Journal of Manufacturing Science and Mechanical Engineering
ISSN: 2959-989X
DOI: https://doi.org/10.61784/msme3009

STUDY ON THE PERFORMANCE OF STEEL STRUCTURE OF WAVY SUPER-LONG CENTRAL CORRIDOR

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Abstract: Based on the structural design and analysis of the Hangzhou Convention and Exhibition Center project, this paper focuses on the self-vibration characteristics, buckling performance and seismic resistance of the central corridor steel structure. The numerical simulation of the overall structure and key nodes was carried out by finite element software to verify the rationality and safety of its design. The research results show that the wave-shaped steel structure has good structural performance while improving the architectural aesthetics, and meets the seismic performance requirements under moderate and large earthquakes. The research in this paper provides a theoretical basis and technical reference for the design of steel structures similar to large convention and exhibition centers.
Keywords: Hangzhou convention and exhibition center; Wave-shaped structure; Steel structure performance; Self-vibration analysis; Seismic performance; Finite element analysis

INTRODUCTION

With the development of economic globalization, Hangzhou, as an important economic, cultural and transportation hub in eastern China, has attracted much attention for its urban construction projects. As an important part of the Hangzhou Airport Economic Demonstration Zone, the Hangzhou Convention and Exhibition Center project is not only ranked first in Zhejiang Province and fifth in China in terms of scale, but also reflects the integration of Hangzhou's unique landscape culture and modern architectural technology in its design concept [1]. The central corridor is the core structure of the entire exhibition center. Its wave-shaped steel structure design not only gives the building a unique visual effect, but also poses new challenges in terms of structural performance [2,3]. Therefore, a systematic study of its structural performance has important academic and engineering significance.

1 PROJECT OVERVIEW

The Hangzhou Convention and Exhibition Center project is located in Nanyang Street, Xiaoshan District, Hangzhou City, close to the estuary of Qiantang River, with a superior geographical location. The total land area of the project is about 740,000 square meters, and the total construction area is about 1.34 million square meters, including 500,000 square meters of underground construction area and 300,000 square meters of indoor net exhibition area. The architectural shape is based on the concept of "folding fan", integrating the cultural elements of "Hangzhou fan and silk", showing the profound landscape culture of Hangzhou.
Among them, the central corridor is 540 meters long, dumbbell-shaped with wide ends and narrow middle, and the overall shape is a multi-wave silk form. The corridor is divided into four parts: the west entrance hall, the west section of the middle corridor, the east section of the middle corridor and the east entrance hall. The structural system is symmetrical and similar. The following Figure 1 and 2 takes the east section of the middle corridor as the research object to deeply explore the rationality of its structural design and performance.

