

# Research on Key Technologies for Construction of Steel Canopy Steel Structure in Chengdu Open Air Music Square

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**Abstract.** Taking the steel canopy project of the main stage of Chengdu Open-air Music Square as the research object, the project analyzes the construction difficulty, tight schedule and high quality requirements of the steel canopy from the aspects of construction difficulties, installation methods and construction process; puts forward reasonable structure division and construction steps; at the same time, the project innovatively puts forward the large-scale inverted "7" At the same time, the project innovatively proposes a large inverted "7" truss structure lifting method and an anti-deformation structure and its lifting method for the lifting of hyperbolic mesh shell structure; and fully utilizes construction simulation analysis, monitoring and testing technology, etc., to ensure the safety and quality of the construction of the steel canopy. The results show that the overall deformation of the steel canopy structure after molding is small, the construction efficiency has been improved by 38%, and all the nodes docked with the curtain wall project are within the installation design allowable values. The research results provide technical references for the application of similar canopy structure construction in China in the future.

**Keywords:** stadium; Steel canopy; Construction technology; Finite Element Analysis; construction monitoring.

## 1. Introduction

In the past 30 years, with the continuous improvement of China's engineering construction and design level, the large-span spatial shaped steel structure has also been developing vigorously in the direction of modernization, complexity and art. Engineers for different characteristics of large-span space alien steel structure, under the premise of ensuring the installation quality, safety and economy, put forward many innovative construction technology and monitoring means. For example, Guangzhou 100,000-seat soccer stadium will use the installation method of negative angle vertical rotation for the installation of steel canopy [1]; Bengbu Stadium ensures the quality of steel canopy installation by combining the whole process of construction simulation and monitoring technology [2]; Kaifeng Sports Center Stadium adopts the construction process of whole grouping of ground bulk, one-time lifting in place by large cranes outside of the span, and whole joining after unloading in the zones to finish the The installation of the canopy [3]; Hangzhou Olympic Sports Expo Center main stadium using large crawler cranes across the internal and external segmental lifting method for the installation of the ring-shaped canopy structure [4].

The steel canopy of the main stage of Chengdu Open Air Music Square has innovatively proposed two construction methods, namely the coordinated operation of multiple cranes for the overall assembly of the truss and the rigid transformation of the hyperbolic grid shell, for different structural characteristics. The implementation of the above methods has ensured the safety of steel shed construction and improved construction efficiency. At the same time, to ensure the quality of structural installation, construction process simulation analysis and monitoring technology were adopted, providing a good installation interface for the subsequent construction process. Project overview

The main stage of Chengdu Open-air Music Plaza is located in Chengdu City, east of a section of Beixing Avenue, north of the third section of North Third Ring Road, northeast of Phoenix Interchange; the main stage consists of two independent structural units, namely, the crescent-shaped grandstand and the arch-supported double-curved parabolic single-layer cable network[5]; there is an underground passage under the grandstand locally, which is connected to the

ground level of the stage under the cable network; the concrete part of the grandstand consists of five floors, and the plane is in the shape of a semicircular ring, with a maximum structural height of 23.95m and a maximum width of 31.70m and a maximum length of 116.30m. The maximum width of the ring is 31.70m, and the maximum length is 116.30m; the upper steel canopy of the grandstand is in the shape of a crescent moon, with grounding at both ends of the canopy and a projected area of 11,331 m<sup>2</sup>, the maximum height of the middle part is 48.85m, the maximum width is 36.50m, and the maximum span is 180.70m, which belongs to the ultra-limit large-span space structure, with a total weight of about 872t; the elevation structural diagram is shown in Fig. 1:

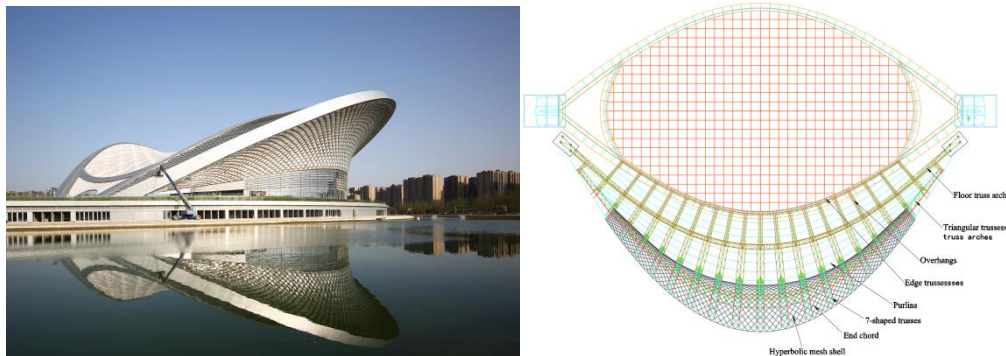


Fig. 1 Elevation of the main stage of Chengdu Open Air Music Plaza

The main structure of the steel canopy consists of 7-shaped trusses, floor truss arches, hyperbolic mesh shells, triangular trusses, capping trusses, end chords, overhangs, purlins, etc., which is structurally a very complex hybrid structure [1]. Among them, the number of 7-shaped trusses is 21 bays, 3 bays at each end and 15 bays in the middle are placed on the platform of the grandstand at the elevation of 15.75m; the front end of the 7-shaped trusses is connected with the floor truss arch, and it works with the floor truss arch; the tail is connected by the end three-dimensional trusses and strings and is connected by the outer claw to the double curved mesh shell, which is connected with the inverted quadrangular cone shaped aluminum veneer.

## 2. Difficulties in Construction Technology of the Canopy

### 2.1 Analysis of key points and difficulties

The whole canopy trusses have many styles, complex nodes, large spans, and special structural stresses; especially the center of gravity of the 13-bay 7-shaped trusses in the middle is placed outwardly, and the structural section diagram is shown in Fig. 2. During the installation, the trusses produce a backward tension on the whole floor arch, and only when all the 7-shaped trusses and the floor arch trusses are connected as a whole, the canopy tends to be in a relatively stable state. Therefore, how to segment the trusses, determining the reasonable installation order, and setting the support position is the key to ensuring the stability and safety of the whole canopy installation and reducing the deformation of the trusses.

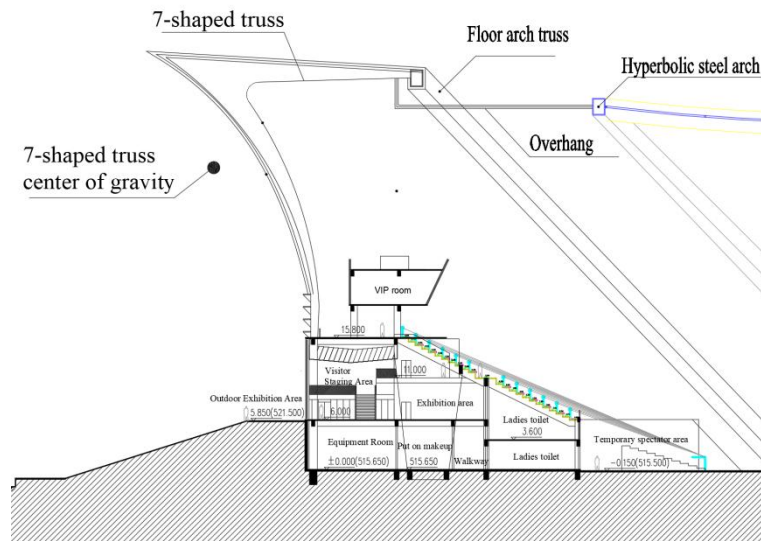


Fig. 2 Schematic diagram of section

## 2.2 Delineation of the construction area

The whole steel canopy is a symmetrical structure, in order to facilitate progress management, combined with the construction program, the canopy will be divided into four areas A-D, corresponding to the regional division and construction sequence shown in Fig. 3:

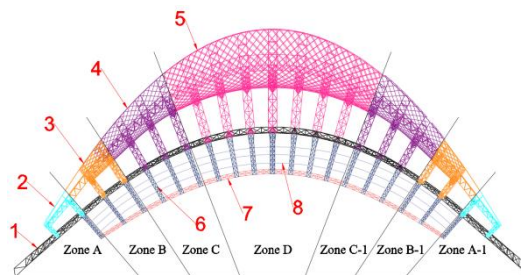


Fig. 3 Zoning and construction sequence diagram

## 2.3 Division of structural units

The division of structural units mainly considers two kinds of structures: floor-arched and mesh-shell and the rest of the structures can be divided into sections according to structural types. Among them, because of its large span and lightweight, the floor-arch truss is divided into as few sections as possible under the premise of minimum installation deformation, and the length of each section is controlled at 15m-20m, with a total of 8 sections, and the weight of each section is about 14.3t. Because of the hyperboloidal surface, the mesh shell is divided into the sizes of 8m\*8m~12m\*12m.

