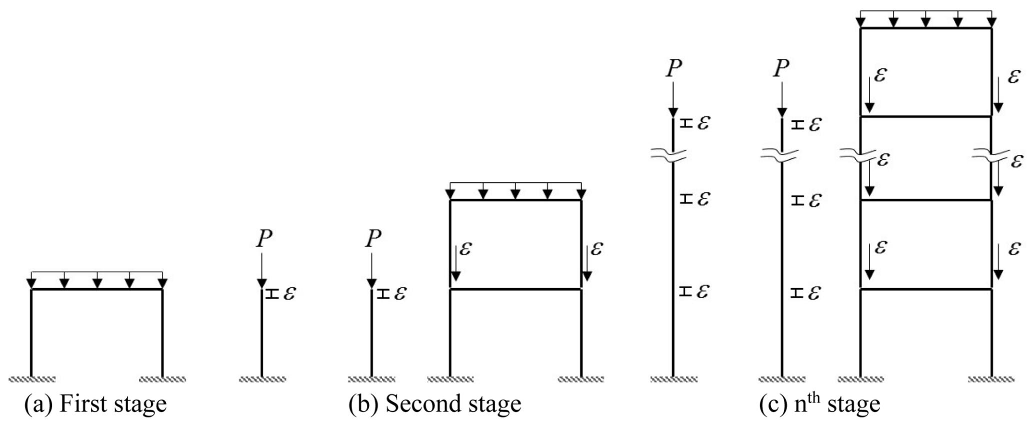


Figure 2. Construction stage analysis

time-dependent shortening and frame analysis for considering the restraining effects of horizontal members. The algorithm of construction stage analysis is to perform an individual structural analysis for every important construction step as concrete casting and installation of curtain wall, and to combine the results with time-dependent deformation to determine the vertical and horizontal deformation. For every construction stage, a two-step analysis is iterated to proceed to next stages as shown in Fig. 2.

At the first step, shrinkage and creep deformation of individual structural members including columns and wall are calculated. The calculations are done for the time interval between construction stages. The column shortenings due to shrinkage and creep are changed to strain loads for the second step analysis. At the first construction stage, calculation of shrinkage and creep is not performed because the elapsed time is equal to zero.

At the second step, structural analysis on deformed structure is carried out to account for newly applied loads and strain loads which are calculated from the first step. Structural restraints of neighboring members on the shrinkage and creep shortening are considered at this analysis. The intermediate location of each node including vertical and horizontal displacement is designated and stored for the next stage. The construction sequence of a building is modelled by assigning birth date or extinction date to each element of the structural model for self-weight and to other additional loading stages. Overall algorithm for staged analysis is shown in Fig. 3. After each iteration for staged analysis is performed (left of Fig. 3), the results are classified into UPTO and SUBTO parts (center) and non-structural construction (right).

3.2. Time dependent material model

While elastic deformations are simply calculated from the applied load and modulus of elasticity, creep and shrinkage deformations are influenced by various factors such as member size and shape, reinforcement ratio, relative humidity, modulus of elasticity, duration of load application, and age of curing at the start of loading. Currently, several predicting models such as ACI 209, CEB-FIP, PCA, B3 and GL2000 are recommended. From these models, ACI209 and PCA models, which can consider the restraint effect of steel reinforcement, are selected to predict the shrinkage and creep deformation.

Estimation of creep strain is carried out by Eq. (3), where various factors including loading time, concrete age, size effect, and relative humidity are considered.

$$\varepsilon_{cr} = \varepsilon_{cr\infty} \cdot CR_t \cdot CR_{la} \cdot CR_{vs} \cdot CR_{RH} \cdot CR_{sr} \quad (3)$$

where $\varepsilon_{cr\infty}$ is the specific creep, CR_t is a factor to allow for progress of creep with time, CR_{la} is a factor of age of concrete at loading, CR_{vs} is a member size factor, CR_{RH} is a relative humidity factor and CR_{sr} is a factor determined by reinforcement.

