Study on Seismic Behaviour of Cold Formed Steel Structure Based on Simplified Mechanical Model

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Abstract. Cold-formed thin-walled steel buildings adopt the process of layered assembly, which is easy to disassemble and assemble and conforms to the requirements of industrial construction. But there is no clear method of seismic design. Taking a cold-formed thin-walled light steel structure house in Dazhou city as an example, the Pivot connection unit that can characterize the structural damage and the finite element software SAP2000 are used to establish a model, then this model is used to analyse the basic dynamic characteristics of structures and to analyze the time-history response of structures under seismic action. The results show that the simplified modeling analysis of the structure has a strong feasibility, and the lateral stiffness of the structure can resist the action of multiple earthquakes. Under the action of rare earthquake, the displacement between the layers of the structure is lower than the limit of the code, and the hysteretic performance of the structure is good, which can ensure the safety and reliability of the structure.

1. Introduction
Cold-formed thin-walled steel structure has the characteristics of high recovery rate of components and short construction period. It is mainly used for three-story and below civil residence and two-story to three-story villa. The utilization rate of steel is high, and it can meet the requirement of sustainable development. All the structural parts and components are manufactured in the standardized workshop, and assembled on site, so the processing quality is guaranteed. Site construction has little impact on the environment, and it has the advantages of low comprehensive cost and short construction period, therefore it has the value of promotion. Taking a cold-formed thin-wall steel structure building in Dazhou as an example, we study the structure design method of the project. At the same time we use the finite element software SPA2000 to calculation and analysis. Through the established model, we analyse the basic vibration information of the structure. And then we study the linear analysis of structure under the frequent earthquake and the nonlinear analysis of structure under the rare earthquake, through the structural time-history response analysis. Through our research, we hope to provide reference for the engineering application of this kind of structure.

2. Project profile
This project is located in Dazhou, Sichuan province. It adopts cold-formed thin-wall steel structure and adopts new honeycomb wallboard material. The building is a small three-story residential house...
with a building area of 649.24m² and a total building height of 10.86m. Seismic fortification intensity is 6 degree, and design seismic acceleration is 18cm/s², and seismic grouping is one group. Site soil category for II class, site characteristic period of 0.35s.

The main frame of the structure is composed of 100×100×2mm, 120×120×2mm, 120×100×3mm square steel tubes. The support adopts C section steel of 120×50×20×1mm, 120×50×20×3mm and square steel tube of 120×60×2mm, 100×50×2mm. The wall material adopts double layer ousong plate sandwich honeycomb com-pound wall paper material, and the floor is composed of pressed steel plate, and the roof is square steel pipe slope roof frame plus C steel purlin ousong plate. The layout of cold-formed thin-walled steel wall is shown in Fig. 1.

Figure 1. Structural wall layout.

3. Finite element model

The cold-formed thin-walled steel structure residential steel is made of Q235 steel with yield stress of 235MPa, limit stress of 375MPa, elastic modulus of 2.06×10⁵MPa and poisson's ratio of 0.3.

Due to the complexity of structure and connection of cold-formed thin-walled steel walls, there is no theoretical calculation of shear bearing capacity of such walls at home and abroad. The shear performance index is obtained through full scale test [1]. According to the nonlinear simplified analysis method of wall in reference [1], cold-formed thin-walled steel wall can be approximately equivalent to equal-generation pull rod model, in which the pull rod is replaced by Pivot connection unit in SAP2000, and the simplified wall is assembled accordingly according to the shaking table model to obtain a simplified calculation model of the house.

In recent years, it is proposed to simplify the shear bearing capacity of cold-formed thin-walled steel wall by equal-generation pull rod method [2-5]. There are still the following problems to be solved: (1) the nonlinear finite element analysis model of the wall is complex, and the modeling process is tedious and inefficient, and it is difficult to be popularized in practical engineering applications. (2) the calculation model of this method is only applicable to the elastic stage, and nonlinear analysis is no longer applicable.

