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The New Structural Design Process of Suspended Structure

Bao Lianjin[1,2†], Chen Jianxing[1,2], Ji jun[1,2], Xiao Jian[1], and Liu Yingxue[1]

[1]*East China Architectural Design & Research Institute Co., Ltd., Shanghai 200002, China*
[2]*Shanghai Engineering Research Center of Super High-Rise Building Design, Shanghai 200002, China*

Abstract As a type of vertical transformation of structures, the Suspended Structure System can provide flexible building space and achieve simple architectural effects and is increasingly used in high-rise buildings. This paper summarizes the force characteristics of the suspended structure, explains the force transmission path of the suspended structure from structural system selection, layout, detailing, construction plan, etc., and achieves an organic balance between simplicity of stress and structural redundancy. Suspended structures have injected new vitality into the development of high-rise building structural systems.

Keywords Suspended structure, High-performance Structural material, Transfer structure, Construction simulation, Structure monitoring

[†]Corresponding author:
Bao Lianjin
E-mail:
Lianjin_bao@ecadi.com

1. Introduction

As a relatively new structural system, the suspended structure is able to realize the special functions required by public buildings, perfect architectural effects, and flexible use of space.

Suspended structures can cross obstacles such as rivers, railways, and subway sections, such as the London Stock Exchange (Figure 1, crossing the railway), the Chinese Academy of Sciences Quantum Innovation Institute (Figure 1, crossing the spillway), etc. In addition, the column-free space under the suspended floors of the suspended structure can flexibly arrange building functions and provide continuous public shared space, such as the Hong Kong HSBC Bank (Figure 2).

Suspended structures have unique advantages in shaping building facades. The exterior columns of the suspended structure are not supported on the ground, which has a special effect of suspension, such as Kaohsiung Library, Shenzhen DJI Sky City, etc. The peripheral hangers have smaller cross-sections, which appear to be lighter and more transparent from the facade, such as Shanghai Jinqiao Guopei Center. Using key components such as transfer structures as exposed components can demonstrate the beauty of structural mechanics, such as the London Stock Exchange, Shenzhen DJI Sky City

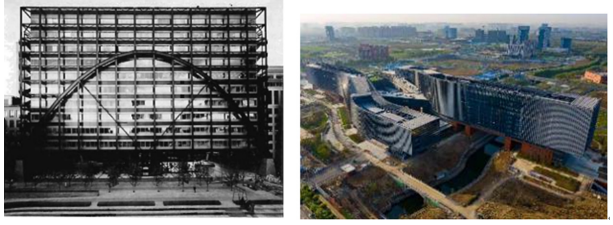


Fig. 1. London Stock Exchange and Chinese Academy of Sciences Quantum Innovation Institute



Fig. 2. Hong Kong HSBC Bank and Shenzhen DJI Sky City

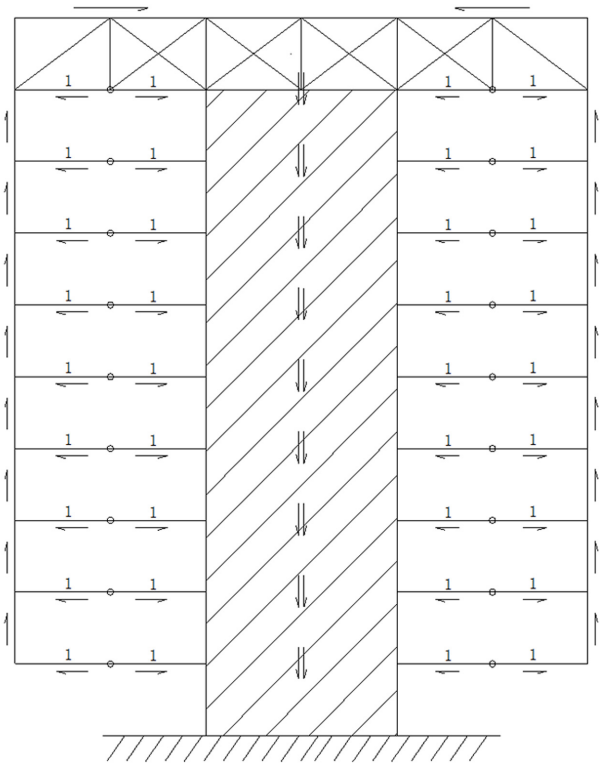


Fig. 3. Vertical load path of suspended structure.

(Figure 2), etc.