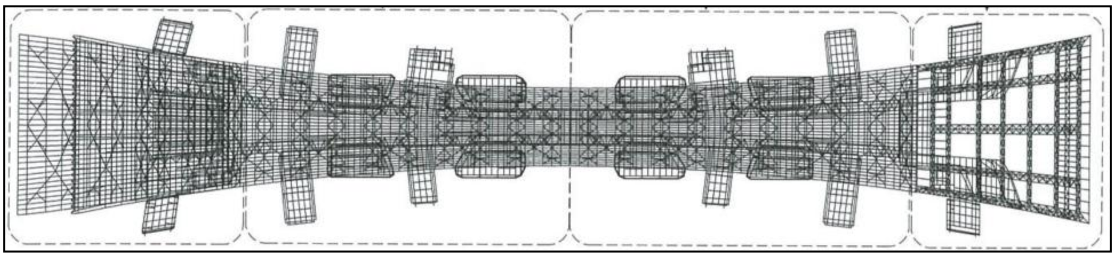

Figure 1 Plan of the Central Corridor

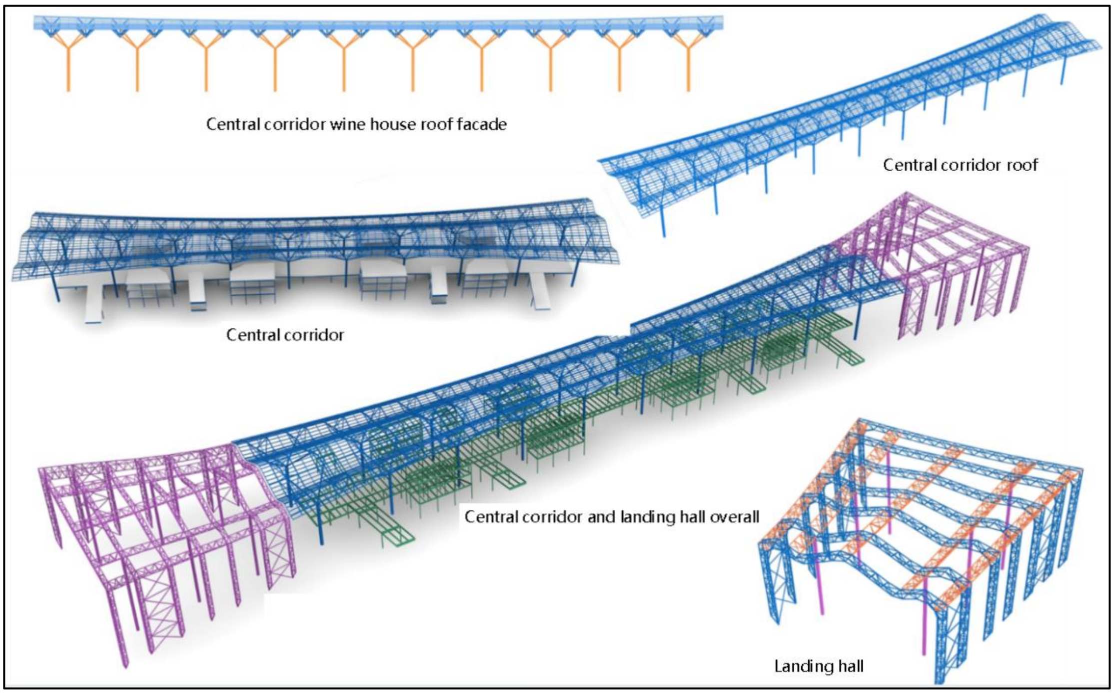

Figure 2 Schematic Diagram of the Steel Structure of the Central Corridor

2 DESIGN OF THE WAVY STEEL STRUCTURE OF THE EAST SECTION OF THE MIDDLE CORRIDOR

2.1 Structural System

As shown in Figure 3-5, the east section of the middle corridor is divided into two parts: the roof support structure and the lower frame. The roof and the roof of the lower frame are open. The roof of the east section of the central corridor is 180m long and 40m-66m wide. The highest point of the ridge is about 39m. The roof support structure is composed of tree-shaped columns and transverse triangular trusses, and the longitudinal direction is connected by roof beams. The horizontal column distance of the tree-shaped column is 21m-32m, the vertical column distance is 36m, the main trunk height is 22m, the main trunk top is divided into 4 branches, and the branch top supports the lower chord node of the transverse triangular truss. The roof is six-slope wavy, and the foot of the tree-shaped column is rigidly connected to the pedestal or transfer beam. The lower part is scattered with four three-story steel frames, the roof is 19m high, and is connected in series through the corridor on the second floor. The corridor bridge is connected to each exhibition hall through a sliding support. The lower frame is equipped with a V-shaped horizontal support on the second floor plane and is hinged to the main trunk of the structural column of the roof structure.

