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STUDY ON THE PERFORMANCE OF LARGE-SPAN STEEL STRUCTURE OF DOUBLE-LAYER EXHIBITION HALL

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Abstract: This paper systematically studies the performance of large-span steel structure of double-layer exhibition halls 6# and 7# of Hangzhou Convention and Exhibition Center. Through detailed analysis of the structural system, material selection, node design and seismic performance of the exhibition hall, its structural performance under large span and heavy load conditions was evaluated. The research results show that the steel frame and floor truss structure system adopted in the double-layer exhibition hall not only ensures stability and bearing capacity, but also reflects the advantages of green building and prefabricated building. Finite element analysis verifies the safety and durability of the structure, providing an important reference for the design and construction of similar large-span exhibition buildings in the future.
Keywords: Large-span steel structure; Double-layer exhibition hall; Seismic performance; Node analysis

1 INTRODUCTION

With the development of economic globalization and the rapid rise of the exhibition economy, high-level exhibition infrastructure has become an important manifestation of urban competitiveness [1-3]. As an important exhibition venue in Hangzhou, the design of the 6# and 7# double-layer exhibition halls of the Hangzhou Convention and Exhibition Center must not only meet the needs of large-scale exhibition activities, but also ensure the safety and economy of the structure under large span and heavy load conditions. This paper aims to analyze the structural characteristics and performance of the large-span steel structure of the double-layer exhibition hall through in-depth research, and provide theoretical and practical support for similar projects in the future.

2 PROJECT OVERVIEW

The Hangzhou Convention and Exhibition Center is located in Nanyang Street, Xiaoshan District, Hangzhou City. The building area is about 740,000 square meters and the total construction area is 1.34 million square meters. The volume ranks first in Zhejiang Province and fifth in the country. Among them, the exhibition halls 6# and 7# of the Convention and Exhibition Center are precisely double-layer steel structures, with a length of 222 meters, a width of 104 meters, a building height of about 42 meters, and a roof elevation of about 19 meters. The main structural system includes a combination of steel frames and layer trusses, and the roof is a triangular space truss structure, which can effectively bear the above-mentioned loads of the building which can be seen in Figure 1.