Since the hangers are not supported on the ground, the vertical load path of the suspended structure is significantly different from that of the conventional frame-core structure (Figure 3). The weight of the suspended floor is transferred to the supporting core through one or more sections of the transfer structure. The difference in vertical deformation of the structure is greater. In addition, the vertical comfort problem of human-induced vibration in suspended floors has become relatively prominent. Under horizontal loads, the supporting core bears almost all seismic shear forces and wind loads. Additionally, the structural mass is no longer uniformly distributed along the vertical direction of the supporting core, and it has a relatively large height-to-width ratio. Therefore, the second-order effect of gravity loads needs to be considered in the overall analysis of the structure and the components. The vertical seismic effect of the structure shall not be ignored. Finally, due to the special force transmission system, the construction plan of the suspended structure also needs to be specially formulated.

2. Structural System and Layout

2.1. Structural system selection

The suspended structure consists of multiple sub-structures such as supporting core, transfer structure, hanging structure, floor structure and etc. The core structure is located in the center or exterior of the tower and bears all the vertical and horizontal loads of the structure. The transfer structure is located at the top or middle of the supporting core. It is supported on the core structure, and is used to support hangers and transfer the load of the hangers to the core. The hanging structure includes hanger columns and perimeter beams, which transfer the loads from the floor to the transfer trusses. The floor structure consists of secondary beams and floor slabs, which transfer loads to the hanging structure.

Suspended structures can be divided into overall suspension or partial suspension according to the level of transfer structure. Beijing Poly Building partially adopted diagonal bracing suspension. Shanghai Jingdong Headquarters Building adopted a combination of suspended structure and vertically supported structure. Due to the inclined building shape, the CCTV Building used transfer trusses on the MEP level to suspend the lower part of the floors in the middle and high areas with large spans, supporting the upper part of the floors and reducing the span of the beams. The bottom skirt structure of Shanghai North Bund Center adopted inclined columns to suspend the podium floor outside the tower plane (Figure 4). This paper focuses on the overall suspended structure.

The suspended structure can be divided into single-core, double-core, triple-core, or multi-core according to the number of supporting core structures, which is usually less than four. The aspect ratio of the single-core structure is large, and the requirements for the lateral force-resistant structure of the core are relatively high. Two or more supporting cores form a mega frame through transfer

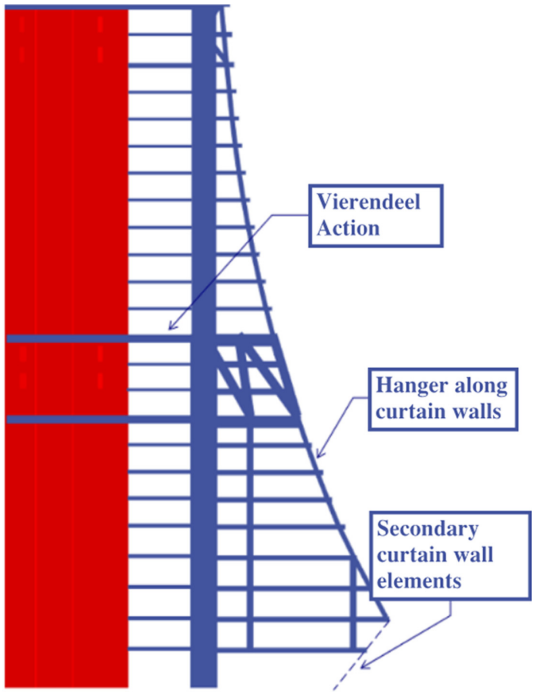


Fig. 4. The skirt suspended structure of Shanghai North Bund Center.



Fig. 5. Jinqiao National Training Center.

trusses with large spans, such as the double-core Hong Kong HSBC Bank, the triple-core Shanghai Caohejing Beiyang Artificial Intelligence Town, and the quadruple-core Kaohsiung Library.

According to the height of the building and the setting of the refuge level, the suspended structure can be in one or multiple sections. According to the specification, the distance between fire protection zones in high-rise buildings is less than 50 m. Therefore, in high-rise buildings with a building height greater than 100 m, multi-section suspension can be adopted in combination with the refuge level. The total number of floors in a single-suspension is about 8 to 10. When divided in sections, no column or vertical element is required on the floor between the upper and lower suspended levels, creating a column-free space such as sky gardens. Of course, exceptions exist in high-rise buildings of about 100 meters, which do not need a refuge floor in the middle. In order to save the space occupied by the conversion structure, single suspension can also be adopted. The Jinqiao National Training Center has 16 suspension floors, which is one of the suspended structures with the largest number of suspension floors and internationally (Figure 5).

