Key Technologies for Vertical Construction Accuracy Control of Super-Tall Buildings

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Abstract. Buildings above and below skyscrapers are prone to problems such as uneven structure, shape changing with temperature, shrinkage or slow deformation, and wrong assembly time. Taking a representative super-high-rise building project as an example, an overall fine management framework combining multi-stage measurement, axis projection, elevation transfer, on-site rectification and steel-column rectification is established. The results show that the system can reduce the accumulation of vertical errors and improve construction coordination between the core tube and the perimeter steel structure.

Keywords: super-tall building; vertical construction; accuracy control; dynamic monitoring; construction surveying.

1 Introduction

Vertical construction accuracy is very important for the safety and installation quality of skyscrapers. After the building rises, the errors of axis-transfer, elevation and steel-column will gradually accumulate. During this period, due to the influence of temperature, shrinkage of concrete, creep, timing of construction, etc., there will be different deformations between the core tube and the surrounding frame. Previous studies have found that time-varying deformation accounts for most of the overall vertical shortening, which needs to be revised and controlled. In this study, we came up with a method of using hierarchical surveying, dynamic monitoring, deformation correction and staged adjustment together. In this way, the state of vertical can be adjusted and the engineering deviation of accumulation can be reduced.

2 Project Overview

This skyscraper is about 400 meters high and uses a structural system consisting of an outer steel frame and a reinforced concrete core tube. The shape of the building is a setback shape. From the 3rd floor to the 49th floor, the four corners of the core tube have been tapered inward, and the corners are chamfered at 135 degrees. The surrounding structure consists of 56 steel column, which are inclined by about 1 to 3

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degrees along the height, becoming a spatial shape that initially expands outward and then contracts inward. Complex cross-section changes and long-distance vertical movement put forward very harsh conditions for shaft positioning, height management and parts installation accuracy. During the construction period, the subsequent influences of different deformations caused by the temperature between steel structure and core tube, concrete shrinkage, creep and welding deformation on the accuracy of vertical position must also be considered[1], which lays a foundation for future layered management, motion monitoring and deviation correction.

3 Key Technologies for Vertical Construction Accuracy Control of Super-Tall Buildings

3.1 Hierarchical Survey Control Network and Segmented Transfer Technology

For super high-rise buildings, a multi-stage measurement framework is used. This is a hierarchical survey control system, which connects the site reference point, the nearby control mark and the internal reference point of the building in sections. The first control grid is the basis of datum coordinates, and the second grid is expanded accurately along the first line. Datum marks inside the building are directly used to locate core tube and perimeter steel columns. In this way, the accuracy of the main straight line is always kept within ±2 mm. The hierarchical control network and its moving route are shown in Fig.1. Because the height of the building will become higher, a moving level is set about every 50 meters. The datum point moved to the new position has been checked by angle measurement, distance measurement and coordinate value. Then, in order to avoid the error from becoming too large when moving up and down, the three-dimensional coordinates are reconfirmed by GNSS[2].

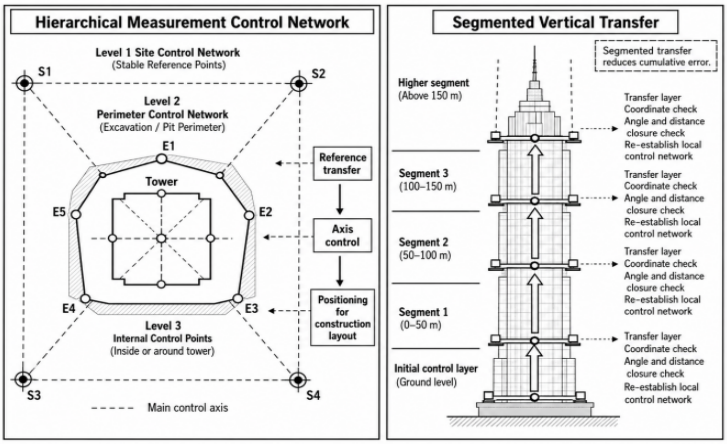


Fig. 1. Schematic of Hierarchical Measurement Control Network and Segmented Transfer

3.2 Vertical Axis Projection and Core-Tube Positioning Control Technology

Vertical axis transfer was carried out using the internal control-point projection method, in which a laser plummet projected the control points to the construction floor through reserved openings in the floor slabs. During observation, projection points were obtained at 0°, 90°, 180°, and 270°. When the diameter of the projection circle was less than 2 mm, its geometric center was taken as the control point, and a total station was then used to verify the angles, distances, and axes. The steps of positioning operation are shown in Fig. 2. During the construction of core-tube, the control points are moved up step by step by using climbing formwork system. The correct axis is made by polar-coordinate method, and the three-dimensional coordinates are confirmed by GNSS. Therefore, the overall vertical error can be kept less than 30 mm.

