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# Advanced Construction Stage Analysis of High-rise Building Considering Creep and Shrinkage of Concrete

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## ABSTRACT

A construction stage analysis program was developed and used to predict and to solve the problems during the construction of the IB Tower, a 58-story reinforced concrete building. The building is simulated for its movement and forces for all stages of construction best possible. In addition, the developed program was used to set the preset amount at each level for axial shortening, and to predict the building verticality at the time of structural construction at each level and the remaining lateral movement until target time. Three types of field monitoring for actual movement of the building was also performed: strain measurement of column deformation using vibrating wire gauge, optical survey for lateral movement, and 3-dimensional laser scanning of as-built shape of the building for axial and lateral movement. The results of field monitoring confirmed the predicted value of the building movement.

## 1. INTRODUCTION

Construction stage analysis for reinforced concrete structures is usually applied to bridges, of which the structural stability during construction is as much important as for the finished structure (Grabow 2004). This requirement is equally applicable to high-rise buildings. Long-termed construction period of high-rise building may induce axial shortening of the structure over several hundred millimeters at higher levels of the building during construction. For buildings with mass eccentricity or irregularity, the differential shortening combined with applied moment could also make the building move laterally due to the mechanism similar to bimetallic strip (Ha 2011, Baker 2007).

The amount of axial or lateral movement can be ignored for ordinary buildings but is very important to high-rise buildings, since it causes adverse effects to the construction and performance of elevators (Bast 2007) and façade, and also develop locked-in forces in outriggers or belt trusses (Baker 2006) which are vital to the lateral resistance of the high-rise buildings.

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In this research, a construction stage analysis program was developed to directly relate any construction item with the amount of building movement both in axial and lateral direction. It was then used to predict and to solve the problems during the construction of a 58-story reinforced concrete building.

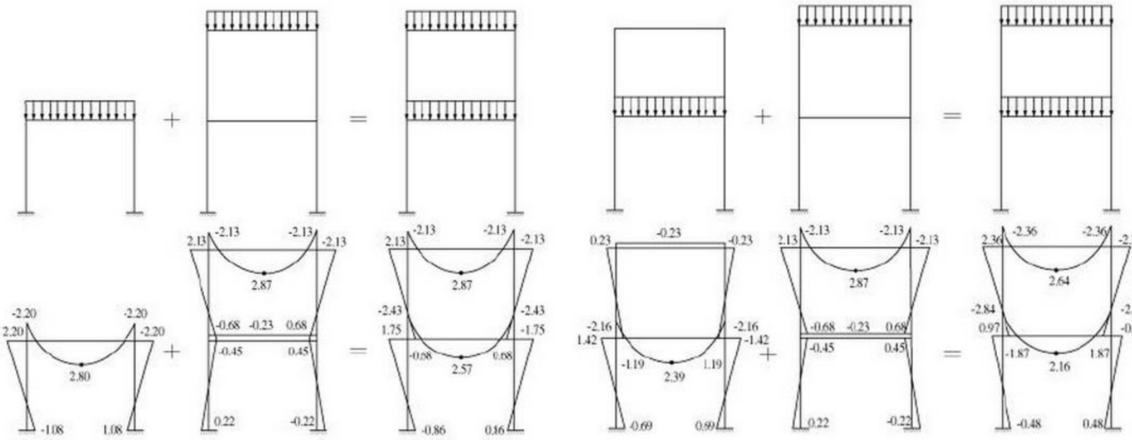
## 2. CONSTRUCTION STAGE ANALYSIS

Ordinary structural analysis and design for buildings are conducted on the completed structures for their safety, stability and serviceability. The structural conditions during construction are not of great concern, since they are usually not more severe than those at occupancy after construction. This might not be true for tall buildings and irregular structures. For these structures, there are more critical situations during construction than in final structural configuration in terms of structural safety and stability as in the case of CCTV Tower (Carroll 2008) during its construction of cantilevered part (Fig. 1). There are two main issues which distinguish construction stage analysis from ordinary structural analysis: consideration of construction sequences and time-dependent properties of concrete such as modulus of elasticity, creep, and shrinkage, which shall be explained in detail in subsequent sections.