The supporting core system can be divided into two categories: reinforced concrete structure and steel structure. Steel components such as H-shaped steel and steel plate shear walls can be embedded in the reinforced concrete structure to form a composite structure. The selection of supporting core is mainly determined based on factors such as building height, earthquake intensity, detailing, cost, and period of construction. The reinforced concrete core has good vertical and lateral stiffness. When the earthquake intensity is moderate and the transfer truss is set up to be suspended on the roof, the reinforced concrete core is suitable and more economical. The steel braced frame core has the advantages of good seismic ductility, simple detailing, and fast construction speed. When multi-section suspension is used, since the connection between the transfer truss and the concrete shear wall in the middle floor is relatively complex, it is more appropriate to use steel braced frame supporting core. Suspended structures in high seismic intensity zone usually adopt steel braced frame as supporting cores. Compared with reinforced concrete structures, the cost of steel frame support tubes is higher, and the requirements for fire protection and corrosion protection are higher.

The transfer structures used to support hangers in suspended structures usually include steel trusses, arch structures or reinforced concrete prestressed girders. Steel truss structures are widely used, but the diagonal web elements of the trusses also bring difficulties to the use of building space. The Standard Bank Building in South Africa adopted prestressed concrete girders to hang steel hangers to suspend 12 floors. The London Stock Exchange used a steel arch structure to realize the construction over the existing railway line.

The cross-section of the hanger can be box-type, wide flange, steel rod or flat steel, depending on the axial force of the hanger, splicing method and the requirements of the building facade effect. If the number of suspended floors is moderate, it is ideal to use high-strength steel rods with a slender cross-section. The hangers in Kaohsiung City Library and Shanghai Library East Branch are both made of steel rods with a yield strength of 850MPa. If the axial force of the suspension column is large, it is necessary to use wide flange or box-type cross-section. For example, the Shenzhen DJI Headquarters Building and Guiyang 201 Building use box-type cross-sections for the hangers with large tensile bearing capacity and strong bending resistance.

The suspended floor usually adopts steel beam & composite floor structure, mainly to reduce the dead load of the structure. The key of floor layout is to make sure that the force distribution in each hanger is as even as possible. In addition, the suspended structure also has a relatively high demand for the bearing capacity of the foundation. The pile foundation with a better bearing layer is usually arranged under the mat slab within the projection range of the supporting core.

2.2. Energy dissipation

The suspended structure integrates a load-bearing structure and a lateral force-resisting structure, and is a single



Fig. 6. Photo Kaohsiung Municipal Library.

lateral force-resisting system. Except that the link beams or steel braces that are allowed to enter plasticity zone under maximum considered earthquakes, the concrete shear walls or steel frames basically remain elastic, and there are not many energy-consuming components in the structure. Therefore, it is necessary to arrange energy-dissipating devices in the suspended structure.

The energy dissipation device mainly depends on the type of core. The supporting structure of Jinqiao Guopu Center adopts a single-core shear wall structure, and 68 sets of viscous dampers are arranged between the shear wall to provide an additional damping ratio of 1.0% under frequent earthquakes, which can reduce 10% seismic shear force. The four supporting cores of the Kaohsiung Municipal Library adopt a steel frame with buckling restraint braces (BRB) as the supporting core. The BRB will yield under design-base and maximum considered earthquakes, dissipating seismic energy and protecting the safety of the main load-bearing structure (Figure 6).

2.3. Application of high performance material

The transfer structure is used to support the hanger of the suspended structure. It has a high bearing capacity requirement and a low degree of plasticity under the action of maximum considered earthquakes. In theory, it is very suitable to use high-strength steel (with a yield strength higher than 460 MPa according to Chinese standards). However, due to the large thickness of the steel plates of these steel components and the huge axial force, it is very difficult to use high-strength bolts to connect the component. Most of them are welded, and high-strength steel has the problem of reduced strength in the welding heat affected zone. Therefore, it is relatively rare to use high-strength steel above Q550 in the transfer components of the suspended structure. The hangers mainly bears vertical tension with no stability issue. The cross-section can be designed into an open cross-section such as wide flange and spliced with high-strength bolts. Therefore, the suspender column is one of the most suitable components for using high-strength steel. The hanging column of the Shanghai Financial Lingang West Nine Building, whose architectural scheme has not been completed, adopted Q690 high-strength steel.

Reducing the structural weight of suspended floors is crucial to improving the mechanical performance of suspended structures. In addition to using lightweight partitions, using lightweight concrete on the floor is also one of the measures that can effectively reduce the weight of the structure. The suspended floors of the Jinqiao Guopu Center use lightweight aggregate concrete with a bulk density of 16.0 kN/m^3, which greatly reduces the weight of the suspended structure, and also reduces the foundation bearing capacity requirements and the seismic effects of the tower.