Estimation of shrinkage is carried out by Eq. (4), where various factors including concrete age, size effect, and relative humidity are considered.

$$\varepsilon_{sh} = \varepsilon_{shu} \cdot SH_t \cdot SH_{vs} \cdot SH_{RH} \cdot SH_{sr} \quad (4)$$

where ε_{shu} is the ultimate shrinkage, SH_t is a factor to

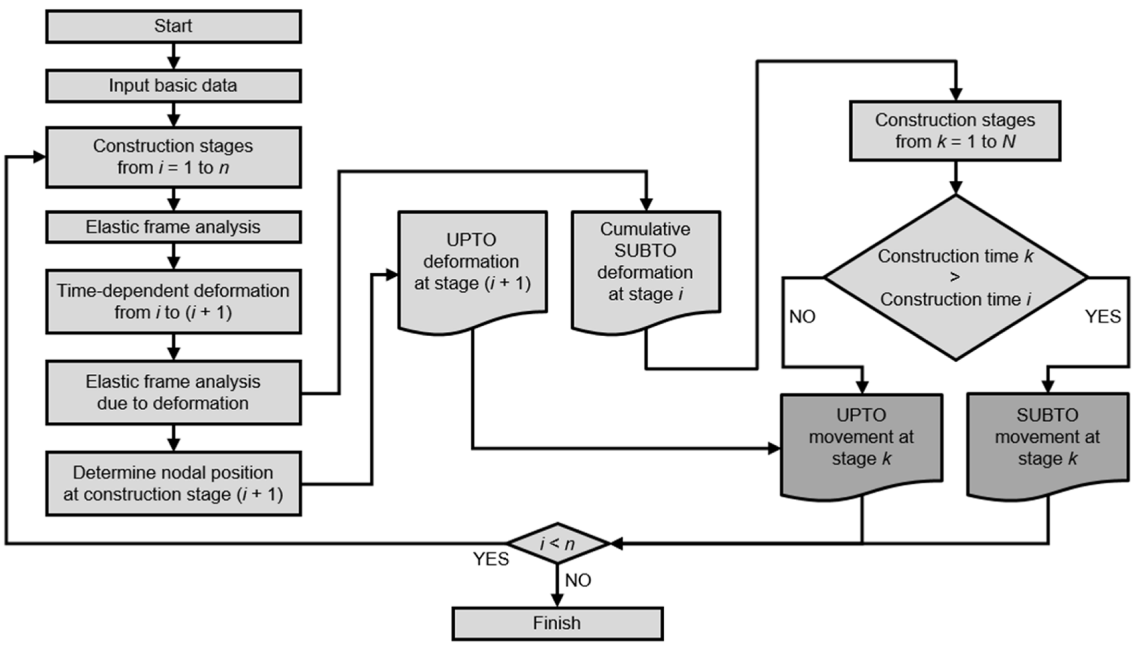
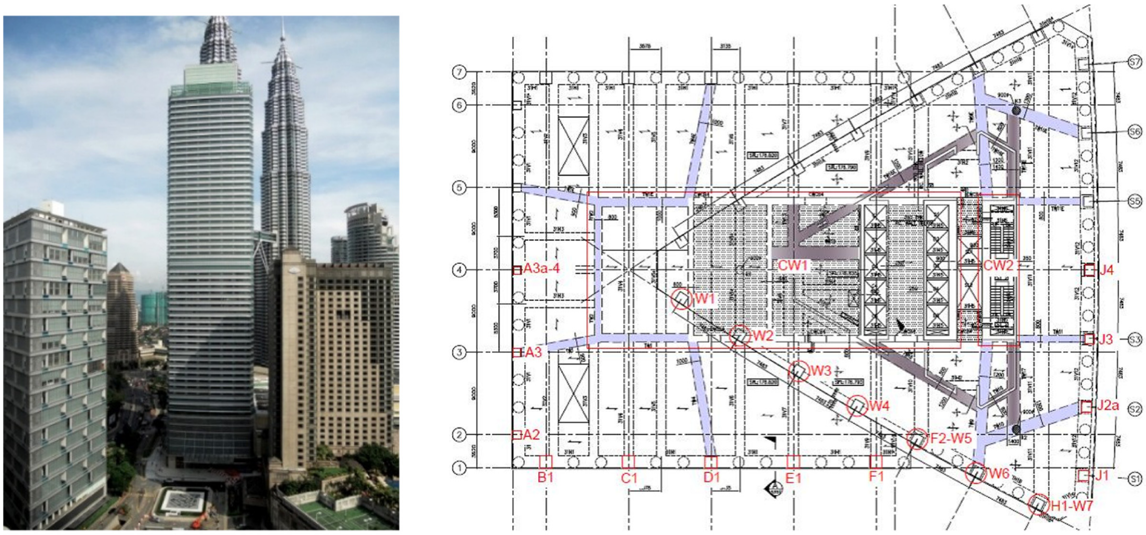


