Seismic Analysis of Large-span Steel Truss Structure Based on PKPM

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Abstract. In the construction industry, large-span steel truss structures are widely used. In order to test their seismic performance under different structures, select truss structures with better seismic performance, and use PKPM software to establish two cross-sectional triangular arch truss models with different web member arrangements, one cross-sectional trapezoidal arch truss model. Using the mode decomposition response spectrum method, simulate and analyze the displacement and stress changes of three sets of finite element calculation models under different load combinations during earthquakes. The results showed that all truss models meet seismic requirements. The change in the arrangement of the web members did not significantly improve the seismic performance of the cross-sectional triangular truss, the seismic performance of the cross-sectional trapezoidal arch truss was significantly better. The lower chord of the triangular arch truss support and the mid-span top chord are under compression, while the top chord is only compressed on one side and tensioned on the other side. The top chord of the trapezoidal arch truss is mainly under pressure.

Keywords: PKPM; large-span; steel truss; seismic performance.

1. Introduction

The truss is a very common building structure, its structural performance is very excellent, often used in a variety of buildings. Steel has high-temperature resistance, high strength and good processing performance. Steel is often used as truss material in large-scale construction and bridge engineering and factory buildings with long service life. The large-span spatial structure is also popular in factory roofs, bridges and other scenes due to its advantages of light weight, large span, beautiful form, high stability, and good seismic performance. Therefore, large-span steel truss structures have been widely used in the construction industry.

However, its application also faces some challenges to its strength and safety performance. Earthquake is one of the important challenges. China is an earthquake-prone country with high seismic intensity, high frequency and wide range. In 2013, a 7.0-magnitude earthquake occurred in Lushan County, Ya'an City, Sichuan Province, which led to the collapse of large-span spatial structures such as the Lushan County Middle School Gymnasium and Lushan County Gymnasium [1]. Multiple earthquakes will cause huge economic losses, endanger people's life safety, and affect the rescue and reconstruction work in the disaster area after the earthquake, people pay more and more attention to the seismic performance of space structures. Especially with the improvement of construction technology, the span of the truss increases, the weight becomes lighter and the section size becomes thinner. The seismic analysis of large-span steel trusses has become an important and necessary research content.

At present, a large number of scholars have conducted special research on the seismic performance of steel trusses. Cao et al. [2] took the giant long-span steel truss of a multi-story commercial building as an example and analyzed the seismic resistance by comparing the diagonal brace of the steel structure with the reinforced concrete shear wall. Taking a long-span steel truss bridge as an example, Li et al. [3] analyzed the seismic response of the bridge structure by using the nonlinear time history analysis method, considering the damage of the fixed support or not. Zhou et al. [4] studied the
seismic performance of the steel truss arch bridge in the construction stage with a basket-type steel truss arch bridge as the engineering background. Liang and Chen [5] proposed a new method to study the seismic performance of steel arch bridges under strong earthquakes. Strong earthquakes in two and three directions were applied to the arch bridge to observe the seismic response of the structure and analyze the seismic performance. These scholars use different methods to carry out seismic analysis of truss structures with different structural forms.

In this paper, PKPM software is used to design three kinds of multi-span arch trusses with different structural forms, and a model in line with relevant specifications is established. Then, the displacement and internal force of the above three structures under 8-degree (0.2 g) seismic intensity are simulated, their seismic performance is compared, and suggestions for optimizing their seismic performance are put forward.

2. Finite Element Model Analysis

2.1. Research Method

In this study, PKPM software is used to establish the finite element calculation model. Considering the torsional coupling of the structure, the seismic calculation and analysis of the structure are carried out by using the Mode-superposition Response (Complete Quadratic Combination) [6]. The mode decomposition response spectrum method is the most commonly used in seismic analysis. This method uses the orthogonal method of each mode of vibration to transform the calculation of the complex multi-degree-of-freedom system of the structural system into the calculation of multiple single-degree-of-freedom systems. Then, by combining the results of each single-degree-of-freedom system, the seismic response of the multi-degree-of-freedom system is obtained, and the influence of seismic action on the structure is calculated [7, 8].

2.2. Model Parameter

The truss studied in this paper is mainly used for large-span space pipe truss of roof structures. Three different structural forms of the truss are established, which are NO.I triangular arch truss, NO.II triangular arch truss and NO.III trapezoidal arch truss. The three trusses are all spatial pipe truss structures with a span of 30,000 mm. According to GB 50011-2011 “Code for seismic design of buildings”, the limitation of deflection of the large-span roof structure is 1/250, which means the maximum deflection value of the structure is 120 mm [9]. The structure is four-span, and the spacing between each span is 6000 mm. Lateral bracing trusses are used between each span to ensure the stability of the trusses, and the lateral bracing trusses are arranged between the mid-span and the supports [10].