### *2.1 Construction Sequences*

Generally, construction stage analysis is performed to simulate crucial stages of a structure under construction and, if necessary, to obtain deformations and forces at each of the stages. Furthermore, it is also used to consider the cumulative effects of the member forces and deformations from one stage to another (Ward 2010). In real world, dead loads from the self-weight of structure develop progressively as a building is constructed story by story and external loads are also applied to partially completed structures. The differences in load application between the real world situation and structural model assumption – full loading at completion – leads to discrepancies in the distribution of internal loads and deformations in structural members as shown in Fig. 2 for 2-story concrete frame (Midas IT 2009). In the case of construction stage analysis, dead loads on a particular floor are typically acting on the structure without the presence of upper floors during the construction (Refer to Fig. 2 (a)). For ordinary structural analysis, the dead loads on a particular floor involve upper floors in its transfer (Refer to Fig. 2 (b)) and, the analysis generally results in less internal forces in the particular floor and more internal forces in the floors above. Not only the structural condition in the particular floor at the time of loading but also that of overall structure at final stage become different. The discrepancies become significant as the number of floors increases.

Fig. 1 Construction of CCTV Tower in Beijing




(a) Construction stage analysis (b) Ordinary structural analysis

Fig. 2 Comparison of analysis results (moment diagrams) for 2-story concrete frame

*2.2 Time-dependent Concrete Properties*

Even if a building is constructed with conventional sequence, the accumulated differences in forces and deformations in structural members between construction stage analysis and ordinary structural analysis get bigger due to creep and shrinkage of concrete during the long-termed construction period of tall building. 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 (Fintel 1986). Input values for concrete properties during construction stage analysis are usually based on provisions from codes of practices and published papers. Examples of codes of practices are report from ACI 318, 363 and 209 committees (2008) and Eurocode 2. B3 (Bazant 1995) and GL2000 (Gardner 2004) models are generally accepted models for the prediction of creep and shrinkage. These two models are different from each other and from the codes of practices in the pattern of development of deformation according to elapsed time. Although these theoretical models for creep and shrinkage give a good guideline at the preliminary stage of construction stage analysis, rigorous tests on concrete used in the actual construction should be performed as early as the mix design of the concrete is established due to the following reasons:

First, laboratory database for the theoretical models is relatively outdated in terms of current progress of technology development in concrete industry. Concrete with high strength and multi-performance has quite different creep and shrinkage properties from ordinary normal strength concrete;

Second, measured database for the theoretical models is mainly from bridges, not from building. The effect of creep and shrinkage on bridge girders is increased deflection, while that on building is regarding the axial shortening of concrete column, which is in compression during its entire life. Since the structural behaviour of bending and compression is different, the creep behaviour under sustained loading should also be discriminated.

The material tests for creep and shrinkage are conducted at least three months long in climate chamber where the temperature and relative humidity can be maintained at levels specified in the codes. Values of specific creep and ultimate shrinkage are derived from nonlinear regression on the results of tests. However, these values are for specimens of standard size and in standard environment, which can be quite different from those in the construction field. Measurement of member deformation in the course of construction is therefore a good practice to compare the predicted values based on material tests with actual deformation (Russell 1989). The measurement is better to be conducted in the early stage of construction for the predicted values to be revised according to the measured values. If preset were scheduled to compensate the structural deformation, it can also be rescheduled based on the revised prediction.

## 3. ADVANCED STAGED ANALYSIS PROGRAM

Construction stage analysis is available nowadays in various commercial structural analysis programs including SAP 2000, MIDAS/GEN, SOFiSTiK, LUSAS, GSA, and Scia Engineer. They were originally developed for the construction stage analysis of bridges but have evolved to be applied to tall building analysis. The construction stage analysis for tall buildings were mainly focused on column shortening analysis beginning in 1970s in US (Fintel 1986). The deformations in columns and walls were calculated isolated from the whole building and the amount of deformations are usually divided into UPTO (up to slab casting) shortening and SUBTO (subsequent to slab casting) shortening based on the construction of respective floors. The famous structural design firms had their in-house program to perform column shortening analysis.

