Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Research and engineering application of the cable supported arch shell structure

Wen Yang*, Tian Qiu, Liwei Wang, Kejian Xiao, Yuan Feng, Xinan Xiang

* China Southwest Architectural Design and Research Institute Corp., LTD
866 Tianfu Avenue North Section, Chengdu, China
xnyfy@vip.163.com

Abstract

Hyperbolic parabolic surfaces have good shape stiffness and are commonly used in single-layer cable mesh structures. The load-bearing cables arranged along the valley line of the hyperbolic paraboloid mainly bear gravity loads, while the stable cables arranged along the ridge line of the hyperbolic paraboloid mainly bear wind loads. In architectural design, when using single-layer cable mesh, the roof covering material is often lightweight membrane material. If heavy glass materials are used in the building, in order to meet the deformation requirements of the main structure and glass, a significant prestressing force needs to be applied to the cable mesh when the structural form is determined. The increase in prestressing not only makes the design of the supporting boundary structure difficult, but also increases the difficulty of construction. At this point, it is considered to replace the upper convex stable cable with a steel component, and the lower concave cable and the upper convex steel component jointly bear the force to resist vertical gravity loads. This structure is called a cable supported arch shell structure. The cable supported arch shell structure has good vertical stiffness, which can reduce the pre tension requirements of the cables and facilitate cable tensioning and glass top installation construction. This article analyzes the stress characteristics of the cable supported arch shell structure and applies this system to the design of the Hugo Award venue at the 81st World Science Fiction Congress, which can provide reference for this type of engineering design.

Keywords: Hyperbolic paraboloid, cable supported arch shell structure, pre-tension.

1. Introduction

The concept of the cable- supported structure system comes from the cable-stayed structure. Its working mechanism is to hang continuous cables on the vertical components on both sides of the structure or directly anchor them to the ground, and then use two sections of angled cables at the intersection of the cable rods. The resultant force generated forms a vertical elastic support for the main structure, thereby reducing the bending internal force of the main structure and increasing the structural stiffness.

The single-layer cable net structure is composed of two sets of cables with opposite curvatures. The entire structural surface is a hyperbolic paraboloid. The downwardly concave load-bearing cables bear the gravity load, and the upwardly convex stabilizing cables bear the upward suction force generated by the wind load. Designing a single-layer cable net requires a form-finding analysis of the structure to obtain the geometric position of the single-layer cable net structure in its tensile forming state. The cable supported arch shell structure is also composed of two groups of components with opposite curvatures. It is similar to the single-layer cable network. The concave components are load-bearing cables, which mainly bear the gravity load, but the upward convex components are steel components. The load-bearing cables and steel components at the intersection, the resultant force generated by the cables forms vertical elastic support for the steel components, which is similar in concept to the cable- supported structural system. Steel components can not only bear the gravity load together with the load-bearing cables, but also bear the effect of upward wind suction. The cable-supported arch shell does not require form-finding analysis and has high vertical stiffness. It is a new type of long-span space structure.

2. Structural composition and force mechanism

2.1. Structural composition

Figure 1 shows a single-layer cable-supported arch shell structure. The overall curved surface of the structure is a hyperbolic paraboloid. The cables are arranged in parallel along the hyperbolic paraboloid in the upward parabola direction. Steel members are arranged in parallel along the hyperbolic paraboloid in the downward parabola direction. Each cable is Continuously passing through the steel members, the cables and steel members are connected to the surrounding edge members in a hinged manner. Edge members can be concrete ring beams, solid web steel beams or space structures with compressive stiffness.

