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MOVEMENT CONTROL OF HIGH-RISE BUILDINGS DURING CONSTRUCTION

Taehun Ha[1], Sungho Lee[1] and Bohwan Oh[2]

[1] Senior Researcher, Daewoo Institute of Construction Technology, Suwon, South Korea
[2] Research Fellow, Daewoo Institute of Construction Technology, Suwon, South Korea
Correspond to taehun.ha@gmail.com

ABSTRACT: High-rise buildings are widely being constructed in the Middle-East, South-East, and East Asia. These buildings are usually willing to stand for the landmark of the region and, therefore, 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 building's movement during construction and after completion are required for precise and safe construction. This is often called the Building Movement Control during construction. This study describes Building Movement Control of the KLCC Tower, a 58-story office building currently being built right next to the famous PETRONAS Twin Towers. The main items of the Building Movement Control for the KLCC Tower are axial shortening and verticality. Preliminary prediction of these items are already carried out by the structural design team but more accurate prediction based on construction stage analysis and combined with time-dependent material testing, field monitoring, and site survey is done by the main contractor. As of September 2010, the Tower is under construction at level 30, where the plan abruptly changes from rectangle to triangle. Findings and troubleshooting until the current construction stage are explained in detail and implementations are suggested for future applications.

Keywords: Building movement, axial shortening, construction stage analysis, material testing, creep, shrinkage, monitoring, survey, measurement

1. INTRODUCTION

High-rise buildings are widely being constructed in the Middle-East, South-East, and East Asia. These buildings are usually willing to stand for the landmark of the region and, therefore, 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 building's movement during construction and after completion are required for precise and safe construction. This is often called the Building Movement Control (BMC) during construction.

Important terms regarding BMC are as follows:

- Axial shortening of a building is defined as the vertical displacement of the building and results from the sum of axial deformation of vertical members at each level. Three major factors affecting axial shortening are loads, geometry, and material properties of the vertical members in the building.
- Target time is usually designated as 10,000 days after the start of the construction. It is noted that, however, different target time will be adopted in the theoretical analysis of building movement whenever it is necessary, e.g. building movement at construction of transfer beam level, etc.
- UPTO movement at a specific time refers to the movement amount 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 amount vanishes if a building is constructed so that every element of the building conforms to its de-signed location at the time of construction.
- SUBTO movement at a specific time refers to the movement amount which has developed and accumulated at target time subsequent to the time when the building elements under consideration are installed. This amount causes the relative movement of adjoining/adjacent building element and, therefore, additional (locked-in) forces on structural members and adverse effects on non-structural elements such as façade and elevators.

This study describes the BMC of the KLCC Tower, a 58-story office building currently being built at the city center of Kuala Lumpur. The main items of the BMC for the KLCC Tower are axial shortening and verticality. These two items are important for this building since its height is over 250m and the mass is eccentrically populated above certain level of the building.