As more tall buildings are constructed worldwide and problems related with building movement are identified, the focus has shifted from structural viewpoint to construction and maintenance ones. This shift came from observation of actual happenings in existing tall buildings. The misalignment of slab level with vertical pipe shaft and dismantling of elevator rails from brackets on elevator core wall are some representative problems due to building movement in the axial direction. When the movement occurs in lateral direction, verticality of the elevator cores is impaired even before the installation of elevators (Bast 2007). According to anonymous documents from actual construction of a famous tall building, the authors have identified design changes in elevator itself to accommodate its installation within the reduced projected area of elevator core. On the other hand, structural problems due to locked-in forces developed from differential movement of adjacent members are hardly recognized except for members with high stiffness such as outriggers and belt walls. Most of the locked-in forces can be assumed to be redistributed in the course of construction. Construction and maintenance problems related with building movement could be prevented when process of building construction is considered. When most of tall buildings are designed and constructed as rectilinear, the problems are caused by the deviation from horizontal or vertical datum line for each construction items such as floor finishing, elevators, façade, other than building structure itself. The construction stage analysis should also focus on the time of construction of these items even if significant loading is not applied at that stage. It can be done by adding additional staged analysis after SUBTO (subsequent to structure construction) deformation is calculated as shown in Fig. 3. This patented feature is still not available in aforementioned commercial programs but first implemented in this research as Advanced Staged Analysis Program (ASAP) developed by authors'.