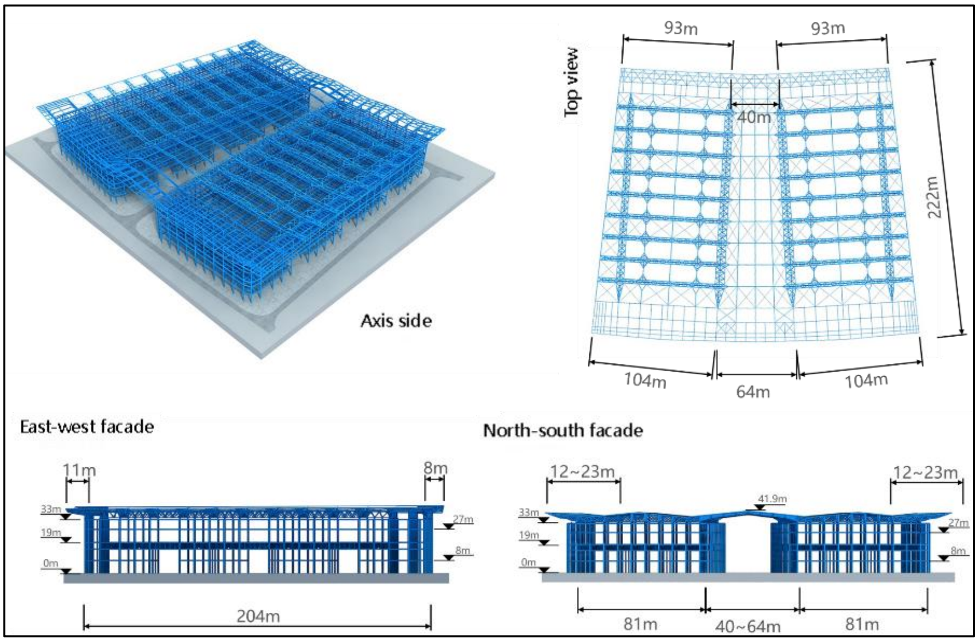


Figure 1 Overview of Double-Layer Steel Structure Exhibition Halls

3 CURRENT STATUS OF EXHIBITION HALL FLOOR SYSTEMS AT HOME AND ABROAD

By comparing the characteristics of large-span, heavy-load floor slabs and structural systems of domestic exhibition buildings, the following table 1 shows some existing double-layer or multi-layer exhibition hall floor slab systems in China. The results show that the floor span is in the range of 20-30m, and the structural form is mainly prestressed concrete floor slabs and steel trusses + concrete floor slabs.

Table 1 Floor System of Domestic Exhibition Buildings

No.	Projects	Column grid/m	Floor height/m	Floor system
1	Guangdong Modern International Exhibition Center	30×21	12	prestressed
2	Guangzhou International Convention and Exhibition Center	24×24	10	prestressed
3	Wuhan International Convention and Exhibition Center	32×17	-	prestressed
4	Hongdao International Convention and Exhibition Center	36×24	14.7	prestressed
5	National Convention and Exhibition Center (Shanghai)	36×27	16	prestressed
6	Jinan International Convention and Exhibition Center	24×24	10	prestressed
7	Hunan International Convention and Exhibition Center	21×21	12	prestressed
8	Shandong Lutai Convention and Exhibition Center	27×24	16	steel truss
9	Hangzhou International Expo Center	36×27	16	steel truss

From the perspective of overall cost, the material cost of prestressed concrete floor is lower than that of steel truss floor, but considering the current national industrial policy of vigorously developing green buildings and prefabricated buildings, steel structure is obviously a more suitable structural form for the current main development trend. Comparison of Advantages and Disadvantages of Floor Forms can be seen in table 2.

Table 2 Comparison of Advantages and Disadvantages of Floor Forms

No.	Comparison content	Floor type	
		Steel truss floor	Prestressed concrete floor
1	Comprehensive cost	3500-3800 Yuan/m^2	2700-3300 Yuan/m^2
2	Green energy saving	Meet the requirements of green building, the main materials are renewable	Does not meet green building requirements
3	Prefabricated	Meet the requirements of prefabricated steel structure	Does not meet prefabricated building requirements
4	Construction speed and difficulty	Steel structure is directly assembled, and the construction is fast. The floor truss and steel beams directly form rigidity, and the floor deck can be laid directly without formwork	Concrete structures require high formwork scaffolding, and it is difficult to bury corrugated pipes on site for prestressing and post-tensioning
5	Structural deadweight	Light weight, small earthquake response	Heavy deadweight, large earthquake response
6	Clear height	The space of the truss web can be used to arrange mechanical and electrical pipelines and maintenance horseways, which is beneficial to the clear height	Solid cross-section, pipelines need to run under the beam

4 FLOOR STRUCTURE ANALYSIS

4.1 Main and Secondary Trusses

The second floor of the double-layer exhibition hall is 81m east-west and 174m north-south; the east-west column span spacing is 27m, and the north-south column span spacing is 36m. The structural model is as shown below figure 2.

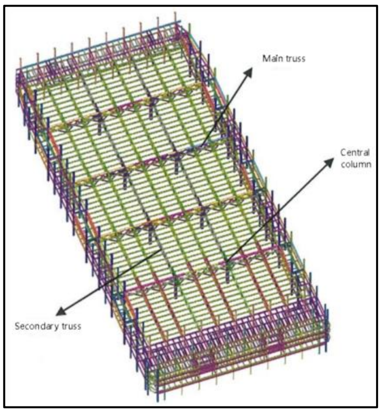


Figure 2 Double-Layer Exhibition Hall Floor Structure Model

Taking into account the secondary beam span, truss spacing and other factors, 4 3-span continuous main trusses are set in the east-west direction, with a span of 27m, supported on steel columns. There are 8 secondary trusses in the north-south direction, with a spacing of 9m, supported on steel columns or main trusses. Considering that there is still a need to pass through the horseway and large smoke exhaust pipes between the trusses, the center spacing between the upper and lower chords of the truss is 4.0m. Due to the large overall shear force at the truss support, the web members are arranged in a cross X shape, and in the middle of the truss, the web members are arranged in an inverted V shape to facilitate the passage of the horseway and pipelines. In order to reduce the inter-section distance of the upper chord of the secondary truss, a vertical web member is set every 6m. The truss elevation is shown in the figure 3 and 4 below.

