Analysis of seismic performance of assembled steel structure staggered truss system

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Abstract: In order to adapt to the application and development of large-span steel structure, this paper takes a 19-story assembled hybrid staggered truss structure office building as the background. SAP2000 finite element analysis software is used to establish two different forms of assembled steel structure staggered truss system, namely the hybrid staggered truss structure and the vierendeel staggered truss structure. The seismic performance of the structure was analyzed by modal analysis and dynamic elastic-plastic time-history analysis. The main conclusions are as follows: According to the modal analysis of the structure, the directions of the first three modes of the hybrid staggered truss structure are different from those of the vierendeel staggered truss structure. However, the natural vibration period of the two structures gradually decreases with the increase of the vibration mode. The natural vibration period of the vierendeel staggered truss structure is obviously larger than that of the hybrid staggered truss structure, which indicates that the stiffness and quality of the hybrid staggered truss structure are both larger than that of the vierendeel staggered truss structure. Through the dynamic elastic-plastic time-history analysis of the structure, the seismic performance of the two staggered truss structures in the X direction is basically the same. The difference is mainly reflected in the seismic performance in the Y direction. The seismic performance of the hybrid staggered truss structure is obviously better than that of the vierendeel staggered truss structure.

1. Introduction

As a new type of building structure, staggered truss system of assembled steel structure is widely used in multi-high-rise residential buildings, hotels, office buildings, etc., due to its characteristics of high efficiency, practicality and economy and in line with the development trend of building industrialization[1-2]. The basic structure of the assembled steel staggered truss system is composed of columns, trusses and floor panels. The height of the truss is the same as the height of the story, the span is equal to the width of the house, and the truss is interlaced in the adjacent columns. The staggered truss system can be divided into hybrid truss, vierendeel truss and Pad truss according to the different structural forms of the web member [3]. The research on this structure system will help to
popularize the development and application of steel structure in China and support the national green building policy.

In recent years, scholars at home and abroad have conducted a large number of studies on the seismic performance analysis and design theory of assembled steel structure staggered truss systems, and achieved fruitful research results\(^{[4-6]}\). KIM et al. \(^{[7]}\) used MIDAS software to analyze the seismic performance of 4-story, 10-story and 30-story staggered truss structures, and compared them with frame structures and frame-braced structures. Su Mingzhou et al. \(^{[8]}\) studied the experimental research and analysis on the mechanical performance of a single truss of concrete filled steel tubular column and assembled casing joints under vertical monotonic loading. Two kinds of model specimens with different casing joint forms are tested according to the actual stress and the equivalent strength principle. Chen Xiangrong et al. \(^{[9]}\) adopted the Pushover method to analyze the 12-story staggered truss structure. He found that the deformation of the floors of the staggered truss structure system designed by the plastic design method was relatively uniform, which met the requirements of relevant codes and had good seismic performance.

Based on this, this paper takes a 19-story assembled hybrid staggered truss structure office building as the background, and uses SAP2000 finite element analysis software to establish two different assembled steel structure staggered truss systems, namely hybrid staggered truss structure and vierendeel staggered truss structure. Through modal analysis and dynamic elastic-plastic time-history analysis, the seismic performance of the above structure is analyzed, which provides reference for the further development of the staggered truss system of steel structure.

2. Engineering background

The purpose of this paper is to study the seismic performance of assembled steel staggered truss system in high intensity areas, and to compare the seismic performance of hybrid and vierendeel staggered truss systems. Based on a 19-story assembled staggered truss office building, two different assembled staggered truss systems, 19m hybrid staggered truss structure and 19m vierendeel staggered truss structure, were established in this paper. The horizontal building size of the office building is 19.0 meters of hybrid staggered truss, the vertical building size is 12 span 8.0 meters of frame structure. The number of floors is 20, the height of the floor is 3.9 meters, and the total building height is 78.0 meters. The structure is fortificated according to 7 degrees (0.1g) seismic fortification, site category is \(\text{II}\) class, design earthquake group is the second group, Constant load value is 2.0kN/m², (not including the self-weight of components), live load value is 2.0kN/m². The truss column and frame column of the office building structure adopt rectangular concrete filled steel tubular solid column. The frame beam and the longitudinal connection beam of the truss are made of Q355B I-section steel. The floor is 200mm reinforced concrete slab. The dimensions of the main structural components, concrete grades and reinforcement bar grades are shown in Table 1 to Table 3.

