Seismic Behavior of Connection of Steel Frames and Composite Wall Panels

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Abstract. Steel frames and composite wall panels are usually connected by welding. In this paper, a flexible bolt connection method is designed, and the cross section of the original composite wall panel is optimized to form a new envelope structure system. The new envelope structure is analyzed as a whole using the finite element software ABAQUS. In order to compare the performance of the welding and the flexible bolt connections, an experimental study is carried out to investigate the bearing capacity and displacement of single bolt and two bolts flexible bolt connection and the welded connection. The seismic bearing capacity, ductility and energy consumption capacity of the different envelope structures are analysed. The results of the theoretical analysis and experimental verification indicate that the flexible bolt connection is superior to the rigid welded connection in terms of bearing capacity, ductility, energy consumption and impact on the stiffness of the main structure. It is believed that such findings are of great value for further application of steel frame structure in practice.

Keywords: Steel Frame, Composite Wall Panel, Bolted Connection, Welding, Ductility, Energy Consumption Capacity, Bearing Capacity

1. Introduction

With the development of building industrialization, steel frame structure has become the future direction of building development in China, due to its numerous advantages, such as light weight, short construction period, green and sustainable development, etc.[1]. The design theory and construction technology of the main structure of the steel frame are relatively mature. The connection between the wall panel and the main body in the envelope structure (generic term of composite wall panels and connection) is believed to be the key to further application of such structures as its performance affects the stiffness, bearing capacity and seismic performance of the steel frame structure system. Li Guoqiang et al.[2] carried out shaking table tests on the full-scale model of a steel frame residential system with wall panels. Their results showed that the contribution of the hanging wall panels to the stiffness of the steel frame is about 20%. Kim et al.[3] studied the steel frame with composite wall panels, which indicated that the existence of external wall panels could reduce the section size of structural members and increase the seismic performance of the structure.

From the above research, it can be seen that the beneficial effect of the envelope structure on the main body of the steel frame is significant. However, if the envelope structure is set unreasonably, the harm to the main structure cannot be ignored. For example, during earthquakes, loss of life and
property could be caused by damage to the connection and falling of the envelope structure, and insufficient ductility of the envelope wall panel could also lead to cracking and collapses of the walls, and further blocking the evacuation channel and so on. Therefore, the Code for Seismic Design of Buildings (GB 50011-2010)[4] states that the envelope wall and the main body of the frame structure should be flexibly connected or separated from each other, with only the weight of the envelope structure being considered, but not the effects of its stiffness and strength. In the seismic design, the frame should bear all the vertical and horizontal loads while contribution of all the envelope structures to the lateral force resistance of the frame is not considered. Therefore, flexible connection between the steel frame and the envelope wall is preferred to ensure that the envelope structure and the steel frame is well coordinated, so as not only achieving a reliable connection but also preventing premature cracking, and separation of the connectors resulting in earthquake disasters.

2. New Connection Structure of Composite Wall Panels and Steel Frames

According to the production and installation conditions, a welding connection method between composite wall panels and steel frame beams was designed by an enterprise in Jilin Province. The connection details are as follows: after the connection position is calculated, take the 1/4 span from the end of the wall panel, and set up two connecting nodes at the top and bottom. When the wall panel is made, the sleeve with the inner diameter of 14mm should be embedded in the connection place. In the installation, a Q235 long strip steel plate with the cross section of 70×400×5 should be placed at the sleeve of the inner surface of the wall panel, and in its corresponding position should be opened a 15mm round hole, and then tighten the steel plate with M14 ordinary Class C bolts; after it is installed in place, the steel plate and the frame beam are welded, as shown in Figure 1. In order to reduce the influence of welding on the flange of the frame beam, a pair of corresponding steel plates are pre-welded in the corresponding position of the frame beam and welded with the steel plate on the wall panel.

![Figure 1. Welding Connection Structure](image)

In the practical application, it was found that construction quality of the welding connection was difficult to guarantee due to the constraint of the site and space. During the use, cracks first appeared in the welding seam, and poor seismic performance was noted, among other shortcomings affecting the applicability of the building. Thus, further optimization of the design is required. On this basis, the authors have optimized the structure of the composite wall panel and designed a bolted connection method. This paper reports the theoretical analysis and experimental study carried out for the new optimized connection, in comparison to the existing welding connection.