Figure 3. Algorithm of construction stage analysis.



(a) Full view of tower (b) Floor plan

Figure 4. Case study building, KLCC Tower no.3.

allow for the progress of shrinkage with time, SH_{vs} is a member size factor, SH_{RH} is a relative humidity factor, and SH_{sr} is a factor determined by reinforcement.

4. Case Study

4.1. Structural layout

KLCC Tower No. 3 which is located in Kuala Lumpur, Malaysia is the 3rd highest building in the city with a height of 267 m (refer to Fig. 4(a)). This building has 58 floors above ground and four basement levels. The gross area of building is 84,000 m^2. The first six floors above street level contain commercial space. Upper floors of the building contain office space. The structure is symmetrical to horizontal axis with a plan of 63×55 m. As shown in Fig. 4(b), the shape of floor plan is rectangular. From the level 30, it changes from rectangle to triangle. The structural systems are composed of RC cores and columns. Central cores and transfer floors at level 29~31 acting as outrigger are provided to resist lateral loads. Perimeter columns and flat slab are designed to carry vertical loads.

4.2. Construction Staged Analysis

4.2.1. Input data

Based on the structural drawings, the three-dimensional construction staged model is created as shown in Fig. 5. Properties of concrete used in vertical members are summarized in Table 1. Creep and shrinkage values are

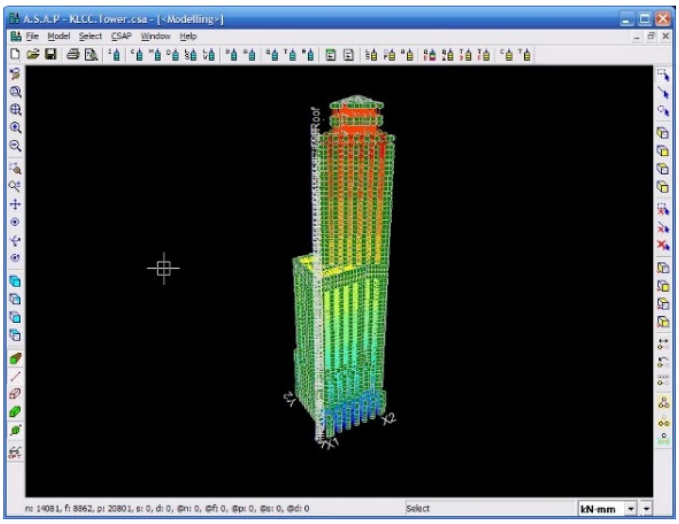


Figure 5. Three dimensional construction stage analysis model of KLCC Tower no.3.

Table 1. Properties of concrete used in vertical members

Compressive strength (f_{cm}, MPa)	Elastic modulus (MPa)	Specific creep (mm/mm/MPa)	Ultimate shrinkage (mm/mm)	Poured levels
68	43,064	23E-06	253E-06	B4 ~ L17
61	40,995	17E-06	216E-06	L18 ~ L32
58	40,076	*	*	L33 ~ L44
53	38,495	29E-06	276E-06	L45 ~ L59

*Test data for 58 MPa concrete are not available and theoretical values are used.

taken from laboratory testing results.

