Optimization Design Analysis of Large Span Cantilevered Cross Bracing Truss of Tai’an Tourism Distribution Center

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Abstract. The main structure of Tai’an Tourism Distribution Center is a steel frame structure system. On its west side, there is a large span cantilever structure with a maximum cantilever length of 22 meters, which adopts a space steel truss structure. The cantilever structure has great visual impact and excellent ornamental value, but it also has irregular items such as irregular torsion, irregular vertical lateral stiffness, and sudden change of floor bearing capacity. The overall stress of the structure is complex, and the design and construction of seismic performance are highly required. The seismic performance of the structure is calculated and analyzed by performance-based seismic design method, and the cantilever structure is modeled and analyzed by 3D3S, a space steel structure design software. The results show that cross support is more reasonable for cantilever structure. In view of the difficulties in the design analysis, this paper also proposes effective strengthening measures to ensure the safety of the structure, and makes technical reserves for later construction of the project, which is also of certain reference significance for similar projects.

1. Introduction

The tourism distribution center project is located in Tai’an City, Shandong Province, with a total construction area of 22,927 square meters (including 13,327 square meters above the ground and 9,600 square meters underground parking lot). It is a tourism public service platform integrating tourist distribution area, consultation service area, and other functional areas (Figure 1). The overall span of the building is large, 131 meters long from east to west, 132 meters wide from north to south. There are three floors above the ground and one floor underground. The stories are all 6 meters high, and the total building height is 23 meters.

The distribution center is a steel frame structure, supported by concrete-filled steel tube columns, steel-reinforced concrete columns with h-shaped steel, the torsion effect of flat-torsional should be considered as well as the box columns, the roof is irregular and its structure form is inverted triangle truss. A large-span inverted triangle external cantilever structure is arranged between 2 and 3 floors on the west side, which adopts a spatial steel truss structure system (Figure 2) with a length range of 7 to 22 meters.
2. Design Parameters
The safety class of building structure of this project is I and design working life is 50 years. Structural importance coefficient =1.1, the seismic fortification intensity is 7 degrees, and the designed basic seismic acceleration is 0.10g. Design earthquake group is the first group, and the site category is II, and ground roughness is class B. The horizontal earthquake influence coefficient is 0.08, characteristic of the cycle Tg is 0.40 s. According to the Code for Seismic Design of Buildings (GB50011-2010) [1], the seismic grade of the steel structure is determined to be level three, based on the value of intensity and height of the building. According to Load Code for the Design of Buildings Structure (GB50011-2012) [2], the basic wind pressure of Tai’an City 50-year recurrence period is 0.4kPa.

3. Engineering difficulties
There are several difficulties in the structural design of the distribution center and its elevation and plan of the building are shown in Figure 3 and Figure 4:

The roof is inclined to the inside, and the height of the external frame column of the structure varies with the plane of each floor of the building. The overhanging structure on the west side has low lateral stiffness, which cannot effectively resist the external load and produces large deflection.

The bottom layer of the cantilevered structure is connected with the main beam and plate, and the rest is supported by the frame column on the west side of the main body. Due to the internal causes of wind and earthquake, the deviation between the center of mass and the center of stiffness causes the torsion of the structure [3]. Therefore, special nonlinear analysis method should be adopted to analyze the seismic performance and internal force [4].

The overhanging part of the facade is inverted triangle, resulting in abruptness of lateral stiffness. Owing to the large overall rotational inertia of the structure, it is difficult to control the torsion and overturning, and damage degree increases accordingly. According to Technical Specification for Concrete Structure of Tall Buildings [5], torsion effect of flat-torsional should be considered.

The distribution center is a space structure with a large size of axis network. The force of cantilever must be transferred to the foundation through frame column, causing the stress ratio of outer frame column to exceed limit. Improving the transfer state between cantilever part and main frame column is the key to determining whether the cantilever structure and the main structure can work well together.

4. Cantilever scheme optimization
According to detailed requirements, aseismic performance targets that specific components need to meet are shown in Table 1. The seismic analysis of complex structures, no less than two suitable different mechanical models should be used for comparative analysis of internal forces and deformation under action of multiple earthquakes. This project is a complex multi-layer steel frame structure, so 3D3S and SAP2000 is the supplement to conduct interactive optimization design and analysis of structure.
Table 1. Seismic performance objectives

| Seismic Fortification Level | Performance Levels | Damaged Part          |
|----------------------------|--------------------|-----------------------|
|                            | Key Member         | Ordinary Vertical Member | Dissipative Member |
| Frequent Earthquakes       | 1                   | No Damage             | No Damage          | No Damage          |
| Fortification Earthquakes  | 2                   | No Damage             | Mild Damage        | Partial moderate Damage |
| Rare Earthquake            | 4                   | Mild Damage           | Partial moderate Damage | Serious Damage     |

4.1. Software equivalent calculation model

The bottom layer of cantilever structure is connected to the main beam and plate, while the part not connected to the beam and plate is directly supported by the straight column on the left side of the main body. The equivalent building model in the software is shown as follows (Figure 5). The cantilever stiffness of the straight column support can control the deformation of the structure to a certain extent, so the upper part of the right column of the model is equivalent to sliding support.

