The Exploration of Construction Process and Calculation Points of Steel Structure Roof for Sports Arena

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Abstract. With the rapid development of domestic sports, the large-scale construction of gymnasiums has also risen. Due to the special characteristics of the large-span roof of the gymnasium, the steel structure construction faces many technical challenges, so thein-depth study of the construction process and key calculation points is particularly important. Through the analysis of the jiangmen Riverside Sports Center project, this study proposes a lifting and assembly scheme for the steel roof cover of a large-span stadium. Through the analysis of structural stress and deformation by finite element software Midas Civil and Midas Fea, this study provides a reference for the design and construction of similar projects, and verifies the stability and feasibility of the steel roof cover under different load combinations.

Keywords: gymnasium roof, construction process, midas Civil, overall calculation

1 Introduction

At present, the research on the steel roof cover of large-span stadiums mostly focuses on the discussion of a single construction technology or calculation method, while this study makes up for the lack of research on the structural behavior under the standardization of the construction process and multiple loading conditions through the systematic analysis of the lifting and assembling process as well as the key calculation points, which provides an all-around reference for the engineering design and actual construction [1]. Unlike existing studies on the construction process of steel roof covers for gymnasiums, this study not only adopts the traditional finite element analysis method, but also combines the dual analysis of Midas Civil and Midas Fea software to ensure a multi-dimensional examination of the structural stresses and deformations. This joint application of dual software has not been widely used in similar studies, thus providing more accurate and comprehensive analysis results.

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2 Summary of Work

Taking Jiangmen Riverside Gymnasium as an object(as shown in Figure 1), the museum covers an area of 42,360㎡, with a total building height of approximately 53m. The steel structure of the stadium roof is composed of a main truss, secondary truss, stabilizing truss, bracing, tie rods, and a peripheral roof. The main truss consists of two rectangular trusses intersecting vertically in the north-south and east-west directions, with the upper and lower chords of the main truss primarily composed of round steel pipes (Φ760x16, Φ560x16). The web members are mainly round steel pipes with cross-sections ranging from Φ245x12 to Φ402x16. The secondary truss serves as the supporting skeleton for the roof shape of the gymnasium, designed as an east-west plane truss. One end of the secondary truss is supported by the surrounding concrete columns, while the other end is connected to the main truss. The upper and lower chords of the secondary truss are primarily made of round steel pipes (Φ245x8 to Φ299x12), and the cross-sections of the web members are mainly round steel pipes (Φ133x5). Stabilizing trusses, supports, and tie rods are arranged along the vertical direction of the secondary truss, with the cross-sections of these stabilizing members also primarily consisting of round steel pipes. The building is predominantly a single-story structure with a one-story basement.

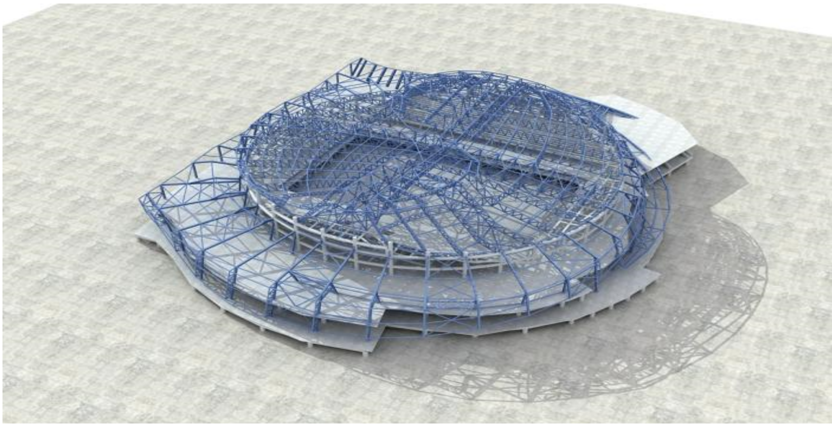

Fig. 1. Three-dimensional schematic of the gymnasium

3 Construction Process of Steel Roof Cover

3.1 General Components of a Steel Roof and Their Roles

A structural steel root 1s typically composed of trusses or primary and secondary beams, root covering materials, support columns, roof wings or eaves, bracing, and connecting elements, These components may vary from one type of stadium to another and from one design to the next, but in general, a structural steel roof is used to provide stable coverage and support to protect activities in the arena from the effects of the weather.