## 2.4 Arrangement of supports

According to the structural unit division, 4 aspects of safety, economy, high efficiency, and small deformation are considered. The layout of the support frame is shown in Fig. 4.

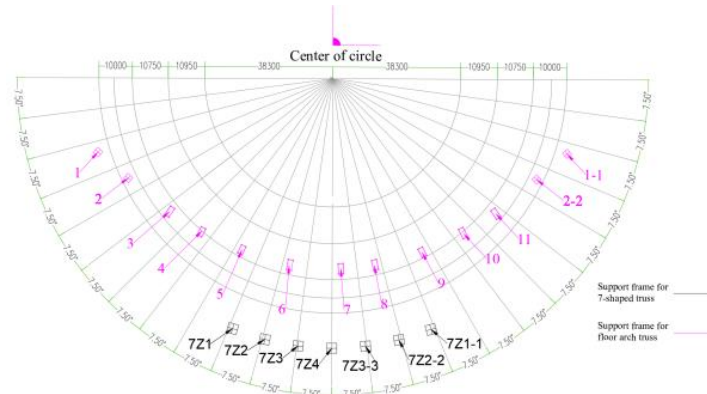


Fig. 4 Arrangement of the support frame

### 3. Key construction programs

#### 3.1 The overall flip over lifting method of the 7-shaped truss

The maximum size of the 7-shaped trusses is 32.84m (projected width)\*33.1m (vertical height), and the weight is 15t. If the method of segmental assembling is adopted, it not only increases the construction period and the cost of construction measures but also tends to result in low precision of installation. Therefore, it is proposed that all the 7-shaped trusses are assembled on the ground and then lifted. To minimize the deformation of trusses caused by lifting and to facilitate the control of installation angle, three cranes are used for turning over lifting; one of them is the main crane and the other two are auxiliary cranes; the main measures and steps are as follows[6]:

1、The hook of the main crane is set at the center of gravity of the upper edge of the 7-shaped truss structure; the main lifting points are tied to four points of the truss, one of which is the fixed rope, and the remaining three points are connected with the hand chain hoist, and the fixed rope and the free end of all the hand chain hoists are connected with the main hook of the main crane. In addition, the lifting point of auxiliary crane 1 is set not far from the end of truss; the lifting point of auxiliary crane 2 is set at the position  $h$  ( $h=1/3H$ ) from the support, and all the auxiliary lifting points are tied to the truss with fixed ropes. At the same time, the cable is set up at the end of the upper chord and the end of the lower chord of the 7-shaped truss structure; one end of the cable is tied to the truss, and the other end is manipulated by human beings; the way of setting up each lifting point of the 7-shaped truss is shown in Fig. 5.

2、Three cranes lift the height of  $h$  together; then, auxiliary crane 2 does not move, main crane continues to lift and adjust the hand hoist, auxiliary crane 1 cooperates with the main crane until the truss support falls to the ground under force, auxiliary crane 2 withdraws. Auxiliary crane 1 continues to cooperate with the main crane and keep the stability of truss until the truss structure as a whole turns over  $90^\circ$  and withdraws.

3、Main crane continues to lift the truss to the installation position and adjusts the installation angle of the truss at any time during the process by utilizing the cable.

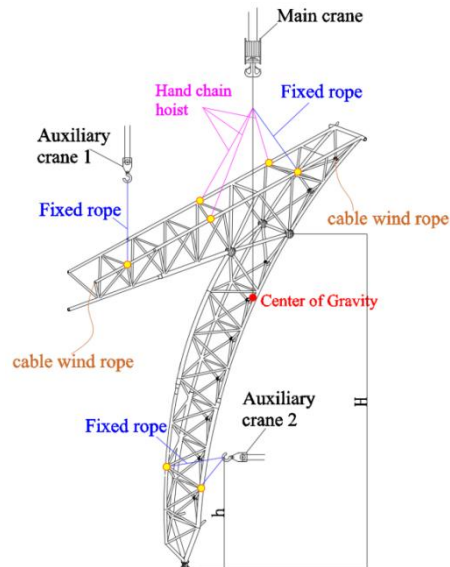


Fig. 5 Setting method of the lifting point for the 7-shaped truss

### 3.2 Analysis of the installation process of hyperbolic mesh shell

Double curved mesh shell external inverted quadrangular cone modeling aluminum veneer support is set at each intersection of the mesh shell, the requirement of the node after the molding of the mesh shell error control in  $\pm 15$  mm. at the same time, due to the mesh shell for installation in pieces, a single piece of mesh shell is lightweight, prone to deformation, it is not easy to control the linearity and installation accuracy.

