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Structural Design of Sail-shape Steel Structure of Beijing Subcenter Station

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Abstract

The sail-shape steel structure is quite impressive as the entrance of Beijing Subcenter Station. Some key design issues will be discussed in the present article. The structure is comprised of two layers. The upper layer, relatively rigid, is a cable-supported reticulated shell structure with triangle mesh supported by six group of branch columns, and the lower one, relatively flexible, is a reticulated shell structure with polygon mesh. The two shell structures are connected by spring elements. The use of spring members not only achieves the hanging effect of the upper rigid roof to the lower flexible roof, but also reduces the force interactions between the two layers under variable loads.

Keywords: Beijing sub center station, sail-shape steel structure, spring element

1. Introduction

Beijing sub-center comprehensive transportation hub, being construction, is an underground station with railways and subways. Upon completion, it is expected to become Asia's largest of its kind and help meet the Beijing(City)-Tianjin(City)-Hebei(Province) region's transportation needs.

At the upper ground level of the station, ten roof structures will be built, which are looks like sail-shapes with different sizes (Figure 1). Roof structure at the main entrance will be mainly discussed in this article (Figure 2).

The structure is designed with steel, with upper roof covered by membrane panel and lower roof by air-bubble membrane. Ethylene tetrafluoroethylene (ETFE) type of membranes are implemented in the project, which are highly transparent.

Figure 1: Overall isometric view

Figure 2: Roof structure at main entrance

2. Structure System

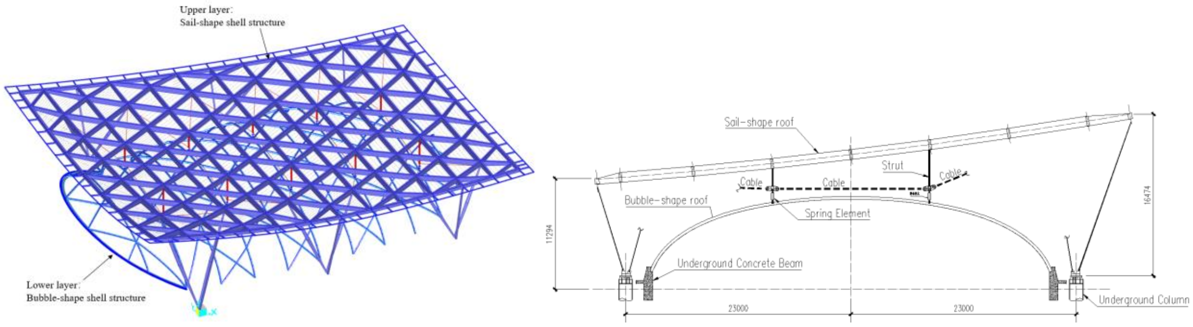
The structure consists of two layers of shell structures connecting by spring member (Figure 3-a,b).

The upper layer, relatively rigid, is a cable-supported reticulated shell structure with triangle mesh supported by six group of branch columns (Figure 3-c). The architecture shape of the upper roof is a spatial curved surface, with the plan size about 77m and the height above ground about 27m. Roof surface is meshed as triangle grid with X-direction (Cross-direction) and Y-direction beams, and the size of grid is about 6m. Beams are welded rectangular tube sections with 1000mm height and 250~300mm width, except the side beams with 600mm height and taper-section connecting beams with variable height.

Five groups of cable support systems are arranged under the sail-shape roof shell (Figure 3-d). The middle horizontal main cables with diameter Φ75 and length about 16.1m are spaced 12m. Side cables with diameter Φ65 and length about 13.5~17m are arranged inclined. Zinc-5% Alum-mischmetal alloy-coated cables, with good corrosion resistance performance, are applied in the project. The shell roof is supported by strut members with pipe section Φ250x16.