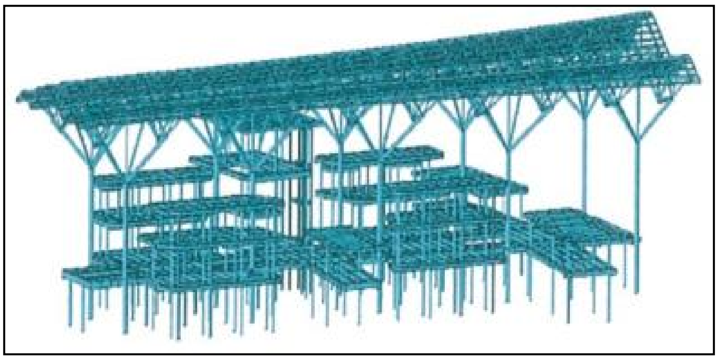

Figure 3 Overall Structural Model of the East Section of the Central Corridor

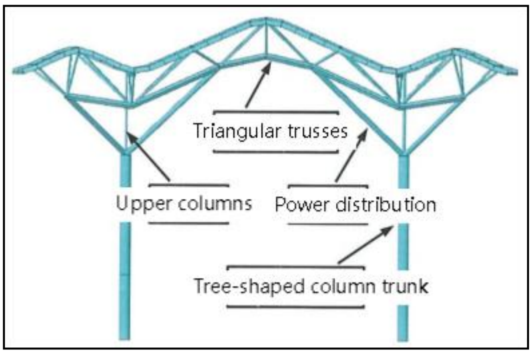

Figure 4 Horizontal Composition of the Roof Structure

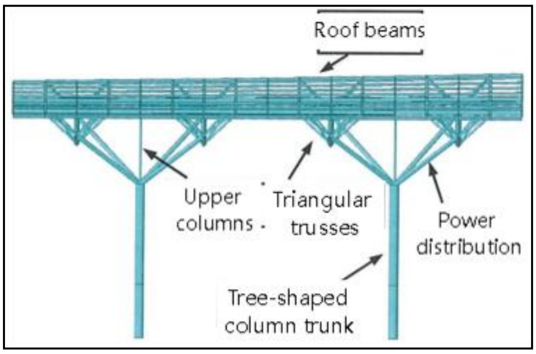

Figure 5 Vertical Composition of the Roof Structure

2.2 Structural Calculation and Analysis

2.2.1 Self-vibration analysis

Using finite element spatial structural analysis software, the natural vibration period and vibration mode are obtained through eigenvalue analysis under the action of (1.0×constant+0.5×active). The frequencies and periods of the first 6 vibration modes of the structure are detailed in the table 1 below.

Table 1 Frequency and Period of the First 6 Vibration Modes

Mode number	Frequency/Hz	Period/s
1	0.2406	4.1566
2	0.3154	3.1707
3	0.3410	2.9323
4	0.5467	1.8292
5	0.5539	1.8055
6	0.5902	1.6942

Due to the sliding support, the first 3 vibration modes are the lateral swing of the bridge, and the 4th to 6th vibration modes are shown in the figure below. From the vibration mode results, it can be seen that starting from the 4th vibration mode, the roof is longitudinal translation, torsion and lateral translation in turn. The span of the west column is small and the stiffness is large. The roof has good integrity and no local vibration occurs which can be seen in figure 6-8.

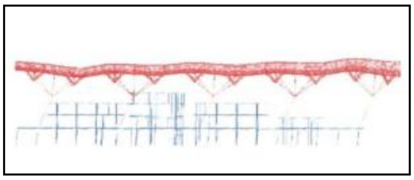

Figure 6 Order Vibration Mode Diagram

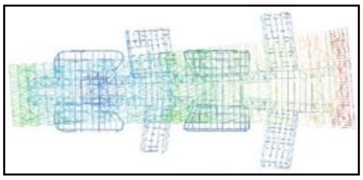

Figure 7 5th Order Vibration Mode Diagram

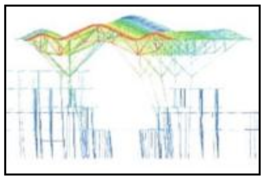

Figure 8 6th Order Vibration Mode Diagram

2.2.2 Buckling analysis

The force characteristics of the tree-like structure are typical spatial structural mechanics problems. The good shape effect makes the rod bear a large axial force, so the stability problem is particularly important. Since the tree-like structure system is still relatively rare in domestic engineering applications, there is still a lack of systematic theoretical research results on the calculation length coefficient of the rod. The following uses elastic buckling analysis and the Euler formula to inversely calculate the calculation length coefficient β of the rod.

$$\beta = \sqrt{\frac{\pi^2 EI}{kNL^2}} \tag{1}$$

Where, E is the elastic modulus (N/mm2); I is the moment of inertia around the corresponding neutral axis (mm4); k is the first-order buckling coefficient; N is the buckling analysis unit force (N); L is the geometric length of the rod (mm). A 100kN pressure is applied to the top of the tree-shaped column trunk and both ends of the branch on the east section of the central corridor. The load diagram is as follows Figure 9 and 10.

