Deformation Monitoring of Steel Structures based on Measuring Robots and Global Navigation Satellite Systems During Unloading Construction

Lishan Xu¹, Jie Peng²,³*, Yongbin Wei²,³, Kai Jiang¹, Wenqi Wang¹, Meng Liu¹

¹China Construction Third Engineering Bureau Group Co., Ltd., Wuhan, Hubei, 430040, China
²China State Construction Engineering Corporation, Beijing, 101300, China
³China Construction Industrial Engineering and Technology Research Academy Co., Ltd., Beijing, 101300, China

*Corresponding author’s e-mail: pengjie1@cscec.com

Abstract. The steel-structured corridor project of the Industry Innovation Park (IIP) in Beijing adopts an overhanging design with a large size and span. In the demolition stage of the overhanging support, the steel structures will deform. In order to understand the deformation degree of the steel structures in IIP in real time and ensure construction safety, it is necessary to monitor the deformation process of the steel structures. We select the points sensitive to deformation and key parts of the steel structures as monitoring points, and make an automatic deformation monitoring scheme. We use the deformation monitoring system based on measuring robots and Global Navigation Satellite Systems (GNSS) to monitor the steel structures. Then we compare and analyze the deflection values measured by the two monitoring systems. The results from the two monitoring systems are relatively consistent and mutually verify. The results also show that the steel structures are obviously deformed due to the influence of unloading construction. In addition, deflection values obtained by deformation monitoring are compared with the deformation limit of the key steel components derived from the design code. The results show that the deflection values are within a reasonable range, indicating that the construction design of the steel structures in IIP is reasonable and the steel structures are in safe conditions. The deformation monitoring systems based on measuring robots and GNSS technology used in this paper meet the monitoring requirements in the construction phase and can play their value in similar projects.

1. Introduction

Due to the advantages of lightweight, good plasticity and toughness, easy manufacturing, etc., steel structures have been widely used in industrial and civil buildings[1]. Construction technology and construction process affect the forming state of steel structures. Certain deviations will occur in the process of positioning, installation and welding of steel components. In addition, during the unloading construction process, the structural load changes greatly, resulting in different degrees of deformation in different areas of the steel structures. Through real-time deformation monitoring of the structure, we can control the structure deformation in the unloading process to ensure the construction safety. At the same time, we can also acquire basic data for understanding the deformation law of the steel structure.
In traditional engineering measurement and monitoring, the most commonly used instruments are measuring robots. The measuring robot obtains the deformation information by measuring the angle and coordinate changes with high precision. Combined with the laser, communication module and charge-coupled device, the measuring robot can automatically, continuously and repeatedly observe the deformation of multiple targets. Measuring robots are widely used in high-precision measurement or deformation monitoring of steel-structured buildings, underground engineering construction and other projects. For example, previous studies use measuring robots to monitor the settlement during the construction of Changsha metro line four crossing the existing line two[2].

With the development of GPS and GLONASS and the successful networking of China's Beidou System, RTK technology has been widely used in various fields[3-6]. Global Navigation Satellite Systems (GNSS) monitoring based on Beidou, GPS and GLONASS has the advantages of high precision, high frequency, no need for visibility, being able to measure three-dimensional coordinates and work stably all day. GNSS monitoring can provide real-time and accurate deformation information to meet the deformation monitoring requirements of steel structures, bridges, slopes and other projects[3, 5-6].

This paper relies on the unloading construction project of the steel-structured overhang in the Industrial Innovation Park (IIP) in Beijing. In order to understand the impact of unloading on the deformation of the steel-structured overhang, and to ensure safety in the entire construction process, we deployed the deformation monitoring systems based on measuring robots and GNSS technology separately. The two systems automatically measure the same area at the same time. Then, we compare and analyze the deformation results obtained by the two monitoring systems.