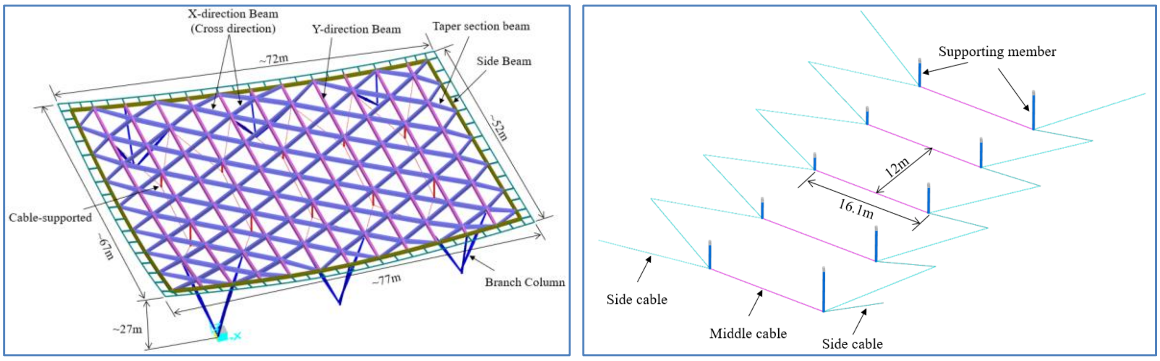
The roof cable braced shell is supported by six groups of branch columns to the ground level (Figure 3-e). Branch column base intervals 24m in X direction and 46m in Y direction. Each branch composes of a V-shaped inner inclined column and a single outer inclined column. The inner inclined columns are designed as shuttle pipe section with relatively larger diameter at the middle, section sizes Φ550~300x25, Φ600~300x30, Φ700~300x30. The outer inclined column sizes are Φ300x16, Φ350x20, Φ380x25.

The lower bubble-shape roof, relatively flexible, with plan size about 70m*41m, is a reticulated shell structure with polygon mesh. At left side of the shell, open entrance to the underground station, is strengthened by a side arch. To satisfy the requirement of architecture, that section size of the members shall be as small as possible, the lower bubble-shape roof is structurally designed hanging by the upper sail-shape roof. Spring elements are used as the connecting member, which will be discussed in detail in the following chapter.



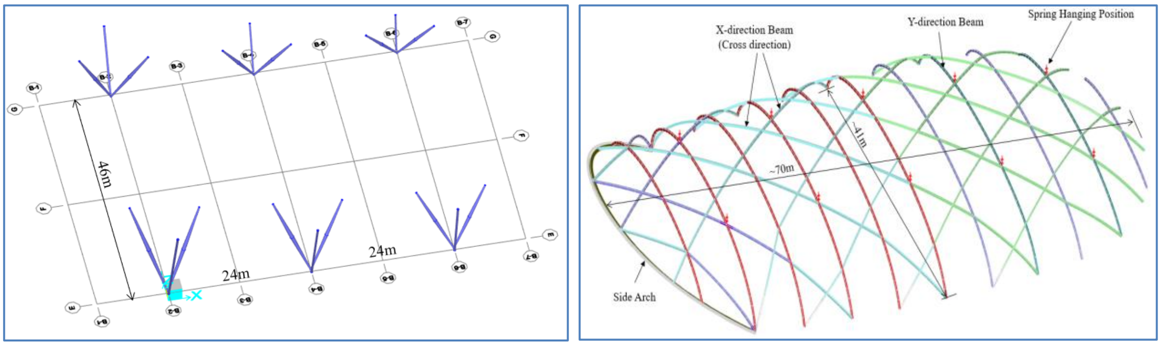
(a) Overall view of the structure

(b) Typical section



(c) Upper layer: Sail-shape shell structure

(d) Upper layer: Cable-supported system



(e) Upper layer: Six group of branch columns

(f) Lower layer: Bubble-shape shell structure

Figure 3: Arrangement of the roof structure at main entrance

3. Design Conditions

1) Dead loads

Self-weight of structure members is automatically considered by the calculation software.

Self-weight of upper roof maintenance of membranes and aluminum ceiling panel, 0.65kN/m^2.

Self-weight of lower roof maintenance of membranes, 0.13kN/m^2.

2) Live loads

Both the upper and lower roofs are unoccupied, thus considers only 0.5kN/m^2 and 0.3kN/m^2 respectively.

3) Snow loads

The upper roof considers snow load is 0.45kN/m^2, with 100-years return period. Nonuniform distribution is also considered.

4) Wind loads

Basic wind pressure is 0.50kN/m^2, with 100-years return period. Wind tunnel test is implemented for the structure since it is sensitive to wind action. Wind loads of 12 directions with and without surrounding interference are considered based on the comprehensive test results.

5) Thermal Action

Since the structure is exposed to the outdoor, and considering the solar radiation effect, temperatures variations of -50℃ and +50℃ are applied in the calculation.

