The Experimental Research on Seismic Capacity of the Envelope Systems with Steel Frame

Jiuyang Li, Bingbing Wang and Hengxu Li
1 School of Civil Engineering, Changchun Institute of Technology, Changchun, China
E-mail: 429838648@qq.com, 504921917@qq.com, 634692900@qq.com

Abstract: In this paper, according to the present application situation of the external envelope systems steel frame in the severe cold region, the stuffed composite wall panels are improved, the flexible connection with the steel frame is designed, the reduced scale specimens are made, the seismic capacity test is made and some indexes of the envelope systems such as bearing capacity, energy consumption and ductility, etc. are compared, which provide reference for the development and application of the steel frame envelope systems.

1. Introduction
The application of steel frames in the civil buildings has become more and more mature. The research on light composite wall panels in the severe cold region has begun to take a shape, but the welding is mostly taken by the connection of composite wall panel with steel frame at present, so the welding connection has some advantages such as simple construction process and high speed, etc. and the bearing capacity is ensured in the case of no earthquake. In recent years, with the frequency happening of earthquakes, people have paid more attention to the seismic capacity of the building structures. The welding connection of the light composite wall panel with the steel frame is often become the weak link of the seismic capacity. Therefore, the external envelope wall panel is chosen and improved in the severe cold region, the flexible connection with the steel frame is designed and the experimental research on the seismic capacity of the envelope system (envelope wall panel and connection) is carried out in this paper.

2. Test conditions of the envelope wall and connection
According to the climatic conditions and the local energy conservation requirements in the severe cold region B, the stuffed composite wall panel is improved and the new flexible connection mode (bolt connection) is designed to establish the building envelope systems W1, W2 and W3, respectively and the 1:2 reduced scale specimen (1.5m×1.3m) is made to carry out the seismic capacity research in the test. See Table 1 for the types of W1, W2 and W3 wall panels and connection modes. The structure of the stuffed composite wall panel and the detailed structure and process of the relevant connection are as follows:
Wall panel Y1: The stuffed composite wall panel Y1’s structure: C20 volcanic ash light concrete panels are on both the external and internal sides with average thickness: 50mm, built-in Φ3@50HRB400 steel wire gauze; the thickness of the middle stuffed heat preservation layer are 200mm, EPS; the three-layer materials are wrapped with Φ8HRB400 steel grids around the wall panel to establish the framework with total thickness of the wall panel 300mm[1].
Wall panel (G1, G2): the new stuffed composite wall panel has been improved by the project group on the basis of the stuffed composite wall panel (Y1). Its structure: C20 volcanic ash light concrete panels
are on both the external and internal sides with thickness of 50mm, built-in\(\Phi5\times 200\) CRB500 steel wire gauze; XPS for the middle stuffed heat preservation layer, with thickness of 150mm; the three-layer materials are stringed and connected with the\(\Phi5\times CRB500\) steel bar truss; the total thickness of the wall panel is 250mm[2].

| Envelope System | Type of Wall Panel | Connection Mode |
|-----------------|-------------------|-----------------|
| W1              | Y1                | Existing YZ1    |
| W2              | G1                | Improved GZ1    |
| W3              | G2                | Improved GZ2    |

The connecting mode of the three wall panels and the steel frame in the experiment is the semi-outer hanging, that is, the inner concrete panel is put on the steel frame, the heat preservation layer and the external concrete panel are wrapped on the external steel frame to establish the semi-outer hanging connection[3]. Such a connection mode prevents the cold bridge of the principal structure. The connecting positions of the three wall panels with the steel frame are on the steel frame beam, that is, 1/4 of the span of the wall panel, with the detailed structure as follows:

See Figure 1 for the YZ1 connection mode, with the detailed structure as follows: in the wall panel processing, a slot steel frame (10×10×10cm, thickness of steel sheet: 5mm) or the same specification of U-bar is embedded in the designed connecting position; the lower flange of the steel frame is reserved with the bolt hole (12+1.5mm); the same as the upper flange of the design position of the steel frame. In order to reduce the impairing of the steel frame beam by the flange opening, a steel sheet can be welded and the same bolt hole can be opened on the steel sheet; after the wall panel is hoisted in place, the M12 bolt penetrates the flange, welded steel sheet and the bolt hole of the lower flange of the steel frame from the lower side of the upper flange of the steel frame, the bolt cap is screwed and finally the foam concrete or polyurethane are used to fill and block the steel frame.