| Type of component       | Dimensions of components (mm) |
|-------------------------|------------------------------|
| Truss column            | 800×800×28×28, 700×700×20×20, 600×600×15×15 |
| Frame column            | 700×700×20×20, 600×600×15×15 |
| Chord rod of the truss  | 400×300×10×20, 450×300×10×18 |
| Abdomen rod of the truss| 200×200×10×10, 200×200×14×14, 200×200×6×6 |
| Longitudinal connection beam of truss | 400×180×6×14, 500×200×8×16 |
| Frame beam              | 450×200×8×16, 400×200×8×16, 600×10×16×16 |

Table 2 The grade of main concrete component

| Building number | Column | Slab |
|-----------------|--------|------|
| First to fifth floors | C60     | C40   |
Sixth to tenth floors C55  C35
Eleventh to fifteenth floors C50  C30
Sixteenth to twentieth floors C45  C30

Table 3 Main type of the steel and reinforcement bar

| Component                      | Type of the steel and reinforcement bar |
|--------------------------------|----------------------------------------|
| Reinforced concrete slab       | HRB400                                 |
| Concrete filled rectangular    |                                        |
| steel tubular solid column     | Q355B                                  |

3. Computational model design
In this paper, SAP2000 software developed by CSI Company is used to analyze the seismic performance of assembled steel staggered truss system. The SAP2000 software is very powerful in analysis and calculation, providing a variety of analysis methods, such as modal analysis, response spectrum analysis, pushover analysis and dynamic elastic-plastic analysis, which can be used to calculate the seismic problems of structures composed of various special components. SAP2000 software was used to build a three-dimensional model of the structure, simulate the floor panels and roof panels as shell units, and simplify the frame beam, column and truss components into rod units for simulation [10]. In order to better study the seismic performance of assembled steel structure staggered truss system, two systems, 19m hybrid staggered truss structure and 19m vierendeel staggered truss structure, were established respectively. The three-dimensional models of each system are shown in Fig. 1 and Fig. 2.

![Figure 1 hybrid staggered truss structure](image1)

![Figure 2 vierendeel staggered truss structure](image2)

4. Modal analysis
Modal analysis is one of the basic methods of ground motion analysis for structures. In this paper, Ritz vector method is used to solve the first 20 order modes of four staggered truss systems. The first 12 order modal analysis data of hybrid and vierendeel staggered truss structures calculated by SAP2000 software are shown in Table 4 and Table 5.

Table 4 Mass participation coefficient of 19m hybrid staggered truss structure

| Modal | Period(s) | UX  | UY  | UZ  | RZ  | SumUX | SumUY |
|-------|-----------|-----|-----|-----|-----|-------|-------|
| 1     | 3.197109  | 0.77| 1.31E-12 | 2.058E-16 | 6.552E-09 | 0.78  | 1.542E-12 |
| 2     | 1.598115  | 1.178E-12 | 0.79  | 1.547E-08 | 0.000864 | 0.78  | 0.79    |
| 3     | 1.548507  | 8.172E-09 | 0.000860 | 5.235E-09 | 0.79  | 0.78  | 0.79    |
| 4     | 1.022489  | 0.0917| 7.833E-12 | 1.15E-14 | 5.156E-11 | 0.87  | 0.79    |
$$\text{Table 5 Mass participation coefficient of 19m vierendeel staggered truss structure}$$

| Modal | Period(s) | UX   | UY   | UZ   | RZ  | SumUX | SumUY |
|-------|-----------|------|------|------|-----|-------|-------|
| 1     | 0.568542  | 0.0444 | 1.534E-11 | 2.49E-14 | 7.442E-10 | 0.91 | 0.79 |
| 2     | 0.520872  | 6.94E-12 | 0.1 | 2.027E-08 | 0.000225 | 0.91 | 0.89 |
| 3     | 0.504901  | 2.848E-11 | 0.000227 | 1.053E-08 | 0.1 | 0.91 | 0.89 |
| 4     | 0.368757  | 0.0233 | 2.65E-12 | 1.626E-13 | 4.415E-10 | 0.93 | 0.89 |
| 5     | 0.298918  | 5.29E-12 | 0.0345 | 0.0000127 | 0.0000434 | 0.93 | 0.92 |
| 6     | 0.29018   | 8.06E-10 | 0.0000486 | 4.435E-08 | 0.0346 | 0.93 | 0.92 |
| 7     | 0.256723  | 0.0157 | 3.05E-12 | 2.924E-13 | 7.671E-11 | 0.95 | 0.92 |
| 8     | 0.209088  | 6.55E-12 | 0.0171 | 0.0000185 | 0.000181 | 0.95 | 0.94 |