6) Seismic Action

The design peak ground acceleration is 0.2g, and the design characteristic period of ground motion is 0.55s.

4. Key Design Issues

4.1. Completion State

In order to minimize the force interaction between upper and lower roof, the spring elements are implemented and installed after the formation of upper roof structure (completion of temporary support unloading). Therefore, it is necessary to consider the construction process while analyzing the structure. The completion state of the construction process should be the initial state of the structure, to sustain subsequent variable loads. More detailed construction sequences are shown in Figure 4.

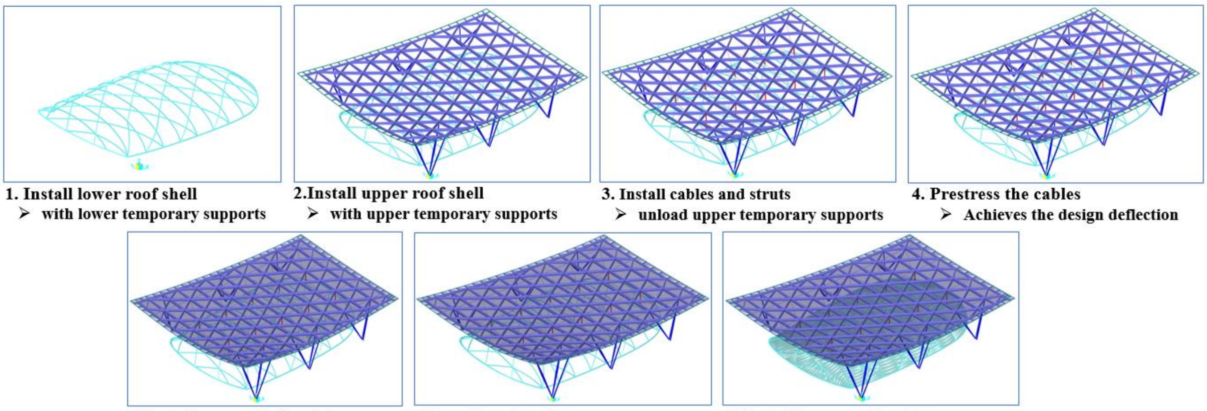

1. Install lower roof shell
➢ **with lower temporary supports**
2.Install upper roof shell
➢ **with upper temporary supports**
3. Install cables and struts
➢ **unload upper temporary supports**
4. Prestress the cables
➢ **Achieves the design deflection**
5. Install upper roof maintenance (membrane and ceiling)
6. Install spring elements
➢ **unload lower temporary supports**
7. Install lower roof maintenance (membrane)

Figure 4: Construction sequences

(1) Cable forces and roof deflections

Tension forces of five main cables during the construction are shown in Figure 5. The deflection of the roof observation point in the construction process is shown in Figure 6.

At the 3rd stage, after the cables are installed (without prestress) and the upper temporary supports are unloaded, the cable forces will be 275kN ~ 469kN, and the deflection of the roof is significant, about -53mm ~ -61mm at the observation points.

At the 4th stage, after the cables are prestressed, the cable forces will be 972kN ~ 1111kN, and the deflection of the roof becomes smaller, about -18mm ~ +22mm at the observation points.

At the completion state, after all the dead load finishes, the final tension forces of the main cables will be 1153kN ~ 1281kN, and the deflection of the roof is about -28mm ~ -42mm at the observation points.