To this end, an anti-deformation structure for lifting hyperbolic mesh shell structures and a lifting method thereof are proposed. The main methods are as follows[7]:

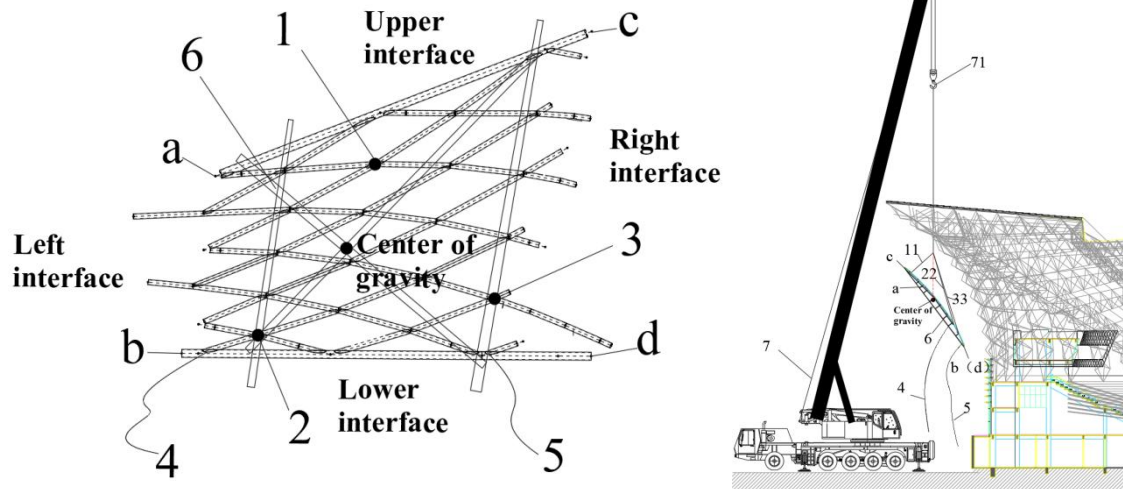
1、 After the assembly of hyperbolic mesh shells is completed, cross-shaped anti-deformation frame connecting rods are set on the mesh shells, so that the hyperbolic mesh shells as a whole are changed from a flexible structure to a rigid structure; at the same time, three lifting points and two adjusting pull ropes are set on each piece of hyperbolic mesh shells before hoisting.

2、 Two adjusting pull ropes are set at the lower corners of both sides of the hyperbolic mesh shell. The three lifting points are divided into fixed-length lifting points and variable-length lifting points; the fixed-length lifting points are set as far as possible at the intersection of the nodes of the upper hinge rods and are connected to the hook by a fixed rope; the variable-length lifting points are connected to the hook by a hand-operated hoist. The hook always passes the center of gravity of the mesh shell in the vertical direction.

3、 During the lifting process, manpower pulls the left and right adjusting pull ropes, and an operator is set up to operate two hand hoists at the seating place of the hyperbolic mesh shell, so that the left hinge of the hyperbolic mesh shell, points a and b, are aligned with the seating mounting point, and the spot welding is completed.

4、 Keep the left adjusting pull rope immobile, adjust the right hand puller and the right adjusting pull rope, and when the 3D coordinate measurements of points c and d of the right closure of the hyperbolic mesh shell coincide with the theoretical installation values or are within the error range, fix points a and b and complete the welding of the remaining connection points. The relevant settings are shown in Fig. 6.