5. Dynamic elastic-plastic time-history analysis under rare earthquakes

By comprehensive analysis of Table 4 and Table 5, it can be seen that the first mode direction of the hybrid staggered truss is mainly X direction translation, the second mode is mainly Y direction translation, and the third mode of the structure is mainly Z direction torsion. Compared with the hybrid staggered truss structure, the directions of the first three modes of the vierendeel staggered truss structure are changed. The first mode is mainly Y-direction translation, the second mode is mainly Z-direction torsion, and the third mode is mainly X-direction torsion. The natural vibration period of the two structures decreases gradually with the increase of the vibration mode. But the natural vibration period of the vierendeel staggered truss structure is obviously larger than that of the hybrid staggered truss structure, which indicates that the stiffness and mass of the hybrid staggered truss structure are greater than that of the vierendeel staggered truss structure. In terms of specification requirements, in the hybrid staggered truss Tt/T1=0.48<0.9, SumUX=93%>90%, SumUY=92%>90%; In the vierendeel staggered truss Tt/T1=0.72<0.9, SumUX=91%>90%, SumUY=92%>90%, both meet the requirements of relevant specifications.

5. Dynamic elastic-plastic time-history analysis under rare earthquakes

Time-history analysis is to obtain the dynamic response of the structure in each transient earthquake by direct integration method, and then we can understand the process of the displacement, acceleration, internal force and other changes with time of the structure under the action of seismic wave. Then we can calculate the dynamic response of the structure in the nonlinear stage. Based on this, this paper uses SAP 2000 software to conduct dynamic elastic-plastic time-history analysis on the two types of staggered truss structure models proposed above. By applying El Centro seismic waves in X and Y directions respectively, the seismic performance of staggered truss structures under rare earthquakes is studied.
5.1. Selection and adjustment of seismic waves
In this paper, El Centro seismic wave suitable for the second site was selected with a duration of 30 s, a time interval of 0.02 s, and a peak acceleration of 341.4 cm/s². The results were normalized, and the results were shown in Figure 3 below. During the seismic wave loading, in order to correspond to the loading conditions in the finite element software, that is, the peak acceleration of the loading wave corresponds to the seismic intensity, thus corresponding to the specification, frequency modulation processing is required for the loaded El Centro seismic wave, which is selected according to Table 6.

![Normalized El Centro seismic wave](image.png)

**Figure 3. Normalized El Centro seismic wave**

| Effects of earthquakes | 6 degrees | 7 degrees | 8 degrees | 9 degrees |
|------------------------|-----------|-----------|-----------|-----------|
| Frequent earthquake    | 18        | 35 (55)   | 70 (110)  | 140       |
| Rare earthquake        | 125       | 220 (310) | 400 (510) | 620       |

5.2. Dynamic elastoplastic time-history analysis results in X direction
In this paper, the time-history curve of the peak displacement is selected to analyze the seismic performance of the staggered truss of steel structure under earthquake, which can directly reflect the displacement change. Figure 4 shows the time-history curve of the structure's peak displacement under the action of rare El Centro seismic wave in X direction. It can be clearly observed that, under the loading of El Centro seismic wave, the time-history curves of the peak displacements of different structures in the early stage are very similar. And the time of the peak displacements is basically the same, indicating that the structures have similar top displacements. With the increase of the effective duration of the earthquake, the peak acceleration gradually increases, and the displacement trend of the structure begins to show a difference, and the displacement difference gradually increases. The peak displacement of the 19m vierendeel staggered truss is significantly greater than that of the 19m hybrid staggered truss.
The interlayer displacement angle is also an important reference factor to consider the deformation results of the structure under the action of load acts and mainly reflects the relative deformation of the structure. Figure 5 shows the variation of the interlayer displacement angle of the two staggered truss systems with the increase of floors under the rare El Centro seismic wave in X direction. It can be seen that the interstory displacement angle limits of the two structures meet the requirements of the code. Under rare El Centro seismic waves, the interstorey displacement angles of the hybrid staggered truss structure and the vierendeel staggered truss structure are roughly the same, showing a trend of “increasing first, then decreasing, then increasing, and finally decreasing”. The interlayer displacement angle between the first and fourth layers increases successively, while the interlayer displacement angle between the fourth and tenth layers decreases gradually. And the variation trend of the interlayer displacement angle between the tenth and above layers changes continuously. The peak value of interlayer displacement angle appears in the fourth and tenth layers. It can be seen that the fourth and tenth floors of the structure are weak layers with relatively low stiffness and weak ability to resist deformation. Therefore, appropriate strengthening design should be carried out.