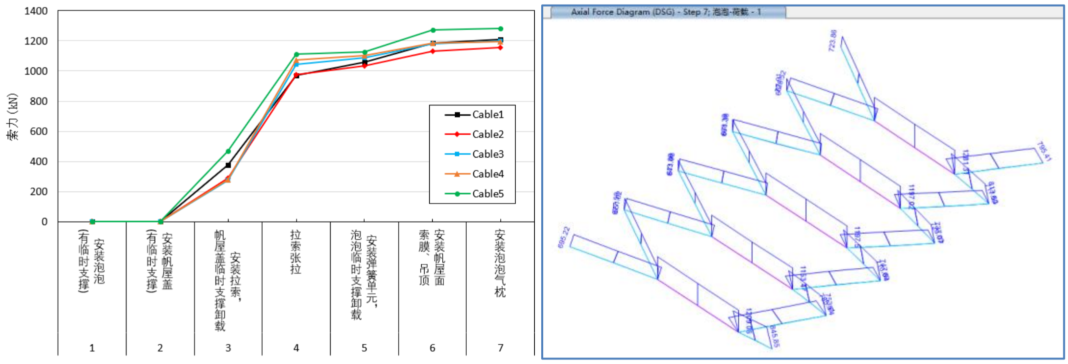


Figure 5: Cable tension forces during the construction

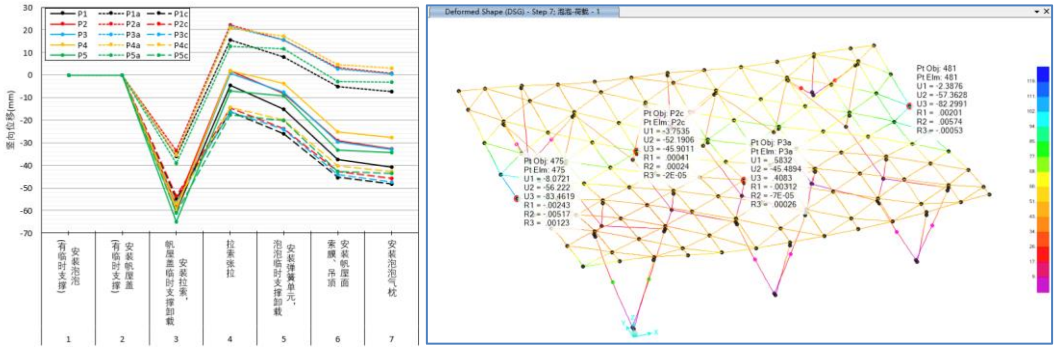


Figure 6: Deflection of upper roof during the construction (mm)

(2) Horizontal displacement of the roof

Since the shape of the sail roof is relatively complicated with different height of branch columns, -Y horizontal deformation will occur when the structure is formed, as shown in Figure 7.

At the 3rd stage, after the temporary support of the sail roof unloaded, the deformation in the Y-direction is about -36mm. At the completion state, the value reaches about -52mm. The deformation value meets 1/154<[1/150] of the minimum column height of 8m, which meets the requirements of Chinese Codes.

The above displacement value is near the limit, and the spring element will be inclined. So, pre-displacement of +Y direction 50mm is required

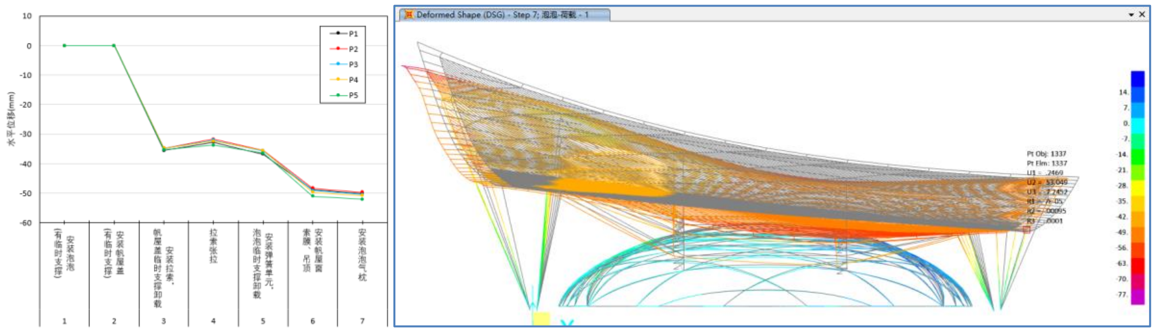


Figure 7: Horizontal displacement of upper roof during the construction (mm)

(3) Spring forces

The spring element is an important component of this project.

Figure 8 shows the variation of axial force of the spring elements during the construction process. After the spring element installed and the bubble roof unloaded at the 5th stage, the spring unit begins to function. At the completion state, all permanent loads are loaded, the westernmost spring element has a tensile force of +81.4kN, and the easternmost spring element has a small force of -34kN.

