Design and mechanical performance analysis of V-joint of new steel structure

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Abstract: Aiming at the Beijing 2022 Winter Olympic Games, a new type of steel-wood combination sunshade structure system was proposed, and its selection was analyzed. The related joint forms were studied, and the new joint forms were put forward. The mechanical performance of the new joint was analyzed through tests and finite element simulation.

1. Introduction

1.1. Structure Introduction
The National Snow bobsleigh Center is located in the core area of the Yanqing Winter Olympic Games. The National Ski and Luge Center will compete in snowmobiles, steel skis and luge for the Beijing 2022 Winter Olympics. It is the fastest event in the Winter Olympics, known as the Winter Olympics "snow on the F1"[1][2]. It is the first and only snowmobile and sleigh track in China and the only one in the world that is located on the south slope of the mountain. The track has a total construction area of about 70,000 square meters. The track's core area is the track, and the top of the track is the sunshade structure system, with a length of about 1,986 meters. This paper analyzes the selection of the sunshade structure system and related nodes. Figure 1 is a typical diagram of the sunshade.

Figure 1. Layout plan of structure.
1.2. Structure selection

As for the snow bobsled track, the site of this event is different from other venues in the world because it is located on the south slope. The south slope has higher heat than the north slope. In order to make full use of the advantage of the south slope after race and avoid the defect of the high heat and energy consumption of the south slope, we put forward the design strategy of "changing the south slope to the north slope" in the snowmobile and sleigh competition area. The center of the snowmobiles and sledges on the south slope is no less efficient than the north slope.

The structural system selects the large-span and long-cantilevered sunshade structural system, and the structural selection is the steel-wood composite structure. Compared with the general steel structure system, in the steel-wood composite structure scheme, the V-shaped column top node is sandwiched between two wooden beams, and the two columns are connected by the steel sheet to form a stable and non-deformable rigid node, and the system is stable. Compared with steel structure, steel-wood structure has fewer joints, more standard parts, less deepening difficulty and shorter cycle. The roof system of steel and wood composite structure adopts more common practice, and the connection members used are standard parts, and the construction is relatively simple. Steel and wood structure system space is clean, simple, no cumbersome link bar. Wood for green environmental protection materials, more suitable for the Winter Olympics venues. The main stress system is the long-span cantilever system formed by steel V-column and steel beam. This is shown in Figure 2. For this new type of structure, the main structure adopts inverted V column and steel beam connection, it is necessary to analyze the stress form and study its stress mechanism.

![Figure 2. Structural form diagram](image)

2. Finite element analysis of steel structure joints

The inverted V-shaped steel joints are made of Q355B\(^{[3]}\)\(^{[4]}\) steel. In this paper, ABAQUS/Standard is used to establish the finite element model analysis of the assembled steel joints. The nonlinear finite element analysis of the assembled steel joints was carried out by using the boundary conditions and loading conditions similar to the actual working conditions. The working mechanism of the assembled steel joints (cross beam V-column) was analyzed by ABAQUS software.

2.1. Material constitutive relation

The uniaxial stress-strain-curve of low carbon steel commonly used in construction engineering can be generally divided into five stages: elastic section, elastoplastic section, plastic section, strengthening section and secondary plastic flow section. The expression is as follows:
Where, \( f_p \) and \( f_y \) are respectively proportional limit and yield limit of steel
\[ \varepsilon = 0.8 \frac{f_y}{E} \]
\[ A = \frac{0.2}{f_y} (\varepsilon_{e1} - \varepsilon_{e2})^2, \]
\[ B = \frac{2}{A \varepsilon_{e1}}, \]
\[ C = 0.8 f_y + A \varepsilon_{e2}^2 - B \varepsilon_{e2}, \]
\[ \varepsilon_{e1} = 1.5 \varepsilon, \]
\[ \varepsilon_{e2} = 10 \varepsilon_{e1}, \]
\[ \varepsilon_{e3} = 100 \varepsilon_{e1}. \]

For the belly chord end plate, it is simplified to a rigid body for calculation
\[ E_s = 1E10, \]
\[ \mu_s = 1E-10. \]

The metal elastoplastic model in ABAQUS software was used to simulate steel. The average value of the test results was obtained, and the material parameters were as follows:

| Physical quantity | Mass density | Elastic modulus | Poisson's ratio | Yield strength | Tensile strength | Fracture strain |
|-------------------|--------------|-----------------|----------------|---------------|----------------|----------------|
| Unit              | kg/m³        | GPa             | -              | MPa           | MPa            | -              |
| Numerical value   | 7850         | 218             | 0.3            | 336           | 549            | 0.15           |

### 2.2 Selection of cell types and meshing

In the finite element simulation of this paper, the Chinese steel tube is a three-dimensional solid eight-node linear hexahedron element (C3D8R) controlled by the reduction integral hourglass, while the circular steel tube on both sides and part of the nearby square steel tube is a 10-node quadratic tetrahedron element (C3D10).