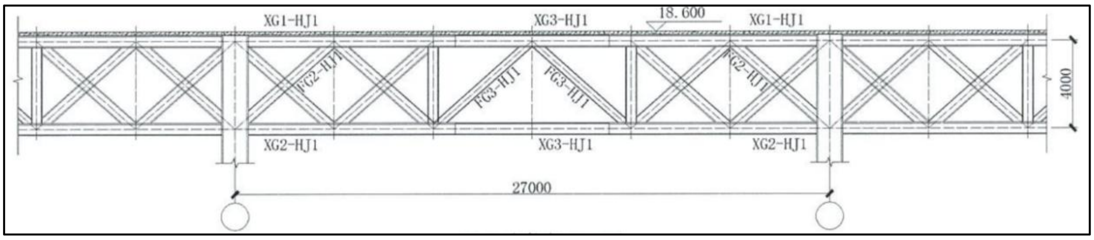


Figure 3 Main Truss Elevation

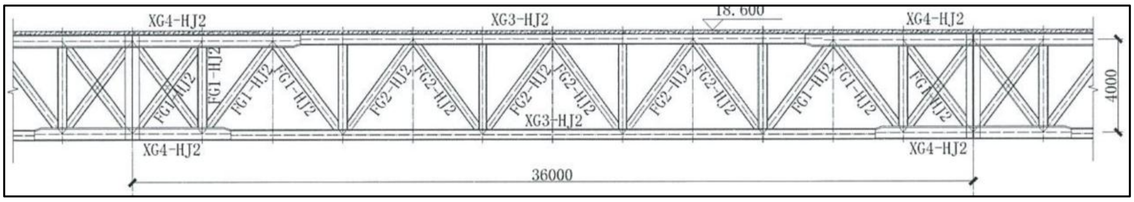


Figure 4 Secondary Truss Elevation

The truss is calculated as a whole using finite element software, and the components are inspected according to the corresponding specifications and design criteria. After empirical calculation, the maximum stress ratio of the components at the truss support is 0.91<1. The stress ratio of most members is controlled below 0.70. Taking into account the factors such as the type of cross-section of the truss members and making full use of the stress of the members, different chord and web sections are used for the support and the mid-span according to the stress section, taking into account the processing difficulty and the balance of the structural cost. The calculation results of the truss deformation are shown in the following table 3. The truss meets the corresponding deformation requirements of the specification under the action of live load and dead load + live load.

Table 3 Calculation Results of Truss Deformation

Loading conditions	Dead load + live load	Live load
Main truss deformation	35mm（1/771）	18mm（1/1500）
Secondary truss deformation	73mm（1/493）	37mm（1/972）
Deformation limit	1/400	1/500

4.2 Floor Secondary Beam

The live load of the second-floor exhibition hall floor is 15kN/m2. If the plate thickness is 150mm, then combined with the plane column grid modulus and the inter-node distance of the secondary frame, the 3m plate span is more reasonable. The floor slab adopts TD3 steel truss floor slab, in which the height of the steel truss is 120mm. The secondary beam section adopts welded H-shaped steel H600×350×12×20, with a span of 9m, and both ends are hinged to the secondary truss. The calculation results show that the maximum stress ratio of the component strength verification is 0.98. Because the rigid concrete floor is laid on the upper part of the secondary beam, the overall stability of the steel beam can be ignored. The repetition rate of the secondary beam on the floor is very high, and the steel consumption accounts for about 20% of the entire truss floor. As shown in table 4, by setting two rows of Φ19@200 bolts on the upper flange of the secondary beam to cooperate with the upper concrete floor slab to form a composite beam, the overall steel consumption is effectively reduced, and the maximum stress ratio of the secondary beam is reduced to 0.6.