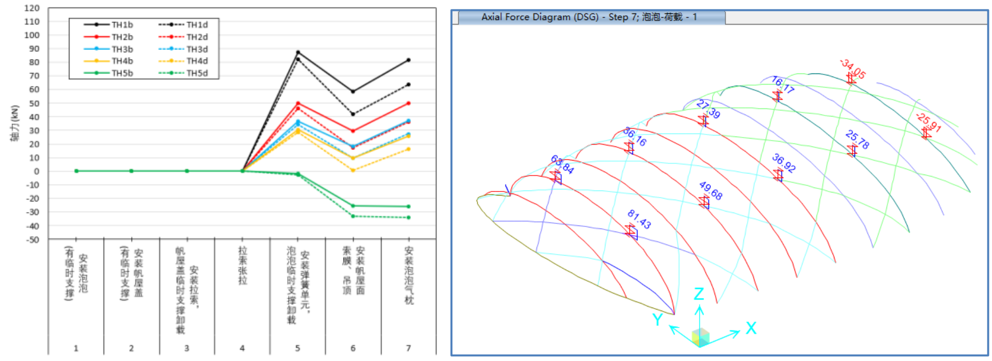


Figure 8: Axial forces of the spring elements during the construction (kN)

4.2. Mechanical Characteristics

The upper roof structure is a spacial grid shell supported by cables and branch columns. Figure 9 shows the mechanical characteristics of the typical structure unit. Y-direction beams are in pressure to balance the cable tension force. The strut members act as vertical supports to the roof shell, with compression force about -511kN. However, one of the struts shown in the figure is in low compression force, since the angle difference between middle and side cables are quite small. Y-direction beams also show negative bending moments at column and strut positions.

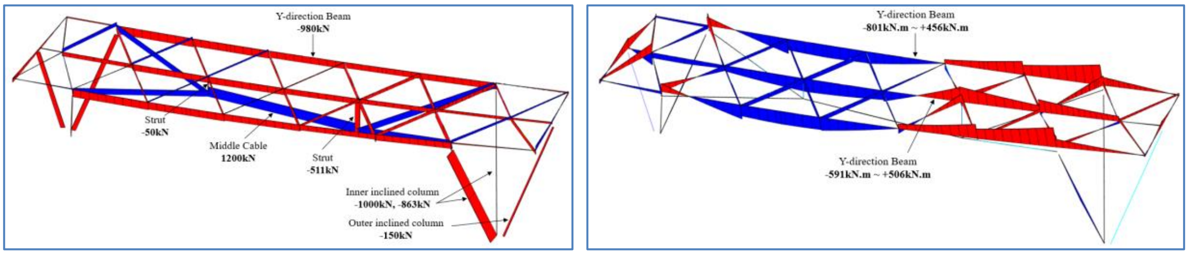


Figure 9: Axial forces (kN) and bending moment (kN.m) of typical upper roof under dead load

The lower roof structure is a spacial grid shell supported on the ground and hanged by ten spring elements. Under dead load, almost all the members are in compression, except the ones near entrance. Since the span is large and effect of spring element is limited, bending moment of the Y-direction members are apparent.

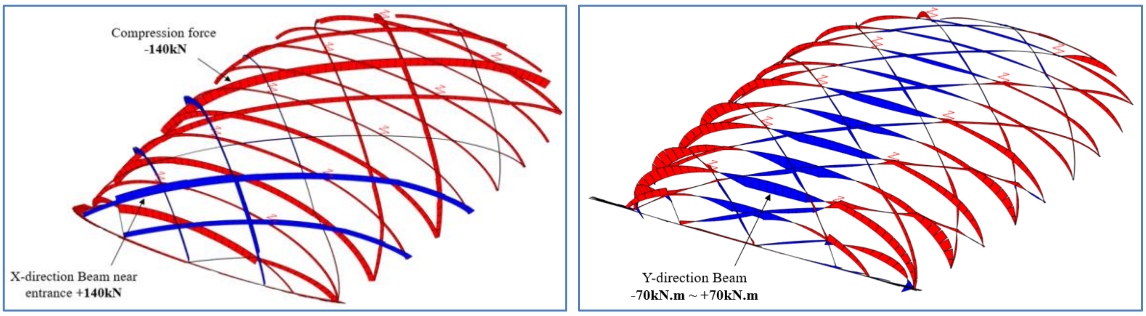


Figure 10: Axial forces (kN) and bending moment (kN.m) of lower roof under dead load

4.3. Why Spring Element?

What if an ordinary member used will be like? In some critical conditions as the wind pressure from upper roof transmitting to the lower roof, if ordinary member is used, the compression force would be -297kN in the member and -250kN in the arch (Y-direction beam) which may be overstressed. While the spring elements are used, the compression forces will be much lower. The spring effect can reduce the interaction between upper and lower roof.