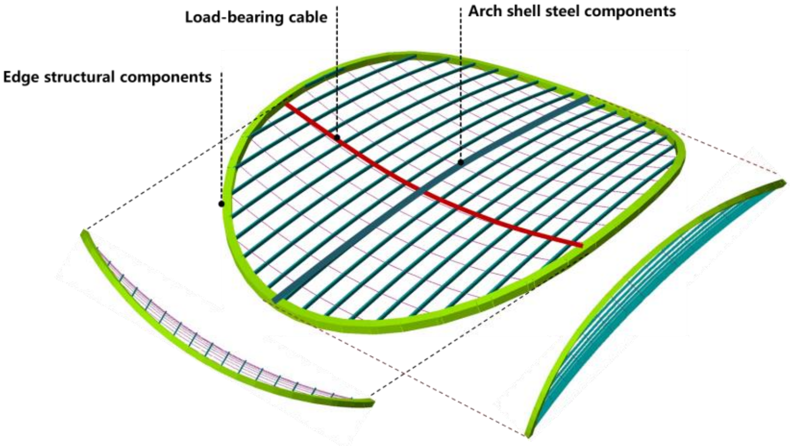


Figure 1: Schematic diagram of the composition of the cable-supported arch shell

2.2. Force mechanism

The prerequisite for the establishment of the cable-supported arch shell structure is to apply appropriate pre-tension to the cables. However, unlike the single-layer orthogonal cable network, the able-supported arch shell does not need to perform a form finding. The geometric shape after applying pre-tension is the initially given shape. Before structural analysis of a single-layer orthogonal cable network, it is necessary to perform a form-finding analysis on the structure and calculate the geometric position of the structure's tensioned forming state through the force density method, dynamic relaxation method, or nonlinear finite element method. Through a calculation example, the force mechanism of the cable-supported arch shell is analyzed. The surface of the calculation example is a hyperbolic paraboloid, with a length of 80m in the long axis direction, a sagittal height of 5m, a width of 60m in the short axis direction, and a sagittal height of 3.75m. Arrange 19 load-bearing cables with a cable diameter of 70mm and 14 steel members with a cross-section of B600x300x16x16. The outer ring uses a concrete ring beam with a ring beam size of B1000x1400. The additional dead load on the roof is 1.5KN/m^2, and the wind suction load is -1.2KN /m^2. The models were calculated for three cases where the initial pretension of the cable is 100KN, 500KN, and 1200KN. The calculation results are shown in Figures 3 to 5.

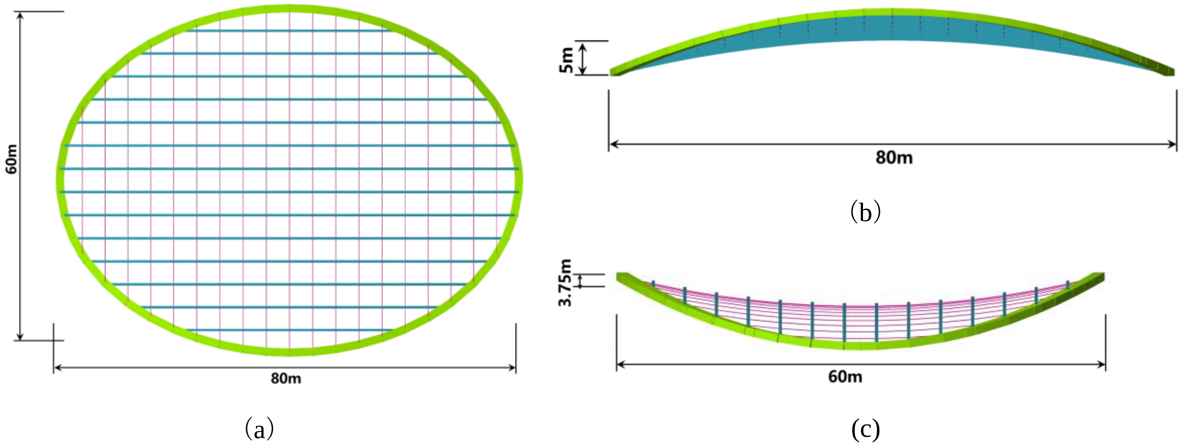


Figure 2: Example model information

It can be seen from Figure 3 that when the initial pretension of the cable is 100KN, when the tension is completed, the steel components are all compressed, and the resultant force of the cable acts on the vertical elastic support of the steel component; compared with the tensioned state, under the action of constant load under the influence of wind load, the axial force of the stay cable increases, and the axial pressure of the steel component further increases, and the stay cable and the steel component jointly transmit the vertical load; under the action of wind load, the axial force of the stay cable decreases, and the axial pressure of the steel component decreases.