1-Fixed length lifting point; 11-Fixed lifting rope; 2-Left variable length lifting point (left); 22-Chain hoist (left side); 3-Variable length lifting point (right); 33-Chain hoist (right side); 4-Adjustment Rope(left); 5-Adjustment Rope(right); 6-Anti-deformation structure; 7-crane; 71-The lifting rope of the crane;

Fig. 6 Schematic diagram of lifting of hyperbolic mesh shells

## 4. Construction Process Study

### 4.1 Construction Simulation

The calculation software adopts the general finite element analysis software Midas/Gen, the overall model of the structure is established according to the drawings, the specifications of the components are consistent with the drawings, and the structural deadweight (deadweight coefficient of 1.2) is calculated automatically by the program. As the model is huge and involves a lot of calculation units, it mainly focuses on the beam unit and truss unit, in which the structural part is calculated by using beam unit, and the beam end constraint release is carried out by considering the effect of insufficient welding constraints in part of the nodes; the vertical support rods and stringers of supporting trusses are all used in the beam unit, and the web rods are used in the truss unit. Both ends of the floor arch are connected with the ground by cementation, and the 7-shaped trusses bearings are connected with the ground or the grandstand by articulation. The support frame of floor arch and 7-shaped trusses are connected with the ground in articulated form.

The connection between the supporting truss and the main structure has a great influence on the stress distribution of the members in the construction process, and the improper connection form may make the structural members have local stress concentration in the construction process, which may lead to the destruction of the members. In the calculation simulation, in order to avoid the possible stress concentration, the support truss and the main structure are not directly connected by rods, but the nodes of the two connected parts are coupled and bound by intermediate nodes, which are set to transfer only the displacement load, not the corner load. This not only can smoothly transfer the load from the main structure, but also effectively avoid the possibility of stress concentration in the connection part. The specific form of node binding between the canopy support frame and the main structure is shown in Fig. 7.

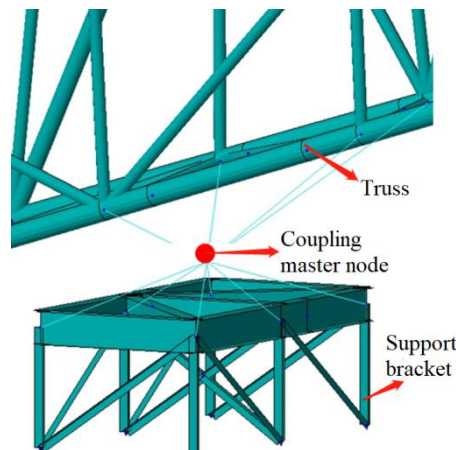


Fig. 7 Coupling diagram between support frame and main structure

The construction process analysis of the entire canopy is mainly divided into 5 stages (36 working conditions) according to the installation steps of the canopy, and the details of each stage's working conditions are shown in Table 1.

Table 1. Detailed Table of Working Conditions at Each Stage

Stage	Working condition name	Analysis location
Stage 1	Condition 1 - Condition 4	Installation of floor arch trusses
Stage 2	Condition 5- Condition 15	Installation of 7-shaped trusses, hyperbolic lattice shell, triangular truss, and end chord
Stage 3	Condition 16- Condition 24	Installation of overhangs and edge trusses
Stage 4	Condition 25- Condition 28	Removal of the support frames for the 7-shaped trusse
Stage 5	Condition 29- Condition 36	Removal of the support frames for the floor arch truss

The simulation analysis results are as follows:

1) As the steps of steel canopy installation increased, the stress and displacement values were getting bigger and bigger, and the maximum stress and displacement values were in the fifth stage of working condition 36, with values of -188.9MPa and 123.15mm. After the installation of the floor arch truss, the subsequent maximum stress and displacement deformation positions are mainly distributed in the area of the floor arch truss corresponding to the connection of the 7-shaped trusses without supporting frames.

2) The deformation control of the floor arch truss is the key to the installation control of the steel canopy, especially during the dismantling process. The floor arch truss mainly occurs in the vertical deformation and out-of-plane deformation of the arch, and the deformation is mainly distributed in the middle of the span, which should increase the monitoring efforts[8,9].

## 4.2 Construction process monitoring

### 4.2.1 Deformation monitoring method and monitoring point layout

As the main core connection object of the steel canopy, its deformation directly affects the molding error of other structures, and the monitoring object of the solid steel canopy is mainly the floor-arch truss.

For the convenience of narration, the right-angle coordinate system used for displacement measurement is explained as follows: X-axis is the spanning direction of the floor-arch truss, from west to east as the positive direction, and  $X=0$  at the position of  $1/2$  span; Y-axis is the perpendicular direction to the spanning direction of the floor-arch truss, from south to north as the positive direction; Z is the vertical direction, and the upward direction as the positive direction, and the above coordinate system conforms to the right-handed helix rule.

Seven observation sections, numbered LDG01~LDG7, are set at the place where the deformation of the floor arch truss is large and at the section junction. Each observation section is set with five Deformation monitoring points according to the structural style. The layout of the monitoring points is shown in Fig. 8.

