Pseudo-Dynamic Tests of Cold-Formed Thin-Walled Steel Wall

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Abstract. This paper presents the dynamic response and failure mechanism for the cold-formed thin-walled steel wall. Based on current seismic provisions and previous research, full-scale pseudo-dynamic tests (PDTs) were conducted on a 3m high cold-formed thin-walled steel wall. The time-history response, hysteretic behaviour, failure mode, stiffness degradation and ductility were investigated to analyse the dynamic response of the cold-formed thin-walled steel wall structure under a series of ground motion records. The results showed that the structural deformation position was concentrated at the intersection of the cross bar and the diagonal bar in the middle of the wall, and other joints had no obvious plastic deformation; The structure was still elastic under the frequently occurred earthquake of 7 degree and 8 degree. Under the rare earthquake, the stiffness degradation was developed rapidly and the bearing capacity was still higher, and also had better ductility. Cold-formed thin-Walled steel structure which exhibits excellent seismic behaviour and ductility, can be used as a reliable and effective assembly structure in seismic regions.

1. Introduction
At present, the application of cold-formed thin-walled steel structure technology is increasingly extensive. Such as the United States, Australia, Japan, the design method, construction and management system has been developed and construction assembly technology is also mature. The study of cold-formed thin-walled steel structures started earlier. For example, Gad et al. they studied the seismic performance of cold-formed thin-walled steel skeleton walls. Shaking table tests were carried out on a single piece of non-wallboard skeleton structure and single room model. According to the experimental analysis, the frequency, damping ratio and vibration mode of the steel frame system of the plug-in connection and the welded connection were the same [1]. Serrette studied variation of shear resistance of cold-formed thin-walled steel structure with various panel materials and X-cross flat steel bracing support under monotonic and cyclic loading conditions [2]. However, in China cold-formed thin-walled steel structure technology is still at an initial stage. The characteristic of local buckling on cold-formed thin-walled steel flexural members were analysed by Lai Tian et al[3].The property of distortion buckling behaviour on cold-formed thin-walled steel members were investigated by Wen Qiuping[4].Between 2003 and 2004,in order to analyse the shear strength of cold-formed thin-walled steel composite wall structure under different aspect ratios and loading modes, Xi’an University of Architecture and Technology and Beixin Housing Co., Ltd. conducted the first 1:1 full-scale model test on the cold-formed thin-walled steel composite wall in China for the first time.
Shi Yu et al. used the ANSYS software system to analyse the shear performance of the composite wall under monotonic loading by establishing a reasonable finite element model. The results showed that the shear strength of the composite wall decreased with the increase of the aspect ratio [5-6]. Liu Qiang conducted an experimental study on the vertical bearing capacity of the wall of the cold-formed thin-walled steel structure residential building. The test results showed that the wall panel had a great effect on the compressive bearing capacity of the wall column and proposes the wall panel supporting effect, and also obtained that the column can be flexed and bent according to the minor-axis of the section to calculate its bearing capacity, excluding bending and torsional buckling [7].

In China, many researches have been carried out on features of shear strength and axial compression of cold-formed thin-walled steel wall structure, but pseudo-dynamic seismic tests on cold-formed thin-walled steel wall structure have not been conducted. In order to reveal the dynamic performance and failure mode of cold-formed steel wall structure under earthquake. In this study, the pseudo-dynamic test of cold-formed thin-walled steel wall structure was carried out, and the failure mode was also obtained. By analysing the strain and acceleration time history curves, the hysteretic behaviour, stiffness degradation, ductility and energy dissipation capacity of the wall were studied.

2. Experimental programme

2.1. Test specimen

![Figure 1. Section form of steel member](image)

The design ratio of the test wall body is 1:1, and the length of the wall structure is 4200mm, width 89mm, height 3000mm; The spacing between adjacent columns is 600mm and the spacing between adjacent bars is 1500mm. The wall structure is made of G350 cold-formed thin-walled C-section steel. The cross-section types and dimensions are shown in Figure 1. At the junction of column and beam in the wall structure, the beam with web openings, and the column passes through the openings, the beam to column joints in the wall structure were connected by three self-tapping screws.