Table 4 Slab Span-Load

Plate thickness/mm	Board span/m		
	Use live load 10-11kN/m^2	Use live load 12-13kN/m^2	Use live load 14-15kN/m^2
150	4.2-4.5	3.9-4.2	3.3-3.5
180	5.0-5.5	4.5-5.0	4.0-4.5

5 STRUCTURAL CALCULATION AND ANALYSIS

Since the steel roof structure of the double-layer and single-layer exhibition halls is the same, the single-layer exhibition hall is taken as an example to focus on the stress performance of the large-span steel roof structure. The roof of the exhibition hall is fan-shaped when viewed from above and folded line-shaped when viewed from the facade. It is a light steel roof system. Plane trusses are used in the cantilevered area outside the column. The change from two upper chords to one upper chord is completed at the steel column of the exhibition hall, and the lower chord bending point of the truss in the cantilevered area is set within the curtain wall line to minimize the height of the truss in the cantilevered area. A connecting truss and a cross steel tie rod are set between each truss, which not only enhances the integrity of the roof structure, but also serves as a force transmission path perpendicular to the span direction of the truss, and plays a role in lateral support for the main truss.

The upper and lower chords and webs of the main truss are all round tubes, with a material grade of Q355, and the main cross-section is 500×20 for the upper chord, 800×30 for the lower chord, and 245×8 for the web; the secondary chord is Φ351×12, and the web is Φ203×8; the steel column is Φ1200×40. The upper chord of each truss is in a broken line shape on the facade, which fits the design concept of the building. The truss section and side view are shown in the figure 5 and 6 below.

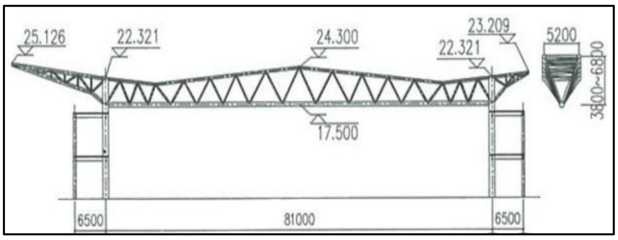


Figure 5 Main truss section

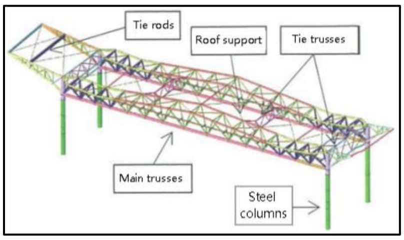


Figure 6 Main truss axonometric view

The finite element method is used to model, calculate and analyze the steel structure roof of the exhibition hall, and the three-dimensional calculation model is shown in the figure 7 below.

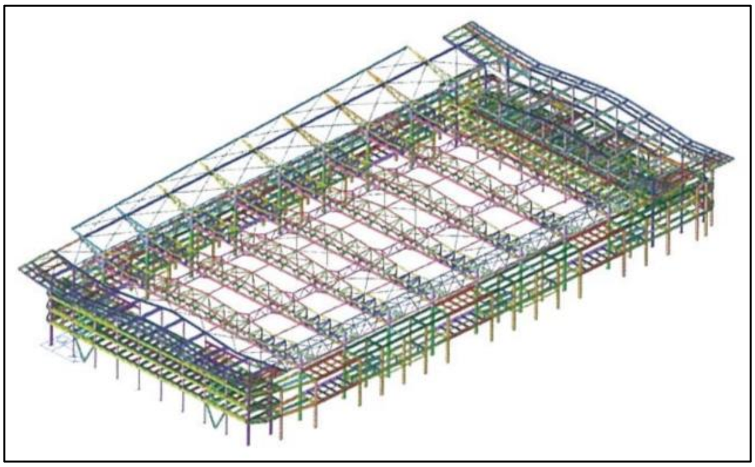


Figure 7 3D Calculation Model of the Exhibition Hall

5.1 Self-Vibration Analysis

In table 5, by performing eigenvalue analysis on the exhibition hall, the first ten vibration modes of the structure are obtained, and the first three vibration modes are shown in the figure 8-10 below. From the vibration mode results, it can be seen that the exhibition hall structure has good integrity and uniform stiffness distribution, which meets the requirements of the period ratio.