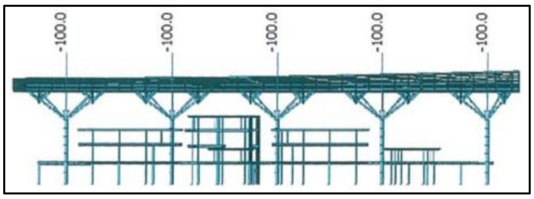

Figure 9 Schematic Diagram of Buckling Load of Tree-Shaped Column Trunk

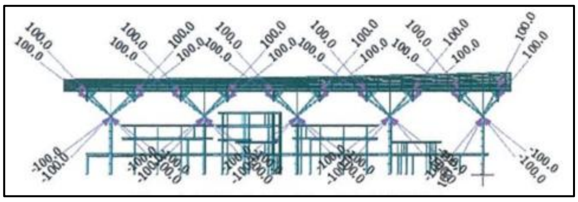

Figure 10 Schematic Diagram of Buckling Load of Tree-Shaped Column Branch

Buckling analysis was performed separately. The first-order buckling coefficient of the tree-shaped column trunk is k=680, and the first-order buckling coefficient of the branch is k=393. The buckling mode is shown in the figure 11 and 12 below.

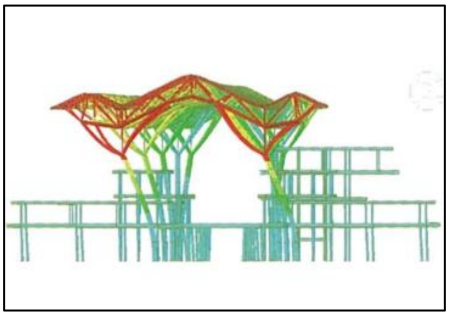

Figure 11 First-Order Buckling Mode of Tree-Shaped Column Trunk

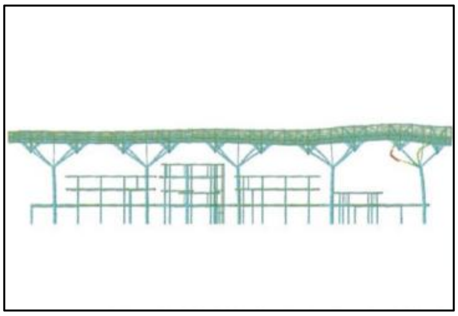

Figure 12 First-Order Buckling Mode of Tree-Shaped Column Branch in the East Section of the Central Corridor

Tree-shaped column trunk geometric parameters: P1300×40, column length L=22m, moment of inertia $I=3.145\times10^{10}mm^4$; calculated length coefficient β=1.4, which is between one end fixed, one end free and one end fixed, one end hinged. Slenderness ratio t=1.4×22000/446 =69.1<100（$235/f_{ay}$）$^{1/2}$ =81.4.

The geometric parameters of the tree-shaped column branch are: P700×40, rod length L=17.6m, moment of inertia $I=2.472\times10^{10}mm^4$; the calculated length coefficient β=0.64, which is between one end fixed, one end free and one end fixed, one end hinged. The slenderness ratio t=0.64×17600/241=46.7<100（$235/f_{ay}$）$^{1/2}$ =81.4.

2.2.3 Seismic performance analysis

Taking into account the complexity and importance of the central corridor steel structure, the performance target C is adopted. Small earthquake: all steel components remain elastic; medium earthquake: all steel components remain elastic; large earthquake: key components do not yield. The key components are the main trunk and decentralization of the tree-shaped column, the chord and web of the two grids of the roof truss close to the support, the column transfer beam and the connected column, see the figure below for details.

Under moderate earthquake, the equivalent elastic method is adopted, the bearing capacity seismic adjustment coefficient γRE is not considered, the load partial coefficient is not considered, the earthquake action considers bidirectional earthquake, and the internal force amplification adjustment of the component seismic grade is not considered; both key components and ordinary components are checked according to the material strength design value. The stress ratio of all components is shown in the figure 13-16 below.

The maximum stress ratio under moderate earthquake is 0.86<[ρ]=1.0. The test results show that the structure can meet the performance target requirements of moderate earthquake elasticity of all components.

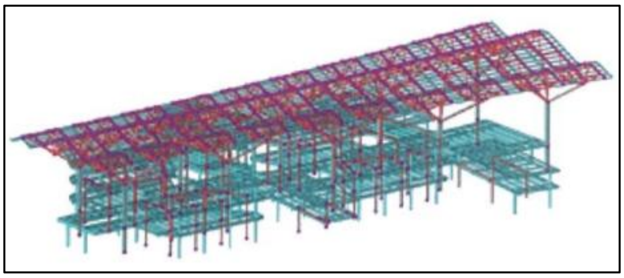

Figure 13 Scope of key components (red)