3.2 Selection of Lifting Solutions

At present, overhead bulk forming, overall lifting, segmental lifting, overhead splicing, and overhead sliding are usually adopted domestically. The aerial bulk forming scheme typically involves large steel structure components being assembled and connected in the air to complete the installation of the whole structure. The integral lifting scheme involves the entire steel structure components being lifted as a single unit, rather than being broken down into partial components for assembly. Integral lifting is a method where an entire steel assembly (usually a complete modular structure) is lifted as a single unit to a target location [10]. In the segmental lifting method, a steel structure is broken down into smaller components, which are then lifted and assembled on site, one by one. Aerial skidding is a method where large structural steel components are lifted to a high altitude and then slid into the correct position at the target location.

3.3 Preparation of Steel Structure Before Entering the Site

Before steel erection begins, careful planning and preparation is necessary to ensure the successful completion of the project.

(1) Set up a temporary component yard at the location specified in the general layout plan, and lay wooden squares on the ground, which is to minimize the deformation of steel components that may occur during stacking. When stacking the components, it is important to pay special attention to the direction of drainage to ensure that the normal operation of the ground drainage system will not be impeded [5]. This treatment ensures the efficiency and safety of the construction site while preventing unnecessary damage or delays.
(2) During on-site inspection, the number and installation location of each steel component should be confirmed according to the design drawings and component release drawings, and they should be stacked in an orderly manner according to the corresponding categories so that the correct matching and installation work can be carried out conveniently [12].
(3) In order to ensure the construction quality of the steel structure project of the high-rise building, it is necessary to check the steel column foundation. Checking the centerline and elevation of the foundation and determining the position of the marked positioning axis and elevation, determining the position of the foundation level of the columns and taking this position as the position of the high-level point of the foundation are steps to ensure that the manufacturing, transporting and installing process of the steel structural components can be carried out in an orderly and efficient manner.
(4) Most of the cross sectional dimensions of the steel components of the stadium roof cover are larger than the load carrying capacity of the vehicle, so most of the components are fabricated off-site and then transported to the site for assembly [8].

3.4 On-Site Assembly

3.4.1 Tire Rack Assembly.

The design form of the tyre racks should be finalized in line with the project, and the arrangement of the tyre racks should be maintained at a reasonable spacing to ensure the balance of the structure. In determining the arrangement, sufficient calculations must be carried out to ensure that the bearing of the lower part of the tyre racks meets the required settlement and deformation requirements. The tyre frames can be connected to each other by guide beams to form a temporary support system, which together constitutes the support network of the main structure [11]. This structural design allows the guide beams to play a key role in the entire overhead erection process of the steel structure, acting as the main force-bearing points. Once the layout of the tyre racks is completed, the coordinates and elevations of the support points should be reviewed, which can be accomplished with the help of a total station and level. It should be noted that the location of the tyre rack positioning blocks must be positioned to avoid collisions with the trusses when they are lifted. Finally, suitable temporary bracing should be installed to reinforce the frame, to prevent the structural tipping of the trusses during the subsequent installation. Additionally, in the early stage of frame installation, the temporary bracing may be required to share some of the structural loads, which can be used to alleviate the load pressure on the lower part of the frame. The process of assembling the stadium roof tyre frame typically includes the following steps, as shown in Figure 2.