Table 5 Natural Vibration Period of the Exhibition Hall Structure

Mode	Period/s	Translation coefficient（X+Y）	Torsion coefficient
1	1.3938	1.00(0.00+1.00)	0.00
2	1.2316	0.95(0.95+0.00)	0.05
3	1.1421	0.04(0.04+0.00)	0.96
4	1.1223	0.94(0.06+0.88)	0.06
5	1.1040	0.24(0.24+0.00)	0.76
6	1.0292	0.84(0.84+0.00)	0.16
7	1.0154	0.85(0.08+0.77)	0.15
8	1.0008	0.50(0.11+0.39)	0.50
9	0.9478	0.31(0.15+0.16)	0.69
10	0.9317	0.47(0.47+0.00)	0.53

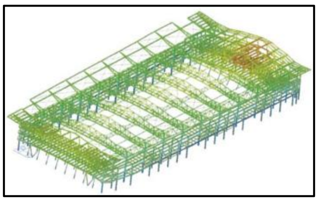


Figure 8 First-Order Translation (1.3938s)

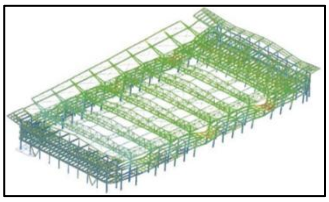


Figure 9 Second-Order Translation (1.2316s)

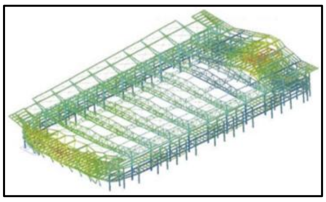


Figure 10 Third-Order Translation (1.1421s)

5.2 Deflection Analysis

The maximum roof deflection of the exhibition hall roof under the standard values of dead load and live load is 165mm, which occurs in the span, as shown in the figure 11-13 below. The arch is 100mm in the span of the truss, and the actual deflection-span ratio is: (165-100)/81000=1/1246<1/400.

The maximum roof deflection of the exhibition hall roof under the standard value of live load is 61mm, located in the middle of the truss span, see Figure 7 for details. The actual deflection-span ratio is: 61/81000=1/1327<1/500.

The maximum roof deflection of the exhibition hall roof under the representative value of gravity load and the standard value of multiple vertical earthquake action is 141mm, see the figure below for details. The actual deflection-span ratio is: 141/81000=1/575<1/250.

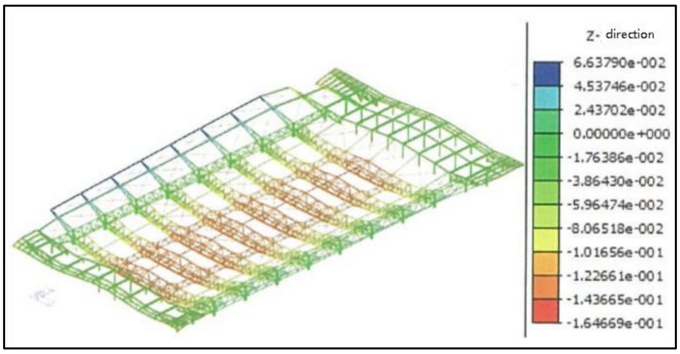


Figure 11 Vertical displacement Contour of Roof Structure under Standard Constant + Live Load