The axonometric drawing of NO.I triangular arch truss structure is shown in Fig. 1. The cross-section shape is triangular, and the upper chord and the lower chord are 30 equal parts along the full length. According to the relevant provisions in JGJ 7-2010 “Technical specification for space frame structures”, the design upper chord width B is 800 mm, the section height H is 1200 mm, the detailed parameters are shown in Fig. 1, the truss rise-span ratio is 1/5, and the arch rise is 6000 mm [11]. The material of the upper chord and the lower chord of the truss is Q355, and the material of the web member and the lateral support truss is Q235. The material parameters are shown in Table 1. The specific cross-sectional dimensions of different types of bars are shown in Table 2.
Fig 1. NO. I Truss Axonometric Drawing and Cross-section Detail Drawing.

Table 1. Material Properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>Young’s Modulus (N/mm²)</th>
<th>Poisson Ratio</th>
<th>Density (kg/m³)</th>
<th>Coefficient of linear expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q355</td>
<td>206000</td>
<td>0.3</td>
<td>7850</td>
<td>1.2e-05</td>
</tr>
<tr>
<td>Q235</td>
<td>206000</td>
<td>0.3</td>
<td>7850</td>
<td>1.2e-05</td>
</tr>
</tbody>
</table>

Table 2. Material Selection and Size of Bar in Space Truss.

<table>
<thead>
<tr>
<th>Upper Chord</th>
<th>Lower Chord</th>
<th>Web Member</th>
<th>Lateral Support Truss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q355</td>
<td>Q355</td>
<td>Q235</td>
<td>Q235</td>
</tr>
<tr>
<td>Φ114*6</td>
<td>Φ114*6</td>
<td>Φ89*4</td>
<td>Φ89*4</td>
</tr>
</tbody>
</table>

The structural axonometric view of the NO.II triangular arch truss is shown in Fig. 2. The whole truss is divided into 30 equal parts, and the section shape is triangular. The parameters are the same as those of the section triangular arch truss. The arch rise is 6000 mm. The selection of truss member materials and the specific cross-sectional dimensions of different types of members are the same as the cross-sectional parameters of the triangular arch truss members.

Fig 2. NO. II Truss Axonometric Drawing and Cross-section Detail Drawing.

The structural axonometric view of the NO.III trapezoidal arch truss is shown in Fig. 3. The cross-section shape is trapezoidal and the arch is 30 equal parts. The upper chord width B is 800 mm, the section height H is 1200 mm, the lower chord width B1 is 600 mm, and the arch rise is 6000 mm. The detailed parameters are shown in Fig. 3. The selection of truss member material and the specific section size of different types of bars are the same as the section parameters of the triangular arch truss members.
3. Displacement and Axial Force Analysis

3.1. Seismic Selection and Load Combination Design

According to the “Code for seismic design of buildings” GB 50011-2010, this study only sets the horizontal earthquake and uses the Mode-superposition Response (CQC) for calculation [9]. The seismic fortification intensity is 8 degrees, and the basic seismic acceleration is 0.20g. The design earthquake group is the second group, the site category is Class II, and the characteristic period can be obtained as 0.4s. The maximum horizontal seismic influence coefficient is 0.16, and the structural damping ratio is 0.03. According to GB 55002-2021 “General code for seismic precaution of buildings and municipal engineering”, the seismic grade of the component is set to two levels, the internal force increase coefficient of the key member is 1.15, and the representative value of the gravity load (GE) under earthquake action is 1 *constant load + 0.5*live load [12].

According to the requirements of GB 50009-2012 “Load code for the design of building structures”, the structure is a truss applied to the roof structure, and the roof may bear loads such as snow loads [13]. The structure is subjected to 3.75 KN/m² roof constant load and 3.75 KN/m² roof live load, and the load direction is parallel to the Z-axis downward. The weight of the component is calculated by the software according to the steel weight of 78.5 KN/m³. The structural load combination is shown in Table 3.