See Figure 2 for the GZ1 connecting mode and structure: in the making of the wall panel, a I-shaped embedment is embedded in the designed connecting position (consisting of 2 steel sheets and 2 sleeves, dimensions of the steel sheet: 150×120×6mm, embedded in the internal and external concrete of the wall panel, it is required that the steel sheet embedded in the internal side of the wall panel and the internal side surface of the wall panel should be on the same level; the internal diameter of the steel sleeve is\(\phi14\), 210mm long, the sleeve and the internal side surface of the wall panel are on the same level, the built-in threaded sleeve is in the range of 1/2 of the length close to the internal side of the wall panel and the solid structure is in the residual part; the surface of the steel sleeve should be blocked so as to prevent the concrete falling into it.); the upper surface of the designed connecting position of the steel frame beam is welded with the angle steel of L90×10, the vertical limb is opened with 2 bolt holes (14+1.5mm); after the wall panel is hoisted in place, the bolts are used to connect the vertical limb of the angle steel and the sleeve in the embedment of the wall panel.

Specimen GZ2: the connecting mode and process of GZ2 are completely the same with those of GZ1.
and the only difference is that there is 1 bolt for each connecting node.

It is considered that there are the multiple specimens in the project which should be connected and loaded to the same frame. With the design and calculation; the loading frame is made. The Q345 steel is taken for the loading frame and support, which includes the support beam, two frame columns, two frame beams (upper beam and bottom beam), corbel and diagonal stay. The hot-roll H steel is taken for the steel beam and steel column; the type of the beam section is HW350×350×12×19; the type of the column section is HW350×350×12×19; the type of the support beam is HW350×450×12×19; the U bar is taken for the steel diagonal stay and the type of the section is [250×82×11×12]. See Figure 3 for the vertical view of the loading frame and support and see Figure 4 after the wall panel is installed.

![Diagram](image1)

**Fig. 3 Loading Frame and Support**  
**Fig. 4 Loading Frame and Connecting Position**

3. Loading test

The test adopts the pseudo-static low-cycle repeated loading to directly impose the simulated earthquake load on the composite wall panel and transmit the load to the steel frame via the connection to research the force mechanism and destruction form of the envelope system on the seismic effect. The loading plan is the mixed loading method of force control and displacement control. The destruction principle of the envelope system is that the envelope system fails when the load obviously declines (to less than 85% of the peak load) or one of the following phenomena occurs: ① the bolt is sheared; ② the local concrete of the wall panel is crushed; ③ the serious crack occurs on the surface of the wall panel and penetrates the wall panel.

In order to assure the accurate test data and reliable result analysis, before the formal loading in the test, pre-loading to the specimen are first carried out to test the working performances of the equipment and the loading system. First pre-impose 2kN, second to 5kN and then return to 0 and this repeats twice. In the pre-loading process, whether the strains or displacements of all the test points tend to increase in the linear way has been observed; when the unloading is 0, if the reading numbers of all the test points return to the initial readings. In the formal loading, the force control method has been first take to impose the horizontal repeated centralized force on the middle of the specimen via the hydraulic servo actuator, taking the horizontal pushing force of the actuator as the positive direction and the pulling force as the negative direction. First the pushing force is imposes and then the pulling force. The initial value is 0kN, taking ±5kN as the loading step to gradually increase the load and keep each level of load for 2mins and then impose the next-level load. After the envelope system yields and the displacement control method is taken according to the 1 time yielding displacement and twice yielding displacement, etc. until the envelope system fails.

Measurement of displacements: In the test, the displacements of the wall panel on the effect of the load are collected by the displacement sensor of the actuator system. It is considered that the relative sliding may happen or is produced between the loading frame bracket and the floor on the effect of the
repeated load, so the displacement sensor is also laid on the bottom of the frame bracket so as to assure the accuracy of the displacement of the wall panel measured. The layout of the displacement gauges for the test loading is shown in Figure 5.