Software 3D3S can only design and check the same type of structural components, so the model takes equivalent measures. The members of the main steel frame structure and the roof inverted triangle space grid tube truss structure are unified into two kinds of welded I-steel with symmetrical section: H1000×400×20×30 and H800×300×16×20. Only the connection between the members is considered.

According to Code for Design of Steel Structure [9], the overall stability of the beam may not be calculated when there are slabs (all kinds of reinforced concrete slabs and steel plates) on the compressed flange of the beam, which are firmly connected to it and can prevent the lateral displacement of flange.

4.2. Seismic performance analysis of cantilever

Long span cantilever structure has low redundancy. Once the cantilever member is destroyed, the consequence will be serious. In order to ensure the safety of structure under earthquake, the seismic performance design method is adopted to investigate the stress performance of structure under frequent earthquake, fortification intensity earthquake and rare earthquake [7]. Seismic design of structures based on elastic-plastic time history analysis of large earthquakes can be used as an design method to guide designers to carry out targeted structural scheme adjustment and local component adjustment, optimize structural design, and achieve economy while improving structural safety by applying this design [8].

According to Technical Specification for Concrete Structure of Tall Buildings and Code for Seismic Design of Buildings, bidirectional horizontal seismic action should be considered with asymmetrical distribution of mass and stiffness. For large overhanging structures with seismic fortification intensity of 7 degrees, vertical seismic action should be considered [9-10]. Therefore, the coupling is considered according to the two-way horizontal seismic action, and the vertical seismic action is considered.

4.3. Comparative analysis of cantilever forms

4.3.1. Elastic analysis under frequent earthquakes. 1) Vibration mode analysis: according to Technical Specification [9], the number of vibration modes of complex high-rise buildings and multi-tower structures should not be less than 15 and 9 times the number of towers accordingly. The number of modes of vibration selected in this model is 18. The period of translation and torsion of truss cantilever and beam cantilever is shown in Table 2. The result above shows the big difference between two cantilever modes. The first five modes of truss cantilever are translational, while the first mode of beam cantilever is torsional, which means that torsional deformation of beam cantilever is more obvious; 2) Main parameters indexes: the project carried out software analysis on the two cantilever forms, and the main parameters after calculation were shown in Table 3. The setting of support not only increases the number of overhanging anti-lateral force components, but also improves the lateral stiffness of structure, so as to share the bearing capacity of the column, making bearing stress ratio of column less than 1, and
changing duration of each overhanging period. The mode decomposition response spectrum method is adopted to calculate the vertical seismic force. The torsional mass participation coefficient of cantilever structure with beam support is only 76.62%, less than 90%, while cantilever period ratio of truss support is 0.46, less than 0.9, and much higher than that of beam support. It can be seen that torsion of beam cantilever is more obvious than that of truss cantilever.

Table 2. Different mode of vibration of cantilever modes

| Cantilever Type     | X Translation period | Y Translation period | Torsion period |
|---------------------|----------------------|----------------------|----------------|
| Truss cantilever    | 2, 5, 8, 9, 13       | 1, 3, 4, 7, 10       | 6, 11, 14, 15, 16, 17 |
| Beam cantilever     | 3, 4, 6, 9, 10, 14, 15, 17 | 2, 5, 11, 16 | 1, 7, 13, 18 |

Table 3. Main parameters of structure

| Parameter                          | Truss cantilever | Beam cantilever |
|------------------------------------|------------------|-----------------|
| Bearing stress ratio of the column | < 1              | 3 column transfinite |
| Periodic time difference           | The maximum difference is 0.2s; | The difference is more than 20% |
| Mass participation coefficient     | X 99.61%         | 99.53%          |
|                                   | Y 99.82%         | 99.58%          |
|                                   | Torsion 92.99%   | 76.62%          |
| Maximum interlayer displacement Angle | X 1/1729(1st. Floor) | 1/1124(2nd. Floor) |
| Most story drift                   | X 3.47(1st. Floor) | 6.24(3rd. Floor) |
| Floor minimum shear-weight ratio   | X 2.99%          | 4.51%           |
|                                   | Y 3.96%          | 4.21%           |

The maximum displacement Angle in layers of multi-storey and high-rise steel frame structure is 1/250. The damage degree of the structure will increase with the increase of the displacement Angle between layers. The maximum inter-storey displacement of the structure is 6000×1/250=24mm and a sign that the structure has a large stiffness abrupt change along the direction of height and the weak layer appears.