Three categories of loadings in the model, i.e. dead load (DL), superimposed dead load (SDL), and live load are applied in vertical and horizontal members. Reduction factor for live load is chosen to be 0.5, which is sufficient as compared with the minimum value of 0.4. Target time is set to be 7 years after the completion of construction, which is recommended from the particular specification of KLCC Tower project. Creep and shrinkage components of axial shortening are influenced by the environmental condition such as relative humidity. Relative humidity of Kuala Lumpur is set to be 80%. Loading sequence used in the analysis is based on the construction schedule planned by the construction team. The core walls are set up first followed by the construction of perimeter columns and the slab outside of core walls. The slab inside the core walls are intentionally assumed to be cast at the same time as the slab outside of core walls due to lack of information and to avoid complexity. The date of application of SDL is set equivalent to the installation sequence of the curtain walls in the construction schedule and the live load is assumed to be applied on 1,008 days after the start of construction, which is the next date of the completion of construction.

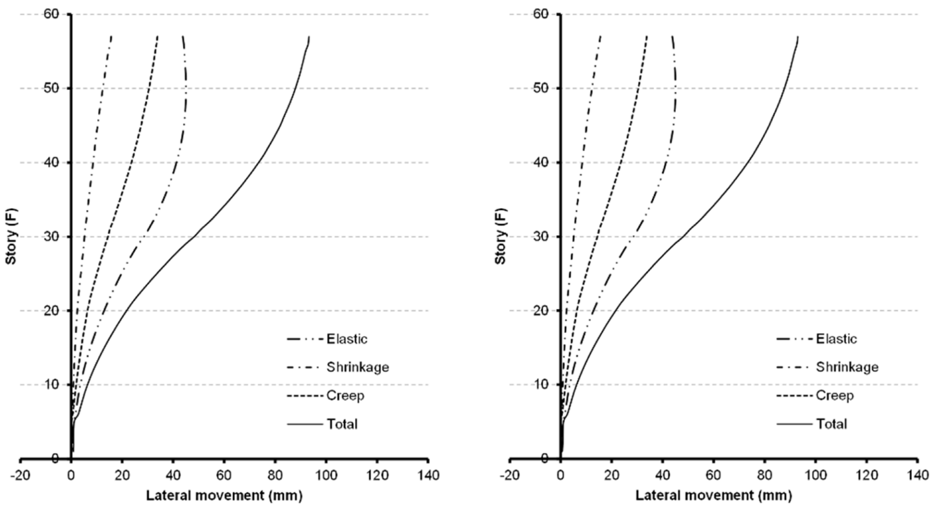
4.2.2 Time dependent material properties

To enhance the accuracy of the prediction values, the material tests for creep and shrinkage were conducted for three months in climate chamber where the temperature and relative humidity could be maintained at levels specified in the ACI 209R-92 (ACI Committee, 2008). 150×300 mm test cylinders were cast at the construction site from concrete being used in the vertical members. Concrete strain gauges were attached on the side surface of the cylinders in the middle and the obtained data were averaged in doing nonlinear regression analysis. Values of specific creep and ultimate shrinkage were derived from nonlinear regression on the results of tests. Laboratory test results used in the construction staged analysis are presented in Table 1.

4.3. Analysis Results

4.3.1. Lateral movement induced by differential shortenings

J1, J3 columns and CW1, CW2 core walls are selected to analyze the horizontal deviation. The cross section of J1 and J3 are varied from 1.8×1.8 m to 0.8×0.3 m along the building height. The thickness of CW1 and CW2 are changed from 1.3 m and 0.7 m to 0.5 and 0.6 m, respectively. The prediction results of lateral movement are pre-



(a) J1 column (b) J3 column

Figure 6. Lateral movements of columns.

sented in Figs. 6 and 7 for columns and walls, respectively. Total lateral movement can be divided into elastic, shrinkage, and creep components. The maximum values of J1 and J3 columns at the top floor are predicted to be 93.2mm and 93.0mm, respectively, which consist of 47% elastic, 17% shrinkage, and 36% creep. The total values including the shrinkage and creep are 2.13 times larger than the elastic values.