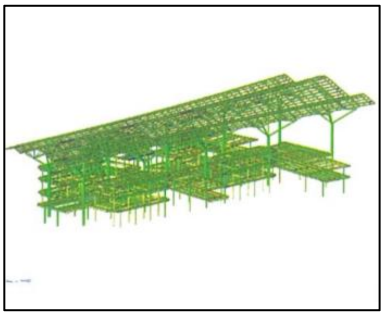

Figure 14 Stress ratio diagram (calculated according to design strength for moderate earthquake)

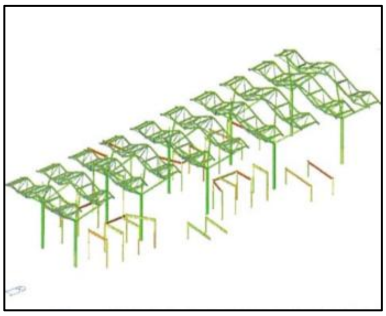

Figure 15 Stress Ratio Diagram of Key Components (Calculated According to Yield Strength for Large Earthquake)

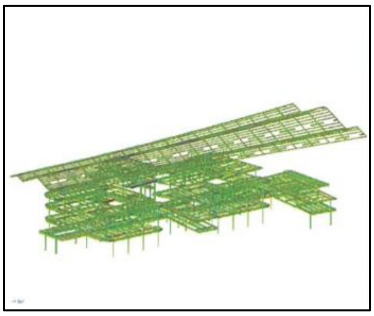

Figure 16 Stress Ratio Diagram of Ordinary Components (Calculated According to Ultimate Strength for Large Earthquake)

Under the action of large earthquake, the equivalent elastic method is adopted, the bearing capacity seismic adjustment coefficient γ_{RE} is not considered, the load partial coefficient is not considered, the earthquake action considers bidirectional earthquake, and the internal force amplification adjustment of the component seismic grade is not considered; the key components are checked according to the material yield strength, and the ordinary components are checked according to the bearing capacity limit value; the static elastic-plastic analysis method is adopted to examine the deformation and seismic performance of the entire structure under the action of large earthquake. The stress ratio of key components and ordinary components is shown in the figure above.

The maximum stress ratio of key components under large earthquake is 0.97, and the maximum stress ratio of ordinary components is 0.87. The structure can meet the performance target requirements of non-yielding of key components and non-destruction of ordinary components in large earthquakes.

2.3 Calculation and Analysis of Main Nodes

The tree-like structure has many oblique nodes and complex structure. The rod unit cannot simulate the stress of the node, so the finite element software is used to perform entity unit modeling and analysis. The steel used in the model is the same as the design. The materials take into account geometric nonlinearity and material nonlinearity, and the Mises yield criterion and multilinear kinematic hardening criterion are adopted. The stress and strain relationship of the steel adopts the three-fold line model with an elastic modulus of $E=2.06\times10^5$MPa and a Poisson's ratio of $\mu=0.3$.

2.3.1 Bifurcation top node

The entity unit model of the bifurcation top node is shown in the figure below. It is the intersection node of the bifurcation top and the lower chord of the transverse triangular truss. The bifurcation section is Φ700×20, the section of the lower chord of the truss is B500×20, and the section of the truss web is Φ325×14. There are 4 16mm thick stiffening plates in the node domain. The finite element model uses the C3D8M entity element type, the steel material is Q355, the design strength is 290MPa, the yield strength is 355MPa, the fixed support is at the lower branch, and the ends of the other rods are all loading parts. The input load of the node is the most unfavorable load combination derived from the overall calculation model, and its stress distribution is shown in the figure 17 and 18 below. The results show that the maximum stress is located at the junction of the lower branch and the lower chord, which is about 286MPa. The rest of the parts remain in an elastic state and can meet the design requirements.