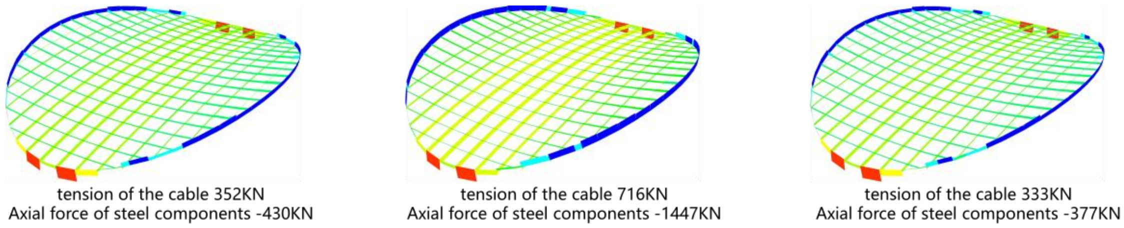


Figure 3: Internal force diagram of the component under various loads when the initial pretension of the cable is 100KN

It can be seen from Figure 4 that when the initial pretension of the cable is 500KN, when the tensioning is completed, both the cable and the steel member are under tension; compared with the tensioned state, under the action of the constant load, the axial force of the cable increases, and the steel component The axial force of the member changes from tension to pressure, and the cable and the steel member jointly transmit the vertical load; under the action of wind load, the axial force of the cable decreases, but the axial tension of the steel member is greater than the axial force of the tensioned state.

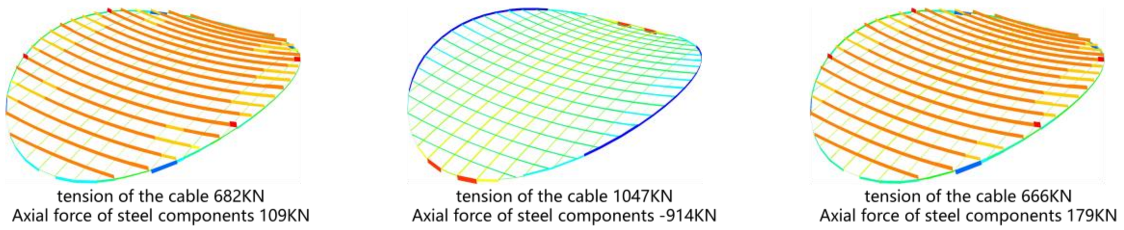


Figure 4: Internal force diagram of the component under various loads when the initial pretension of the cable is 500KN

It can be seen from Figure 5 that when the initial pretension of the cable is 1200KN, when the tensioning is completed, both the cable and the steel member are under tension; compared with the tensioned state, under the action of the constant load, the axial force of the cable increases, and the steel component The axial force of the member is reduced, and the cable and the steel member jointly transmit the vertical load; under the action of wind load, the axial force of the cable is slightly reduced, but the axial tension of the steel member is greater than the axial force of the tensioned state.

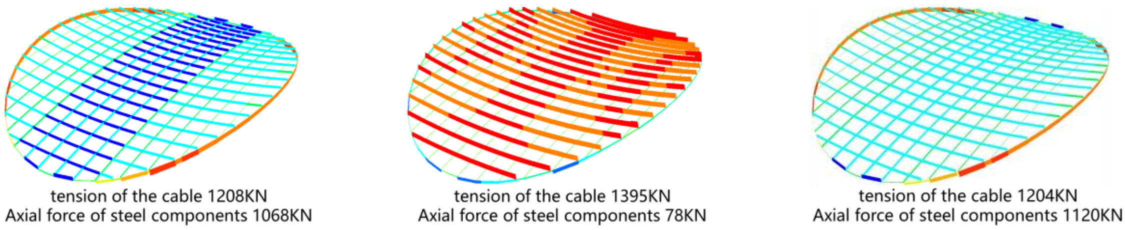


Figure 5: Internal force diagram of the component under various loads when the initial pretension of the cable is 1200KN