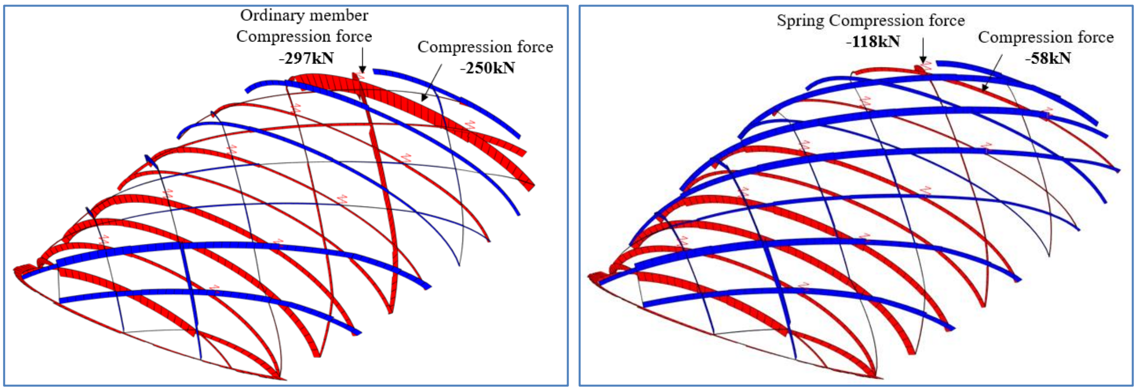


Figure 11: Axial forces (kN) of lower roof under a critical condition without and with spring element

As illustrated above, to reduce the interaction between upper and lower roof structure, spring elements are implemented. The spring effect acts only in compression, and the elastic stiffness is set as 2kN/mm which is especially chosen by trial. When the element is in tension, the stiffness is achieved by hard contact of the steel plate which is relatively rigid and the disk springs are unloaded. Upper and lower sides of the spring element are designed as hinge which are hidden in the connections for architectural aesthetic.

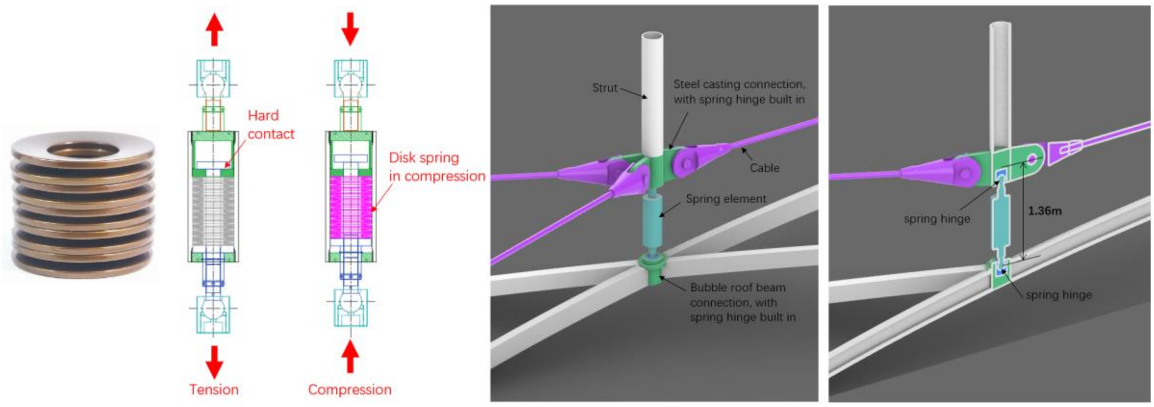


Figure 12: Schematic and configuration of spring element

5. Conclusion

The steel structure at the entrance of Beijing Subcenter Station is design with an upper sail-shape roof shell and a lower bubble-shape roof, with spring elements connected. This paper briefly describes the mechanical characteristics of the two roof layers and expounds the key issues in the design. To reduce the interaction between two roofs, one is more rigid and the other relatively felaxible, spring elements are necessary in the design. Till now, the static and fatigue experiment of the spring is being in progress and the construction of the entrance roof structure is almost complete.

Figure 13: Experiment of the spring element (left) and the construction of structure (right)

References

[1] JGJ 7-2010, Technical specification for space frame structures[S].

[2] GB 50017-2017, Standard for design of steel structures[S].

[3] GB/T 1972.1-2023, Disc spring – Part 1: Calculation[S].

[4] GB/T 1972.1-2023, Disc spring – Part 2: Technical specifications[S].