2. Overview of Deformation Monitoring Project
The steel-structured corridor project of IIP in Beijing is located at the junction of Zone D and Zone E, between the fifth and sixth floors above the ground (figure 1). The steel-structured corridor adopts an overhanging design with a large size and span, and is mainly composed of steel trusses, steel beams and floor decks (figure 1). The maximum section size of the steel structures in IIP is H900*700*24*60mm and the steel materials used are Q390B and Q345B. The steel structures will deform during the construction stage of steel structure dismantling. In order to ensure safe construction and to understand whether the deformation of the steel structures in IIP meets the requirements of the design code, it is necessary to monitor the deformation process of the structures. We choose the top layer of the steel-structured overhang as the deformation monitoring layer. According to the finite element simulation, we arrange the monitoring points 6011-6018 in the positions sensitive to deformation and key parts of the steel structures (figure 1b). Then, we carry out the deformation monitoring during the unloading process of the steel structures.

Figure 1. (a) The steel-structured corridor in IIP and (b) its floor plan
The red triangles in figure (b) indicate the positions of the deformation monitoring points
3. Deformation monitoring system and measurement & control platform

3.1. Deformation monitoring system based on measuring robots
The deformation monitoring system based on measuring robots consists of measuring robots, prisms, wireless transmission systems, a server, a monitoring terminal, and software systems such as real-time data processing systems, data storage and backup systems, etc (figure 2a). In this project, we use the measuring robot Leica TS50 to complete the deformation monitoring of the steel-structured overhang in IIP (figure 2b). The measurement accuracy of angle and distance for the measuring robot used are 0.5" and 0.6 mm ± 10^{-6} mm respectively, which can meet the requirements of high-precision measurement.

![Figure 2](image_url)

Figure 2. (a) The deformation monitoring system based on the measuring robot and (b) on-site installation of the measuring robot

The deformation monitoring network of the measuring robot is composed of measuring stations, reference points and monitoring points. We set up a measuring station on the top of the overhang according to the on-site visibility. Then we fix the measuring robot on a stable base in the range of the station. We arrange the reference points in a relatively stable place far away from the deformation zone in the monitoring area, and set three reference points to ensure the accuracy of measurements. We arrange the monitoring points in the positions sensitive to deformation and key parts of the steel-structured overhang (figure 1b), and install prisms at each reference point and monitoring point. The measuring robot has the advantages of automatically and quickly searching for the position of the prism, focusing and measuring, and has the ability to intensively observe the distance, horizontal angle, vertical angle, and relative vertical distance to each measuring point. Before the formal observation, we input the meteorological values such as temperature and air pressure, instrument height and front and back prism height. After these, we manually measure the spatial positions of each reference point and monitoring point, and send the position information to the remote terminal. Then, under the control of the monitoring program running in the remote terminal, the measuring robot can perform fully automatic and uninterrupted measurements. Finally, by comparing and calculating the continuous repeated observation results of the reference points and the monitoring points, we can obtain the deformation of the monitoring points.
3.2. Deformation monitoring system based on GNSS technology

The GNSS mainly include GPS of the United States, Galileo of the European Union, Russia’s GLONASS and China’s Beidou. The GNSS monitoring system is mainly composed of reference stations, monitoring stations, communication systems, a server and a monitoring terminal (figure 3a). In this project, we set the reference station at the far end of the top layer of the overhang where it is not affected by the unloading construction, and set the monitoring station in the positions sensitive to deformation and key parts of the steel structures (figure 1b).

In GNSS measurement, the satellite signal receiver not only receives the GNSS satellite signals directly, but also receives satellite signals reflected by objects in the surrounding environment. The interference between the reflected signals and the direct signals may cause large measurement errors. The direct satellite signals mostly reach the antenna from above the receiver antenna at high elevations, while the reflected signals mostly reach the antenna from below the antenna plane. We use the choke antennas in both the reference stations and the monitoring stations (figure 3b), which can well suppress the reflected signals from below the antenna plane.

During monitoring, the receiver simultaneously receives the satellite data of GPS, Beidou, Glonass and Galileo. This is because the mixed solution of multi-satellite data helps to improve the measurement accuracy and data stability [7]. Through real-time kinematic differential analysis of the carrier phase, the GNSS monitoring system can obtain the unified time information and three-dimensional coordinates of the measuring points, thereby monitoring the deformation of the target in real time. The monitoring system is under a sampling frequency of 0.02 Hz and can detect millimeter-level deformation.