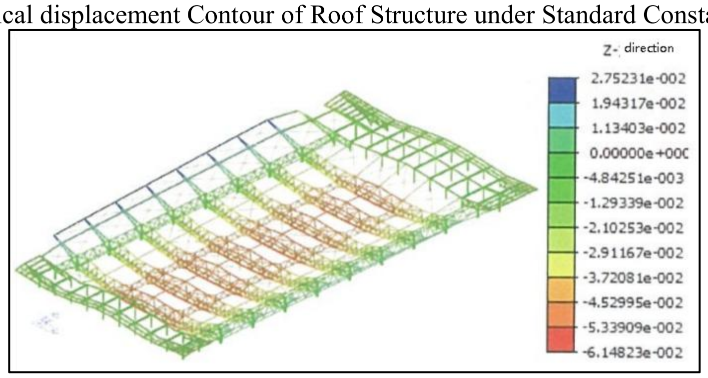


Figure 12 Vertical Displacement Contour of Roof Structure under Standard Live Load

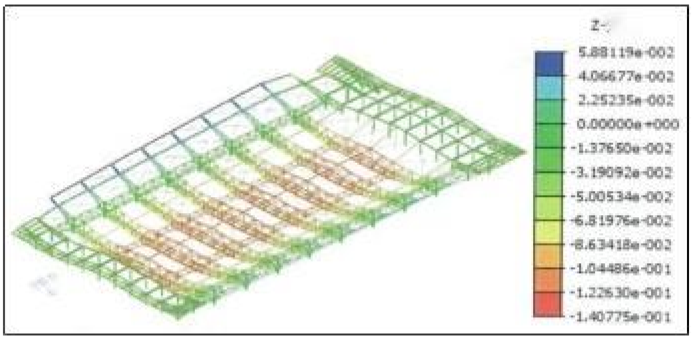


Figure 13 Vertical Displacement Contour of Roof Structure under Representative Value of Gravity Load and Standard Value of Multiple Vertical Earthquake Action

5.3 Seismic Performance Analysis

When considering moderate earthquakes, the seismic partial coefficient is taken as 1.0, and the component material partial coefficient is taken as 1.0. The figure 14 below is a stress ratio cloud diagram of steel columns and main truss members of the roof under moderate earthquake. It can be seen from the results that the steel columns and main truss members of the single-story exhibition hall are in an unyielding state, and the maximum stress ratio of the members is 0.96.

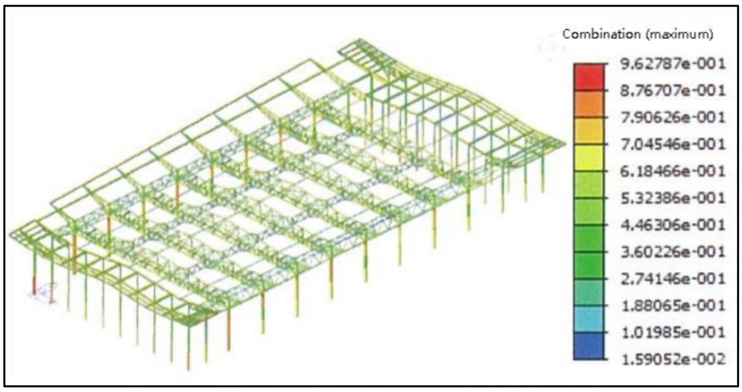


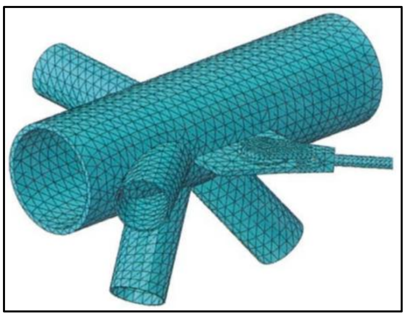
Figure 14 Stress Ratio Cloud Diagram of the Roof Structure Members of the Single-Story Exhibition Hall under Moderate Earthquake

6 CALCULATION AND ANALYSIS OF COMPLEX NODES

By selecting two typical complex stress nodes, a refined finite element analysis is performed to improve and perfect the node structure. The ideal elastic-plastic model is used for the steel constitutive model, the elastic modulus E is 2.1×105MPa, and the Poisson's ratio v is 0.3; the yield strengths of the steel pipe and the tie rod are 355MPa and 460MPa respectively.

