Stability Analysis of Prefabricated Steel Structure Building Based on Pushover Method

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Abstract: Prefabricated steel structure building is a kind of structural system which is widely used in recent years. It is very necessary to study the stability of it by Pushover method. Through the investigation of a building under construction in Hebei Province, China, the finite element analysis software SAP2000 is used to establish numerical simulation models of four kinds of staggered truss steel structure, so as to calculate its static pushover performance. It includes base shear-peak displacement curves, performance points and plastic hinge development. The main conclusions are as follows: the terminal shear and displacement of the hybrid staggered truss structure are obviously better than that of the Vierendeel staggered truss structure in the process of pushover. The base shear of the structure can be greatly increased and the overall deformation of the frame can be reduced when the side spans is set up. Until the end of the pushover, there is no plastic hinge on the column, which meets the seismic design requirements of "strong column and weak beam", indicating that the prefabricated steel structure staggered truss system has good seismic performance.

1. Introduction
Prefabricated steel structure building is a new and efficient housing construction system [1]. With its continuous development and progress, it has been widely applied in the construction of high-rise buildings all over the world [2]. Due to the large number of this type of building in recent years, the analysis of its stability under various types of external forces has become a research hotspot of many scholars in recent years [3-4].

Pushover method is an analysis method for nonlinear static calculation of structural seismic response [5-6], also known as static elasto-plastic analysis method, plastic hinge analysis method, etc. The main calculation basis is the lateral displacement at the top of the structure, which is a beneficial combination of response spectrum theory and static method [7]. China's Code for Seismic Design of Building Structures takes it as a method for checking and analyzing the elastic-plastic deformation of structures subjected to rare earthquakes [8-9]. The calculation method of this method can be summarized as follows: loading a single increasing horizontal load along the height direction on the structural calculation model until the component forms plastic hinge, cracks or local failure, and according to the failure process, the pushover curve of the load deformation structure of the base shear force and the top displacement of the structure is drawn.

Based on the above background, this paper takes a prefabricated steel structure building under construction as the research background, and carries out Pushover stability analysis on it by establishing a finite element analysis model. By applying lateral forces in different directions, the base shear-peak displacement curves, performance points and the development of plastic hinges of truss
structures under earthquake were studied. The pushover stability analysis conclusion of prefabricated steel structure is obtained, which can guide engineering construction and provide important reference for the development of related projects at home and abroad.

2. Engineering background
The engineering background of this study is a building under construction in Hebei Province, and the seismic design grade of its steel structure is Grade one. There was a "Tangshan earthquake" near the building area, causing heavy casualties and property losses. In addition, a total of six earthquakes of magnitude 7 or above have been recorded in Hebei province, and more than 40 fault zones of different sizes are distributed. Major fault belts are composed of Xingtai-Tangshan fault zone, Pinggu-Qianxi fault zone, Zijingguan fault zone, Xianghe fault zone and Taizhang Mountain piedmont fault zone [10-11]. Therefore, it is necessary to carry out Pushover stability analysis for the building. The project overview of the building is shown in Figure 1.

| Classification of the project                      | Parameters and grades       |
|---------------------------------------------------|-----------------------------|
| Structural design base period (reliability)       | 50 years                    |
| Structure design service life                     | 50 years                    |
| Structural design durability                      | 50 years                    |
| Safety rating of building structure (importance factor) | Level 1(γ0=1.1)           |
| Building height                                  | 79.9m                       |
| Structure type                                   | Staggered trusses - braces |
| Seismic fortification intensity                   | 8 degrees                   |
| The basic peak seismic acceleration of the design | 0.20g                       |
| Seismic grouping of the design                    | The second group            |
| Site category                                    | II class                    |
| Characteristic period Tg                         | 0.40s (small and medium earthquakes) |
| Damping ratio                                    | 0.45s (large earthquakes)   |
| The period reduction factor                      | 0.04                        |
|                                                   | 0.7                         |