3.1 Wall body modeling

The modeling in this paper [1] refers to the experimental data and modeling method of Huang[1] and the idea of equal-generation pull rod method. Based on the hysteretic rule of line segment plastic Pivot connection ele-ment in SAP2000, this connection element is used to simulate cold-formed thin-walled steel wall according to the experimental data, so as to realize reasonable simplification of the wall, as shown in Fig. 2. In this paper, a degenerate four-line model is adopted to simulate the skeleton curve of the wall, as shown in Fig. 3. The stiff-ness of each section can be calculated according to equation (1).
As the displacement amplitude increases, the unloading stiffness of the curve decreases gradually, as shown in Fig. 4. The unloading stiffness of specimens at each stage can be calculated according to equation (2). When the characteristic points of specimens are unloaded, the unloading stiffness coefficient can be obtained through displacement difference.

\[
K_i = \frac{+ P_i - |+ P_i|}{\Delta_i + |+ \Delta_i|} \\
K_i = \frac{+ P_i - |+ P_i| - |+ \Delta_i| - |+ \Delta_i|}{+ \Delta_i + |+ \Delta_i| - |+ \Delta_i| - |+ \Delta_i|} \\
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K_i = \frac{+ P_i - |+ P_i| + |+ \Delta_i| + |+ \Delta_i|}{+ \Delta_i + |+ \Delta_i| + |+ \Delta_i| + |+ \Delta_i|}
\]

(1)

There, \( K \) - unloading stiffness of wall, \( \Delta \) - displacement of the wall during unloading, \( k \) - unloading stiffness coefficient.

Steel tension strips are set between walls on different floors, and rigid supports and horizontal bracing bars can effectively improve the lateral stiffness and integrity of the combined wall [6]. The tension belt in the wall can only bear tension, while the solid unit in SAP2000 can bear both tension and pressure. In the modeling process, the steel tension belt is simulated by Hook unit. The mechanical behavior of Hook unit is described as equation (3)

\[
f = \begin{cases} 
  f(d - \text{open}) & \text{if } d > \text{open} \\
  0 & \text{if } d \leq \text{open}
\end{cases}
\]

(3)

There, \( k \) - spring constant, \( D \) - element displacement, \( \text{Open} \) - initial crack, \( \text{Open}=0 \) in the formula can simulate the single pull component.

Figure 2. Pivot hysteretic rule of wall body.

Figure 3. Skeleton curve of wall.

Figure 4. Unloading stiffness of wall body.

Figure 5. Finite element model diagram.
3.2 The load arrangement
The dead load of the first and second floor composite floor is set as 1.42 Kn/m², and the live load is set as 0.5kn /m² and 4.0kn /m² respectively according to the room function and the building load code. The dead weight of the outer wall of cold-formed thin-walled steel wall shall be 1.0kn/m², and the dead weight of the inner wall shall be 0.5kn /m². The simplified finite element structure model is shown in Fig.5.

3.3 Basic dynamic characteristics of the structure
Since the y-direction stiffness of the structure is relatively small, the first mode is translational motion in the Y direction, and the second mode is translational motion in the X direction, and the third mode is torsion around the Z-axis. The basic vibration information of the structure is shown in Table 1, and the first three modes are shown in Fig. 6. According to the American approximate formula of the basic natural vibration period (4), the basic vibration period of the structure is calculated as 0.2992s.

\[ T = 0.05 \frac{H^3}{\pi} \]  

The difference between the results of structural modal analysis and this value is 5.24%, which indicates that the results of structural modal analysis are reliable. According to the basic information of structural vibration, the lateral stiffness of the structure in the Y direction is small, so the first mode of vibration of the structure is the translation in the Y direction. Although the plane arrangement of the structure is irregular, the torsion effect can be effectively restrained by the reasonable arrangement of the stiffness.

| Structural vibration mode       | T(s)     | Mass participation coefficient |
|---------------------------------|----------|-------------------------------|
|                                 |          | UX               | UY       | RZ       |
| The first mode                  | 0.31488  | 0.01195          | 0.85015  | 0.29699  |
| The second order modal          | 0.27979  | 0.77242          | 0.03852  | 0.14332  |
| The third order vibration mode  | 0.24734  | 0.14413          | 0.03614  | 0.48712  |

Figure 6. The first three vibration modes of the structure.

4. Structural time-history response analysis

4.1 Seismic oscillation
Structure in region belongs to II. The EL-centro wave is selected to simulate the three elements of earthquake. The continuous energy of the seismic wave is uniformly distributed in time-frequency space. Its energy is mainly distributed between [1,5.5]Hz, with a wide distribution range. The energy of [1.5,2.5]Hz frequency band is concentrated between [1.2]s and [4.5]s. The energy of [2.5,5]Hz band is concentrated in the narrower time domain of [2,2.5]s. The peak acceleration of seismic wave is 341.7cm/s².
4.2 Structural linear analysis under frequent earthquakes
The building is located in Dazhou city, Sichuan province, and its fortification intensity is 6 degree. For the analysis of the structure under frequent earthquakes, it adopts 6 degree and its peak acceleration is 18gal.