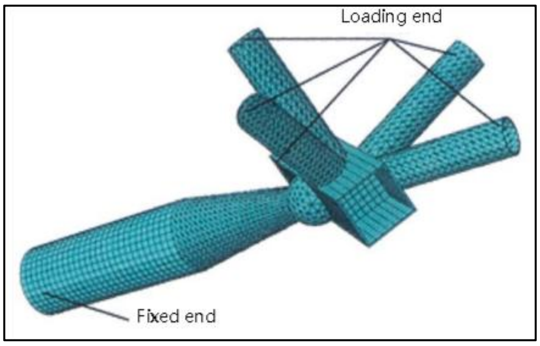

Figure 17 Finite Element Model of the Top Node of the Branch

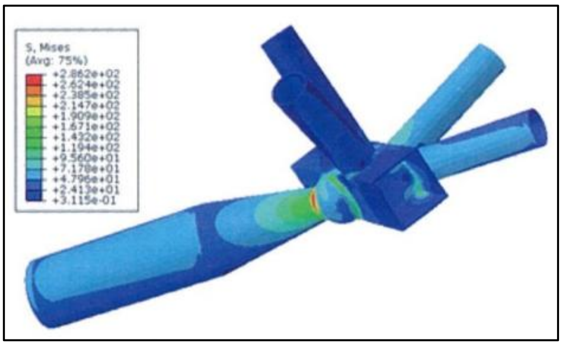

Figure 18 Stress Cloud Diagram of the Top Node of the Branch

2.3.2 Tree-shaped column branch cast steel node

The entity element model of the tree-shaped column branch cast steel node is shown in the figure below, which is the intersection node of the tree-shaped column trunk and the branch. The intersection of the main and secondary pipes of this type of node needs to be continuous and smooth, and the processing and construction requirements of the node are relatively high. However, traditional welded nodes are difficult to ensure the safety of the node, so cast steel nodes are often used. The finite element model uses the C3D4 entity unit type, the steel is G20Mn5QT (design strength 235MPa, yield strength 300MPa), the fixed support is at the right end, and the ends of the remaining rods are all loading parts. The input load of the node is the most unfavorable load combination derived from the overall calculation model, and the stress distribution is shown in the figure 19and 20 below. The results show that the maximum stress of the node is about 66MPa, and the whole is in a linear elastic state. The force performance of the cast steel node meets the requirements.

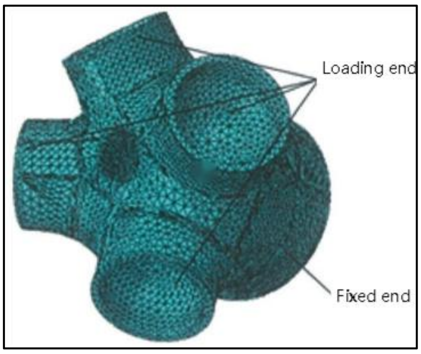

Figure 19 Finite Element Model of Tree-Shaped Column Branched Cast Steel Node

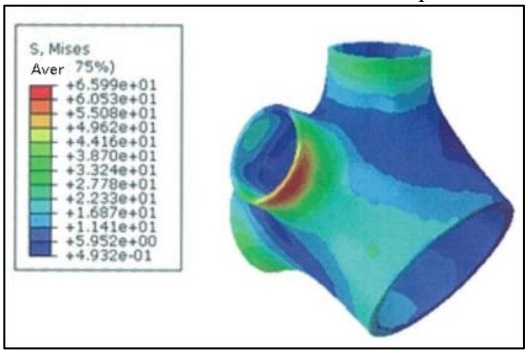

Figure 20 Stress Cloud Diagram of Tree-Shaped Column Branched Cast Steel Node

Based on the above overall structure and main node simulation analysis, although the roof structure is a single span in the horizontal direction, due to the effect of the tree-shaped space structure and the roof triangular truss, the lateral stiffness is good; the longitudinal tree-shaped structures are only connected as a whole by the roof beam, similar to the multi-span continuous frame, and the longitudinal stiffness is weak. Due to the large difference in the horizontal and vertical scales and the gradual increase in the horizontal column span from west to east, the stiffness distribution of the roof structure is asymmetric and the torsion effect is obvious. Corresponding strengthening measures should be taken to ensure the safety of the structure.

3 CONCLUSION

The rationality and safety of the design of the wavy steel structure of the eastern section of the central corridor of the Hangzhou Convention and Exhibition Center were verified through structural calculation and analysis. The self-vibration analysis shows that the structure has good vibration characteristics, and the buckling analysis and seismic performance test show that the structure can meet the design requirements under both moderate and large earthquakes. The finite element analysis further confirmed the stress performance of the key nodes and ensured the stability and safety of the entire structure. The wavy steel structure not only has unique advantages in architectural aesthetics, but its structural performance also fully meets the use requirements of large exhibition complexes. This study provides valuable experience and reference for the design and optimization of similar large steel structure buildings in the future.

COMPETING INTERESTS

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

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