Contrastive Analysis of Two Connection Modes of Enclosure Wallboards and Steel Frames

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Abstract. According to the application status of the connection between enclosure wallboards and steel frames in the cold area, a new type of connection mode is designed in this paper. The seismic performance indexes of the two connections such as bearing capacity, energy dissipation and ductility, etc. are obtained through the experimental study of the reduced-scale specimens. Both connection modes can meet the local seismic fortification requirements, but the new connection mode has more advantages than the original connection in many aspects.

1. Introduction of Connection Modes

In the steel (light steel) frame envelope system with the seismic fortification intensity less than or equal to 8 degrees in severe cold areas, the connection between the enclosure wallboards and the main steel frames is mostly rigid. The rigid connection has no rotational ability outside the plane, and is prone to cracking under the earthquake. Moreover, the influence of the enclosure structure on the stiffness of the main structure is difficult to accurately measure in calculation. To solve this problem, the research group designs a flexible connection mode, which is connected with the main structure through the angle steel. The two limbs of the angle steel can realize the slight rotation of the wallboard outside the plane. In order to verify and compare the bearing capacity, energy dissipation, ductility and stiffness degradation of these two modes, according to the production and application status of light steel structures in local enterprises, the research group optimizes the original wall structure of enterprises, makes the same size 2:1 scale enclosure wallboard and loading frame, and carries out experimental research on the connection performance. The new and old connection modes are called Y1 and Y2, respectively.

The enclosure wallboard adopts the sandwich form[1]. The inner and outer surfaces and the periphery of the wallboard are C20 volcanic slag lightweight concrete embedded with CRB500 3@50 steel mesh, with the thickness of 50mm, and the middle insulation layer is 200 mm molded polystyrene board (EPS plate). In order to increase the stiffness of reinforcing steel mesh, one CRB500 reinforcing bar is used as cross skeleton to reinforce the front and back surfaces of the wallboard, as shown in Figure 1.
Each wallboard is only connected with steel frame beams, and the connecting joints are located at 1/4 of the spans of the upper and lower sides of the wallboard, with two upper and two lower joints, respectively. The structure of the flexible connection Y1 is as follows: First, the embedded part is made, which is composed of welded I-beam and bolts. The section of the welded I-beam is 150×85×8×8mm, and the length is 80 mm. There are two holes in the outer flange of the I-beam, and two M12 C-grade ordinary bolts are tightened through the holes. When the wall panel is made, the I-beam and the inner surface of the wall board are even; and then, a 150 mm-long L80 ×10 connection angle steel is needed at each connection node. Bolt holes are reserved at the corresponding positions of the angle steel. The front bolt and the angle steel are tightened before installation of the wall panel, and the angle steel is welded on the upper flange surface of the steel beam (or bolted to the upper flange of the steel beam) after it is in place, as shown in Fig. 2.

The location and number of each wall board in the rigid connection are the same as those of the flexible connection, but they are constructed differently. The structural scheme of the rigid connection Y2 is as follows: an embedded sleeve with the length of 200 mm and 14 mm inner diameter is welded on the reinforcing mesh when the wallboard is made; before the wallboard is installed, a 5mm-thick 70mm×400 mm Q235 long strip steel plate with a 15 mm hole is made, and the long strip steel plate with a hole is welded on the side of the steel beam, and the ordinary M14 C-grade bolts are tightened with the embedded sleeve through the steel plate with a hole in the installation; after it is installed in place, a full external rigid connection is formed. The structural diagram is shown in Figure 3.

2. Test Loading

2.1. Loading scheme
The loading steel frame is manufactured by the research group. The wall board is connected in a fully external mounted structure. The loading device is the 50T hydraulic servo actuator loading control system, which can directly measure the load and displacement. The load is directly imposed on the composite wallboard. The main consideration is that the force on the main structure cannot be transferred directly to the non-load-bearing structure. The main structure must be deformed...
sufficiently greatly to act on the enclosure. The loading frame of this research needs to be repeatedly loaded for the multiple times and should not be destroyed. Therefore, the actuator is directly acted on the enclosure wallboard. This loading method can intuitively simulate the stress mechanism and failure mode of wall boards and connection joints under the seismic force, and the test data are more real.