The transverse building size of the building is 19.0 meters of hybrid staggered truss, and the longitudinal building size is 12 spans of 8.0 meters of frame support structure. The number of floors is 20, the height of more than two floors is 3.9 meters, and the total building height is 79.9 meters. The design values of dead load and live load are both 2.0kN/m². The truss column and frame column are rectangular concrete-filled rectangular steel tubular solid column, the frame beam and the longitudinal connection beam of the truss are made of Q355B 1-section steel, and the floor is 200mm thick reinforced concrete slab. Limited to space, not specific component parameters are introduced.

3. Finite element model
For the seismic response analysis of steel structure building system, a numerical simulation model can be established based on the finite element analysis software SAP2000 to obtain [12-13]. In order to study the seismic performance of high-rise buildings in high intensity area, this paper takes the upper 19 story structure for analysis. Four different types of prefabricated steel structure building systems are adopted, including hybrid staggered truss structure, hybrid staggered truss structure plus unilateral frame structure, Vierendeel staggered truss structure and Vierendeel staggered truss structure plus unilateral frame structure. The established models are shown in Figure 1.
According to Article 3.4.5 of Technical Specification for Concrete Structures of High Rise Buildings (JGJ3-2010), the ratio of the first natural vibration period dominated by structural torsion to the first natural vibration period dominated by translational motion shall not be greater than 0.9 for high-rise buildings with A-level height, and shall not be greater than 0.85 for high-rise buildings with B-level height and mixed structure buildings with A-level height. The quality participation requirement of modal analysis should meet the horizontal quality participation coefficient of more than 90%. The modal analysis results calculated in this paper are shown in Table 2, where X direction is the short-axis direction and Y direction is the long-axis direction. The calculation shows that all the models are in line with the relevant regulations of the code.

### Table 2. Results of modal analysis

| Structure type                                | Torsional period ratio | Modal cumulative mass parameters |
|-----------------------------------------------|------------------------|----------------------------------|
| Hybrid staggered truss structure              | 0.47                   | 93% 92%                          |
| Hybrid staggered truss structure plus unilateral frame structure | 0.51                   | 94% 92%                          |
| Vierendeel staggered truss structure          | 0.73                   | 91% 92%                          |
| Vierendeel staggered truss structure plus unilateral frame structure | 0.85                   | 91% 93%                          |

### 4. Analysis results of Pushover method

#### 4.1 Analysis steps

In the Pushover analysis of this paper, the stress state of the structure under gravity load is solved firstly. Subsequently, horizontal loads in X and Y directions were applied to the structure, and the M3 plastic hinges provided by SAP2000 were adopted to analyze the front frame beam, truss contact beam,
truss braces, truss chord. The designated position is the relative position of 0.05 and 0.95 on both sides of the rod end, the PMM plastic hinge is used for frame column and truss column. The designated position is also the relative position of 0.05 and 0.95 on both sides of the rod end, as shown in Figure 2. The following steps are mainly used in the analysis:

(1) The type of plastic hinge is selected according to various components forms of staggered truss structure and defined to the corresponding position of components.

(2) Two kinds of loads in X direction and Y direction are set, in which the dead load coefficient is 1.0 and the Pushover coefficient is 0.5. The nonlinear elastic-plastic condition was defined. Considering P-Δ effect, the monitoring displacement of the monitoring point was 390mm (0.01 times the floor height). The analysis results of multiple states are saved, the minimum number of saving steps is 70, the maximum number of saving steps is 150, and the rest of the nonlinear parameters use the system default values provided by SAP2000.

(3) After the analysis step stops, the deformation shape of the model, the results of the static pushover force-displacement curve, the value of the performance point, the development process of the plastic hinge, etc., are examined to analyze the seismic performance.