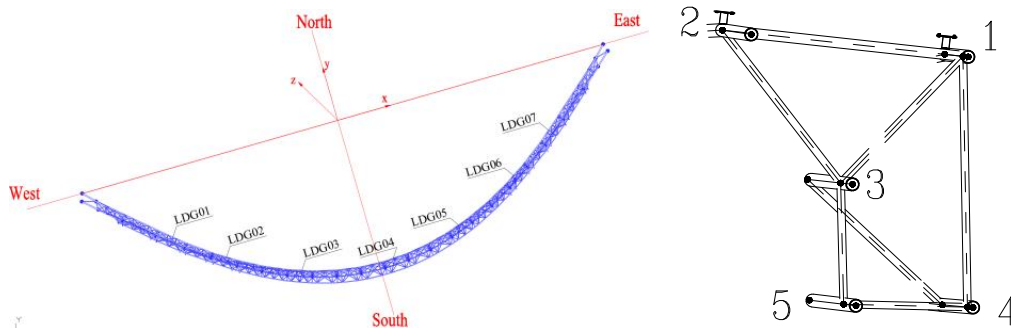


Fig. 8 Layout of Monitoring Points for Floor Arch Truss

Through monitoring, the relative displacement values of the monitoring points corresponding to the 7 observation sections after the installation of the steel canopy are obtained, as shown in Fig. 9.

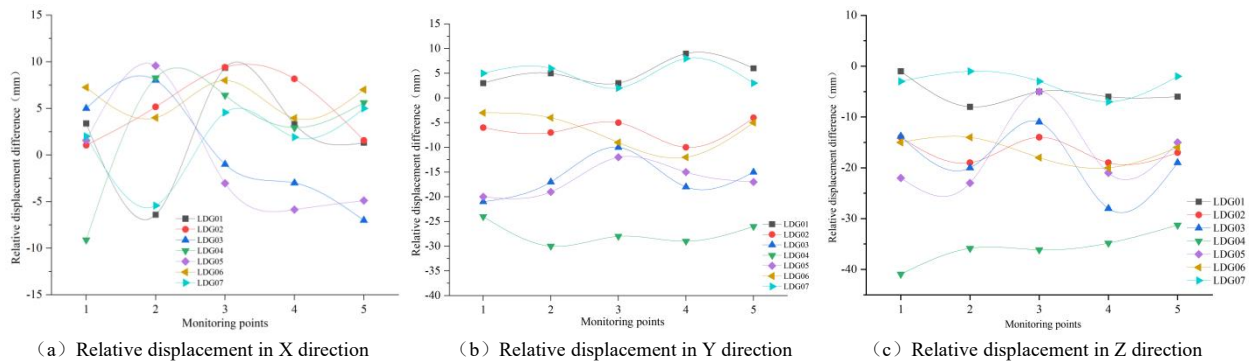


Fig. 9 Relative displacement difference of monitoring points for floor arches

#### 4.2.2 Measurement results and analysis

From Figure. 9, it can be seen that the deformation of the floor arch truss is mainly caused by vertical displacement and out of plane displacement, while the displacement along the span direction of the arch is relatively small, with the maximum relative displacement controlled within  $\pm 10\text{mm}$ . The deformation is mainly concentrated in the middle area of the floor arch truss, and the measured value of this distribution pattern is the same as the theoretical one. From the specific distribution values of each component, the maximum measured value of vertical displacement is  $-40\text{mm}$ , and the theoretical calculation value is about  $-35\text{mm}$ . The two are basically close, and both are located at the mid span. The maximum measured deformation in the y-direction (north-south direction) is  $-30\text{mm}$ , which is almost the same as the theoretical calculated value of  $-26.5\text{mm}$ .

### 5. Conclusion

(1) The quality control measures adopted for the steel canopy of the main stage project of Chengdu Open Air Music Plaza have greatly reduced construction costs, effectively eliminated rework, and provided a reference for the quality control of similar projects in the future.

(2) The 7-shaped truss lifting construction method and the grid shell block lifting method proposed based on the characteristics of the steel canopy have strong operability, improving the construction efficiency by 38% and ensuring the schedule node.

(3) A reasonable monitoring and detection plan not only ensures that the deformation value of the steel canopy after installation meets the design requirements, but also meets the installation of the curtain wall, effectively ensuring the quality of subsequent construction processes.



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