The loading method is the force-displacement mixed loading method, and the force control is adopted before yielding. According to the theory, the loads of the non-structural members are calculated on the effect of frequent earthquakes, fortified intensity earthquakes and rare earthquakes in the 8-degree seismic fortification area, respectively. The loading step is ±5kN (+4kN), and the load is increased step by step. Each displacement lasts for 2 minutes and each step of load is circulated once; the displacement is controlled once after the specimen is yielded. The yielding displacement ±Δy of the specimen is taken as the control displacement step, and the displacement is increased step by step. Each displacement lasts for 2 minutes at each stage, and the displacement is circulated once at each step until the member is destroyed[2].

According to the theoretical analysis results, the displacement meter is arranged in the monitoring position. At the same time, it is considered that during the cyclic loading, the rigid connection between the loading frame support and the ground cannot be realized and the relative sliding will occur, the displacement sensor is also arranged on the support seat of the loading frame to measure the absolute displacement caused by the sliding of the support so as to ensure the accuracy of the displacement of the wallboard.

The signs of connection failure and end of the test are defined. When the load decreases obviously (below 85% of the peak load), or one of the following phenomena occurs, it is considered that the specimen has lost the bearing capacity and reached the failure state: ① the angle steel at the connection joint of the main structure is damaged or the steel plate at the connection joint is damaged; ② the bolts in the connection joint are damaged; ③ The embedded parts in the enclosure wall board are pulled out; ④ The concrete around the embedded parts is damaged [3].

2.2. Test loading

2.2.1. Y1 connection failure process
According to the theoretical calculation, the loading step of Y1 connection test is 5 kN before yielding. Before loading to 20 kN, no deformation or sliding occurs between the wall board and the joint, and the whole specimen is in the elastic state; after loading to 60 kN at the first level of 20 kN, no deformation or sliding occurs between the wall board and the joint; when loading to 70 kN, the angle steel slips slightly relative to the peripheral wall plate, the displacement growth is accelerated, and the connection begins to yield; Subsequently, the displacement value (+3.9 mm, -4.0 mm) at 70 kN is taken as the datum, and the displacement control loading is taken and the displacement control step is +8 mm, +12 mm. In the two-step loading process, the bolt deforms remarkably, and a slight slamming sound is heard at the connection node. When it is loaded to the displacement of 14.5 mm, a sudden slamming occurs, the bolt at one connection node on the lower side is sheared, and two bolts at the other connection point are sheared. The connection is broken and the test is terminated. At this time, the limit load is 130 kN. The joint damage is shown in Fig. 4.

2.2.2. Y2 connection loading process
According to the theoretical calculation, the four-step loading step before Y2 connection is 5 kN. Under the first three steps of loads, no deformation or sliding occurs at the joints of the wallboard and the loading frame, and the whole specimen is in the elastic state. When the fourth step of 20kN is loaded, the appearance of the wallboard and the joints remains stable, but the joint steel plate is warped slightly out of the plane, the displacement growth rate increases, and the connection begins to yield. And then, the displacement value (+5.5mm, -6.5mm) at 20kN is taken as the loading step, and
the displacement control loading is taken. The first step is + 11 mm, - 13 mm and the second step is + 22 mm, - 26 mm. In the two steps of loading, the joint steel plate bends obviously and deflects outward, the displacement increases rapidly, and there are inclined cracks near the embedded sleeve, and they continue to expand. When the load increases to - 33 mm, the welded part of the joint steel plate is torn, and at this time, the connection is broken and the test is terminated. The limit load is 52 kN at the end of the test. The failure of the joint is shown in Fig. 5.

![Figure 4. Y2 Connection Failure](image)
![Figure 5. Y1 Connection Failure](image)

3. Analysis of Test Data

The load-displacement skeleton curve (Fig. 6) and load-displacement hysteresis curve (Fig. 7) and the energy dissipation coefficient and equivalent viscous damping coefficient (Table 1), displacement ductility coefficient (Table 2) and stiffness degradation rule (Table 3) of the two connection structures can be calculated through the hysteresis curve so as to carry out the contrastive analysis of the bearing capacity and seismic performance of the connection structures.