4.2 Base shear-vertex displacement curve

Fig. 3 shows the base shear-peak displacement curves of the four pushover structures in X direction. It can be seen that the base shear value of the structure increases with the increase of the displacement of the top floor, and the stiffness of the structure degrades after the end of the elastic stage. The maximum base shear of the hybrid staggered truss structure is about 64000kN and the maximum top displacement is about 3200mm at the end of pushover. After adding the side spans (hybrid staggered truss with side spans), the maximum top displacement of the structure is also 3200mm when the static force is pushed to the ultimate state, but its terminal shear force is larger. The maximum bottom shear force is about 78000kN, which is 21% higher than that of the structure without side spans. At the end of pushover, the maximum base shear of the Vierendeel staggered truss structure is about 60000kN, and the maximum top displacement is about 700mm. After adding the side spans (Vierendeel staggered truss with side spans), the maximum bottom shear force of the structure is about 70000kn, which is 16% higher than that of the structure without side span, and the maximum top displacement is 700mm. By comparing the base shear-peak displacement curves of the hybrid staggered truss structure and the Vierendeel staggered truss structure, it can be seen that the terminal shear and displacement of
the hybrid staggered truss structure are obviously better than that of the Vierendeel staggered truss structure in the x-direction pushover process.

![Graph](image_url)

Fig. 3 Base shear-vertex displacement curve of the pushover structure in X direction

That the base shear value of the structure roughly increases with the increase of the displacement of the top floor, and the stiffness of the hybrid staggered truss structure degrades after the elastic stage. However, the static nonlinear analysis curve of the Vierendeel staggered truss is close to a straight line, which indicates that the structure collapses immediately after the end of the elastic stage without the process of stiffness degradation. Among them, the maximum base shear of the hybrid staggered truss structure is about 60000kN and the maximum top floor displacement is about 700mm at the end of pushover. After adding the side span (hybrid staggered truss with side span structure), the curve bending becomes larger at the end of the elastic state, and the structural stiffness decreases and enters the stage of degradation and failure. The maximum displacement of the top floor is 700mm, but the end shear force is larger. The maximum shear force of the bottom floor is about 65000kN, which is 8.3% larger than that of the structure without side span. At the end of pushover, the maximum base shear of the Vierendeel staggered truss structure is about 5000kN, and the maximum top displacement is about 700mm. After adding the side spans (the Vierendeel staggered truss with side spans), the maximum bottom shear value of the structure is about 16000kN, which is 220% higher than that of the structure without side spans, and the maximum top displacement value is also 700mm. It can be seen that the increase of the side span structure has a significant effect on the enhancement of the base shear of the Vierendeel staggered truss. By comparing the base shear-peak displacement curves of the hybrid staggered truss structure and the Vierendeel staggered truss structure, it can be seen that the terminal shear and displacement of the hybrid staggered truss structure are obviously better than that of the Vierendeel staggered truss structure in the Y direction pushover process.
4.3 Performance points

Performance point refers to the maximum force and displacement that the structure can bear under the action of earthquake. When the performance points of the structure meet the requirements of the code, it means that the structure has good seismic performance. In SAP2000, ATC-40 was used in the system to determine the performance points. The values of each performance point of the four models in X direction and Y direction under pushover are shown in Table 3 below.

![Graphs showing base shear-vertex displacement curve of the pushover structure in Y direction.](image-url)

**Fig. 4 Base shear-vertex displacement curve of the pushover structure in Y direction**

| NO | Direction | Base shear (kN) | Peak displacement (mm) | Capacity spectral acceleration (g) | Capacity spectrum displacement (mm) |
|----|-----------|----------------|------------------------|-----------------------------------|-------------------------------------|
| 1  | X         | 16398.9        | 370.2                  | 0.1                               | 293.2                               |
|    | Y         | 34557.9        | 182.6                  | 0.3                               | 141.9                               |
| 2  | X         | 21098.9        | 374.4                  | 0.1                               | 296.9                               |
|    | Y         | 41322.9        | 195.5                  | 0.3                               | 154.4                               |
| 3  | X         | 16399.7        | 370.1                  | 0.1                               | 293.3                               |
|    | Y         | 6415.1         | 945.9                  | 0.1                               | 673.0                               |
| 4  | X         | 21093.5        | 372.8                  | 0.1                               | 296.9                               |
|    | Y         | 12677.2        | 605.0                  | 0.1                               | 444.0                               |