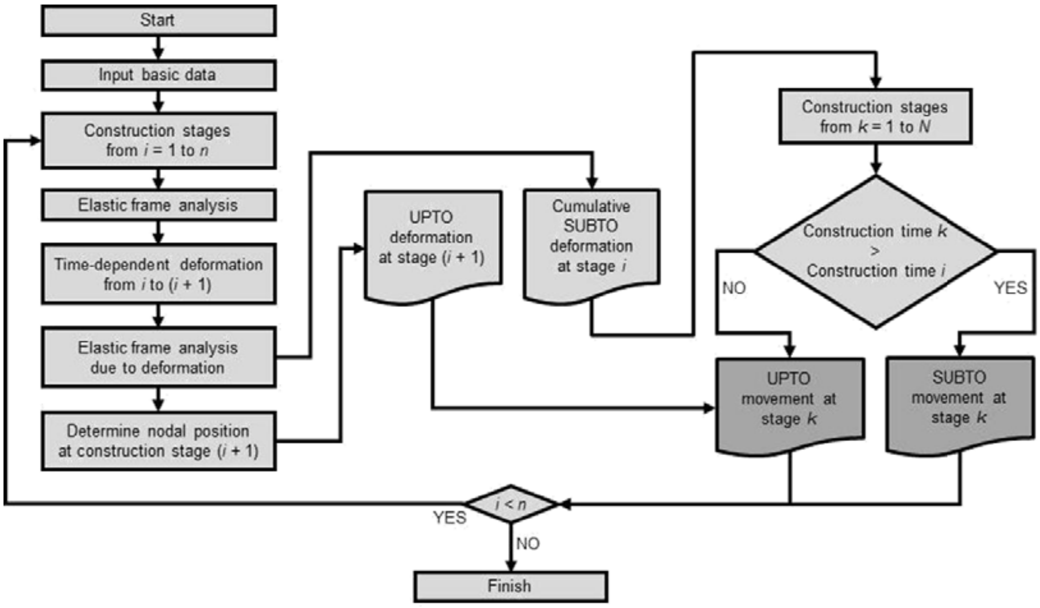



Fig. 3 Program algorithm for Advanced Staged Analysis Program

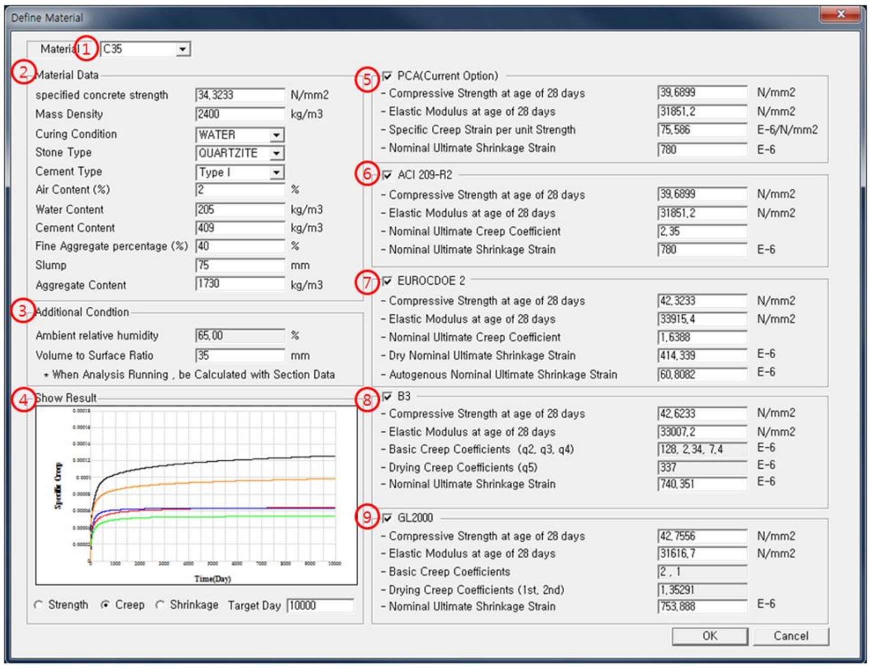



Fig. 4 Input window for time-dependent material properties in ASAP

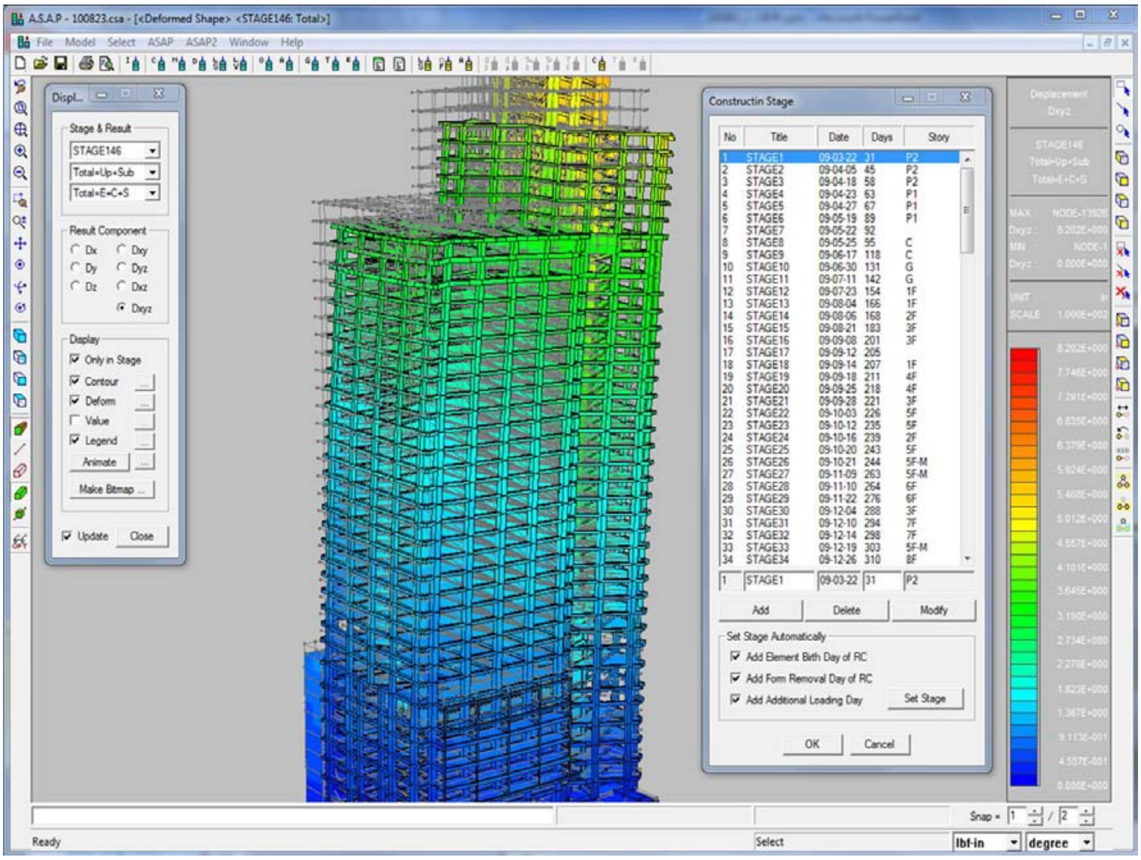



Fig. 5 User interface of ASAP

The program can create or import 3-dimensional structural model of a building for analysis. The user defines the time-dependent material properties like modulus of elasticity, creep, and shrinkage of concrete according to ACI 209, 318, and 363. Other creep and shrinkage models such as Eurocode 2, B3, and GL2000 were recently incorporated into the program for a possibility of better prediction of building movement (See Fig. 4). The amount of reinforcement can also be input to consider the effect of load redistribution between steel and the surrounding concrete for RC and SRC members. 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. In the process of analysis, the model is analyzed at each construction stage for member forces and deformation, and the intermediate results are stored and used as datum values for the next construction stage analysis. As a result, the building is simulated for its movement and forces for all stages of construction best possible. As shown in Fig. 5, the movement of a building can also be exhibited at every construction stages for visual review and inspection.

## 4. APPLICATION

After thoroughly tested in a few pilot projects by simultaneous application with existing analysis method, this program was used for the prediction of movement of

Ilham Baru (IB) Tower, 58-story reinforced concrete building being built in city centre area of Kuala Lumpur, Malaysia (see Fig. 6). Due to the eccentric layout of core walls, greater gravity load is applied toward the front of the Tower, which leads to the overall leaning of the Tower in that direction as shown in Fig. 7. Followings are the summary of predictions and the preset plan resulting from the analysis.

- Overall range of total axial shortening are slightly over 100 mm but the differential values are within 10 mm, which is negligible.
- Regarding the deviation from verticality, the Tower permanently leans forward over 100 mm due to overall differential shortening.
- As a result, all UPTO movements in *x*, *y*, and *z* directions shall be compensated during construction of each floor in collaboration with optical survey team.
- Only SUBTO movement in *x* direction shall be compensated starting from Level 15.