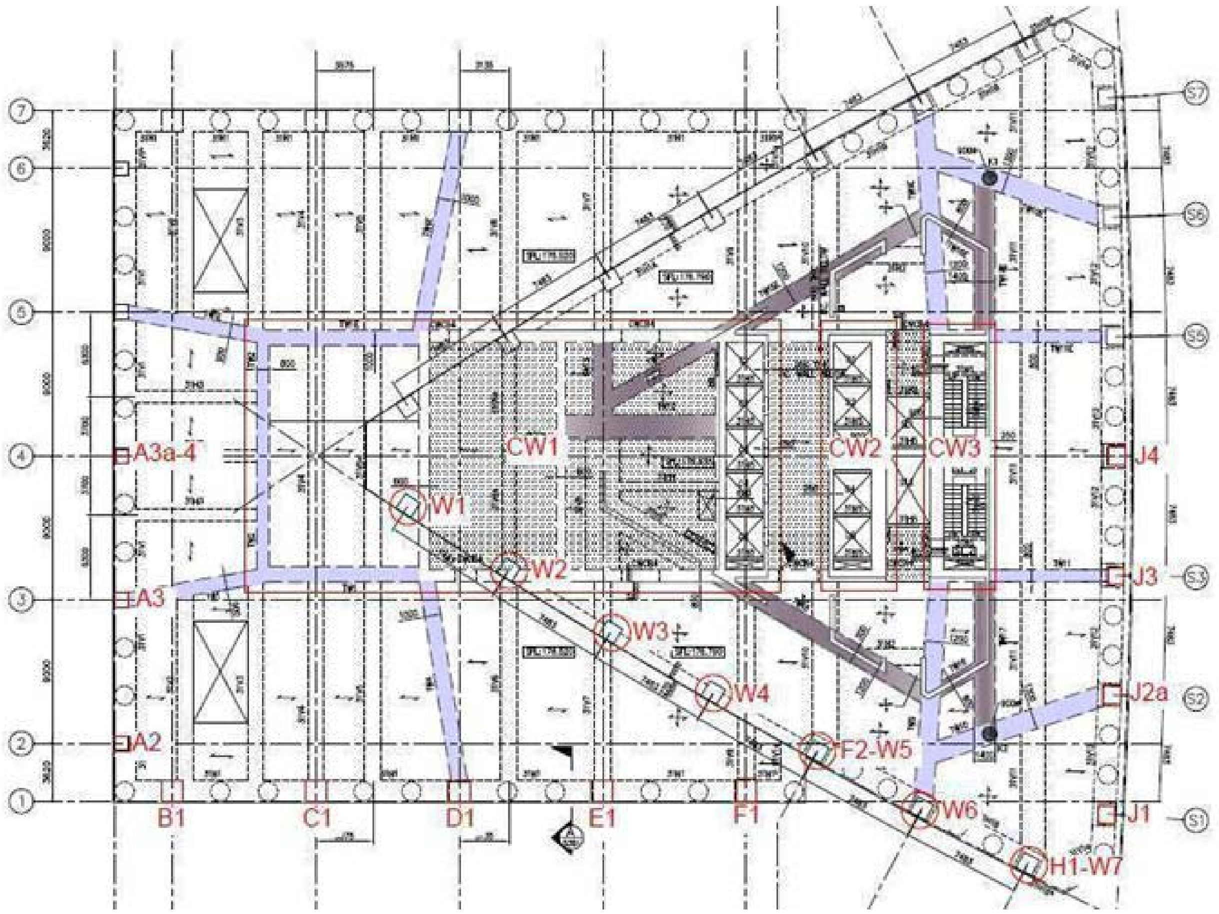


Figure 1. Location of walls and columns under consideration of shortening prediction

2. BASIC DESIGN DATA

2.1 Dimensions and Layouts

- Structural drawings are the basis of the structural layouts, dimensional data of core walls and columns, rebar content, and the grades of concrete, and rebar. Members to be considered for the shortening prediction are selected by the following criteria:
  For symmetry of the Tower's plan and member connectivity, columns located on the lower half of the horizontal center line are considered (See Figure 1);
- Although the difference in the construction sequence breaks the rule of symmetry in terms of shortening calculation, the difference in the construction sequence of each element in the same level is negligible compared with the whole construction sequence along each level and does not take much effect on the shortening values.
- Core walls are put together into three groups (CW1, CW2, and CW3 in Figure 1);
- Transferred columns (A3a and A4a to A4 at Level 6, H1 to W7 at Street Level) are grouped for same behavior.