3. Component and Connection Design

3.1. Transfer structure

Transfer structure in the suspended structure transfers the vertical load of the hangers to the supporting core structure and is the hub of the load-bearing system of the suspended structure.

3.1.1. Selection of Transfer Structure

The transfer structure of the Bundled-Core Suspended System needs to be cantilevered from the core to hang columns. Cantilever truss or a cable-stayed structure can be adopted. The cantilever truss bears a large vertical load and has a long cantilever length, most of which are greater than 9m. Its height-to-span ratio is generally 1/2~1/3, or even close to 1.0, such as Shenzhen DJI Sky City and Guiyang 201 Building. Compared with the cantilever truss, the cable-stayed structure has a simpler load path and higher efficiency in force transmission. It is also one of the reasonable structures for cantilevering, such as the West Coast Broadcasting Building in Vancouver, the Hong Kong HSBC Headquarters Building and the Shenzhen Taohuayuan Project. In order to improve structural efficiency and reduce additional horizontal forces, the height-to-span ratio of the cable-stayed structure is relatively large, generally greater than 1.0.

Transfer structure in Giant Frame Suspension System spans between adjacent cores and is used to hang suspended floors. Transfer trusses, suspended cable structures or arch structures are usually adopted. In addition to vertical load bearing, the transfer trusses not only connect the adjacent cores, but also serve as the giant beams of Giant Frame Structures, and become part of the lateral force-resistant system of the main structure. The seismic performance objective of the giant beam is often improved to unyielding under maximum considered earthquakes.

3.1.2. Transfer Truss Connection Design

3.1.2.1. Truss member connections

Transfer truss of the suspended structure is subjected to large forces, and the cross-section of their components

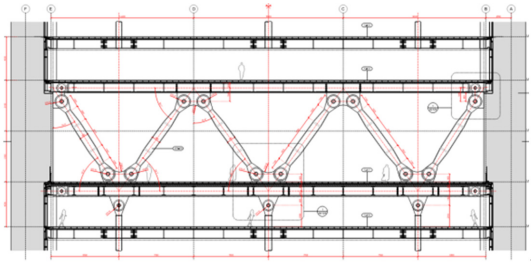


Fig. 7. Shenzhen Kingboard Headquarters Building.

are large. Box-shaped sections are mostly adopted with welded connections. Truss connection should keep the load path simple, avoid the thick plate from bearing tension in Z direction, reduce the number of stiffeners in the box-shaped section, and reduce the welding difficulty, defects and residual stress in welds.

When the slenderness ratio of the truss members is relatively small, a large secondary bending moment may occur at each end due to the relative deformation between the truss segments. The stress caused by the bending moment at the rod end accounts for more than 50% of the total stress of the truss members. To eliminate the secondary bending moment at the member ends, pins joints may be adopted for connection. The force in truss members of the suspended structure is large, therefore the pin size is also larger. For example, in the Shenzhen Kingboard Headquarters Building (Figure 7), the diameter of the pin reaches 340 mm.

3.1.2.2. Connection between truss and core

When the core is reinforced concrete structure, the connection between the trusses and the core should be as simple as possible. Steel members are often embedded in the core wall, and the forces transmitted from the connections are spread into the reinforced concrete wall through the steel members.

When the trusses are located at the top of the core and are arranged symmetrically, in order to reduce the horizontal forces and bending moments transmitted from the truss to the core, the trusses can be placed on the top of the core. During construction, the core bears only the vertical reactions of the supports of the trusses. The truss supports can be made of mild steel or steel with lower strength to avoid excessive stress concentration at the contact points when the truss is bent, thereby distributing the vertical force evenly. After the main structure is completed and most of the dead load has been applied, the top of the core and the lower chord of the truss will be connected to improve the overall structural integrity.

3.2. Hangers

In suspended structure, the hangers can be flexibly arranged according to architectural functions and aesthetic requirements of the building, including hanger spacing, cross-section, etc.

3.2.1. Characteristics of Hanger Forces

The hanger mainly bears the vertical load. Even if the spacing between the hangers is the same, the axial force of each hanger will be uneven due to different tributary areas. In addition, when progressive collapse is required to be considered, the hangers and the perimeter beams are designed to be rigidly connected, frame action is formed in the in-plane direction. When there is a difference in vertical deformation of the transfer trusses at the top of the hangers, the axial force distribution between each hanger will also be uneven. The smaller the vertical deformation at the top of the hanger, the greater the rigidity of the suspending point, and the hanger will bear more vertical load.