Fig. 6 IB Tower in Kuala Lumpur

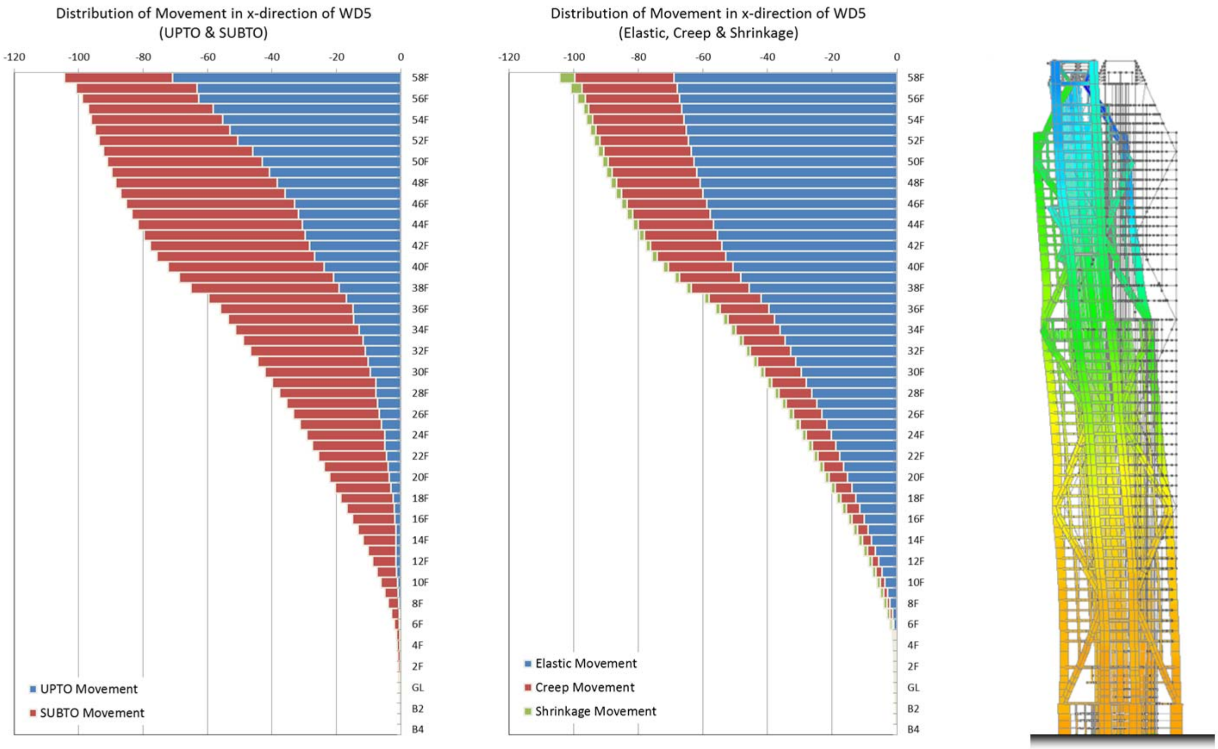



Fig. 7 Results of construction stage analysis regarding lateral movement of IB Tower

Three types of field monitoring for actual movement of the building is also being performed: strain measurement of column deformation using vibrating wire gauge, optical survey for lateral movement, and 3-dimensional laser scanning of as-built shape of the building for axial and lateral movement (see Fig. 8). The results of field monitoring all confirmed the predicted value of the building movement as shown in the graphs in Fig. 9).