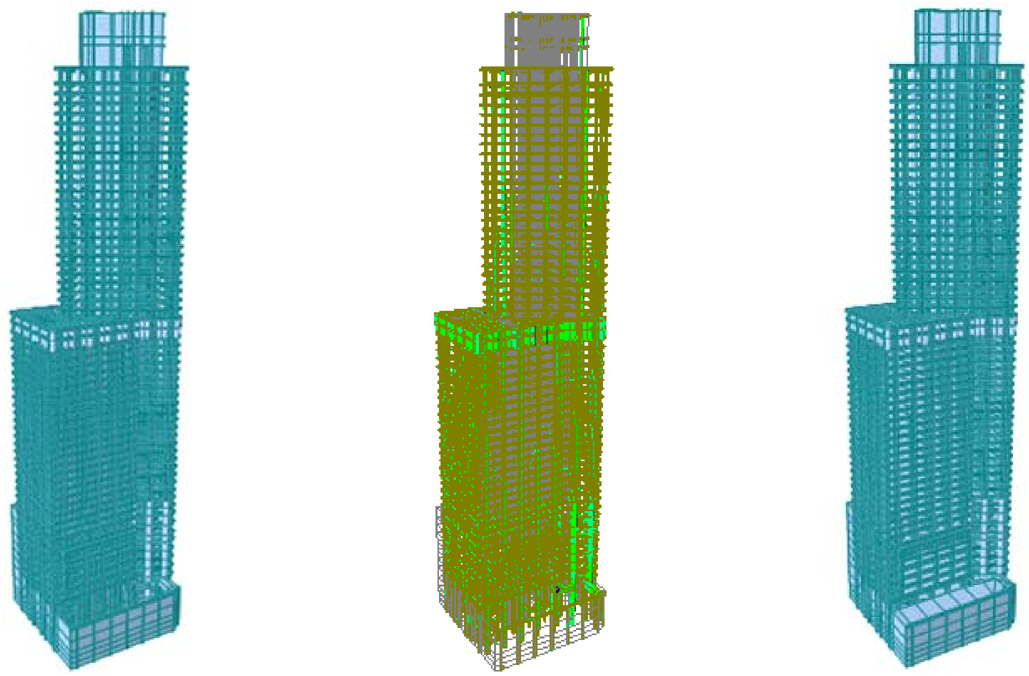
2.2 Materials

Relevant properties of concrete used in the construction are summarized as follows:

- Concrete strength used is mean compressive strength of the cylinder specimens at 28 days, $f_{cm} = f_{ck} + 8$ MPa. The characteristic strength of cylinder speci-

Table 1. Properties of concrete used in vertical members

Strength ($f_{ck,cube}$)	Strength (f_{cm})	Density (pcf)	Specific creep (in/in/psi)	Ultimate shrinkage (in/in)	Poured levels
75	68	150	0.41E-06	750E-06	P4 ~ L17
65	61	150	0.45E-06	750E-06	L18 ~ L32
60	58	150	0.48E-06	750E-06	L33 ~ L44
55	53	150	0.52E-06	750E-06	L45 ~ L59



(a) Structure modeling w/o slab　　(b) Running analysis of model (a)　　(c) Structure modeling w/ slab

Figure 2. Structure modeling of the Tower for building movement control

men fck is drawn from the characteristic strength of cube specimen $f_{ck,cube}$ as suggested in BS EN 1992-1-1:2004;

- Modulus of elasticity of concrete is calculated from strength according to ACI 318;
- Both the specific creep and ultimate shrinkage values are taken from PCA report (Fintel 1986);
- Density of concrete is used for evaluating the dead load of columns;
- Modulus of elasticity of rebar is set to 29,000 ksi and is used for evaluating the transformed area of member cross section and the residual creep and shrinkage strain of reinforced concrete;

Updated values for modulus of elasticity, specific creep and ultimate shrinkage of concrete shall be available when the material testing is complete for each grade.

2.3 Loading

All the design loadings on vertical members are extracted by manipulating 3-dimensional structural model of the Tower using MIDAS GEN as shown in Figure 2. In addition to the existing three categories of loadings in the model, i.e. dead load (DL), superimposed dead load (SDL) and live load (LL), DL is further classified into vertical and horizontal members. Reduction factor for LL is chosen to be 0.5, which is sufficient as compared with the minimum 0.4 for high-rise office building such as the Tower. For discontinued members at transfer levels (L29 ~ L30), such as A2, A3, A3a-4, B1 to F1, the axial loads on the members from the construction of the upper triangular levels are extracted by isolating relevant 3-dimensional construction stage model segments from the whole model and running analyses.

2.4 Environmental Conditions

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 80%, which is taken from BBC weather report.

2.5 Construction Program

Loading sequence used in the analysis is based on the construction schedule planned by the site 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 868 days after the start of construction, which is the next date of the completion of construction. It is noted that the construction schedule shall be updated at the "construction stage analysis phase" and as often as needed after-wards.