Through the above analysis, the following conclusions can be initially drawn:

(1) Under different loads, the axial force properties of steel members depend on the initial tension of the cable;

(2) When the initial pretension of the cable is small, the steel component is mainly compressed. In this case, the tensile properties of the high-strength cable are not fully utilized, and the design cross-section size of the steel component is larger;

(3) When the initial pretension of the cables is large enough, the steel component will always be in tension no matter what kind of load is applied. In this case, the overall stress mechanism of the structure is consistent with that of a single-layer cable network. Although the steel members are under tension and the designed cross-section size is small, excessive initial pretension will increase the difficulty of tensioning construction;

(4) When the initial pretension of the cable is appropriate, when the tension is completed, the steel component is under tension. Under the gravity load, the steel component turns to compression and jointly resists the vertical load with the cable. Under the action of wind suction, Steel members provide wind resistance. The cable-supported arch shell structure mainly refers to the overall structure in this pre-tensioned state.

(5) The cable-supported arch shell has good vertical stiffness. Since the elastic modulus of the steel component is greater than the elastic modulus of the cable, and the steel component can be compressed, when the initial pretension of the load-bearing cables is the same, the vertical deformation of the cable-supported cable arch shell structure under the action of gravity load is smaller than that of the single-layer cable net. , under the action of wind load, the reduction of the pretension of the cables in the cable-supported arch shell is smaller than that of the single-layer cable net.

3. Engineering Applications

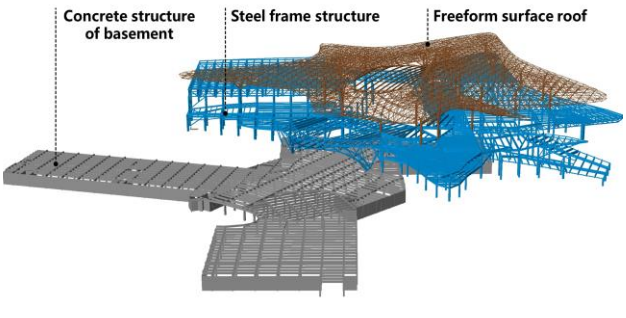
3.1. Project Overview

The Chengdu Science Fiction Museum project is located on the west bank of Jingrong Lake in Pidu District, Chengdu, China. The project site goes deep into the center of the lake and is an irregular polygon. The planned construction land area is approximately 84940m^2. The Science Fiction Museum will serve as the main venue for the opening and closing ceremonies and the Hugo Award Ceremony of the 81st World Science Fiction Conference in 2023. It will also be used as the exhibition function of the Science and Technology Museum after the conference. The project consists of three main functional bodies, namely the awards ceremony theater hall, the Hugo Museum, and the conference hall. The three functional bodies are connected into a whole through walkways, platforms, and large roofs. The highest point of the large roof of the building is about 35m high, and the roof of the theater hall is 20.0m high. The project has 3 floors above ground, the first and second floors are both 6m high, and 1 underground floor has a floor height of 7.5m. The above-ground construction area is about 39,000m^{2,} and the underground construction area is about 16,000m^2. The completed project effect is shown in Figure 6

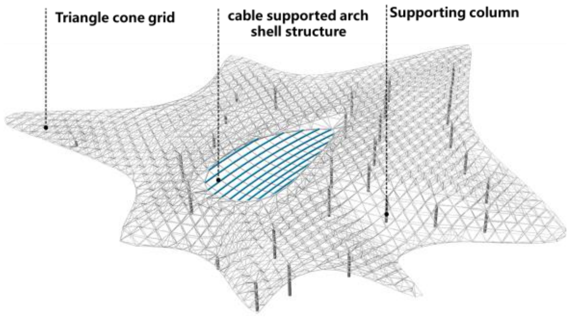
Figure 6: Aerial view and front elevation of the Science and Technology Museum after completion