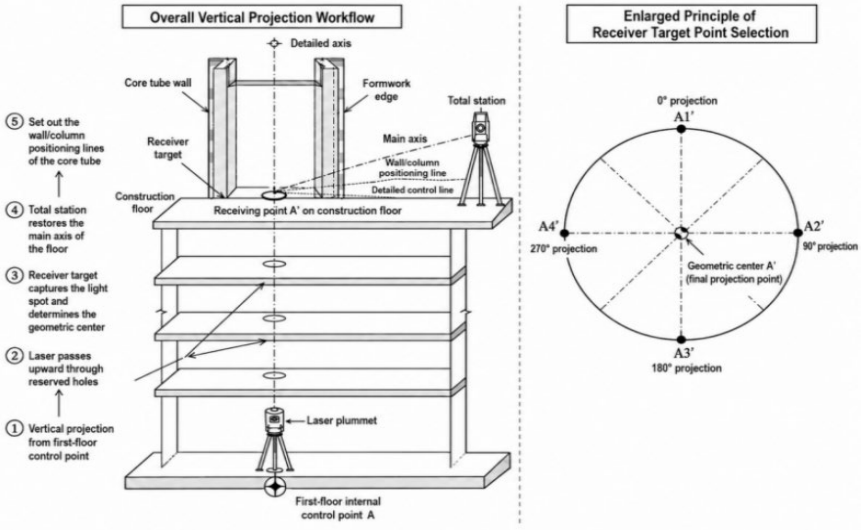


Fig. 2. Schematic of Vertical Axis Projection and Positioning Control for the Core Tube

3.3 Elevation Transfer and Dynamic Three-Dimensional Coordinate Correction Technology

Elevation transfer is carried out step by step according to the height of the project. When the floor is less than 150m, refer to the stable elevation standard of the first floor, and tell the upper floor elevation with total station. At that time, the temperature and pressure were also adjusted. The existing floor elevation control method is to directly place elevation control point on each floor according to the bottom control points. At this stage, no matter what deformation occurs, each floor will be automatically compensated during construction. As a result, the floor elevation reaches the design value, which is equivalent to automatically compensating for the vertical deformation occurring in the first stage. Above 150 m, GNSS, total stations, and tilt sensors were jointly used to correct the three-dimensional coordinates:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} - \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \tag{1}$$

where X_0, Y_0, and Z_0 are the coordinates before correction, in m; Δx, Δy, and Δz are the dynamic offset corrections in the X, Y, and Z directions, respectively; and X, Y, and Z are the corrected coordinates, in m,to reduce cumulative errors in elevation transfer.

3.4 Measurement and Deviation Correction Technology for External-Frame Steel Column Installation

Perimeter steel columns are mainly composed of inclined parts with different cross-sectional shapes. Use “total stations” to align each seam part in the correct position in space. Before assembly, confirm the predetermined coordinates of the top of the upper column and the position of the lower column after welding, and correct the lateral, longitudinal and angular deviations in advance. After the alignment is completed, two total stations are used together to check the middle point on the column before and after welding. In the lower position, the “shim thickness” is 5 mm at most. At a higher position, the adjustment of the backing-plate is 3 mm at most. Weld shrinkage is also considered to correct subsequent installation positions, forming a closed-loop adjustment process.

4 Monitoring and Verification Analysis of Vertical Construction Accuracy

4.1 Construction Accuracy Monitoring Scheme and Measuring-Point Layout

The Monitoring points are placed around the core tube, the iron column on the periphery, and the important position for restraining deformation. The 1st floor, 6th floor, 19th floor, 28th floor, 43rd floor, 56th floor and 66th floor are selected as representative monitoring levels. Using GNSS, total stations, laser plummets, biaxial tilt sensors, core-tube climbing, steel-column erection and control-network transfer together, the static measurement errors were measured and checked for many times when the project was stable, and the structural deformation changing with time was found through continuous measurement at various stages of the project[3]. This difference lays a foundation for future analysis of the influence of temperature, shrinkage and creep of concrete, construction opportunity and steel-column deformation.