3. BUILDING MOVEMENT PREDICTION METHODOLOGY

The methodology adopted at DAEWOO for the theoretical prediction of axial shortening is com-posed of the following three major steps:

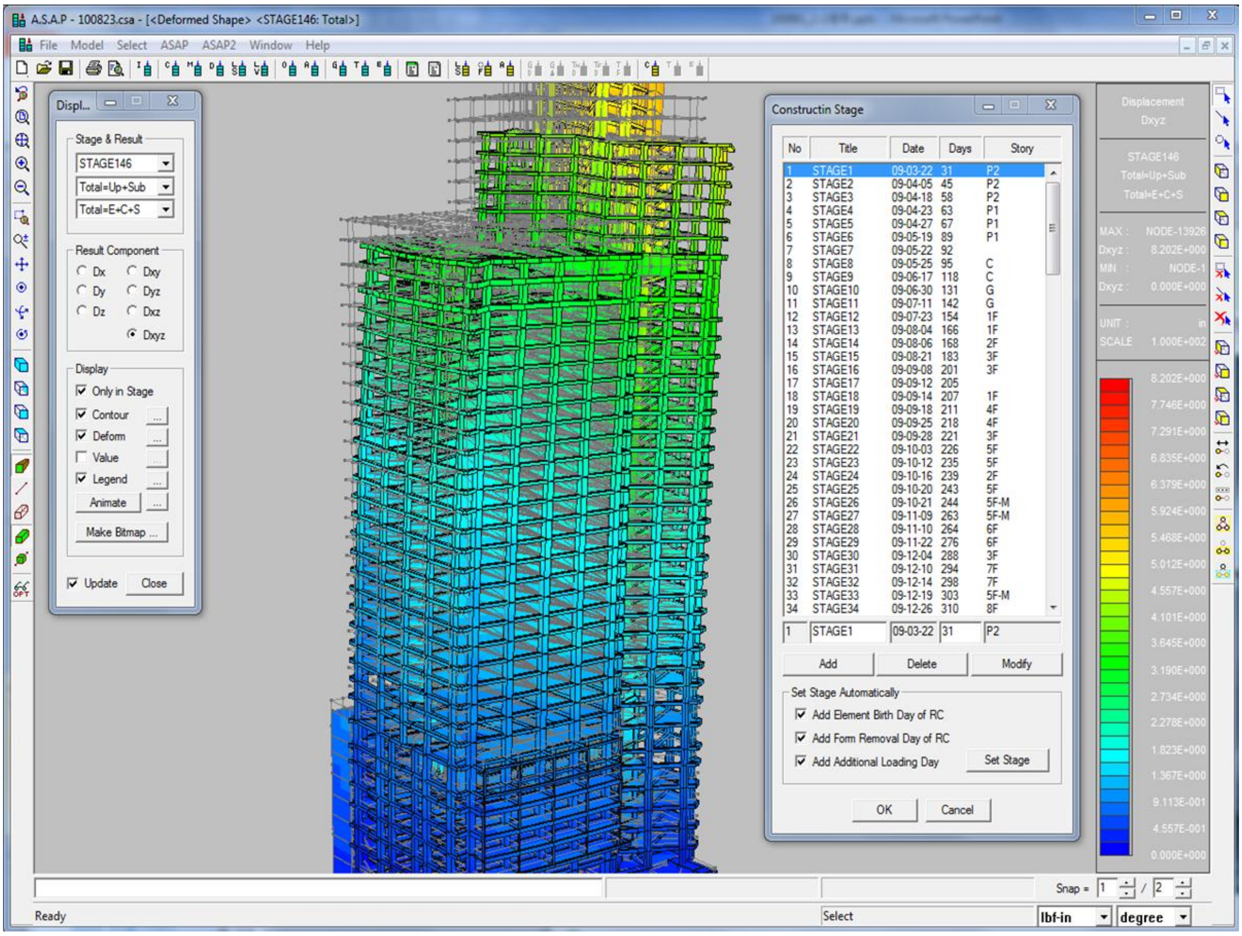


Figure 3. Graphical output presentation for intermediate construction stages

3.1 One-column shortening analysis

In this initial stage analysis, individual vertical members of the Tower is modeled to calculate their respective/relative shortening amount and to suggest corrective actions. This analysis is performed using DAEWOO's in-house programs C-SAP (**C**olumn-**S**hortening **A**nalysis **P**rogram). The applied load on each member is obtained from the analysis results of general-purpose 3-dimensional structural analysis programs such as ETABS and MIDAS. Material and geometric properties are input from code provisions – mostly ACI 209 – and relevant drawings, respectively. This analysis is usually performed before the commencement of the construction of the lowest structure.