The maximum value of wall is larger than that of column due to the shrinkage component. It is considered that wall member, which has relatively small volume-surface ratio, shows the larger shrinkage value. The maximum lateral movements of CW1 and CW2 walls at the top floor are predicted to be 117.6mm and 123.4mm, respectively, which consist of 41% elastic, 24% shrinkage, and 34% creep deformation. The total values including the shrinkage and creep are 2.4 times larger than the elastic values.

4.3.2. UPTO and SUBTO lateral movement

The total lateral movement of a single member at a specific level can be classified in relation with construction schedule by following criteria. A lateral movement up to slab installation (hereafter called as UPTO) at a specific time refers to the movement which has already developed and accumulated up to the time when the building elements under consideration are installed from the start of structure construction. This movement vanishes if a building is constructed in such a way that every element of the building conforms to its designed location at the time of construction. A lateral movement subsequent to slab installation (hereafter called as SUPTO) at a specific time refers to the movement which has developed and accumulated at target time subsequent to the time when the building elements under consideration are installed.

UPTO and SUBTO lateral movements of J1 column and CW2 core wall are presented in Fig. 8. The UPTO lateral movements of column and core wall abruptly increase from the level 30, where framing plan is changed from rectangle to triangle. The eccentricity of mass started from the level 30 effects on the increasing rate of lateral movement below the level 30. The SUBTO values increases to some extent where it decreases again. The maximum SUBTO lateral movements of J1 and CW2 occur at Level 39 and 41, respectively. It is because loads from the upper floors, which contribute to SUBTO value, decrease with increasing stories.

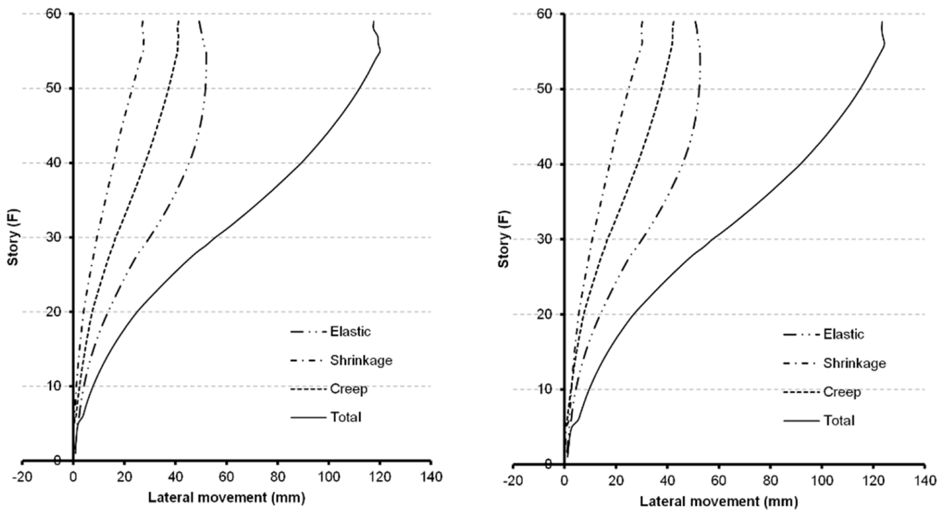
4.3.3. Time history of lateral movement

Fig. 9 shows variation of lateral movement with time. Total value of J1 and CW2 at the top floor are divided into elastic, shrinkage, and creep according to the source of movement. The concrete of structural members at the top floor are poured at 872days after the construction of the lowest vertical members. The whole construction work is finished at 1,007 days. Lateral movements abruptly increase after the slab of Level 30 is casted. It is considered that the mass eccentricity, which starts from Level 30, affects on the UPTO values of top floor. After the construction is finished, the lateral movements continuously develop due to the effect of shrinkage and creep. The percentages of lateral movement after the completion of construction are 14.6% for CW2 and 18.3% for J1 column. Although a large portion of lateral movement occurs during construction, it continuously develops after the completion of construction.