First, the heat insulation material is preferred, EPS is changed to XPS, and the cross-section structure of the composite wall panel is optimized. The three-layer material is connected by the steel truss, and the wall thickness is reduced from 300 mm to 250 mm. And then, the flexible bolted connection between the composite wall panel and the main structure is designed. The structure and technology are as follows: when the composite wall panel
is made, an I-shaped embedded part is embedded at the designed connecting position, which consists of two flange steel plates and one (2) steel sleeve connected. The dimensions of the steel plate are 150×120×6, which is embedded in the wall panel and outer concrete. The steel plate embedded in the inner concrete should be on the level with the inner surface of the wall panel. The inner diameter of the steel sleeve is 14mm and the length is 210 mm. The steel sleeve and the flange steel plate are welded to form the web of the I-shaped embedded parts. Threads are placed in the range of 1/2 length of the steel sleeve near the inner side of the wall panel and the remaining parts are solid. The end of the steel sleeve should be blocked to prevent concrete from falling into it during construction. During the construction of the steel frame beams of the main structure, the angle steel ∟90×10 is welded on the upper surface of the connecting position, and the bolt holes (14mm+1.5mm) are set on the vertical limbs; after the wall panels are hoisted in place, the sleeves in the angle steel, the vertical limbs and the embedded parts of the wall panels are connected with bolts, as shown in Figure 2. The flexible bolted connection reduces the adverse effect of the envelope wall on the stiffness of the main structure, and greatly reduces the cracks caused by the welding quality and the seismic action in the use. The connection is semi-exterior, that is, the inner concrete slab is placed on the steel frame beam, the insulation layer and the outer concrete slab are enclosed with the steel frame, and the semi-exterior connection prevents the influence of the thermal bridge of the main structure on the thermal engineering of the building. [5]

![Figure 2. Bolted Connection Structure](image)

3. Experimental Study on the Connection of the Composite Wall Panel with the Steel Frame

According to the finite element analysis and in combination with the original wall panel structure and connection method, three 1:2 reduced-scale specimens (1.5m×1.3m) are fabricated. The experimental study is carried out under the low cycle reciprocating load. The types of wall panels and connection modes of the three envelope structures are shown in Table 1. Among them, the structural form of the wall panels of the envelope structures W1 and W2 is G1, and the connection mode is bolted connection (GZ1: 2 bolts, GZ2: 1 bolt); the structural form of the wall panels of W3 is Y1, and the connection mode (YZ1) is welding connection. Theoretically, the number of bolts should be determined according to the design and structure, and the number of bolts at each joint should be not less than two. However, in order to verify the bearing capacity of the joint, the experimental study is carried out in two cases: GZ1 and GZ2.

| Envelope Structure | Type of Wall Panel | Connection Mode |
|--------------------|--------------------|-----------------|
| W1                 | G1 Optimized       | GZ1 Bolted connection |
| W2                 | G1 Optimized       | GZ2 Bolted connection |
| W3                 | Y1 Existing        | YZ1 Welding connection |

In order to realize the repeated loading of the multiple wall panels, the loading frame is specially designed and manufactured by the research group. The loading test scheme, the design and connection
of measuring points and the installation of displacement meters, etc.[6] are formulated. The loading position and the arrangement of measuring points are shown in Figure 3.

![Figure 3. Loading Position and Layout of Measuring Points](image)

### 3.1. Loading scheme and process

The loading scheme of the envelope structures (W1, W2) adopts the force-displacement combined control method[7]. The force control method is adopted before yielding, and the horizontal reciprocating concentrated load is applied on the wall panel through a hydraulic servo actuator. The horizontal thrust of the actuator is positive, the tension force is negative, the initial value is 0kN, and the loading step is +5kN. Loading is applied step by step for 2 minutes at each stage, and the loading circulates once for each stage. The displacement control method is adopted after the specimen yields. The displacement ±Δy at the time of yielding is taken as the displacement step, and the displacement is increased step by step. The loading is held for 2 minutes at each stage until the member is damaged. Because the welding connection of the envelope structure (W3) is considered, the force control method is adopted in the whole loading process. Other loading schemes are consistent with those of W1 and W2.

The sign of the end of the test: when the load obviously decreases (below 85% of the peak load) or when one of the following phenomena occurs, it is considered that the specimen has lost the load-bearing capacity and reached a failure state: 1) the bolts are cut off; 2) the wall panel is partially crushed; 3) serious cracks occur on the surface of the wall panel or cracks penetrate the wall panel[8].

### 3.2. Test result

In the loading process, the load, displacement, material stress and surface crack at each stage of loading are observed. In the envelope structures W1 and W2, when it is loaded to 30kN, slight cracks appear; after loading, there is an obvious crack expansion and development process. During loading, the sound of bolt slip can be heard, and the crack development on the wall surface can be observed, and the failure form is remarkable. Among them, when the envelope structure W1 is loaded to 160kN, the reinforcing steel bars break at the pre-embedded part of the wall panel, and the concrete cracks in the joint area are serious, so the stiffness of the wall panel decreases dramatically and it is announced to be damaged due to the serious cracks; the previous process of the envelope structure W2 is similar to that of W1. When the wall panel is loaded to 120kN, the joint bolts of the wall panel are cut and the structure loses the bearing capacity and is announced to be damaged. Before the horizontal push-pull force of the envelope structure W3 is less than 20kN, no cracks are observed on the wall surface, and the loading path is nearly identical with the unloading path, showing good elasticity. And then, in a
On a relatively short period of time, there is a "bang-bang" sound, which lasts until the steel plate is suddenly torn at the welding when it is loaded to 52kN, producing a loud sound, and it is destroyed.