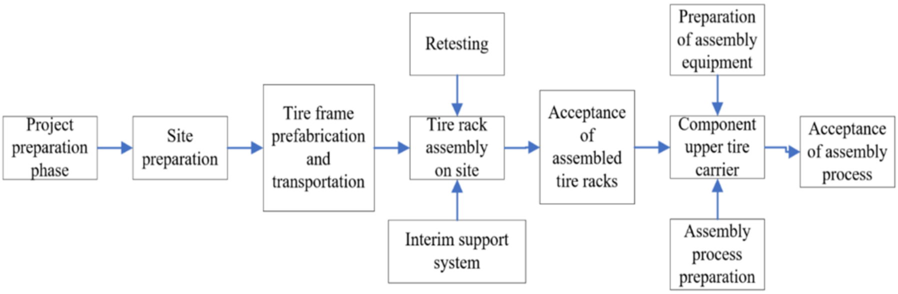

Fig. 2. Flow chart of tire frame assembly

3.4.2 Truss Assembly.

(1) After the acceptance of the tire frame, the installation will be carried out in the order of straight web rods of the bottom chord, straight web rods of the top chord, diagonal web rods of the bottom chord, diagonal web rods of the top chord, and web rods between the top and bottom chords according to the axes of the truss and the arrangement of its butt position (as shown in Fig. 3). The upper and lower chord rods are fixed with temporary ear plates, and the web rods are temporarily fixed by welding or clamping, depending on the design of the structure, construction requirements, and the nature of the rods. After the fixation is completed, the lugs are cut off and

the cuts are polished. This step is mainly intended to ensure the integrity of the weld, reduce the appearance of defects, lighten the stress concentration, and distribute the stresses more uniformly in the connection area.

(2) After the assembly control points are positioned, a level meter is used to carry out elevation retesting to ensure that the elevation of the positioning points is consistent with the elevation on the construction drawings. At the same time, the horizontal control projection points on the analysis frame and the control points labeled on the platform are checked through the latitude and longitude instrument to ensure they are exactly coincident. The goal of this process is to ensure that the error of the measurement points is kept within 2 mm to maintain the accuracy and precision of the assembling work[7,9].

Fig. 3. Schematic diagram of main truss installation sequence

3.5 Truss Suspension

3.5.1 Preparation for Lifting.

(1) Before the lifting begins, a detailed lifting plan can be developed based on the model created by MIDAS CIVIL. This plan should include the lifting sequence, selection of lifting equipment, determination of lifting points, calculation of lifting counterweights, and safety measures.

(2) Reasonable selection of wire ropes: The appropriate wire ropes must be selected for hoisting and lifting operations. Before the start of lifting, the load requirements of the lifting task must be clarified, and the safety factor should be considered to understand the required load weight, shape, and distribution, in order to select the appropriate diameter and construction of the wire rope. The load weight is the basic criterion for selecting wire rope, but the working environment must also be considered, including factors such as corrosion, high temperature, and low temperature, which will directly affect the choice of material and durability of the wire rope. In the current stadium steel roof project construction, wire ropes commonly used include 6 strands of 7 wires, 7 strands of 7 wires, and 6 strands of 19 wires, which should be selected in accordance with the specific conditions of the project [5].

(3) Installation of the support: The support is first temporarily fixed, and then jacks are used to adjust its horizontal position and accurately control it to the actual height of the roof plate. Once the support is adjusted to within the permitted range of the design and specifications, it is detected using a detector before being welded in place. To reduce the negative effects of welding, such as thermal displacement, stress concentration, and fatigue on the steel member, the support is not welded to the

embedded plate until the required steel components are installed, after which welding is performed [5].