3.2 Construction stage analysis

More detailed analysis of axial shortening and other building movements are carried out by ASAP (**A**xial **S**hortening **A**nalysis **P**ackage, see Figure 3) considering the effects of real construction sequence and restraint action of neighboring structural members such as beams and slabs. The main focus of this phase is set to evaluating the building movement induced by the progress of construction, i.e., the increment of gravity load and time-dependent material properties. Building movement in the horizontal direction as well as in the vertical direction can be predicted at any stage of construction. Additional forces developed due to construction in horizontal members such as transfer beams, outriggers, and belt walls/trusses and the effects on other non-structural elements are evaluated.

3.3 Time history analysis

While the one-column shortening analysis and construction stage analysis are carried out for designated target time, in the time history analysis phase, the variations of building movements according to time (with progress of construction) are predicted for necessary cases and compared with the data from field measurement and survey. The results of construction stage analysis phase are updated in this phase as frequently as needed.

4. RESULTS OF CONSTRUCTION STAGE ANALYSIS

4.1 Prediction for Axial Shortening and Lateral Movement

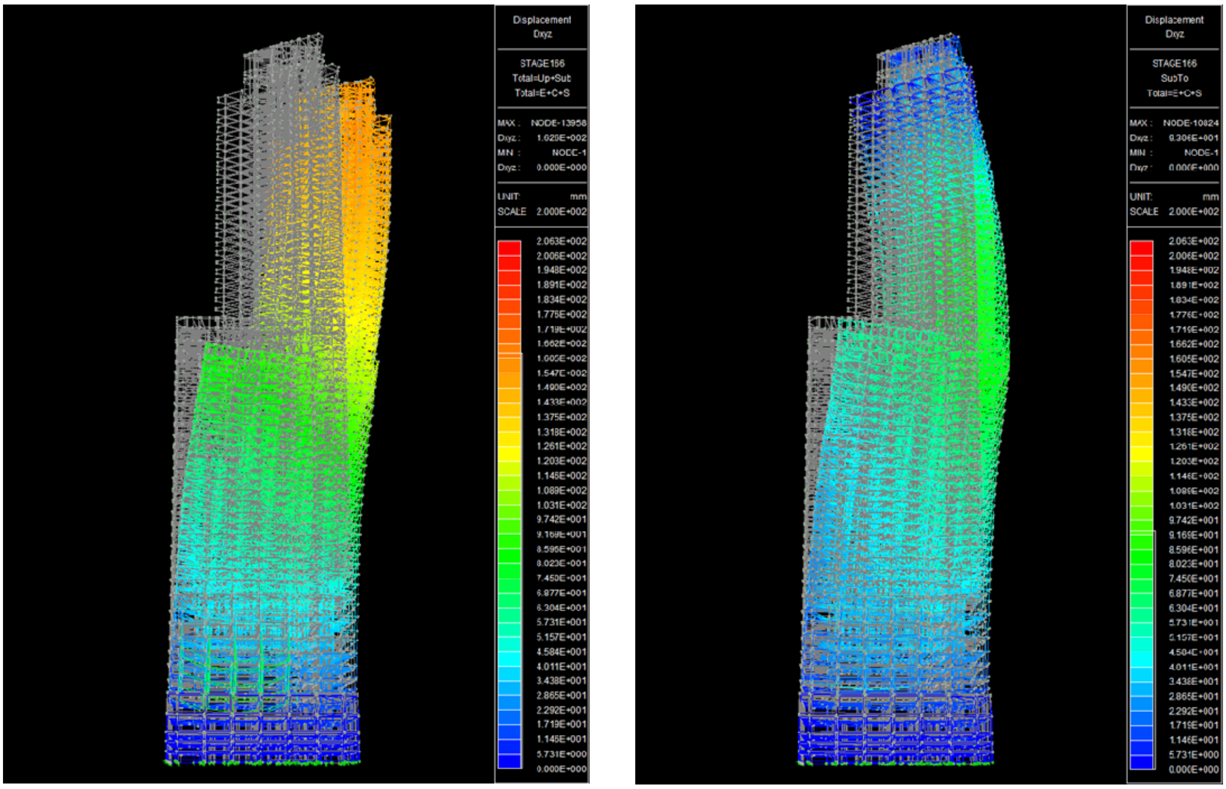


Figure 4. Tower's movement with (right) or without (left) presetting UPTO movement

In construction stage analysis, the movement of the Tower is analyzed in 3-dimensional space and, hence, the lateral movement of the Tower is predicted as well as the revised value of the axial shortening which was already analyzed in one-column analysis. Besides the tabulated analysis result which needs additional manipulation for better presentation of the result, the deformed shape of the Tower itself can be presented in any perspective as shown from Figure 4 due to the OpenGL technology inherent in ASAP. Followings are summary and some conclusions drawn from the analysis result.

- The total shortening decreased in general: the average maximum value changed from 122mm to 115mm. Therefore, the performance target for the overall vertical tolerance and inter-story tolerance are satisfied.
- Due to the eccentricity of the Tower's mass, shortening amounts in triangular region are greater than those in rectangular region but the changes in the shortening amount from one column to the next (neighboring) column is gradual so that the differential shortenings are small. This phenomenon is easily identified in the graphical presentations in Figure 4, which was not possible in one-column analysis.
- Distribution of lateral movement of the Tower is similar to that of axial shortening in lateral direction – the total amount steadily increases in decreasing rate and the SUBTO component increases to some extent level where it decreases again. The maximum lateral movement occurs in CW2 (140mm in total and 107mm in SUBTO) and the movements of columns are somewhat lower.