4.2 Analysis of Core-Tube Axis, Verticality, and Time-Varying Deformation

The core-tube axis was controlled by internal control-point projection combined with total-station, GNSS, and tilt-sensor observations. After each projection, angular, distance, and axis measurements were cross-checked, while stage-by-stage observations were used to identify changes in the structural position. Short-term differences under similar construction conditions were treated mainly as measurement errors, whereas systematic displacement developing with construction progress was regarded as time-varying structural deformation. The maximum horizontal deviation of the core tube is controlled within 30 mm. As shown in Table 1, the limit value of the core tube is stricter than the overall structure. When the building height is about 400 m, the corresponding deviation rate decreases from 0.125 mm/m to 0.075 mm/m. This means that the control limit is strict by 40.0%. When the monitored deviation approached the allowable value, progressive correction over successive floors was adopted to prevent local errors from developing into cumulative vertical deviations.

Table 1. Comparison of Verticality Control Limits for the Core Tube and Overall Structure

Comparison Item	Core-Tube Control Limit	Overall-Structure Control Limit	Difference	Tightening Ratio / %
Overall horizontal deviation / mm	≤30	≤50	20	40.0
Deviation per unit height / ($mm \cdot m^{-1}$)	≤0.075	≤0.125	0.050	40.0

Note: he deviation per unit height was calculated for a building height of approximately 400 m.

4.3 Verification of Elevation Transfer and Steel-Column Installation Accuracy

Elevation transfer is based on the stable first floor benchmark. Total stations is used in the low place, and GNSS is used in the high place to confirm the coordinates. Before steel-column was erected, the coordinates of the upper end of the design and the position of the lower column were confirmed, and then the measurement was carried out after welding. The main installation-control limit values are written in Table 2. According to the coordinate difference before and after welding, the Welding deformation is found to adjust the part of the next column. In this way, it can be repaired before the small shrinkage caused by welding becomes larger. In the lower place, the thickness of the Shim is at most 5 mm, and in the higher place, the adjustment of the backing-plate is at most 3 mm, in order to reduce the deviation of the story-height, the distortion of the column, and the difference of Elevation on the column for closed-loop operation.

Table 2. Main Accuracy-Control Limits for Steel-Column Installation

Control Item	Allowable Deviation / mm	Relative Floor-Height Deviation Ratio	Control Position
Column-section inclination	≤10	2.0	Individual steel column
Story-height deviation	±5	1.0	Adjacent floors
Column torsion	≤3	0.6	Connection joint
Column-top elevation difference	±5	1.0	Same floor
Base-column bottom elevation	±2	0.4	First column section
Building positioning axis	≤3	0.6	Overall positioning

4.4 Analysis of Multi-Factor Coupling and Vertical Accuracy Control Effect

The simulation in the construction stage is helpful to investigate and adjust the upper and lower deformation differences of the super-high-rise core tube-frame system [4]. In this project, the use of MIDAS Gen is divided into 67 stages. Core tube is 6 floors ahead of the outside frame from the 4th floor, while slabs is 7 floors behind. The difference of shrinkage and creep, construction sequence and hardness with time will increase the difference of deformation and need to be adjusted step by step [5]. The influence of temperature is not great. As written in Table 3, the biggest deformation difference between core tube and frame is 44 layers, which is 38.32 mm.

Table 3. Vertical Deformation Difference Between the Core Tube and Perimeter Frame

Floor	Vertical Deformation Difference / mm	Relative to Maximum / %	Variation Trend
10F	24.0	62.6	Initial increase
20F	24.8	64.7	Slight fluctuation
30F	23.6	61.6	Local decrease
40F	31.8	83.0	Significant increase
44F	38.32	100.0	Peak
50F	28.0	73.1	Beginning to decrease
60F	19.5	50.9	Continuous decrease
70F	4.0	10.4	Near the top

5 Conclusion

In order to build a super-high building, an integrated vertical-accuracy control system is made. The lateral deviation of the core-tube is controlled within 30 mm. When the

number of layers is 44F, the maximum deformation is 38.32 mm. Temperature, shrinkage, creep, construction opportunity and welding deformation together affect the accuracy of up and down. By constantly monitoring and correcting step by step, the accumulated deviation is reduced, and the state of Core tube and surrounding iron parts is improved.

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