When the hangers and the perimeter beams are rigidly connected, the hanger will also bear an in-plane bending moment due to the difference in vertical deformation of the transfer truss under vertical load. Due to the force elongation or shortening of the lower chord of the transfer truss, a horizontal out-of-plane deformation difference occurs in the hanger between the lower chord level of the cantilever truss and the level below it. The difference in horizontal deformation will cause an out-of-plane bending moment in the hanger. The value of the out-of-plane bending moment of the hanger is related to its boundary condition at the two ends. When the hanger is pinned-connected with the cantilever truss, its out-of-plane bending moment is significantly smaller than that of a rigid connection. The constraint between the hanger and the floor below the transfer truss is weakened, and the hanger out-of-plane moment will also be reduced significantly.

In addition, fire protection is one of the most important issues that need to be emphasized in the design of hangers. According to the code requirements, the hanger should be painted with thick fire-proof material. Because it is thick and easily damaged under service, it is often necessary to wrap with decorative materials outside the fire-proof coating, resulting in a significant increase in their cross-section and making it impossible to display the slender effect of the hangers.

3.2.2. Hanger Connection

3.2.2.1 Splicing connection of hanger

The hanger is permanently in tension under service stage. The splicing of the hanger should avoid using butt welds as much as possible to prevent full-section failure due to weld defects or delayed cracks. Friction bolt splicing is a reasonable form for the splicing of the hanger. In order to reduce the splice length of the connection plate, the following methods can be used: 1) Increase the anti-slip coefficient of the friction bolt, which is 0.4 for conventional sandblasting and shot blasting, and can be increased to 0.5 by using aluminum spraying on the friction surface; 2) Reduce the bolt hole spacing from $3.0d_0$ to $2.5d_0$ while meeting the installation space; 3) Use large diameter, grade 12.9 high-strength bolts.

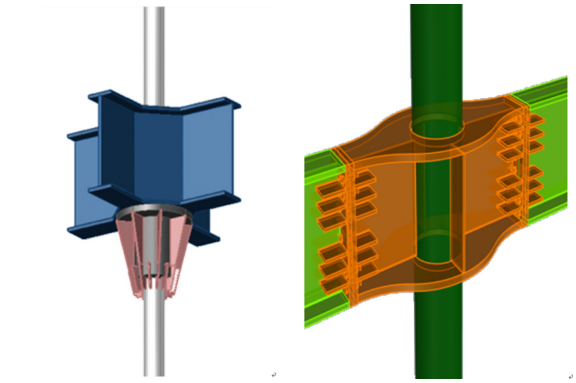


Fig. 8. Kaohsiung Municipal Library beam-hanger connection and beam-hanger connection of Shenzhen Kingboard Headquarters Building

3.2.2.2. Connection between hangers and perimeter beams

The contribution of the frame action from hangers and the perimeter beams to the lateral stiffness of the overall structure is almost negligible, so the hanger and the perimeter beam can be designed to be pinned-connected. However, in order to prevent the suspended floor from collapsing when the hanger fails accidentally, the perimeter beams are designed to be rigidly connected at the hanger. As mentioned above, rigid connection between hanger and perimeter beam will cause uneven axial force distribution and in-plane bending moment. In order to eliminate such bending moment caused by rigid connection, the perimeter beams can be continuous, and the connection between the hangers and the perimeter beam only transmits shear forces, such as the Kaohsiung City Library and Shenzhen Kingboard Headquarters Building (Figure 8) and other projects.

3.2.2.3. Connection between hanger and transfer truss

If the hanger is rigidly connected to the transfer truss, welded connection may be adopted. However, large in-plane and out-of-plane bending moments will occur in the hangers, which is not beneficial in controlling the cross-section size of the hanger. If the hanger and the transfer truss are pinned connected, orthogonal shear plates, pins and nut anchoring may be adopted. The orthogonal shear plate connection is generally suitable for hangers with circular sections. The length of the shear plate shall be long enough to realize the assumption of a hinged connection, which has a certain impact on the appearance of the joint. The connection with pins is simpler and more beautiful, and is suitable for different forms of hangers such as steel cables, steel rods and shaped steel, etc.

3.3. Floor Structure

Due to the cumulative deflection of the transfer structure and hangers, there is a large difference in vertical deformation between the hanger and the core of the suspended structure. The slab near the core is prone to large tensile stress. In addition to strengthening the slab reinforcement, a post-cast strip is provided on the slab near the core. The closure strip will be poured after the self-weight of the suspended floor is basically applied.

The floor slab of the suspended structure is supported on the core at one end and on the hanger at the other end. The support stiffness at the hanger end is relatively weak, which is equivalent to the serial connection between two vertical springs of the transfer structure and the hanger. Compared with the conventional Frame-Core Structure, the vertical stiffness of the suspended floor is poor, and the floor vibration analysis and evaluation should be carried out in the design. If necessary, measures such as Tuned Mass Damper can be taken to satisfy the requirements of human comfort.