- Up to the construction of core walls in Level 32 the Tower moves in the direction of the rectangular part and after that the Tower sways to the opposite direction (triangular part). Therefore the SUBTO component of lateral movement is bigger than total lateral movement up to Level 32.

4.2 Compensation for Building Movement

The purpose of the movement prediction of the Tower during construction is to find the problems associated with the movement and to establish appropriate measures including the preset program. Based on the results of analysis in Sec. 4.1 and the initial analysis report, the following recommendations are given for consideration:

- Preset for differential shortening of columns and walls is unnecessary because the magnitude of the differential shortenings are small (maximum values are 29mm for core walls and columns, and 20mm for adjacent columns; the differential movement between adjacent vertical members is not eliminated by preset; and the accompanying locked-in forces and serviceability problems cannot be solved. This suggestion was originally made in the initial analysis report based on one-column analysis and confirmed in this report based on construction stage analysis.
- To facilitate non-structural construction such as façade, partition wall, and elevator, it was proposed

in the initial analysis report that each level of the Tower is to be constructed at the design level, i.e. only UPTO shortening is to be compensated in construction. The preset program is being carried out in the site with the help of survey specialist Andrew Strachan by transferring the datum points in the core walls from floor to floor including modular presets for UPTO shortening and constructing the columns based on the core datum points. The modular preset values (1.5mm up to Level 29 and 2mm for L30 ~ L59) suggested are still valid based on construction stage analysis. In the case of the axial shortening, the movement occurs in only in downward direction and the total movement is simply divided into UPTO and SUBTO components. Therefore, preset for UPTO shortening mitigates the total amount of the movement; For lateral movement, UPTO movement of the Tower monotonically happens in the direction of the triangular part while SUBTO movement changes the direction to the rectangular part for levels above L32. Figure 4 is the 3-dimensional representation of the Tower with or without presetting UPTO movement when the movements in axial and lateral directions are combined.

5. CONCLUSIONS

KLCC Tower may be the first high-rise building in Malaysia which was constructed with the aid of detailed structural analysis for each construction stage. The BMC technology applied to the Tower will not only make it more stable and safe during the construction period, but also make it function as it was originally designed from the moment it is occupied.

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