![Figure 6. Load-Displacement Hysteresis Contrast Curve](image)
![Figure 7. Load-Displacement Skeleton Contrast Curve](image)

3.1. Hysteresis curve and skeleton curve

From the contrast of the two hysteretic curves, it can be seen that the hysteretic curve of Y1 connection is relatively full, which indicates that the whole structure has better plastic deformation and energy dissipation capacity through the deformation of the joint and the crack development at the joint, while the plumpness of the hysteretic curve of Y2 connection is relatively poor. The energy consumption capacity of Y1 connection is better than that of Y2 connection.

From the contrast of the two skeleton curves, it can be seen that: 1) the yield load of Y1 connection is 70 kN, the yield load of Y2 connection is 20 kN, and the yield load of Y1 connection is about 3.5 times that of Y2 connection; 2) the limit load of Y1 connection is 130 kN, the limit load of Y2
connection is 52 kN, and the limit load of Y1 connection is about 2.5 times that of Y2 connection; 3) on the effect of the multiple earthquake loads, both Y1 connection and Y2 connection have not yielded. Under the rare earthquake load, Y1 connection is still yielding, while Y2 connection has entered the elastic-plastic stage, but all meet the seismic requirements of the seismic fortification area with 8 degrees. Compared with Y2 connection, Y1 connection has more bearing reserves.

3.2. Energy dissipation coefficient and equivalent viscous damping coefficient

The energy dissipation coefficient and equivalent viscous damping coefficient are calculated according to formula (1) and Figure 8 by referring to the Code for Seismic Testing of Buildings[4].

\[
E = \frac{S_{(ABC+CDA)}}{S_{(\Delta\Delta OB+\Delta ODF)}}; h_e = \frac{S_{(\Delta\Delta OB+CDA)}}{2\pi \times S_{(\Delta\Delta OB+\Delta ODF)}}
\]  

Figure 8. Schematic Diagram of p-\(\Delta\) Hysteresis Curve

Combine with the load-displacement hysteresis curves of Y1 and Y2 connections, the energy dissipation coefficient and equivalent viscous damping coefficient can be obtained according to formula (1) as shown in Table 1.

| Connection No. | Yielding E | Yielding \(h_e\) | Limit E | Limit \(h_e\) |
|---------------|------------|-----------------|--------|-------------|
| Y1 connection | 0.566      | 0.090           | 0.620  | 0.09        |
| Y2 connection | 0.352      | 0.056           | 0.429  | 0.068       |

From Table 1, it can be known that the energy dissipation of Y1 connection is better than that of Y2 connection both in the yielding and limit failure.

3.3. Ductility coefficients

Ductility refers to the performance that a structure or member will not be destroyed with the continuous increase of deformation after the total deformation of the structure or member under the external load exceeds the yield displacement and enters the plastic stage. The ductility of a structural member can be measured by the ratio of the limit displacement \(X_u\) and the yield displacement \(X_y\) of the structural member. The ductility coefficients of connections are calculated by formula (2) in accordance with the Code for Seismic Testing of Buildings[5]. The ductility coefficients of the two connections are shown in Table 2.

\[
\mu = \frac{X_u}{X_y}
\]  

(2)
Table 2. Ductility Coefficients

| Specimen | Yield load /kN | Limit load /kN | Yield displacement Xy /mm | Limit displacement Xu /mm | Ductility coefficient |
|----------|----------------|----------------|---------------------------|---------------------------|----------------------|
| Y1       | 70             | 130            | 4.0                       | 14.5                      | 3.63                 |
| Y2       | 20             | 52             | 6.3                       | 33.3                      | 5.28                 |

From Table 2, it can be known that the ductility coefficient of Y2 connection is about 1.45 times that of Y1 specimen, which indicates that the ductility of Y2 specimen is better.

4. Conclusion
According to the test and data analysis of the two connection modes, the limit bearing capacity of the flexible connection is 2.5 times of that of the rigid connection and the energy dissipation capacity is 1.45 times of that of the rigid connection. However, the ductility of the rigid connection is 1.45 times of that of the flexible connection because of the small stiffness of the connecting steel plate, and the stiffness and bearing capacity of the rigid connection is less than that of the flexible connection as a whole. With the convenience and economy of construction considered, the flexible connection can be used as the preferred connection mode of steel (light steel) frame peripheral wallboards.

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