4. Construction Scheme

The construction scheme of the suspended structure can be divided into the forward construction method and the reverse construction method. The forward construction method refers to the construction in sequence along the gravity load transmission path, the suspension part is constructed sequentially from top to bottom, and the hangers are always kept in a tension state. The reverse construction method refers to the reverse construction along the gravity load transmission path, the suspension part is constructed in reverse sequence from bottom to top using temporary support measures, and the temporary support system is removed after the construction is completed, and the hangers are converted from compression to tension.

4.1. Forward Construction Method

The forward construction method constructs the main structure first and then the substructure, that is, the construction is carried out in the order of the core wall, the transfer structure, the hangers, and the floor structure. The load path of the structure during the construction process is basically the same as that during the service stage. No additional temporary support is required during the construction stage, and the direction of the internal force of the hanger will not change during the construction process. According to the forward construction method, there is no construction platform at the bottom when the transfer structure is installed at high altitude. It is necessary to formulate a reasonable construction process, such as the overall lifting of the transfer structure or the cantilever construction process, and take measures to control the construction error and welding quality of the high-altitude installation (Figure 9).

4.2. Reverse Construction Method

In reverse construction, the order of structure construction of the suspended part is the temporary supporting structure, the floor structure, the hanger, the transfer structure, and dis-assembly of the temporary supporting

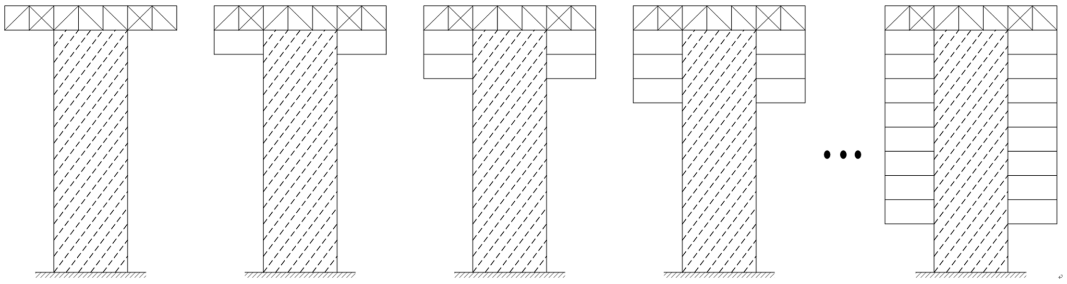


Fig. 9. Forward construction method of suspended structure.

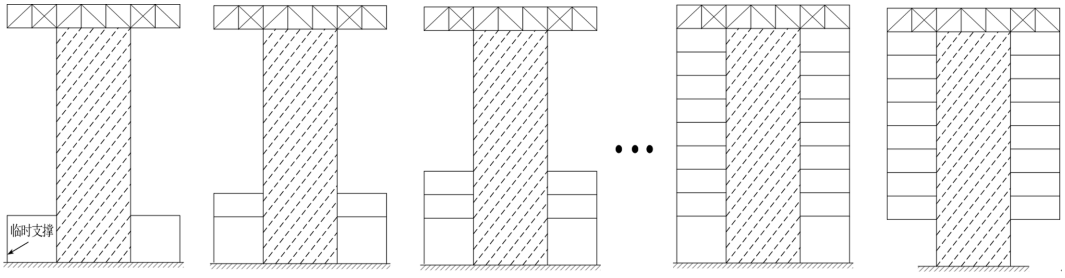


Fig. 10. Reverse construction method of suspended structure.

structure. The structural load path in the construction stage is different from that in the service stage. The direction of the internal force of the hanger changes when the temporary supporting structure is unloaded, and the hanger changes from compression to tension. According to the reverse construction, it is necessary to verify the bearing capacity of the temporary support structure and the hanger in compression state, and adopt a reasonable temporary support unloading process to ensure the safety of the structure and the accuracy of the floor elevation after unloading (Figure 10).

4.3. Control of Deformation and Additional Internal Forces

Suspended floors experience large vertical deformation under vertical load, which can reach 50-100mm under dead load, and there are obvious deformation differences at different hangers. Vertical deformation will bring additional internal forces into the suspended structure, including unfavorable effects such as in-plane and out-of-plane bending moment of the hangers, and tensile stress on the floor slab near the core wall.

The tensile stress of the hanger is high, and its vertical deformation cannot be ignored. Pre-tensioning can be applied or a reasonable pre-adjustment value can be set forth during the fabrication of the hanger. For example, the length of the hanger is “shortened” during fabrication at each level or section to deal with the tensile elongation of the hanger.