![Figure 3. (a) The deformation monitoring system based on GNSS technology and (b) on-site installation of the system](image)

3.3. Measurement & control platform for civil engineering construction

The automatic measurement and control platform for civil engineering construction is independently developed by China State Construction Technical Center, including the server software and the client software. The platform can be used to manage schedules, measurement and control, documents, quality, safety and models (figure 4), and has been successfully employed in the measurement and control in more than 20 large-scale projects in China, such as the Hangzhou G20 venue and Shenzhen Metro. Notably, the measurement and control platform can collect, process and display various monitoring data of the project site in real time, and can perform intelligent diagnosis and early warning of the structural safety status. In addition, the platform also has the capability to load lightweight BIM models (figure 4).
Figure 4. The interface of the measurement and control platform loaded with the BIM model
The loaded model is the BIM model of the steel-structured overhang in IIP, Beijing

4. Deformation monitoring results and analysis
This study focuses on the deformation of the steel-structured overhang in IIP, Beijing during unloading. We deploy the deformation monitoring systems based on measuring robots and GNSS technology at the project site, observing from 1.5 hours before unloading to 4 hours after unloading.

Taking deformation monitoring point 6018 at the outermost end of the overhanging truss as an example, we draw the deflection curves from the measuring robots and GNSS monitoring systems at this point (figure 5). We can see that during the unloading period, the monitoring curves from the measuring robots and the GNSS technology are relatively consistent with a deviation of the monitoring values less than 1 mm, indicating that the measuring robots and the GNSS monitoring systems both have high measurement accuracy, and the results of the two monitoring systems form a good verification with each other. The existence of data deviation may be related to the difference in the equipment used and the positions of the measuring points between the two systems are not completely coincident. In addition, we can see that the cumulative deflection of the outermost end of the steel-structured overhanging truss in IIP is -7.5 mm during the unloading process (figure 5). This shows that with the removal of the temporary support, under the main influence of the gravity of the overhang, the outermost end of the overhang has significant subsidence that is imperceptible to the naked eye.
Figure 5. The deflection curves of the outermost end of the overhanging truss

The deformation results of other monitoring points are as follows: the cumulative deflection of 6012, 6013, 6014 and 6015 monitoring points arranged in the mid-span of the steel main girder of the floor is about -10 mm; the cumulative deflection of 6016 and 6020 monitoring points at the root of the overhang truss is about -2 mm, and the cumulative deflection of 6017 and 6019 monitoring points is about -5 mm. The deflection values of the measuring points on the symmetrical part of the overhang are nearly consistent and form a good verification of each other.

In this project, during the unloading process of the steel structures in IIP, the monitored cumulative deformation of the steel main girder of the overhang is 10 mm, and the cumulative deformation of the overhanging truss is 7.5 mm. According to the "design code for the steel structures", for the steel structure project of IIP, the allowance of deformation of the main girder is < 46 mm, and the allowance of deformation of the overhanging truss is < 64 mm. The monitoring results are far less than the maximum allowance of the design code, indicating that the construction design of steel structures in IIP is reasonable and the structures are in relatively safe conditions.

5. Conclusion
During the unloading construction of the steel-structured overhang in IIP, Beijing, it is necessary to monitor the structural deformation to ensure the safety in construction and to understand whether the deformation of the steel structures meets the requirements of the design code. For this purpose, we deploy deformation monitoring systems based on measuring robots and GNSS technology on the project site. Through monitoring, we get the following conclusions:

The cumulative deflection at the outermost end of the overhang from the deformation monitoring systems based on measuring robots and GNSS technology is about -7.5 mm. The deflections obtained by the two monitoring systems are nearly consistent, indicating that the results from the two systems validate each other. The existence of deviation may be related to the difference in the equipment used in the two monitoring systems and the incomplete coincidence of the measuring points.

In this project, during the unloading process of the steel structures in IIP, the monitored cumulative deformation of the steel main girder of the overhang is 10 mm, and the cumulative deformation of the overhanging truss is 7.5 mm. These monitoring results meet the requirements of the design code for the steel structures and indicate that the steel structures in IIP are in relatively safe conditions.
The real-time monitoring results effectively guide the unloading construction of the steel structures in IIP and ensure the construction safety. In addition, the monitoring results also suggest that the technologies of the unloading construction used in our project are feasible.

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