Table 3. Details of Load Combination.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Load Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>1.30<em>Constant Load+1.50</em>Live Load</td>
</tr>
<tr>
<td>(2)</td>
<td>1.00<em>Constant Load+0.0</em>Live Load</td>
</tr>
<tr>
<td>(3)</td>
<td>1.30<em>GE+1.40</em>+EX</td>
</tr>
<tr>
<td>(4)</td>
<td>1.30<em>GE+1.40</em>+EY</td>
</tr>
<tr>
<td>(5)</td>
<td>1.00<em>GE+1.00</em>+EX</td>
</tr>
<tr>
<td>(6)</td>
<td>1.00<em>GE+1.00</em>+EY</td>
</tr>
</tbody>
</table>

3.2. Displacement analysis

3.2.1. Triangular arch truss

As shown in Fig. 4, under the load combination (2), the structural displacement of the NO.I triangular arch truss and NO.II triangular arch truss shows a small deviation towards the Y-axis and a trend of twisting towards the X-axis in the positive direction. The displacement of the mid-span and lateral support truss is the largest, and the impact on the members at the supports at both ends is the smallest. The displacement of the lateral support truss is mainly affected by the mid-span displacement of the truss.
Under the action of load combination (5), both No.Ⅰ and No.Ⅱ trusses shift in the positive direction of the X-axis, and the entire mid-span area shifts in the negative direction of the Y-axis. The displacement reaches its maximum value on the left side of the mid-span, and only minor displacement occurs at the supports on both sides of the members. The displacement cloud map is shown in Fig. 5.

The structure of the NO.Ⅰ and NO.Ⅱ triangular arch truss undergoes significant displacement towards the Y-axis under the load combination (6). The displacement of the truss at the mid-span and lateral support is the largest, and the displacement of the member at the support is the smallest. The displacement details are shown in Fig. 6.
3.2.2. Trapezoidal arch truss

According to Fig. 7, 8, and 9, the structural displacement distribution of the NO.III trapezoidal arch truss under the load combination (2), (5), and (6) is the same as that of the NO.I and NO.II triangular arch truss. However, the displacement is smaller and the structure is more stable compared to the NO.I and NO.II truss.

![Fig 7. Displacement diagram of the NO.III truss under load combination (2).](image1)

![Fig 8. Displacement diagram of the NO.III truss under load combination (5).](image2)

![Fig 9. Displacement diagram of the NO.III truss under load combination (6).](image3)
The maximum and minimum displacement nodes of the three structures under various load combinations are detailed in Table 4. The nodes with the smallest displacement under seismic action of the three types of trusses are all located at the support, and the node displacement near the support is relatively small. The node displacement of the NO.III truss trapezoidal arch truss under load combinations (2) and (5) is generally smaller than that of the other two trusses. The node displacement of NO.III truss under load (6) is much smaller than that of NO.I and NO.II truss, and the stability performance of NO.III truss is excellent under this load.

**Table 4. Maximum and minimum displacement values of nodes under different load combinations.**

<table>
<thead>
<tr>
<th>Numerical value (mm)</th>
<th>1.00<em>Constant Load+1.00</em>Live Load</th>
<th>1.00<em>GE+1.00</em>+EX</th>
<th>1.00<em>GE+1.00</em>+EY</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO.II triangular truss arch truss</td>
<td>Maximum value</td>
<td>Minimum value</td>
<td>Maximum value</td>
</tr>
<tr>
<td>NO.II triangular arch truss</td>
<td>9.30</td>
<td>0.00</td>
<td>10.55</td>
</tr>
<tr>
<td>NO.III trapezoidal arch truss</td>
<td>6.34</td>
<td>0.00</td>
<td>6.86</td>
</tr>
</tbody>
</table>

3.3. Force Analysis

3.3.1. Triangular arch truss

According to Fig. 10, the NO.I and NO.II triangular arch truss is subjected to tension at the middle and lower chords of the truss under the load combination (1). The lower chords on both sides and the upper chords in the middle are subjected to pressure, and the magnitude of the pressure is much greater than the tension.

![Fig 10. Axial diagram under load combination (1).](image1)

As shown in Fig. 11, under the load combination of (3), the axial force of the truss members of the NO.I and NO.II truss is similar to that of (1). However, the lower chords of the middle part of the left side span of the truss are all tensioned, and the tension value becomes larger and the pressure value becomes smaller.

![Fig 11. Axial diagram under load combination (3).](image2)
As shown in Fig 12, under the load combination of (4), the top chords of NO.Ⅰ and NO.Ⅱ truss are subjected to significant pressure, while the web and bottom chords are subjected to tensile force. The bottom chords at the supports on both sides are subjected to the maximum pressure.