To eliminate the additional internal force caused by the deformation of the suspended structure, a downward pretension force P can be applied to the transfer structure after the truss is installed. During the installation of the suspended floor, the same amount of pretension is released

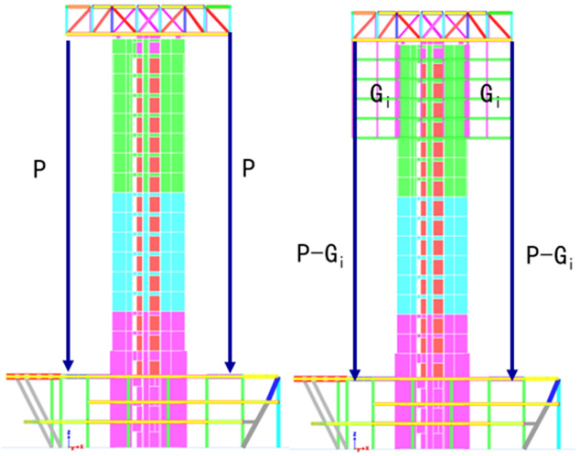


Fig. 11. Construction scheme of pre-tensioning of suspended structure.

according to the weight G_i applied to the structure (Figure 11). During the construction process, the transfer structure is basically kept horizontal. The difference in deformation of each floor before and after construction is only the elastic deformation of the hangers of each floor. The in-plane and out-of-plane bending moments of the hanger under dead load can be generally eliminated, and the additional stress in the floor slab will also be greatly reduced.

5. Experimental Research

5.1. Shaking Table Test

The Shanghai Jinqiao National Training Center is a typical Single-Core Suspended Structure. A simulated



Fig. 12. Shaking table test model.

earthquake Shaking table test study was carried out at Tongji University, as shown in Figure 12.

The design-based seismic intensity of the structure is 7 degrees. The peak values of horizontal seismic acceleration at each earthquake level are shown in Table 1.

Three earthquake records were selected as the input excitation for the Shaking table test, namely Kobe (Japan) in 1995, Duzce (Turkey) in 1999, and Wenchuan (China) in 2008. The test loading conditions are divided into three stages in the order of FE, DBE, and MCE, all of which are under 7 degrees. In addition, an additional set of simulated earthquake excitation at the 8-degree MCE was performed. The main test results are as follows:

1) The vertical acceleration of the suspended floor is much higher than the vertical acceleration of the core wall part, about 2 to 4 times greater.

2) In the elastic stage of the structure, the vertical acceleration of the core gradually increases from bottom to top along the vertical direction. The vertical acceleration of the hanging part gradually increases from top to bottom along the vertical direction.

3) The entire damage development of the core is a gradual process, and the structure gradually enters a plastic state. Under the action of a 7-degree MCE, the number of floors with coupling beam damage further increased, and the coupling beam damage was heavier, but there was no visible damage to the core shear wall.

4) Under the 8-degree MCE, some floor coupling beams were severely damaged, but no significant damage or destruction at the bottom of the core wall.

The Shaking table test study provides the following recommendations for the design of suspended structure:

(1) The vertical seismic action of suspended structures are significantly different from conventional structures. In structural design, attention should be paid to the reasonable vertical seismic action of suspended structures, especially cantilever trusses.

(2) As a single lateral force-resisting system, the suspended structure improves its seismic performance by embedding shaped steel or steel plate in the concrete shear wall. If necessary, its seismic redundancy can be further improved by setting up dampers.

The internal forces of components such as hangers and cantilever trusses are mainly gravity loads, and they are generally in an elastic state under earthquakes. Due to the bearing capacity requirements, it is appropriate to use Q550 and higher strength steel.

5.2. Pin Joint Test

The maximum axial force of the Shanghai Jinqiao National Training Center hangers is 11500 kN. The top of the hangers and the transfer truss are connected by a pin, with the diameter of 230mm and material of 40CrNiMo (Figure 13).

In order to ensure the safety of the thousand-ton tension pin joint, a pin joint test study was carried out, as shown in the Figure 14. The test adopted monotonic graded loading, with a total load of 20 levels, each level of 1000 kN, and a total load of 20000 kN.

The main test results of the specimen under the action of 20000kN axial tension (about 1.74 times the design value) are as follows:

(1) There are no obvious signs of damage (steel plate fracture, hole wall extrusion, etc.), and there is no deformation of the inner and outer ear plate pin hole walls (Figure 15).

(2) The maximum bending normal stress of the pin is about 850 MPa. The pin body component is designed to be safe with reasonable redundancy.