3.5.2 Main Truss Lifting.

The basic sequence of truss installation is as follows: main truss installation, secondary truss installation. The installation of main trusses, which are characterized by higher height, greater structural weight, and more segments, requires careful planning and execution to ensure safety and efficiency. In this project, hydraulic synchronized lifting technology is adopted to install roof trusses, drawing on previous experience from similar successful projects. Inside the stadium, a tower is configured with a hydraulic hoist to act as the upper lifting point. In the section where lifting is to be carried out, the lower spreader is welded accordingly, and ground anchors are placed as the lower lifting point. A 100t tower crane is used for the construction. During the hoisting process, the corresponding order of hoisting must be followed. First, the end joist is hoisted. After the joist is lifted, it is moved slowly, while the direction of movement is controlled with the help of a rope to ensure the joist support and the embedded plate on the top of the column are effectively connected. Once the first joist is installed, support rods and cable ropes are immediately used to reinforce the structure until it is completely stabilized. The spreader is then loosened after the welding is completed [3].

3.5.3 Sub-Truss Lifting.

The secondary truss serves as the supporting skeleton for the roof modeling of the gymnasium, with one end supported on the surrounding concrete columns and the other end connected to the main truss. The secondary truss of the gymnasium is assembled out-of-span and lifted out-of-span by a large-sized crawler crane. When the secondary truss is lifted into position, the secondary truss will be welded to the main truss in time after the crane is lifted in the air for measuring and adjusting the position and elevation, and then the lifting gear will be released after the welding is completed.

4 Calculation Points for Steel Roof Cover

4.1 Civil Modeling

The finite element software Midas Civil was used to establish the structural analysis model of the gymnasium (Figure 4). To facilitate calculation and analysis, the structure is simulated using beam elements, and the supports are generally modeled as fully restrained, restricting the degrees of freedom in all directions. The model consists of 5,214 nodes and 10,726 elements [4]. To simplify the complexity, a unit model connected by 20 nodes is taken as the analytical object (Fig. 5), with all analytical parameters and working conditions of this model being the same as those of the whole model. Because this object is located near the intersection of the main trusses, the force condition of the entire roof can be more effectively reflected [2].