Under the action of frequent earthquakes, the maximum inter-story displacement angles in both directions of the structure appear in the first floor, because the structural deformation is mainly shear deformation, which is inconsistent with other structural systems appearing in the second floor.

As shown in Fig. 7, the envelope curve of inter-layer displacement Angle of the structure can be seen as follows:(1) the maximum inter-layer displacement Angle of the structure in two directions is $2.27 \times 10^{-4}$ and $2.82 \times 10^{-4}$.(2) although the single cold-formed thin-walled steel wall is relatively soft, it is different from the general frame structure. In the stiffness calculation, the contribution of internal partition wall to lateral stiffness should be considered.(3) due to the structure's light weight, the dynamic load generated by acceleration is small.(4) since the connection between components is the response of the structure under the action of earthquakes more than 6 degree, linear analysis is adopted.

The displacement of the top layer of the structure is shown in Fig. 8. It can be seen that :(1)the maximum displacement in both directions of the top of the structure is more than 2mm, which indicates that the lateral stiffness of cold-formed thin-walled steel wall structure can meet the application requirements of low-intensity areas.(2) The displacement in Y direction of the top of the structure is greater than that in X direction, the damping ratio in both directions is the same, and the dynamic amplification coefficient of the structure is the same, so the lateral displacement stiffness in X direction of the structure is relatively large, which is consistent with the results of modal analysis.

The time-history curve of acceleration at each elevation of the structure is shown in Fig. 9, and the maximum acceleration at each elevation of the structure is shown in Table 2. It can be seen that :(1) the maximum acceleration in X direction and Y direction at the elevation of the first layer are 21.572gal and 28.492gal, with a magnification of 1.198 and 1.862 times.(2) the maximum acceleration in X direction and Y direction at the elevation of the second floor are 31.551gal and 40.328gal, and the amplification is 1.753 times and 2.636 times.(3) the maximum acceleration in X and Y directions at the top elevation is 39.266gal and 42.733gal, and the amplification is 2.181 times and 2.793 times, which are similar to the structures of brick and concrete. The magnification factor of acceleration of the structure is related to the soil condition, structural quality, height of the structure floor and seismic intensity, etc. If the self-weight of the structure is reasonably controlled, the magnification factor of acceleration can be effectively controlled.

![Figure 7](image1.png)

Figure 7. Displacement angle envelope of the lower layer under more frequent earthquakes.

![Figure 8](image2.png)

Figure 8. Displacement of the top layer under more frequent earthquakes.
4.3 Structural analysis of rare earthquake

Under the effect of rare earthquakes, the structures are subjected to 6th intensity rare earthquake (peak acceleration 125gal) and 7th intensity rare earthquake (peak acceleration 220gal), respectively, for nonlinear analysis. According to the structural displacement, the acceleration of each layer and the hysteretic curve of the base shear - top layer displacement, the interlayer stiffness and energy dissipation capacity of the structure are analyzed.

As shown in Fig. 10, the envelope curve of inter-story displacement angle of the structure under the action of rarely encountered earthquake is as follows: (1) under the action of 6th intensity rare earthquake, the maximum inter-story displacement Angle in X direction and Y direction appears at the elevation of the first floor of the structure, which are 1/245 and 1/189 respectively. (2) under the action of 7th intensity rare earthquake, the maximum inter-layer displacement angles in X direction and Y direction are 1/119 and 1/118.