2.2. Materials quality testing

In the material test, all specimens were made of G350 cold-formed thin-walled steel and the specimens were taken from the web and flange of the same batch of steel. The stress-strain tensile curve and the mechanical properties of the material were obtained by a uniaxial tensile test. The mechanical data of the test results are shown in Table 1. The stress-strain curve and fracture of the test specimens are shown in Figure 2 and Figure 3.

| Steel category | \(f_y\) (MPa) | \(f_u\) (MPa) | \(\delta\) (%) | \(E\) (GPa) |
|----------------|--------------|--------------|----------------|-------------|
| web            | 409          | 476          | 37.5           | 212         |
| flange         | 408          | 479          | 39.5           | 190         |
2.3. Test setup and test

The weight of 1100 kg mass blocks were placed on the top surface of the wall structure to ensure that the axial compression ratio of columns was fulfilled requirements, the horizontal direction was controlled by a hydraulic servo loading system, which apply displacement to the wall structure with a hydraulic jack of ± 250mm, A displacement meter was placed on the top of the wall structure to measure the displacement response of test specimen, As shown in Figure 4. In this pseudo-dynamic test, the input seismic record is El Centro wave, and the seismic wave duration is 10 seconds, which including the acceleration peak. The load time step was set to $\Delta t=0.02s$, and the total time history was a total of 500 points, and the damping ratio of the 15s steel structure is 0.02. Based on the area where the basic design acceleration is 0.15g, the peak acceleration of 7-degree, 8-degree frequently occurred earthquake and 7-degree rare earthquake were adjusted to 35 cm/s$^2$, 70 cm/s$^2$, 220 cm/s$^2$ respectively. The above three adjusted seismic accelerations were applied as loads to the wall structure. The strain gauge position was determined by finite element analysis of the stress variation of the cold-formed thin-walled steel wall structure. The strain gauge was arranged at the joints where the cold-formed thin-walled steel wall structure was deformed greatly, mainly because the joint was the position where the plastic hinge appeared and the strength weakening leaded to stress concentration.

3. Test results and analysis

3.1. Test phenomenon

In the case of 35cm/s$^2$, the maximum displacement of the wall structure is 2.5mm. Because the seismic response was weak, the horizontal load and displacement are small, Therefore, the wall structure was always in an elastic state during the test; In the case of 70cm/s$^2$, the seismic response was more severe and the maximum lateral displacement of the wall structure was5.5 mm, but the test specimen was still in an elastic state; In the case of 220cm/s$^2$, the wall reacted violently and the yielding area was generated at the weakening of the crossbar in the middle of the wall structure. During the loading process, local buckling deformation occurred at the weakening of the diagonal bars of joints. When loading to the peak of acceleration, the lateral horizontal displacement of the wall structure also
reached the peak value. Each middle joint in the wall structure suffered severe plastic deformation and the component was destroyed with the stiffness decreasing significantly. See Figure 5.

Figure 5. Structural deformation figure of EL-Centro wave at 220gal

3.2. Displacement curve

Figure 6. The time-history displacement curve of the structure under various load condition

Figure 6 shows the displacement time history curve of the monitored structure under different acceleration conditions. By observing the structural displacement time history curve, it was found that the peak of displacement and acceleration appeared at the same time during the test. When the structure is in the elastic phase, the load magnification of the acceleration was approximately the same as the corresponding displacement magnification. The error was caused by the fact that there were many gaps between each component in the joints. When the wall structure was in the plastic state, the residual deformation of the joints increased gradually during the loading process, which causes the deviation of displacement time history curve.