(3) The maximum bending normal stress of the ear

Table 1. Seismic Peak Acceleration a_{max}

a_{max} (cm/s^2)	7 degrees			8 degrees
	Frequent Earthquakes (FE)	Design-Based Earthquakes (DBE)	Maximum Considered Earthquakes (MCE)	Maximum Considered Earthquakes (MCE)
	35	100	200	360



Fig. 13. Hanger Pin Joint.



Fig. 14. Full-scale test of pin joint.



Fig. 15. Pin surface indentation and pin hole wall of lug plate.

plate is 370 MPa, and the ear plate is in elastic state throughout the test.

The test results showed that the large-diameter, high-strength pin connection of this project is designed with safety and bearing capacity under the action of thousands of tons of tension.

6. Structural Monitoring

Due to the special stress of the suspended structure under the gravity load and the complex stress of the structure during the construction process, health monitoring during construction stage and the service stage is required [3]. Suspended structure monitoring shall focus on the following:

(1) Monitoring of stress and deformation of key components such as hangers and transfer trusses.

When the suspended structure is constructed with the "reverse construction method", the force characteristics of the hanger during construction are significantly different from the actual service status. There is a complex internal force change process from compression to tension. It is particularly essential to monitor the internal forces and deformation of the hangers during construction. As the transfer truss is a key component of the suspended structure's force transmission, it is equally important to monitor the health of its internal force and deformation throughout its life cycle.

(2) Floor vibration acceleration monitoring

The aforementioned structural characteristics and layout have shown that the vertical vibration acceleration of suspended structure floors is relatively high compared to conventional projects. Therefore, it is important to monitor the floor vibration acceleration of floors.

Through on-site testing and theoretical analysis, the Jinqiao National Training Center has accurately determined that tuned mass dampers are needed for suspended floors to ensure that the human comfort meets design and service requirements.

7. Conclusion

Due to the special forces of vertical and horizontal loads, suspended structures have injected new vitality into the structural system of high-rise buildings and also brought new challenges to structural design. In terms of structural system selection, structural layout and detail design, the main goal is to achieve building functions and usable space, and maintain an organic balance between structural force-resisting simplicity and redundancy.

The application of lightweight high-strength materials can give full play to the material properties of high-strength materials, significantly reduce the weight of the suspended structure, and reduce the cross-sectional area of the components. However, fire retardant coatings and high-strength bolt connection technology need to be developed to adapt to the promotion and application of high-strength steel in suspended structures.

Energy dissipation devices are a necessary supplement to the single lateral force-resisting system of the suspended structure. They can improve the seismic performance of the suspended structure, and the damaged components after the earthquake can be replaced.

Structural design should conduct construction simulation analysis and fully consider the impact of different construction plans on the internal forces and deformation of the structure. Adopting a construction plan that is basically consistent with the stress characteristics of the suspended structure is conductive to controlling the vertical deformation and internal forces of the structure during the construction process.

Relevant structural tests and structural monitoring results show that the suspended structure design method is reasonable and feasible, and the theoretical analysis results are reliable.

References

Chen Jianxing, Bao Lianjin, Hu Zhenqing, etc. suspended structure design of Jinqiao National Training Center [J]. Architectural Structure, 2022, 52(10): 42-47.

Liu Dahai, Yang Cuiru. Optimal Selection of Structural Schemes for High-Rise Buildings. [M]. Beijing: China Architecture & Building Press, 1996.

Research report on simulated earthquake shaking table test of Shanghai Jinqiao Guopei TA tower [R]. Shanghai: Tongji University, 2022.

Test report on key suspension column pin axis node of Tower A of Shanghai Jinqiao National Training Project [R]. Shanghai: Tongji University, 2023.

Wang Chunlin. Theoretical and experimental research on shock absorption of high-rise building suspended structures. [D]. Southeast University, 2009.

Wang Jingfeng, Guo Lei, Li Beibei. Performance, theory and application of hybrid system of mega frame suspended structure [M]. Beijing: Science Press, 2023.

Wang Xingfa, Lin Chaowei, Xu Bo, etc. Research on the structural system of Guiyang 201 Building [J]. Architectural Structure, 2012, 42(3): 10-14.

Yan Xiaoxiao, Hu Damin, Qi Xiangming, etc. Structural design of gad corporate headquarters building [J]. Architectural Structure, 2017, 47(19): 1-8.

Zheng Ruqin, Lin Hai, Wu Zihong, etc. Structural design of Jiantao Headquarters Building [J]. Architectural Structure, 2022, 52(2): 35-42.

Zhang Yingzhi, Liu Jiahao, Zhou Chenying. Design and construction of fully suspended structure of Kaohsiung Municipal Library [J]. Architectural Structure, 2016, 18(6): 57-71.