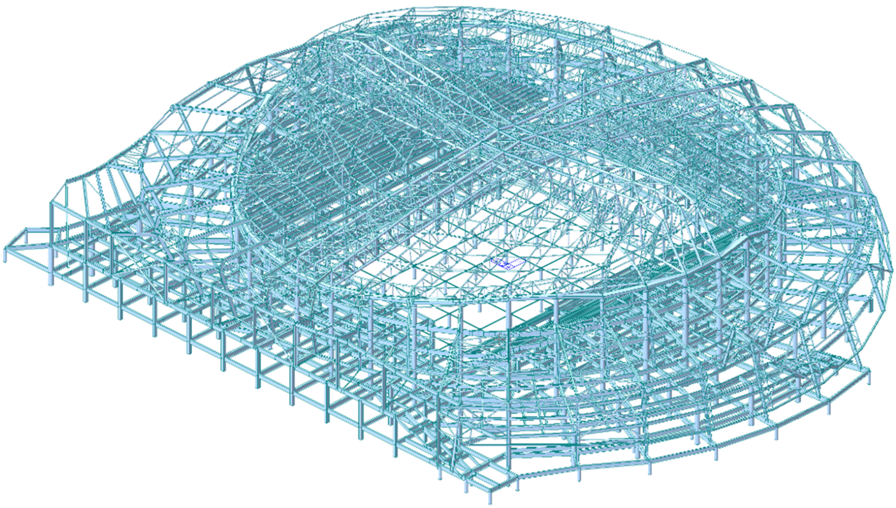

Fig. 4. Civil Finite Element Modeling of Stadium

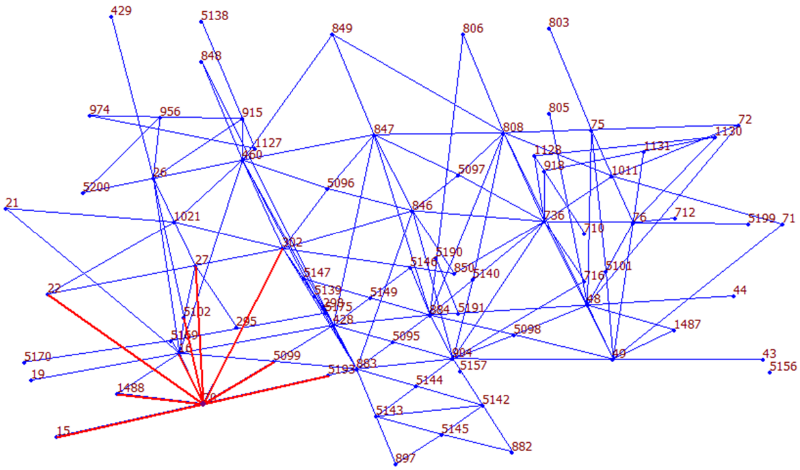

Fig. 5. 20-node truss analysis object

Connection unit lower chord bar with tubular section P760×28, web bar with tubular section have P245×12, tubular section P219×6, tubular section P203×6, tubular section P219×8, the force are calculated by Midas Civil 2021, and the calculation theory is based on the method of allowable stress. Load effects are mainly considered: (1) Constant load: the self-weight of the steel structure is about 76.98kN/m³, and the second-phase constant load is not considered. (2) Temperature load: according to the local climate environment change, the roof truss warming and system temperature take 30°C for consideration. (3) Seismic action: the reaction spectrum function is defined in accordance with the requirements of Code for Seismic Design of Buildings (GB50011-2019). The material properties in the calculation model are shown in Table 1 [6].

Table 1. Q345 Steel and Material Characteristics

Material Characteristics	Q345	C40 concrete
densities /(g/mm3)	7.85×10-9	2.549×10-9
modulus of elasticity /MPa	2.06×105	3.25 ×104
yield strength /MPa	345	26.8(Standard value of axial compressive strength)
Poisson's ratio	0.3	0.2
Coefficient of linear expansion	1.2×10-5	1.0×10-5

4.2 Static Performance and Stability Analysis Under Different Loading Conditions

In this paper, the load capacity and stability of trusses are explored by running different loading conditions. After different loading conditions are defined, the system automatically generates the itemized coefficients for each combination to combine the loads on the structure. The different combinations of working conditions are shown in Table 2.

Table 2. Different combinations of load conditions

load condition	load factor
Working condition I	constant load
Working condition II	constant load + temperature load
Working Condition III	constant load + temperature load+ seismic load

4.2.1 Unit Displacement Analysis.
A comparative analysis of the displacements of 20 nodes under different loading conditions is carried out, and the calculation results are shown in Fig. 8.

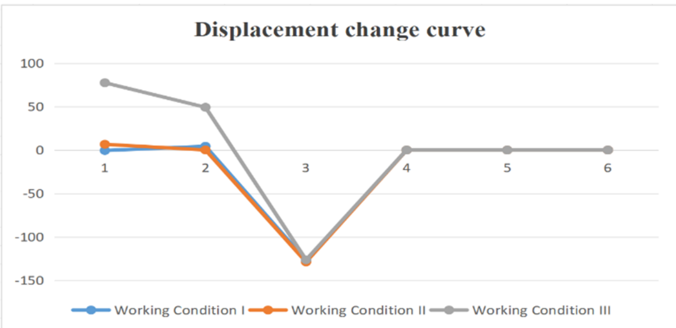

Fig. 6. Different Load Conditions-Displacement Curve

According to Fig. 6, it can be observed that the linear displacement of the 20-node truss under different loading conditions is primarily influenced by the structural deadweight and seismic effects, while the rotational displacement has very little impact under any loading condition. Specifically, the structural deadweight has the greatest effect on the vertical displacement of the structure, resulting in a displacement of 127.2 mm, while the horizontal displacement experiences a maximum change of only 4.33 mm. On the other hand, temperature loads have minimal impact on the horizontal and vertical displacements of the studied object, with a displacement change of about 7.14 mm. Since the seismic load is applied in the X-Y direction, the horizontal displacement in Case 3 increases to 77.41 mm and 49.18 mm, respectively, indicating that the seismic effect on the displacement of the structure is significant. Therefore, it is necessary to arrange the transverse support reasonably, use high-strength bolts, welding, and other connections to improve the stiffness and toughness of the connections, and increase the overall stability of the structure.

