Effect of Joint stiffness on Elastoplastic behavior of Cold-formed thin-walled Steel frames

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Abstract. In this paper, the first-order elastic analysis and second-order elastic analysis of cold-formed thin-wall steel frame (shelf) in practical engineering are carried out by using ANSYS and SAP2000 modeling analysis software, and the influence of semi-rigidity and second-order effect of joints on its overall performance is analyzed. At the same time, on this basis, the static elastic-plastic analysis of the shelf is carried out, and through the comparative analysis of the structural influence coefficient and displacement magnification coefficient of the shelf, the seismic performance of three kinds of beam-column connections (rigid connection, semi-rigid connection, hinged joint) is evaluated. And the structural influence coefficient of the shelf is put forward innovatively.

1. Introduction

In recent years, the concept of semi-rigid joints has been widely accepted by the civil engineering community. The American Code for Design of Steel structures (AISC,1994,1997) and the European Code for Design of Steel structures (Eurocode-3,4) have included semi-rigid (partially constrained) joints in the code provisions. At present, there is no special steel structure connection code in our country, only the general stipulation for beam-column connection is given in the Code for Design of Steel structure (GB50017), but this content has been listed as one of the important topics that should be further improved.

In order to solve the problem of how the properties of nodes affect the performance of the structure, the research on the performance of nodes has been carried out step by step at home and abroad. Claudio Bernuzzi, Carlo A. Castiglioni[1] studied the performance of beam-column plug-in joints under cyclic loading, and proved that the joints have an important influence on the response of the whole shelf structure. Dong Wei[2] used the portal frame test to determine the bending strength and semi-rigid stiffness of the beam-column connection plug joint, determined the influence of the common working function of the column and the crossbeam plug joint on the whole structure. Zhang Xing[3] analyzes the influence of semi-rigid connection on the performance of frame, and mainly studies the performance of top-bottom angle steel and top-bottom angle steel strip double web angle steel joint itself in detail. Hu Xibing[4] carried out the second-order elastic analysis of the semi-rigid frame, pointed out the influence of the interaction between the semi-rigidity and the second-order...
effect on the performance of the steel frame, and carried out the second-order elastic-plastic analysis. The influence of the semi-rigidity of the connection on the ultimate bearing capacity and floor lateral displacement of the structure is analyzed. However, the above studies have not made an in-depth analysis of the node performance and correlation coefficient from the overall point of view.

2. Analytical method
In this paper, according to the general situation of practical engineering, the semi-rigidity of joints is introduced into the design, the second-order effect of steel shelf is analyzed accurately, and the interaction between semi-rigidity and second-order effect is compared and analyzed.

At the same time, the structural influence coefficient and displacement magnification coefficient are introduced to carry out the static elastic-plastic analysis of the semi-rigid shelf.

3. Case analysis

3.1. General situation of the project
In this paper, an assembled steel shelf is selected, the column type is N95 (see Figure 3), the cross beam specification is K100 × 50 (see Figure 3), the total height of the structure is 19.8m, the seismic fortification intensity is 7 degrees, and the designed basic seismic acceleration is 0.1g. The second type of site soil is divided into the second group, the characteristic period of site soil is 0.4 s, the damping ratio is 0.035, and the maximum influence coefficient of ground motion is 0.008. The vertical load acting on the crossbeam is 2KN / m, and the full load is used in this model and the subsequent model analysis. Combined with the parameters of the shelf structure, a three-dimensional finite element model is established, a total of 14000 components, the overall three-dimensional model is shown in Figure 1. Based on the preliminary analysis of the three-dimensional whole model shown in Figure 1, it is found that the first three modes of the three-dimensional whole model are dominated by the X (longitudinal) vibration of the structure, and considering that the steel shelf is limited by its function, Therefore, the whole three-dimensional model is simplified to a single model for simplified seismic analysis, as shown in Figure 2.
3.2. First-order elastic analysis and second-order elastic analysis
In view of the inaccuracy and insecurity of the first-order internal force analysis of the frame, a second-order analysis method of the frame is proposed in this paper, that is, considering the influence of the second-order deformation of the structure on the internal force. The equilibrium condition is established according to the structure after displacement.