3.2. Structural system

The plan projection shape of the building of this project is irregular. The maximum total dimension in the east-west direction is about 208m, and the maximum dimension in the north-south direction is about 251m. There are 3 floors above ground, and the main building is partially equipped with a basement. The building plan and function of the project make the structural column network relatively irregular, and the column span is large. The conventional column span is 9m, and the maximum column span in the atrium is 42m. There are large cantilevered outdoor platform areas around the functional volume on the 3rd floor of the building. , the maximum overhang reaches 21m. The large roof of the project has a complex shape and is a spatial free-form surface. The large roof covers the main building functional areas and part of the roof of the Hugo Award Hall. There is also a glass lighting roof area in the middle of the large roof. According to the architectural shape and internal space usage functions, the main structure above the ground of this project adopts a steel frame structure, the upper roof of the Hugo Award Hall adopts a large-span plane truss structure, the large roof adopts a space grid structure, and the basement adopts a reinforced concrete frame. structure. The structure has no seams.



（a）Overall structural composition diagram

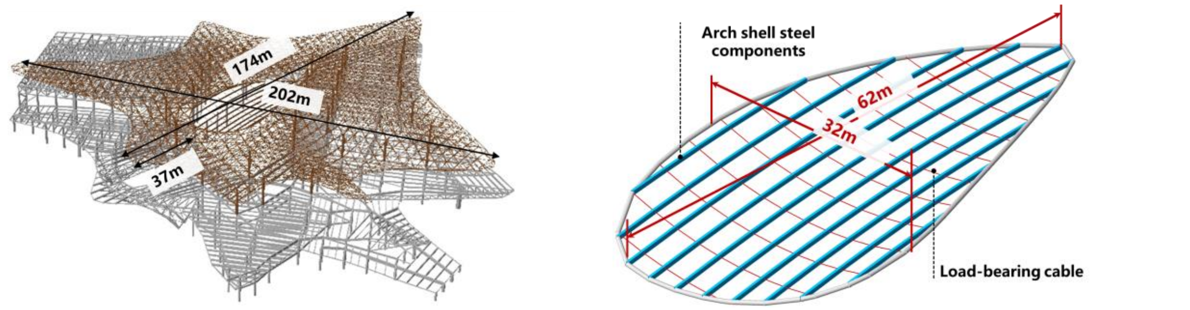


(b) Roof structure composition diagram

Figure 7: Structural composition diagram

The roof plane is approximately 174m long in the north-south direction and 202m wide in the east-west direction. The maximum overhang length at the corner of the roof is about 37 meters, the maximum internal span is 50m, and the elevation of the highest point of the structure is about 35.0m, as shown in Figure 8. The roof is in the form of a metal roof, with a glass skylight in the middle of the roof. In view of the architectural shape, the overall roof adopts a variable-thickness spatial double-layer grid structure. The thickness of the grid is 4m~1.5m, of which the thickness at the mid-span and overhanging root is 4m, and the thickness at the overhanging edge is 1.5m.

The architectural curved surface of the glass area in the middle of the roof adopts a saddle surface, and the plane projection of the curved surface is a quasi-elliptical shape. In order to ensure the transparency of the building, the structure adopts cable-supported single-layer arch shell structure. The structure consists of cables arranged along the direction of the valley line of the saddle surface and steel structure arch shell members arranged along the direction of the ridge line of the saddle surface, as shown in Figure 8. The length of the long axis of the curved surface is about 62m, the length of the short axis direction is about 32m, the height difference between the mid-span and the end of the long axis direction is 1.9m, and the sagittal height ratio is about 1/32. The height difference between the mid-span and the end in the short axis direction is 2.6m, and the vertical span ratio is about 1/12. The cable-supported arch shell structure uses the cables and the arch shell steel members to bear the force together to resist the vertical gravity load. The structure has good vertical stiffness, does not require high pretension of the cables, the edge truss is less stressed, and is economical. It is convenient for tensioning and glass roof installation and construction.