4.2.2 Unit Stress Analysis.

The stress values of chords and webs on 20-node trusses are compared and analyzed for different loading conditions, and the calculation results are shown in Fig. 9.

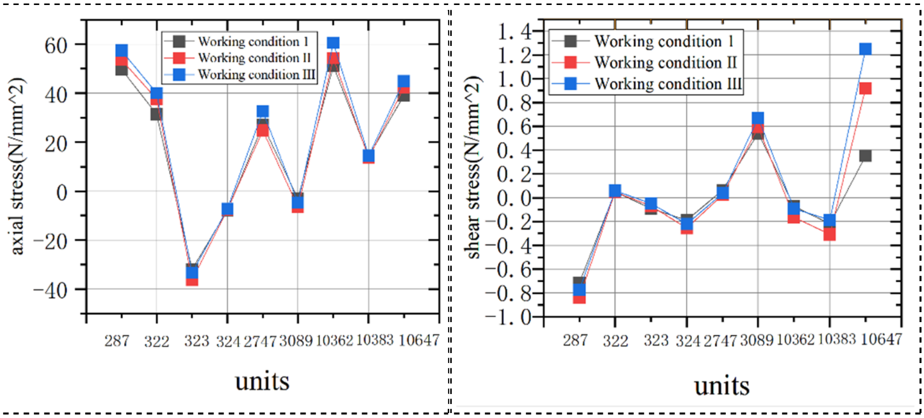

Fig. 7. Beam unit stress diagram

According to Fig. 7, it can be clearly observed that the stress values acting on the research object under different loading conditions tend to increase layer by layer. Therefore, condition three is taken as the analyzed object, and all the stresses are primarily axial. The axial stresses on the middle web rods (units 324, 3089, and 10383) are smaller than those on the other units, with values of 7.26 MPa, 4.67 MPa, and 14.4 MPa, respectively. The stresses on the remaining rods range from 30 MPa to 60 MPa, which are lower than the specification requirements, indicating that the maximum axial stresses of the roof truss meet the design requirements.

4.3 Modeling Fea nx

4.3.1 Generate Finite Element Models.

This model is selected in Midas Civil has been built in the 20 nodes related to the unit model, from the rod model to solid model export, and then imported into Fea nx to generate a solid model, as shown in Fig. 8. then according to the following steps: automatic 2D mesh delineation (mesh size control within 150mm) → apply boundary loads → define the analysis conditions → results view and analysis.