6.1 Typical Truss Intersection Node

The cross section of the steel tie rod is a Φ50 steel bar. The model uses the solid element C3D10M; the left end of the main pipe is fixedly constrained, and the remaining members are considered as free ends; a surface-to-surface contact is set between the tie rod pin and the connecting ear plate; the node load uses the most unfavorable load combination calculated by the overall model, and the members not only consider the axial force but also the influence of shear force and bending moment under the most unfavorable combination. The node stress distribution is shown in the figure 15 and 16 below. The maximum stress is about 284.11MPa, located at the intersection of the tie rod connecting plate and the chord, that is, the stress concentration area, and the node area remains in an elastic state.



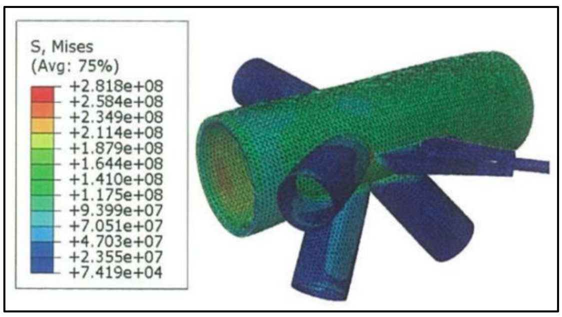


Figure 15 Three-Dimensional Model of truss Intersection Node

Figure 16 Stress Cloud Diagram of Truss Intersection Node

6.2 Roof Support Node

The column spacing of the roof structure between the double-layer exhibition halls is 40-64m. In order to avoid exceeding the length limit, brackets are set on the top of the exhibition hall frame columns, one end uses a fixed support and the other end uses a sliding support. The roof section and support details are as follows Figure17 and 18.

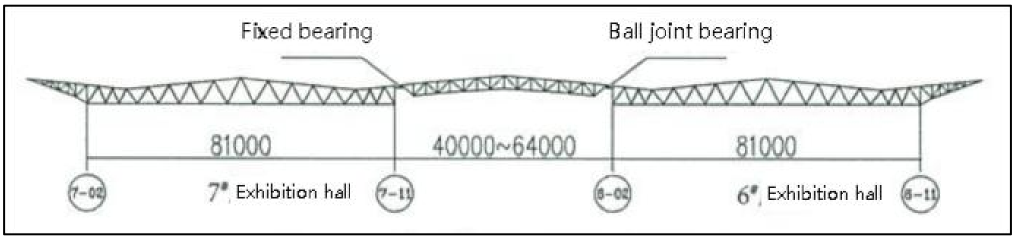
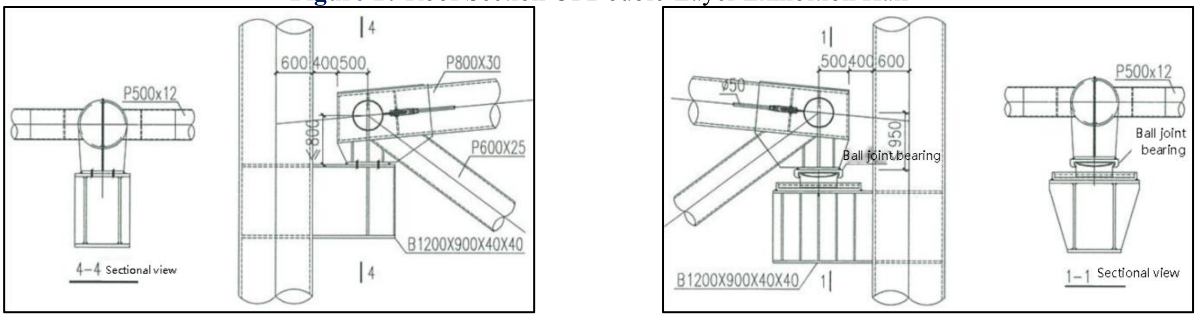