5. Verification

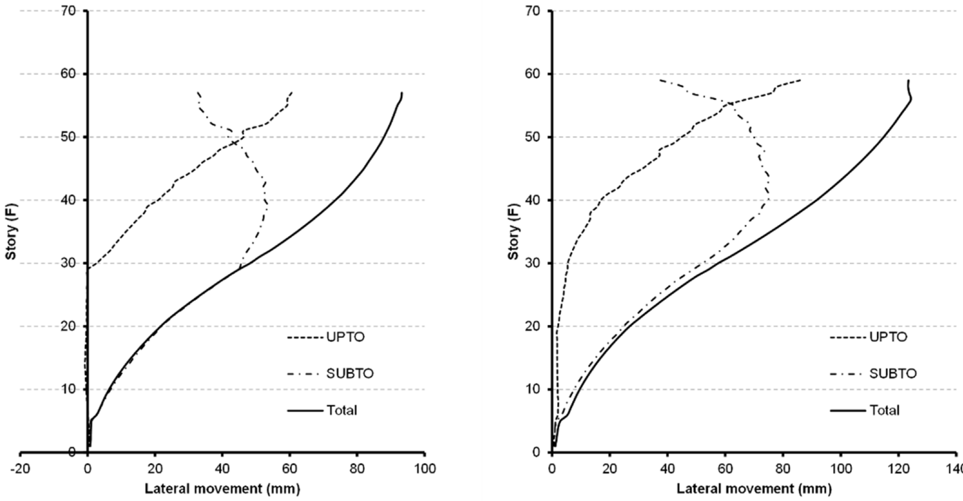
5.1. Field Survey by Three-dimensional Laser Scanner

To monitor building movement during construction,



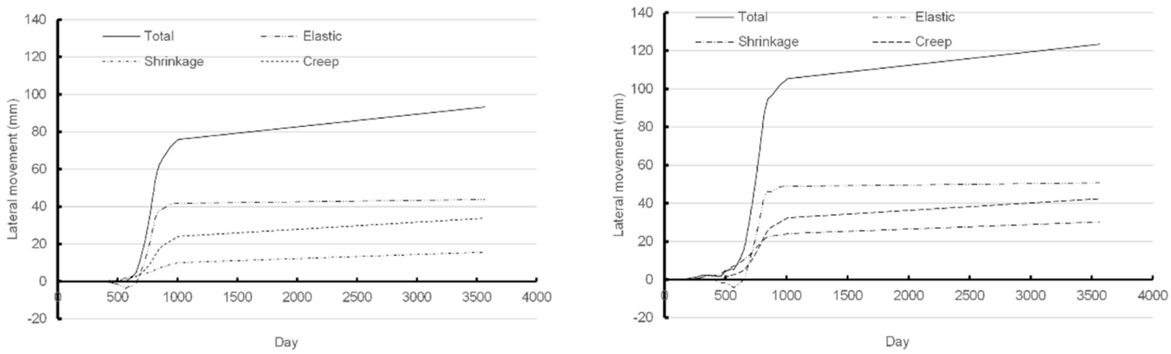
(a) CW1 (b) CW2

Figure 7. Lateral movements of walls



(a) J1 column (b) CW2

Figure 8. UPTO and SUBTO classification of the lateral movement.



(a) J1 column (b) CW2

Figure 9. Time history of the lateral movement.