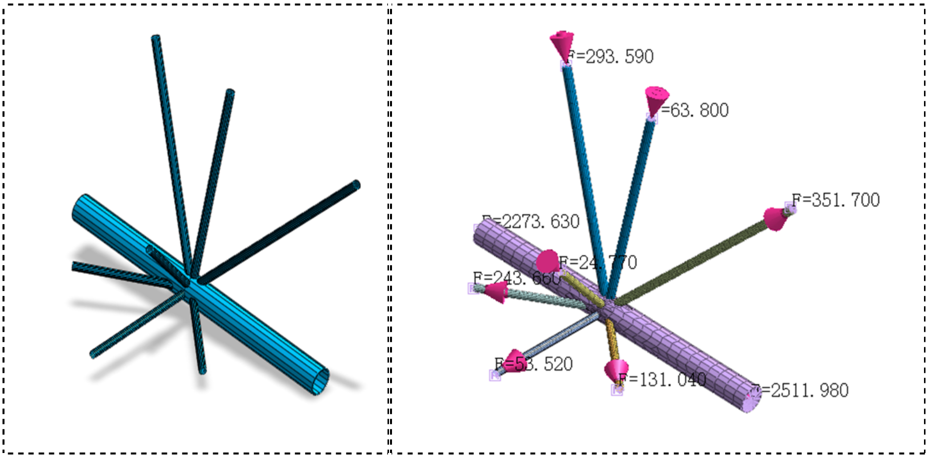

Fig. 8. 20-node truss solid model and 20-node truss loading diagram

4.3.2 Boundary and Load Application.

The materials used in this solid model and their physical property values are the same as those in Midas Civil. Fixed constraints are set on the 287 rods. To apply the axial force more smoothly, a local coordinate system is first established on each rod. Then, a node located at the center of the circle of the rod is generated using the command between two points, followed by the establishment of a rigid connection. Finally, the results obtained from the Midas Civil calculations are applied to the individual rods. The specific axial force applied on each rod is shown in Figure 8.

4.3.3 Analysis of the Results.

The 20-node model displacement and von Mises stress diagrams are shown in Figures 9, respectively.

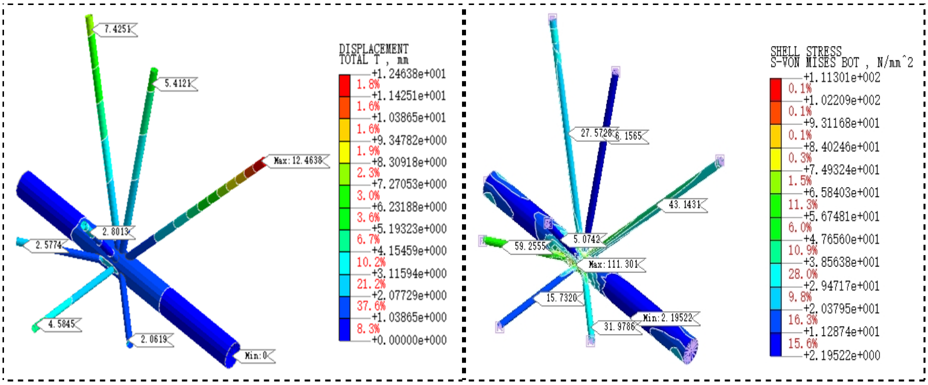

Fig. 9. 20 Nodal displacement and stress cloud

By combining the displacement resultant data from Fig. 9 with the stress resultant data from Fig. 9, it is shown that:

(1) From the displacement diagrams, it is calculated by FEA that the overall displacement of each rod significantly differs from Civil's displacement calculations. For the sake of structural design safety, the amount of displacement change is based on the most unfavorable case.

(2) From the stress diagram, it is observed that the stress distribution obtained from the Civil calculation is roughly the same, with the stress on the middle web bar being smaller than that on the other web bars. The maximum stress on the bars occurs at the junctions, with a value of 111.301 MPa, which fully meets the strength requirements of the steel. This indicates that the nodes of the bars are conservatively designed in the cross-section, and the cross-section size can be optimized to save materials and reduce costs.

5 Conclusion

In this paper, the construction process of the steel roof cover is systematically discussed through the case of the Jiangmen Riverside Sports Center Project, and each step from planning and design to actual construction is briefly analyzed and elaborated upon. Through comprehensive research on related literature and the review of actual cases, a better understanding of the key elements and technical difficulties of steel roof cover construction is achieved. Midas Civil and FEA NX are used to establish unit models for analysis, and working condition analysis is conducted before the construction of the project, which saves a significant amount of calculation time, improves the accuracy of the calculations, and provides a useful reference for the design and construction of roof trusses. It is important to acknowledge that the findings of this study are based on the construction process and analysis specific to the Binjiang Sports Center project, and may not fully generalize to other structures with different designs or construction environments. Future studies could focus on comparing different lifting techniques or exploring the impact of material innovations on the structural performance of gymnasium roofs. Additionally, further research into optimizing the use of finite element software for similar large-scale steel structures could yield more precise and generalized findings.

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