Figure 17 Roof Section Of Double-Layer Exhibition Hall



(a) Fixed End Support (b) Sliding End Support

Figure 18 Support Node Details

The fixed support node has many rods, complex structure and large force on each rod, so a refined finite element analysis is performed on this node. The three-dimensional model of the node is shown in the figure 19 below. The model uses solid unit C3D10; the four sides of the bottom plate are fixedly constrained and the remaining rods are considered as free ends; the node load uses the most unfavorable load combination calculated by the overall model, and the rods not only consider the axial force but also the shear force and bending moment. The stress distribution of the support node under the most unfavorable load combination is shown in the figure 20below. Except for the local stress concentration, the stress in most areas of the node is less than 290MPa, and the support node is basically in an elastic state.

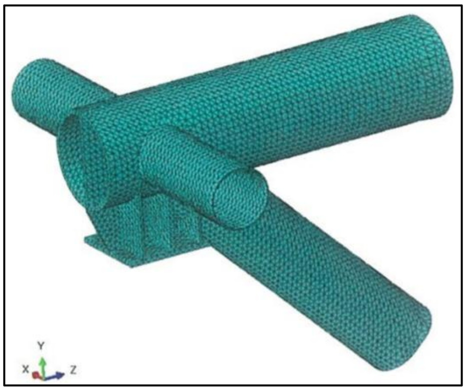


Figure 19 Support Node Three-Dimensional Model

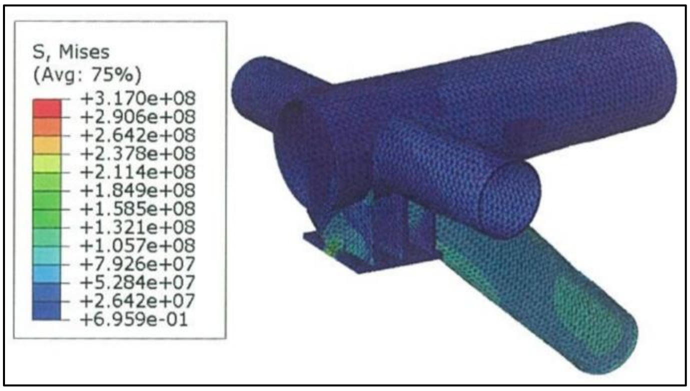


Figure 20 Support Node Stress Cloud Diagram

Based on the above overall structure and main node simulation analysis, the overall performance of the exhibition hall roof structure is good and the stiffness is uniform. However, the main truss of the large span is subjected to greater force at the support, and the triangular three-dimensional truss is transformed into a plane truss at the support. It is necessary to appropriately strengthen the strength and stiffness of this place, and take measures to strengthen the stability of the plane truss in the cantilever area.

7 CONCLUSION

This paper systematically studies the performance of the large-span steel structure of the double-layer exhibition hall of the Hangzhou Convention and Exhibition Center. The study shows that the steel frame and truss structure system of the double-layer exhibition hall has excellent stability and bearing capacity under heavy load and large span conditions, and is in line with the development trend of green buildings and prefabricated buildings. Finite element analysis verifies the safety and reliability of the structure and nodes, and provides valuable experience and reference for the design and construction of similar large-span exhibition buildings in the future. The research results not only promote the engineering practice of the Hangzhou Convention and Exhibition Center, but also have important significance for the development and technological progress of my country's convention and exhibition construction industry.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

[1] Ding Fengyao, Chen Zhaosheng, Jin Ping. Construction technology of large-span inverted triangle tube truss in Guilin New Exhibition Center. Building Structure, 2023, 53(S2): 1790-1794.
[2] Zhang Chenglong. Research on overall stability performance of double-layer cable-supported prestressed steel columns with cross cables. Chongqing University, 2020.
[3] Hu Yi. Construction technology of large-span steel truss roof for single- and double-layer combined exhibition halls. Building Construction, 2015, 37(08): 922-923.