The first-order and second-order elastic analysis of beam-column joints are carried out for rigid connections, semi-rigid connections and hinged shelves, respectively. The shelf lateral displacement curve calculated by the second-order elastic analysis is compared with the shelf lateral displacement curve obtained by the first-order elastic analysis, as shown in Figure 4.

![Comparison of shelf side displacement curves between first and second order analysis](image)

According to the above chart, with the decrease of the stiffness of beam-column connections, the influence of the second-order effect becomes more and more obvious. This is mainly because the weakening of joint stiffness magnifies the second-order effect of the structure. Therefore, for the structure with small joint stiffness, the influence of the second-order effect cannot be ignored.

3.3. Static elastic-plastic analysis

3.3.1. Static nappe curve of structure
In this paper, the Pushover analysis of the structure is carried out by using Sap2000 software. In order to achieve the purpose of accurate analysis, the "standard lateral force mode" PUSH1 and modal load PUSH2 are used to push back the structure. First of all, PUSH1 applies the vertical load to the structure, and the vertical load takes the representative value of the gravity load, and carries on the static analysis of the structure under the vertical load, which is taken as the initial state. On this basis,
PUSH1 applies the horizontal load of inverted triangular distribution. The first order modal load is applied by PUSH2. The Pushover analysis of the structure under horizontal load is carried out by using the control mode of displacement loading in both methods. The nappe curves of the three types of nodes are shown in Figure 5. From the comparison of PUSH1 and PUSH2 nappe structure curves, it can be seen that the nappe effect of PUSH2 with first-order modal load is better, the reason is that the small force in the yield stage will cause larger displacement, and the increase of force will make the displacement result error larger.

![Fig. 5 Three kinds of node nappe curves](image)

3.3.2. Effect of Joint stiffness on plastic hinge Distribution

In order to accurately observe the whole process of plastic development of the structure, several representative joints with plastic hinge distribution are selected for statistics and analysis of the development trend of plastic joints. According to the model, except for the different stiffness of the joints, the other parameters are the same. The typical development stage of plastic hinge distribution after analysis is shown in the following Figure. It can be seen from the diagram that the plastic hinge first develops on the transverse short beam, and then gradually develops to the back pull area, and when there are enough plastic joints in the column area, the structure collapses.

![Fig. 6 position of plastic hinge for the first time](image)
3.3.3. Establishment of capacity spectrum curve model

In this paper, the influence of multi-mode shapes is considered in the process of equating the actual structure to a single-degree-of-freedom system. The specific process of the equivalent single degree of freedom system is as follows:

The jth order response mode of the structure is \( \{ \varphi \}_j \) \( (j=1,2,\ldots,m) \), the corresponding mode participation coefficient is \( \gamma_j \) \( (j=1,2,\ldots,m) \), the equivalent vibration type value of the I degree of freedom of the corresponding structure can be expressed as follows:

\[
\phi_{i,eq} = \frac{\sum_{j=1}^{m} (\phi_{i,j} Y_j)^2}{\sum_{j=1}^{m} \gamma_j^2 (\phi_{i,j} Y_j)^2}
\]

Among them, \( \gamma_j \) can be calculated according to the relevant provisions of the seismic code. As a result, the equivalent mode vector \( \{ \varphi \}_eq \), which can reflect the influence of different response modes of the structure, can be obtained. The modal participation coefficient of the equivalent mode shape of the structure, \( \Gamma_{eq} \), and the equivalent mass \( M_{eq} \) of the equivalent single degree of freedom system are expressed as follows:

\[
\Gamma_{eq} = \frac{\sum_{i=1}^{n} m_i \phi_{i,eq}^2}{\sum_{i=1}^{n} m_i \phi_{i,eq}^2} = \frac{\sum_{i=1}^{n} \sqrt{\sum_{j=1}^{m} (\phi_{i,j} Y_j)^2}}{\sum_{i=1}^{n} \sqrt{\sum_{j=1}^{m} (\phi_{i,j} Y_j)^2}}
\]

\[
M_{eq} = \sum_{i=1}^{n} m_i \phi_{i,eq}^2
\]
There are the following conversion relations between the base shear force $V_b$ and the vertex displacement $\Delta$ and the base shear force $V$ and the vertex displacement $u$ of the equivalent single degree of freedom system.

\[
u = \frac{\Delta}{\Gamma_{eq}}
\]

\[V = \frac{V_b}{\Gamma_{eq}^2}
\]

The capacity spectrum curve of the equivalent single degree of freedom system is represented by spectral acceleration $S_a$ and spectral displacement $S_d$.

\[S_d = u = \frac{\Delta}{\Gamma_{eq}}; S_a = \frac{V}{M_{eq}} = \frac{V_b}{M_{eq} \Gamma_{eq}^2}
\]

Through the above calculation process, the equivalent single-degree-of-freedom system considering the influence of multi-order vibration modes is obtained, and its capacity spectrum curve is obtained.