4.3.2. Elastoplastic analysis of rare earthquake

Two groups of natural waves (El-Centro, TanShanEW) and one group of artificial waves (Lanzhou wave) were selected to analyze the elastic-plastic time-history analysis of the cantilever structure. Under the three kinds of waves, the displacement of the vertical node and the maximum node of each floor of truss cantilever are obviously reduced. The maximum node displacement of TangShanEW wave reduces by twice. There is no vertical support for beam cantilever, so that the vibration is out of step with earthquake. Under Lanzhou wave, the displacement of beam cantilever structure is increasing. If subject to a long period of seismic action, a layer is easy to be destroyed first, eventually leading to the collapse of the structure. In conclusion, the overhanging part is designed as truss, with more uniform distribution of lateral stiffness, more reasonable structural layout and more consistent with the node displacement.

4.4 Comparative analysis of overhanging support

Lateral support has a positive impact in earthquakes. The center support should be adopted for steel structure of three or four grades with height not more than 50 meters. Since support is prone to the instability of slenderness ratio, the optimal choice is obtained by comparing the mechanical performance of cross support and herring-shaped support [11].
4.4.1. Elastic analysis under frequent earthquakes. 1) Vibration mode analysis: the modes corresponding to each period of the two types of support are quite different, and the torsion modes of the herringbone support are less than those of the cross support, indicating that the torsion effect of the herringbone support is weaker; 2) Main parameters indexes: as can be seen from the data in the following Table 3, the period ratio of herring-bone support is much smaller than that of cross support, while the maximum inter-layer displacement Angle in X and Y directions is larger than that of cross support, indicating that the herring-bone support is more likely to be torsional and suffer serious damage. The shear-weight ratio of both of them is greater than the minimum value stipulated in the code, but the shear-weight ratio corresponding to herring-bone support is larger, which indicates that economic index of herring-bone support is worse than that of cross support.

### Table 4. Different mode of vibration of brace

| Brace type      | X Translation period | Y Translation period | torsion period |
|-----------------|----------------------|----------------------|---------------|
| Cross brace     | 2, 5, 8, 9, 13       | 1, 3, 4, 7, 10, 12   | 6, 11, 14, 15, 16, 17 |
| Chevron brace   | 2, 4, 6, 7, 9, 11    | 1, 3, 5, 8, 10, 12   | 13, 15, 16, 18 |

### Table 5. Main parameters of structure

|                        | Cross Brace | Chevron brace |
|------------------------|-------------|---------------|
| Periodic time difference | The difference is more than 20%.
| Mass participation     | X 0.46      | 0.16          |
|                        | Y 99.61%    | 99.64%        |
| Torsion                | X 99.82%    | 99.84%        |
|                        | Y 1/1729(1<sup>st</sup>. Floor) | 1/1877(1<sup>st</sup>. Floor) |
| Maximum interlayer displacement Angle | X 92.99% | 92.55% |
|                        | Y 1/1030(1<sup>st</sup>. Floor) | 1/1056(1<sup>st</sup>. Floor) |
| Most story drift       | X 3.47(1<sup>st</sup>. Floor) | 3.20(1<sup>st</sup>. Floor) |
|                        | Y 5.83(1<sup>st</sup>. Floor) | 5.68(1<sup>st</sup>. Floor) |
| Floor minimum shear-weight ratio | X 2.99% | 4.50% |
|                        | Y 3.47(1<sup>st</sup>. Floor) | 3.20(1<sup>st</sup>. Floor) |

4.4.2 Elastoplastic analysis of rare earthquake

In the dynamic time history and response spectrum analysis, the maximum node displacement of the herring-bone support is slightly larger than that of the cross support, indicating that the seismic performance of the herring-bone support is slightly worse than that of the cross support. Under the action of three seismic waves, the maximum node displacement of herring-bone support along X, Y and Z directions did not change significantly compared with that of the cross support, indicating that the support form had little influence on the node displacement of the cantilever part of the structure. It is more economical and reasonable to choose cross supports for the structure obviously. When cross bracing is adopted, the bar breaks at the intersection, which can solve the problem of instability caused
by the excessive slender-to-length ratio of the bracing, so cantilever form is cross bracing truss.

5. Structural strengthening measures
The optimal structure form was determined by analyzing seismic requirements and others. In order to ensure the stability and reliability of the structure, it has enough redundancy. Since large overturning moment caused by large span of overhanging structure, the column suffers a large bearing capacity for a long time and is easy to be damaged. By injecting cement into steel frame column, the steel tube column is transformed into concrete filled steel tube. The steel tube is wrapped in the concrete in the form of stirrup, which greatly improves the bearing capacity of the frame column. In order to improve the stiffness of the members in the weak layer, the cantilever structure and the frame can be better aseismic.

6. Conclusion
The center of tourism distribution is a long-span steel structure with a span of more than 120 meters. Based on interactive software, the cantilever structure form and component layout are analyzed and optimized. Through further adjustment of the cantilever structure system and component form, the bearing capacity and seismic performance of the cantilever structure under various working conditions are improved, and the structure form with relatively better economic indexes is selected. The results show that the cross braced truss cantilever can not only ensure the safety and stability of the structure, but also meet the goal of economic, reasonable and feasible construction.

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