Mesh division: the application of fine enough mesh can ensure that the results of ABAQUS simulation have sufficient accuracy, rough mesh may produce inaccurate results. With the increase of mesh density, the numerical results produced by simulation analysis will approach a unique solution, but the computer resources needed to run the model will also increase greatly. When the grid is further subdivided, the result changes can be ignored without timing, indicating that the grid has met the accuracy requirements.

![Meshing diagram](image-url)
In this paper, the boundary conditions and loading modes of inverted V-shaped steel joints are clear. In this paper, the bottom of the V-column round steel pipe on both sides is the fixed end constraint, and the vertical square steel pipe is also the fixed limit. The loading is carried out by displacement loading with 5mm as a stage. Specific boundary conditions and loading methods are shown in the figure below:

![Figure 4. boundary conditions](image)

2.3. Analysis Results
Using finite element software ABAQUS, the load-displacement curves of the assembled inverted V-shaped joints under low cyclic loading and the working performance at different stages were analyzed. The hysteretic curve and failure mode of the component are shown in Fig. 5. It can be seen from the figure that the hysteretic curve of the component is shuttle type and relatively full; The final failure mode of the component is the joint failure of V-column and steel tube.

![Figure 5. Finite element failure mode](image)

3. experimental study
Based on the finite element study, the mechanical mechanism of the structure is further analyzed through experimental research. A 1:2 model was designed to test the hysteresis performance.

The length of the square steel tube of the test piece is 3000mm and the size is 400mm×100mm×20mm. The round steel pipe is symmetrically welded on both sides of the square steel pipe at the distance of 2000mm from the loading end. The included Angle between the axis of the round steel pipe and the square steel pipe is 45°, and the length of the round steel pipe is 1000mm. The size is ∅102×6.

Experimental phenomenon:
elastic stage:
The component is loaded vertically at the loading end. During the loading process, there is no obvious deformation of the component and no sound is emitted. When the loading end is pressed, the vertical displacement reaches +3mm (25-50kN), the lateral displacement of the round steel pipe reaches 0.35mm, the vertical displacement of the lower end of the nodal prescriber steel pipe is 0.66mm, and the displacement of the upper end is 0.90mm. When the loading end is under tension, the
The lateral displacement of the round steel pipe reaches -0.85mm, the vertical displacement of the lower end of the joint prescription steel pipe reaches -3.5mm, and the displacement of the upper end reaches -5.2mm.

The yield stage:
When the vertical load is loaded to 392.578kN (displacement is 65mm) at the loading end, the lateral displacement of the circular steel pipe on both sides reaches 3.06mm, the displacement of the lower end of the joint prescription steel pipe reaches 9.79mm, and the displacement of the upper side of the square steel pipe reaches 14.90mm. Under tension, the lateral displacement of the branch pipes on both sides reaches 2.56mm, the vertical displacement of the lower end of the joint prescription steel pipe reaches 9.89mm, and the displacement of the upper end of the square steel pipe reaches 14.05mm. There was a 1.5mm transverse crack on the upper end of the steel tube extending from the middle of the specimen joint.

Failure stage:
When the vertical load at the loading end was loaded to -363.92kN (displacement -90mm), the transverse crack at the upper end of the specimen joint of the steel tube continued to expand to 2mm in width from the middle. After a period of 90mm tensile stress, the weld between one side of the circular steel tube and the main square steel tube was completely torn, and the circular steel tube and the square steel tube were completely separated. The final failure mode is shown in Figure 6.

![Figure 6 failure mode](image)

4. Conclusion
In this paper, a new type of steel structure joint is proposed for the sun-awning structure system. Through experiment and finite element study, the seismic performance of the joint is studied, and the failure mode is analyzed. The mechanical performance of the new type of joint is obtained, and it is verified that this is a good structure form.

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