The corresponding load-displacement values of 3 envelope structures during loading are shown in Table 2. According to the test data in Table 2, the ultimate loads of the envelope structures W1, W2 and W3 are 160, 120 and 52kN, respectively, and the yielding loads of the envelope structures W1 and W2 are all 30kN. The load-displacement curves of the 3 envelope structures are shown in Figure 4.

Table 2. Load-Displacement Test Values of 3 Envelope Structures

| Load | Displacement | Load | Displacement | Load | Displacement |
|------|--------------|------|--------------|------|--------------|
| -130 | -10.216      | -110 | -9.598       | -52  | -35.277      |
| -109 | -8.925       | -103 | -8.785       | -40  | -26.356      |
| -92  | -7.650       | -90  | -7.53        | -35  | -19.707      |
| -78  | -6.375       | -90  | -7.53        | -30  | -11.305      |
| -63  | -5.102       | -82  | -6.275       | -25  | -8.746       |
| -47  | -3.825       | -68  | -5.020       | -25  | -6.324       |
| -37  | -2.55        | -54  | -3.765       | -30  | -4.126       |
| -30  | -1.275       | -36  | -2.510       | -20  | -2.877       |
| -25  | -1.135       | -25  | -1.255       | -15  | -2.877       |
| -20  | -0.894       | -20  | -1.004       | -10  | -2.877       |
| -15  | -0.640       | -15  | -0.759       | -5   | -1.470       |
| -10  | -0.447       | -10  | -0.503       | 0    | 0            |
| -5   | -0.226       | -5   | -0.251       | 0    | 0            |
| 0    | 0            | 0    | 0            | 0    | 0            |
| +5   | 0.221        | +5   | 0.246        | +5   | 1.472        |
| +10  | 0.451        | +10  | 0.494        | +10  | 2.897        |
| +15  | 0.582        | +15  | 0.739        | +15  | 4.026        |
| +20  | 0.739        | +20  | 0.994        | +20  | 5.598        |
| +25  | 0.941        | +25  | 1.226        | +25  | 8.259        |
| +30  | 1.205        | +39  | 2.452        | +30  | 11.949       |
| +40  | 2.410        | +58  | 3.678        | +35  | 17.289       |
| +52  | 3.615        | +75  | 4.904        | +40  | 21.586       |
| +67  | 4.820        | +87  | 6.13         | +48  | 26.086       |
| +86  | 6.025        | +112 | 8.582        | +105 | 9.784        |
| +117 | 8.435        |      |              | +128 | 9.640        |
| +160 | 14.032       |      |              |      |              |
4. Test Analysis

4.1. Analysis of the bearing capacity under the earthquake
Table 2 shows that the ultimate bearing capacity of the envelope structures W1, W2 and W3 is more than the maximum seismic action under the 8-degree fortification calculated. Among them, the yield bearing capacity of the envelope structures W1 and W2 is also more than the theoretical seismic action value, so the bearing capacity is higher. Especially when two bolts are installed at each connection according to the structural requirements, the bearing capacity of the envelope structure W1 is 160kN, which has greater safety redundancy under the earthquake action. It can completely ensure that the envelope structure should not be damaged prior to the main structure under the earthquake action, preventing the disasters and losses caused by the destruction of the non-structural components in the earthquake.

4.2. Checking calculation of deformation of the composite wall panel under rare earthquakes
Under the 8-degree (0.2g) rare earthquake, the limit value of the elastic-plastic deformation of steel frame structures is 1/50[9], that is 1450/50=29mm, the maximum displacements of the envelope structures W1 and W2 under the ultimate loads are 10.216mm and 9.598mm, respectively, which are less than the limit value of 29mm of elastic-plastic deformation, indicating that the envelope structure will not produce the deformation effect on the main structure when rare earthquakes occur. The ultimate displacement of the envelope structure W3 is 35.277mm, which is more than 29mm, indicating that the composite wall panel will have deformation and internal force effects on the main structure under the ultimate destructive state.

5 Conclusion and Recommendations
(1) The flexible bolted connection between the composite wall panel and the steel frame not only offers much higher bearing capacity than the welded connection but also has little impact on the stiffness and internal stress of the main structure when the ultimate failure occurs. It meets the requirement of the code that the envelope structure does not have any effect on the stiffness of the main structure, and guarantees the structural design and calculation of the main steel frame.

(2) The bolted connection scheme is superior to the welding connection scheme in terms of seismic bearing capacity, ductility and energy consumption capacity.

(3) The bolted connection is easier to operate than the welding connection at the stage of construction and installation, and the construction quality is easier to ensure.

Based on the results of the experiments and theoretical analysis, and combined with the structural requirements, it is suggested that the flexible bolted connection method should be used for the connection of the composite wall panel and similar lightweight wall panel with the steel frame structure. For producing the wall panel proposed, the embedded parts should be set first, and then the four-point connection with the frame beam should be adopted. The connection location is at one-fourth span of the wall panel and two bolts with a diameter not less than φ14mm are placed at each connection.

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