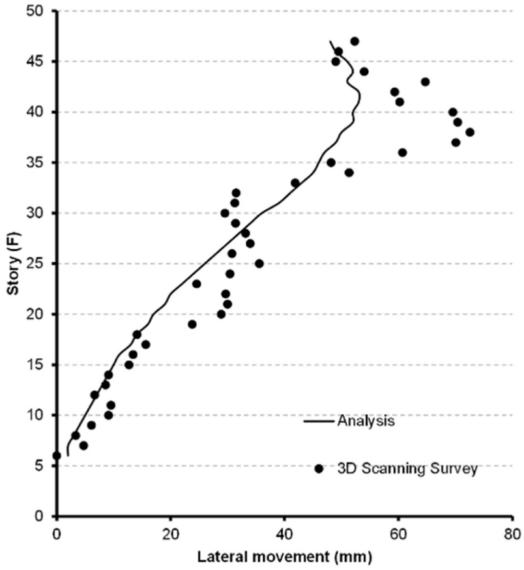
various methods like field measurement by strain sensors (Russell, 1989), survey with using total station and GPS are introduced and used. In addition to these methods, three-dimensional laser scanning is used for the survey of architectural buildings. The light from the laser scanner literally scans the point or surface target and measures the distance by calculating a round trip time of laser or pulse. It can create a point cloud of geometric shape on the surface of subjects. The movements of whole building can be monitored by three-dimensional laser scanning with short working time. This method has been mostly used in low or mid- rise buildings due to the limit of scanning range. A long range laser scanner, which is developed recently and can cover over 1,000m, is applied in this study.

Before installation of elevators at the lift core, three-dimensional laser scanning is performed at CW2, where maximum lateral movement is predicted, to evaluate the verticality of CW2 as shown in Fig. 10. The lift core of CW2 is scanned in the vertical direction using a temporary lift. A middle range scanner, which has the speed of scanning (50,000 pts/sec), 300 m scanning range, and 6 mm tolerance, is used for surveying lower level of building.

5.2. Comparison with field survey

The results of laser scanning survey for CW2 are compared with the analysis results. To square the time of survey with analysis, the predicted lateral movement of CW2 is divided into UPTO and SUBTO based on the time of elevator installation. The verticality of CW2 is evaluated based on scanning results of 9 points. The maximum lateral movement is developed at the level 38 (73 mm). The surveyed lateral movements increase up to the level 38, where maximum value occurs, and steadily decrease again. Compared with predicted movements,

(a) Laser scanning at CW2



(b) Comparison result

Figure 10. Three-dimensional laser scanning and comparison with analysis result.

distribution of surveyed movements shows similar pattern (See Fig. 10). The mean of differences between surveyed and predicted movements is 6 mm, which is not larger than the tolerance of laser scanner. Considering tolerances of construction and surveying instruments, the surveyed results by three-dimensional laser scanning show good agreements with the predicted values.

6. Conclusion

This research described a theoretical study of the behavior of the lateral movement induced by vertical shortenings and construction stage analysis method. The developed analysis method was used to predict the lateral movement of 58 story reinforced concrete building. The time dependent properties of the lateral movements of this building were analyzed and analysis results were verified by field survey method. Based on these studies, the following conclusions are made.

(1) Differential shortenings induced by the eccentricities of a building's mass or stiffness may cause a significant amount of lateral movement, and the time-dependent effects of concrete accelerate the movement.

(2) The lateral movement can be divided into elastic, shrinkage, and creep components. For the building case study, the total lateral movement including the shrinkage and creep was two times larger than the elastic values. Therefore, the lateral movement caused by the time-dependent effects of concrete that occur during the construction stage of tall buildings should be considered in design.

(3) The percentage of lateral movement developed after the completion of construction was in the range of 14 ~18%. It is noted that the long-term effect after the construction should be considered in the prediction of the lateral movement.

(4) Field three-dimensional laser scanning survey was carried out to verify analysis results and satisfactory agreement was obtained. These results show that lateral movement induced by differential shortening can be calculated with a reasonable degree of accuracy by the developed construction stage analysis method. It is also found that three-dimensional laser scanning can be efficiently used in monitoring vertical and horizontal movements of high rise buildings.

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