5.3. Result of dynamic elastic-plastic time-history analysis in Y direction
The seismic response of two staggered truss structures under rare earthquakes is analyzed by calculating the seismic wave after the input of amplitude modulation in Y direction, and the merits and demerits of their seismic performance are compared. Figure 6 shows the time-history curve of the structure's peak displacement under the action of rare El Centro seismic wave in Y direction. Different from the X-direction loading, the peak displacement curves of the two staggered truss structures are separated obviously due to the difference in the stiffness of the structure in the Y-direction. Under the
action of El Centro seismic wave, the difference of displacement response between the 19m hybrid staggered truss and the 19m vierendeel staggered truss mainly occurs at the maximum acceleration, which may be caused by the difference of internal force distribution and structural stiffness.

Figure 6. Time-history curve of El Centro seismic wave peak displacement

Figure 7 shows the variation of the interlayer displacement angle of the two structures with the increase of floors under the rare El Centro seismic wave in Y direction. It can be seen that the interlayer displacement angle limits of the two structures meet the requirements of the code. Under rare El Centro seismic waves, the variation of interlayer displacement angle of the two staggered truss structures is roughly the same, showing a trend of first increasing and then decreasing. The interlayer displacement angle of the hybrid staggered truss increases from the first to the fourth floor, and reaches the peak at the fourth floor, and then begins to decrease gradually. It can be seen that the fourth floor of the structure is weak, with relatively low stiffness and relatively weak ability to resist deformation, so it should be properly strengthened. However, the interlayer displacement angle of the vierendeel staggered truss increases from the first floor to the tenth floor, and reaches the peak at the tenth floor, and then begins to decrease gradually. By comparing the interlayer displacement angle curves of the 19m hybrid staggered truss structure and the 19m vierendeel staggered truss, it can be seen that the interlayer displacement angle of the hybrid staggered truss structure is obviously smaller than that of the vierendeel staggered truss, and its Y-direction stiffness is obviously better than that of the vierendeel staggered truss.

Figure 7. Interlayer displacement angle curve of El Centro seismic waves

6. Conclusion
This paper takes a 19-story assembled hybrid staggered truss structure office building as the background. SAP2000 finite element analysis software is used to establish two different forms of
assembled steel structure staggered truss system, namely the hybrid staggered truss structure and the vierendeel staggered truss structure. The seismic performance of the structure was analyzed by modal analysis and dynamic elastic-plastic time-history analysis. The main conclusions are as follows:

(1) According to the modal analysis of the structure, the directions of the first three modes of the hybrid staggered truss structure are different from those of the vierendeel staggered truss structure. The first to third modes of the hybrid staggered truss structure can be respectively determined as: The translational mode mainly in the X direction, the translational mode and the torsional mode mainly in the Y direction. However, the first to third modes of the vierendeel staggered truss structure can be respectively determined as follows: the translational mode mode mainly in the Y direction, the second mode is the torsional mode, and the third mode is the translational mode in the X direction.

(2) The natural vibration period of the two structures decreases gradually with the increase of the vibration mode. The natural vibration period of the vierendeel staggered truss is obviously larger than that of the hybrid staggered truss, which indicates that the stiffness and mass of the hybrid staggered truss are both larger than that of the vierendeel staggered truss. The first 12 modes of the four models were obtained through modal analysis. The sum of the torsional period ratio and the mass participation coefficients in X and Y directions of the two structures were calculated to meet the requirements of the relevant codes.

(3) The seismic performance of the staggered truss structure under earthquake action is studied through the dynamic elastic-plastic time-history analysis by applying the seismic waves in X direction and Y direction respectively. The results show that the seismic performance of the two staggered truss structures in X direction is basically the same, and the difference is mainly reflected in the seismic performance in Y direction.

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