3.3. Hysteresis curve

The hysteresis curve was established by the displacement and reaction force at the top of the wall structure, as shown in Figure 7. It can be concluded from the figure that the loading and unloading paths are basically straight under elastic load conditions, and overlap in the following cycles because the gaps in joints between the bars in the wall structure.

Under the plastic load condition, the equilibrium position of the wall structure shifted, the envelope area of the hysteresis curve expanded, and the loading and unloading paths are irregular. Under the plastic load condition, the loading and unloading paths were irregular. The equilibrium position of the wall structure was offset, and the envelope area of the hysteresis curve was enlarged.

Figure 7. The hysteretic curve of the structure under various working conditions
3.4. Skeleton curve and lateral stiffness

The structural skeleton curve and secant stiffness can be obtained from the hysteresis curve data, as shown in Figure 8.

As the loading peak acceleration and seismic wave energy increased, the wall structural damage and the lateral stiffness was gradually reduced. The overall lateral stiffness degradation data of the test specimens were shown in Table 2. The secant stiffness was used to represent the stiffness of the wall structure. The secant stiffness $K_i$ can be calculated according to formula (1):

$$K_i = \frac{F_i + F_{i-1}}{X_i + X_{i-1}}$$

(1)

Where: $F_i$ is the peak value of the $i$th load; $X_i$ is the peak displacement value of the $i$th load.

| Acceleration peak ($\text{cm} \cdot \text{s}^{-2}$) | Positive direction | Negative direction | Secant stiffness (kN-mm$^{-1}$) | Ductility coefficient |
|-----------------------------------------------|--------------------|--------------------|---------------------------------|----------------------|
| 35                                           | 2.56               | -2.55              | 1.11                            | 0.37                 |
| 70                                           | 5.53               | -4.3               | 1.04                            | 0.79                 |
| 220                                          | 32.99              | -12.97             | 0.44                            | 4.7                  |

It can be seen from the change trend of lateral stiffness in table 2 that: the peak acceleration of seismic wave changed from 35 cm/s$^2$ to 70cm/s$^2$, the wall structure is in an elastic stage, and the stiffness degradation is not obvious. As the peak value of the seismic wave acceleration increases to 220cm/s$^2$, the lateral stiffness of the wall structure decreases rapidly, which is approximately 39.6% of the lateral stiffness of the elastic stage.

3.5. Joint area strain analysis

Figure 9. Strain curve1
The strain gauges were connected to the static signal acquisition system at the joint’s areas. The strain of each measuring point in the joints areas can be obtained by the data display of the collection system. Therefore, the strain variation in the joint’s areas were analysed. According to Figure 9 and Figure 10, it can be concluded that the cross bar at joint No.2 was larger than the strain at the diagonal bar. This was because the transverse bar at the joint not only bear the axial force, but also bear the oblique force of the diagonal brace, while the diagonal brace bar only bear the axial force. In addition, due to the different bending directions of the two diagonal braces, the transverse bar and the diagonal brace are opposite in direction of strain at the joint. According to Figure 10(a) and Figure 10(b), it can be seen that the strain at the joint No.2 was larger than the strain at the joint No.8, which was consistent with the experimental phenomenon. The component damage position was concentrated at the middle of the wall structure, and the deformation of top and bottom joints were small.

4. Conclusions
Based on the experimental and numerical investigations observations, the following conclusions could be made.

1. The pseudo-dynamic test shows that: the wall structure has better seismic characteristics, In the case of 7 degree and 8 degree frequent earthquake, the structure is in the elastic state, and the reaction trend of the two elastic load conditions are consistent
2. The test shows that the middle row of joints of the wall is subjected to complicated forces, and the stiffness attenuates rapidly, which is the weakest part of the structure.
3. The mechanical properties of the wall at the state are in accordance with the seismic code (GB 50011-2010). Under the condition of 7 degree rare earthquake load, the wall ductility coefficient is 4.7, and the structure has good ductility and energy dissipation.

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