（a）Roof structure dimensions (b) Cable supported arch shell structural dimensions

Figure 8: Roof size

3.3. Structural static performance

A finite element analysis model was established in Midas Gen analysis software and a static analysis considering geometric nonlinearity was performed. The analysis results show that gravity load and temperature play the main controlling role. As shown in the figure 9, the maximum vertical displacement of the cable-supported arch shell structure under the action of 1.0 times dead load and 1.0 times live load is -97mm, and the maximum vertical displacement of the cantilever position of the overall roof structure under the action of 1.0 times dead load and 1.0 times live load. is -184mm, and the calculation results show that the structure has good stiffness.

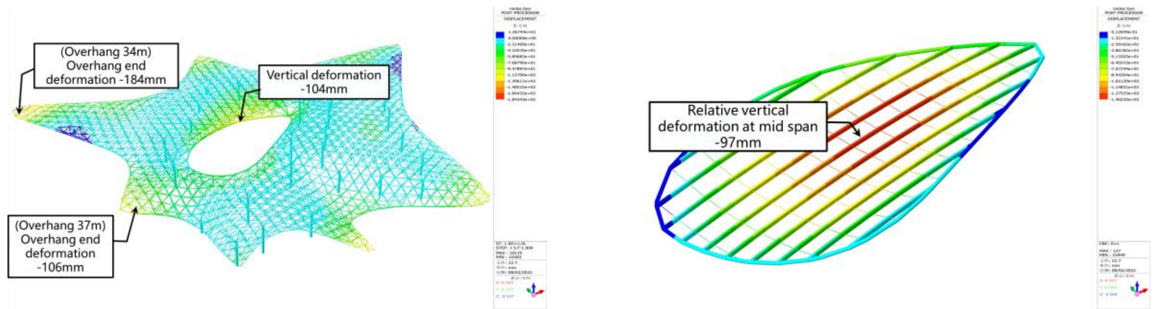


Figure 9: Deformation diagram of cable-supported arch shell structure

The maximum stress of the cables in the cable-supported arch shell structure is less than 0.5 times the breaking force, and the stress ratio of the main steel members is less than 0.75. The structure has sufficient safety. The cable adopts 1670MPa high-strength sealed cable. The maximum diameter of the cable is D52mm, the arch shell is made of H-shaped steel components, and the maximum cross-sectional size is H550x300x16x25.

3.4. Node design

In the cable-supported arch shell, the improtant node is the cables intersect with the steel members. In a conventional cable-supported structure, the cables are located at the bottom of the component and are pre-tensioned to support the upper structure. If the cable-supported arch shell follows this idea, the unbalanced force on both sides of the steel component will produce additional torque on the center of the steel component, affecting the structural safety. Therefore, it is considered that the cable passes through the center line of the steel component. However, since the size of the cable head is larger than the diameter of the cable body itself, in order to ensure that the cable continuously passes through the steel component, holes need to be made in the web of the component, and after the cable passes through, The connection between the hole and the cable body also needs to be processed. Inconvenient for construction.

In response to the above problems, the design uses H-shaped steel beams to reduce the number of interfaces between the cables and the web. At the same time, the lower flange of the H-shaped steel is grooved, so that the cables can extend into the center of the H-shaped steel from bottom to center. Finally, the angle steel is reinforced. Reinforce the lower flange of the H-shaped steel with a steel plate. The design of this node greatly facilitates construction and improves installation efficiency.