![Fig 12. Axial diagram under load combination (4).](image)

### 3.3.2. Trapezoidal Arch Truss

As shown in Fig. 13, under the load combination (1), the web members of the NO.Ⅲ truss trapezoidal arch truss are subjected to tension, and the forces on the upper and lower chords are mainly pressure, with the magnitude of pressure far greater than the tension. However both are less than the axial forces of each member of the NO.Ⅰ and NO.Ⅱ truss.

![Fig 13. Axial diagram of the NO.Ⅲ truss under load combination (1).](image)

As shown in Fig. 14, under the load combination of (3), the force on the truss members of the NO.Ⅲ trapezoidal arch truss is similar to the truss under the load combination (1). However the tension and pressure values are slightly smaller, and the number of pressure members increases, and the tension members decrease.

![Fig 14. Axial diagram of NO.Ⅲ truss under load combination (3).](image)
As shown in Fig. 15, under the load combination (4), the upper chord of the left section of NO.Ⅲ trapezoidal arch truss is subjected to pressure, while the right section is subjected to tension. However, the values of tension and pressure are higher, and the number of pressure members in the web section increases. The pressure on the top chord of each span of the truss from left to right is increasing. The overall stress value of NO.Ⅲ is much larger than that of NO.I and NO.Ⅱ truss.

![Fig 15. Axial diagram of NO.Ⅲ truss under load combination (4).](image)

The maximum and minimum displacement members of the three structures under various load combinations are detailed in Table 5. The axial force of the NO.Ⅲ trapezoidal arch truss under loads (1) and (3) is much smaller than that of the other two types of trusses, but under load (4), the axial force of truss III is much greater than that of NO.I and NO.Ⅱ truss. The difference in axial force values between NO.I and NO.Ⅱ truss is relatively small, and their performance is similar under earthquake action.

<table>
<thead>
<tr>
<th></th>
<th>1.30<em>Constant Load+1.50</em>Live Load</th>
<th>1.30<em>GE+1.40</em>+EX</th>
<th>1.30<em>GE+1.40</em>+EY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum tension</td>
<td>Maximum pressure</td>
<td>Maximum tension</td>
</tr>
<tr>
<td>NO.I triangular arch truss</td>
<td>-248.36</td>
<td>16.56</td>
<td>-159.37</td>
</tr>
<tr>
<td>NO.Ⅱ triangular arch truss</td>
<td>-234.85</td>
<td>16.38</td>
<td>-155.12</td>
</tr>
<tr>
<td>NO.Ⅲ Trapezoidal arch truss</td>
<td>-140.53</td>
<td>11.78</td>
<td>-90.50</td>
</tr>
</tbody>
</table>

4. Conclusion

This article applies a horizontal earthquake intensity of 8 degrees (0.2g) to the large-span spatial pipe truss roof structures of NO.I triangular arch truss, NO.Ⅱ triangular arch truss and NO.Ⅲ trapezoidal arch truss. This paper explore and analyze the structural response to earthquakes from the perspectives of displacement and axial force, and compare and select structures that can better resist earthquake action.

(1) Each truss meets the seismic requirements of the structure, and the stress ratio is controlled within a reasonable range. Through the comparison of structural displacement and axial force, it can be concluded that the NO.Ⅲ trapezoidal arch truss performs better under the combined action of earthquake and load, and its seismic and mechanical performance is relatively excellent.

(2) The arrangement of web members between NO.I and NO.Ⅱ truss is only different, and there is no significant difference between the two structures under various load combinations. Therefore, it
can be seen that the change in web member arrangement does not significantly improve or enhance the seismic performance of the cross-section triangular truss in this study.

(3) Due to the NO. III Truss, the special nature of its cross-section requires more support constraints compared to trusses I and II, making the overall stability of truss III higher than the other two types of trusses. This is also an important reason for its superior seismic performance.

(4) Under the action of earthquakes, the lower chords connected to the supports of NO.I And NO.II truss generate significant axial forces that compress the members, and the upper chords in the mid-span area also generate axial forces that compress the members. The top chord of NO.III truss is mainly subjected to pressure, while the top chord of NO.I and NO.II is only compressed on one side and tensioned on the other side.

This article only uses a finite element model for simulation calculations and lacks a comparison of actual experimental results. To reduce the harm of earthquakes to space tube truss roof structures, it is very important to research isolation, and the authors will be also considered this as the goal of subsequent research.

**Authors Contribution**

All the authors contributed equally and their names were listed in alphabetical order.

**References**