### 3.4. Static elastic-plastic analysis

Formula $R_{\mu} = \frac{V_e}{V_y}$ is called structural ductility coefficient; $R_{\mu} = \frac{V_d}{V_y}$ is called structural superstrength coefficient; the maximum lateral displacement of the structure is equal to the elastic displacement $\Delta_e$ multiplied by the displacement amplification factor under the design earthquake, that is $\Delta_{max} = \Delta_e \cdot C_d$.

Among them, $V_e$, $V_y$ and $V_d$ represent the maximum base shear force when the structure is completely elastic, the base shear force under significant yield and the designed base shear force, respectively, and $\Delta_e$, $\Delta_y$ and $\Delta_d$ are the vertex horizontal displacement corresponding to $V_e$, $V_y$ and $V_d$, respectively. $\Delta_{max}$ is the maximum horizontal displacement of the structural vertex. The specific calculation methods and principles of each parameter can be found in reference [12].

The calculation results of the parameters of the calculation process of the three types of nodes are summarized in Table 2, the calculation results of the structural influence coefficient are summarized in Table 3, and the displacement magnification factors are summarized in Table 4.

| Type of node        | Initial stiffness $K1$ (KN/mm) | Fully elastic vertex lateral shift $\Delta e$ (mm) |
|---------------------|-------------------------------|-----------------------------------------------|
| Rigid connection    | 0.542                         | 77.109                                        |
| Semi-rigid connection | 0.383                        | 90.911                                        |
| Pinned joint        | 0.316                         | 97.806                                        |

| Type of node        | $V_e$(KN) | $V_y$(KN) | $V_d$(KN) | $R_{\mu}$ | $R_{\Omega}$ | $R$  |
|---------------------|----------|----------|----------|----------|----------|-----|
| Rigid connection    | 41.839   | 35.106   | 12.5     | 1.192    | 2.807    | 3.346 |
Comparing the ductility coefficient $R_\mu$ of the three kinds of joints, it can be seen that the ductility coefficient of semi-rigid joints is the largest, that of hinged joints is the second, and that of rigid joints is the smallest. This shows that the energy dissipation capacity of the steel shelf with semi-rigid connection is larger after yield, and the ductility of the semi-rigid joint is similar to that of the hinged joint. Moreover, with the decrease of the joint stiffness, the influence coefficient of the structure decreases, that is, the plastic energy dissipation capacity of the structure under strong earthquake gradually weakens.

The comprehensive comparison of the data in Table 3 and Table 6 shows that the performance point (spectral displacement) of the structure increases gradually with the decrease of the joint stiffness, indicating that the lateral stiffness of the structure decreases with the decrease of the joint stiffness. At the same time, the displacement amplification coefficient of the rigid joint is the largest, which is consistent with the corresponding coefficient of the structure, indicating that the energy dissipation capacity is strong.

4. Conclusion
In this paper, based on the first-order analysis and second-order analysis, the static elastic-plastic analysis of steel shelves with three kinds of connections is carried out. With the decrease of joint stiffness, the structural influence coefficient decreases gradually, but the displacement magnification coefficient of semi-rigid joints is the largest. Considering the influence coefficient and displacement amplification coefficient of the structure, the semi-rigid joint has enough energy dissipation capacity and bearing capacity. At the same time, through the comparison of the influence coefficient of the shelf structure of the three kinds of nodes, it is determined that the influence coefficient of the shelf structure is between 3.0 and 3.3, and the energy consumption capacity is greater than 2.8 stipulated in the code. If the plastic energy dissipation capacity of the upper structure can be used in structural design, the economic benefit will be more significant.

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