As can be seen from Table 3, the peak displacement of the performance points is 370.202mm and the base shear force is 16398.957kN under the action of static force in the X direction. In the Y direction, the peak displacement of the performance points is 182.678mm, and the base shear is 34557.917kN. When the side span structure is added, the peak displacement of the performance points is almost unchanged, but the base shear is increased by 28% under the X direction static pushover. The peak displacement of the performance points increases by 7% and the base shear increases by 20%
under the static pushover in the Y direction. The peak displacement of the performance points is 370.175mm and the base shear force is 16399.706kN under the action of static pushover in X direction. The peak displacement of the performance points is 945.92mm and the base shear is 6415.117kN under the action of static pushover in the Y direction. When the side span structure is added, the peak displacement of the performance points is almost unchanged, but the base shear is increased by 32% under the X direction static pushover. The peak displacement of the performance points is reduced by 35% and the base shear is increased by 97% under the Y direction static pushover. It is shown that the base shear of the staggered truss structure can be greatly increased and the overall deformation of the frame can be reduced when the side span is set up.

4.4 Plastic hinge development

Taking the plastic hinge development of the structure in the process of static pushover in X direction as an example, the plastic hinge development of four models is analyzed. As shown in Fig. 5-8, the plastic hinge of the structure is gradually generated under the horizontal thrust. The development and change of plastic hinges of the four models are basically the same, and pink plastic hinges begin to appear on the fifth layer beam, indicating that the beam begins to yield and the structure is still in the elastic deformation stage. As the loading continues, the pink plastic hinge gradually develops to the upper and lower ends. At about the 18th stage, the five-layer beam plastic hinge turns blue and enters the direct use stage. Until the end of the pushover, there is no plastic hinge on the column, which met the seismic design requirements of ”strong column and weak beam” [15-16]. According to the analysis of plastic hinge distribution, the staggered truss system of prefabricated steel structure has good seismic performance.
5. Conclusion
Prefabricated steel structure building has been widely applied in the construction of high-rise buildings all over the world, it is necessary to study the stability of it by Pushover method, relevant shaking table test research can be carried out in the future. The finite element analysis software SAP2000 is used to carry out pushover analysis on four types of staggered truss structural models. By applying lateral forces in X direction (short axial direction) and Y direction (long axial direction), the base shear-peak displacement curve, performance point and plastic hinge development of staggered truss structures under seismic action are studied. The main conclusions are as follows:

(1) By comparing the base shear-peak displacement curves of the hybrid staggered truss structure and the Vierendeel staggered truss structure, it can be seen that the terminal shear and displacement of the hybrid staggered truss structure are significantly better than those of the Vierendeel staggered truss structure in the process of static pushover in the X and Y directions.

(2) When the side span structure is added, the peak displacement of the performance points is almost unchanged, but the base shear is increased by 32% under the X direction static pushover. The peak displacement of the performance points is reduced by 35% and the base shear is increased by 97% under the Y direction static pushover. It is shown that the base shear of the staggered truss structure can be greatly increased and the overall deformation of the frame can be reduced when the side span is set up.

(3) The plastic hinge development of the four models is basically the same. Pink plastic hinge appears on the fifth layer beam and the beam begins to yield. The whole structure is still in the elastic deformation stage. Until the end of the push, there is no plastic hinge on the column, which meets the seismic design requirement of "strong column and weak beam", indicating that the prefabricated steel structure staggered truss system has good seismic performance.

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