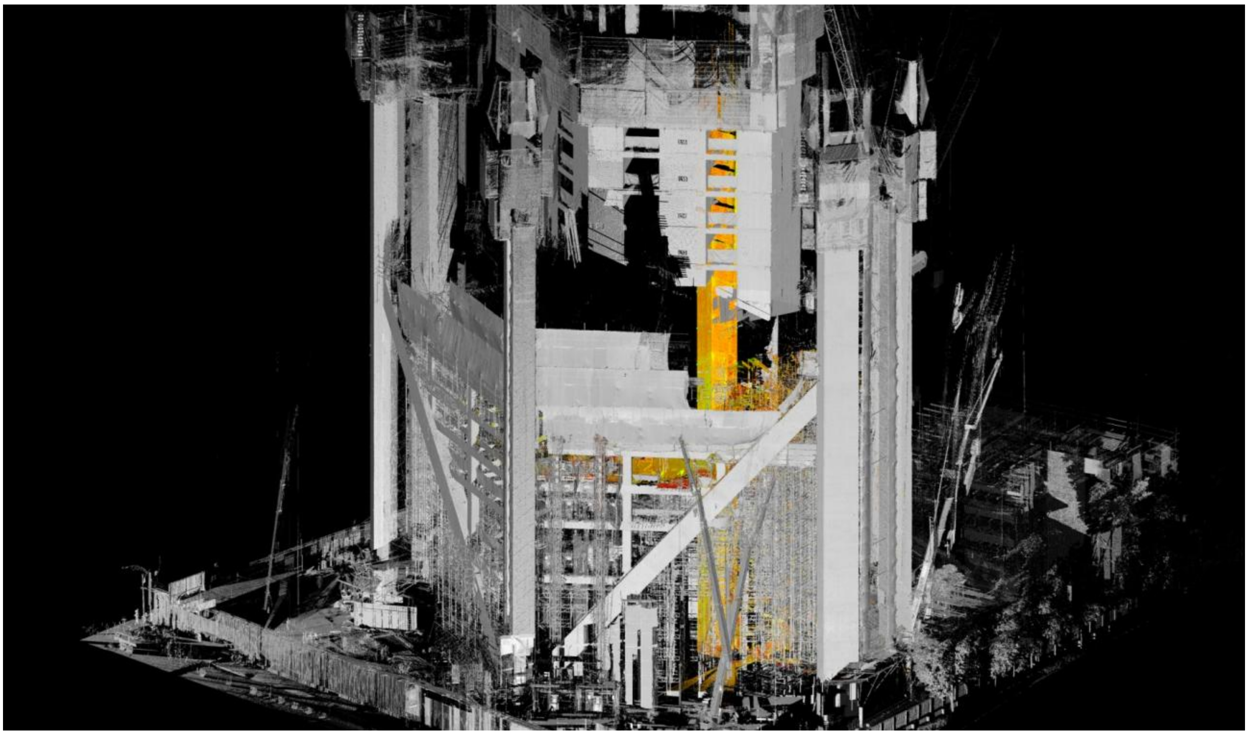


Fig. 8 Integration of scanned images (data cloud) of Tower exterior and the interior of elevator core in IB Tower

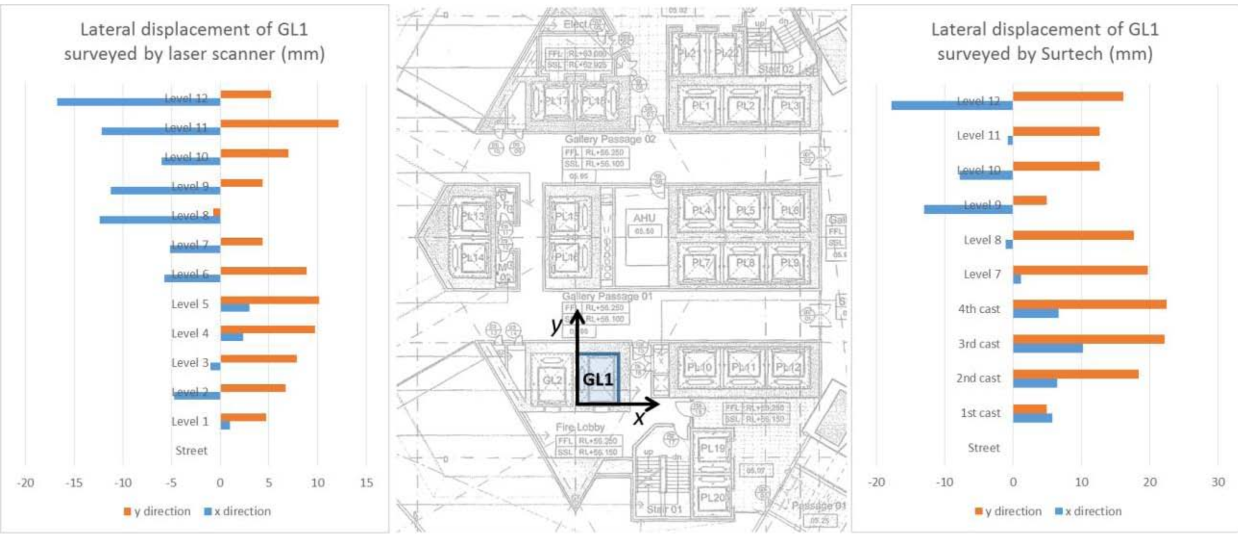



Fig. 9 Comparison of surveyed lateral movement of elevator core GL1 in IB Tower (center) by 3D laser scanner (left) and conventional optical method (right)

## 5. CONCLUSIONS

Problems due to building movement both in axial and lateral direction are rather related with construction and maintenance issues than structural ones. Advanced Staged Analysis Program (ASAP) developed in this research can efficiently respond to these problems by evaluating the movement at target time which corresponds to any construction items such as floor finishing, elevators and façade. The program was used to predict the movement during the construction of a 58-story reinforced concrete building and showed good agreement with the surveyed data from 3D laser scanning.

## ACKNOWLEDGEMENTS

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