According to article 5.5.5 of building seismic code (GB50011-2010), the inter-story displacement Angle of the structure under rare earthquake action is no more than 1/50, and the multi-story cold-formed thin-walled steel structure can meet the requirements of the code under the action of 6th intensity rare earthquake and 7th intensity rare earthquake, so it can meet the requirements of stiffness in high-intensity areas. Under the action of a rare earthquake of 7 degree, when time history analysis is carried out, the stiffness in the X direction is greater, the maximum displacement Angle between layers is greater than that in the Y direction, and the X and Y direction acceleration ax: ay=1:0.85. With the increase of seismic intensity, the difference of acceleration amplitudes in the two directions increases, that is, the displacement angle difference between the two directions depends on the difference of seismic amplitudes under the action of 7th intensity rare earthquake.
The time-history curve of displacement of the top layer of the structure is shown in Fig. 11. Under the action of 6th intensity rare earthquake, the maximum displacement of the top layer of the structure in two directions is 0.028m and 0.031m respectively. Under the action of 7th intensity rare earthquake, the maximum displacement of the top of the structure in two directions is 0.057m and 0.060m respectively. In the time history analysis, the displacement in the X direction is greater than that in the Y direction, and the acceleration in the X direction and Y direction $a_x: a_y=1:0.85$. With the increase of seismic intensity, the amplitude difference of the acceleration input in the two directions increases. In other words, the displacement difference between the two directions is mainly controlled by the amplitude difference of the earthquake amplitude when the earthquake of 7 degree is rarely encountered.

![Figure 11](image1.png)

(a) 6th intensity rare earthquake  (b) 7th intensity rare earthquake

Figure 11. Top displacement of the structure under the action of rare earthquake.

Under the action of 7th intensity rare earthquake, the time-history curve of acceleration at the elevation of each layer of the structure is shown in Fig. 12. The maximum acceleration and acceleration magnification in the earthquake process are shown in table 3. According to article 5.1.4 of building seismic code (GB50011-2010), acceleration response spectrum method is adopted, as shown in equation (5).

$$\alpha \times T = k \beta \times T$$  \hspace{1cm} (5)

There, $k$-the ratio between the peak acceleration of ground motion and acceleration of gravity, $\beta$-acceleration magnification.

The energy dissipation capacity of the structure is mainly evaluated by the hysteretic behavior of the shear - top displacement of the base. The hysteretic curve of base shear-top displacement under the action of earthquakes of 6 degree and 7 degree is shown in Fig. 13. Before the displacement reaches the elastic limit, the hysteretic curve is basically linear. As the top displacement increases, the hysteresis loop gradually becomes full and dissipates more energy. Maximum acceleration information of each level elevation of the structure is shown in Table 3.

On the whole, although the hysteretic curves are pinched, the hysteresis loops are full and the structure has a strong energy consumption capacity. By comparing the figures in Fig. 13, it is found that the structure pinching phenomenon is more serious under the action of 7th intensity rare earthquake, but the hysteresis loop is more full. Generally speaking, the cold-formed thin-walled steel wall structure system can show good nonlinear performance and has a strong energy dissipation capacity under rare earthquake action.

| Table 3: Maximum acceleration information of each level elevation of the structure. |
|---------------------------------------------------------------|
| 6th intensity rare earthquake | 7th intensity rare earthquake |
| One level | Second level elevation | Top level | One level | Second level elevation | Top level |
| maximum acceleration (gal) | X | 217.721 | 275.216 | 306.816 | 303.642 | 438.496 | 412.038 |
| | Y | 170.708 | 192.559 | 273.662 | 277.540 | 352.472 | 407.315 |
| magnification times | X | 1.74 | 2.21 | 2.45 | 1.52 | 2.19 | 2.06 |
| | Y | 1.61 | 1.81 | 2.58 | 1.63 | 2.07 | 2.39 |
5. Conclusion

According to the structural mode information, the simplified structural modeling has a certain degree of reliability. The stiffness and mass of the structure are evenly distributed.

1) Under the action of frequent earthquakes, the lateral stiffness of cold-formed thin-walled steel structure is enough to resist the action of frequent earthquakes with low intensity under the action of horizontal loads. The deformation mechanism is different from other structures.

2) Under the action of a rare earthquake of 6 degree, the maximum inter-layer displacement angles in X direction and Y direction are 1/245 and 1/189. Under the action of a rare earthquake of 7 degree, the maximum inter-story displacement angle is 1/119 and 1/118 respectively, that is, the inter-story displacement of the structure is lower than the limit value, and the inter-story stiffness of the structure meets the requirements. The magnification factor of structural acceleration is equivalent to other structural forms.

Due to the light structure mass, the seismic action of the structure is smaller when the intensity is equal. The hysteretic performance of the structure is good, and the energy dissipation capacity is strong.

Acknowledgement

This research was financially supported by Sichuan Provincial Department of Science and technology (Grant NO. 2019YJ0322) and Deyang “Thirteenth Five-Year Plan” in 2019 (Grant No. DY19C050).
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