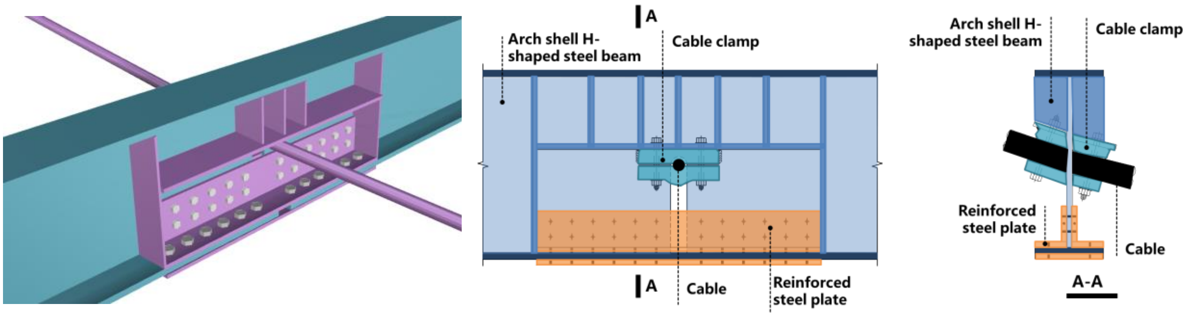


Figure 10: Design of key nodes of cable-supported arch shell

4. Conclusion

The Chengdu Science and Technology Museum project successfully hosted the 81st World Science Fiction Conference in 2023. The structure utilizes the hyperbolic paraboloid in the middle of the roof and adopts a cable-supported arch shell structure. By applying appropriate pretension to the cables, the cables and steel members are used to bear the load under the action of gravity load, which not only reduces the construction difficulty of the prestressed structure, shortened the construction period, effectively reduced the roof cross-section size, reduced the amount of steel used in the structure, and finally achieved the "sci-fi eye" styling requirements of the building's glass roof.

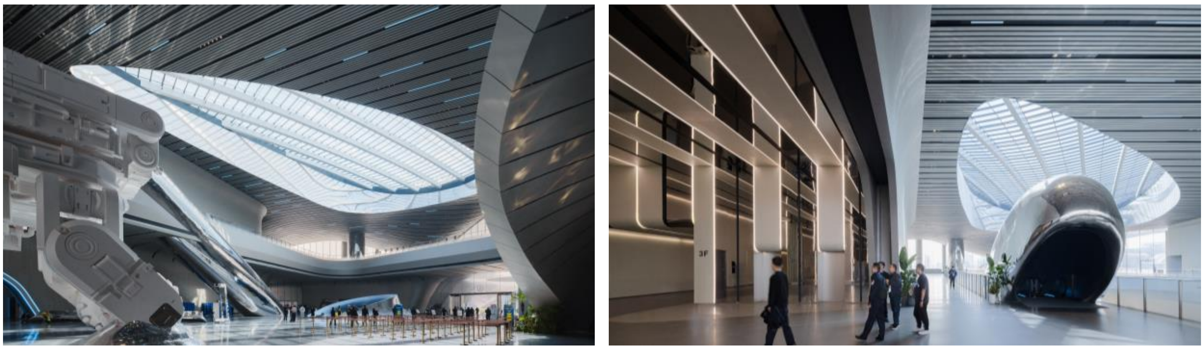


Figure 11: Cable-supported arch shell effect after completion

References

[1] Wang Bohou, Sun Xun, Fang Lixin. Analytical calculation method and morphological optimization of elliptical saddle-shaped single-layer orthogonal cable network structure. *Engineering Mechanics*, vol. 40, no. 1, pp. 103-113, 2024.

[2] Xiao Kangli, Huang Zhuoju, Ding Jiemin. Analysis of static stiffness parameters of elliptical boundary saddle-shaped single-layer cable net structure. *Journal of Building Structures*, vol. 42, no. S1, pp. 203-212, 2021.

[3] Yang Weiguo, Wang Meng, Wang Ya, et al. Research on numerical simulation method of cable-supported node . *Journal of Harbin Engineering University*, vol. 37, no. 8, pp. 1050-1056, 2016.

[4] Wang Zhe, Bai Guangbo, Chen Binlei, et al. Steel structure design of the National Speed Skating Hall. *Architectural Structure*, vol.48,no.20,pp.5-11,2018.