![Fig. 5 Layout Figure of Displacement Gauges for the Test Loading](image)

**4. Test phenomena and analysis**

For the W1 envelope system, in the loading process, before the repeated load is less than 20kN, no any crack is observed on the surface of the wall panel. The loading path and the unloading path nearly completely are coincide with each other and the wall panel is in the elastic phase; when it is loaded to 30kN, a few fine inclined cracks occur around the embedment in the lower left corner of the wall panel and on the back of the wall panel. The obvious displacement occurs to the specimen; when it is loaded to 40kN, the bolt at the connecting node of the wall panel and the connecting steel sheet are displaced to produce the clear friction noise; when it is loaded to 50kN, the connecting node produces the clear “bang bang”. The deformation of the connecting node is expanded. The loading frame slides and the friction displacement occurs between the support beam and the anti-pull anchor arm; when it is continued to the 70kN cycle, the inclined cracks around the lower left corner and lower right corner of the wall panel in the pre-embedded specimens are obviously widened and deepened with the occurrence of the new cracks; when it is loaded to 80kN cycle, the inclined cracks are around the embedment in the lower left corner and lower right corner of the wall panel penetrates the wall panel. The bolt of the connecting node yields. The shearing deformation visible to human eyes occurs to the bolt; when it is loaded to 90kN, the bolt of the connecting node in the lower part of the wall panel is sheared, and at this time, the wall panel loses the bearing capacity and the loading is stopped.

For the W2 envelope system, before the repeated load is less than 70kN, the representations of the specimen and the node are basically the same with those before the Y1 wall panel cracks and later the crack occurs to the wall panel G1; when it is loaded to 80kN, the inclined crack in the upper part of the embedment in the lower left corner and lower right corner of the wall panel is continued to be separated, and cracks occur to the concrete on the side of the wall panel. The “bang bang” noises are produced from inside the wall panel in the pushing and pulling conversion each time; when the load is increased to 165kN, the reinforced bar at the embedment of the wall panel is broken. The concrete at the node area is completely torn. The rigidity of the wall panel is greatly decreased and the degradation is serious. At this time, the wall panel loses the bearing capacity.
For the W3 envelope system, before the repeated load is less than 70kN, the representations of the wall panel and connection are basically the same with those of W2. When the G2 wall panel and the GZ2 connecting node are loaded to the 70kN cycle, the inclined crack in the upper part of the lower left corner and the lower right corner of the wall panel continues to be widened and deepened and the new cracks continuously occur; when it is cyclically loaded to 90kN, lots of inclined cracks occur around the embedment of the wall panel and the inclined cracks of the embedment in the lower left corner and the lower right corner. The cracks in the direction of the middle line on the back penetrate the wall; when it is loaded to 120kN cycle, the embedment concrete is seriously peeled off. The bolt of the connecting node of the wall panel is sheared. The structure loses the bearing capacity.

![Fig. 6 (p-∆) Hysteresis Curve of W1](image1)
![Fig. 7 (p-∆) Hysteresis Curve of W2](image2)

![Fig. 8 (p-∆) Hysteresis Curve of W3](image3)
![Fig. 9 Equivalent Viscous Damping Coefficient Calculation](image4)

In the test, the actuator loading system records the horizontal load-displacement (p-∆) relational hysteresis curves of the models. The p-∆ hysteresis curves of all the models are shown in Figure 6, Figure 7 and Figure 8. Obviously, the bearing capacity of the envelope system W2 is the highest, W3 has one bolt less than W2 in each connection. Its bearing capacity is reduced, and the bearing capacity of the W1 envelope system is the lowest.

5. Energy consumption and ductility analysis

When an earthquake happens to the building structure, for the energy in the earthquake input structure, the structure has a process of absorbing and consuming the energy. The energy consumption capacity of the structural member is measured with the area enclosed by the (p-∆) hysteresis curves. The area enclosed by the hysteresis curves in the loading phase reflects the magnitude of the energy absorbed by the structure. The area enclosed in the unloading phase reflects the energy consumed by the structure. The energy absorbed by the structure is converted to the energy consumption via the internal friction resistance or local injuries. The more the energy is consumed, the less possibility that the structure is destroyed. Therefore, the more saturated the hysteresis circle, the bigger the enclosed area, and the better the energy consumption performance of the structure. In the seismic test of the structure, the energy consumption capacity is one of the important indexes for investigating the seismic capacity of the structure[4]. The energy consumption coefficient E and equivalent viscous damping coefficient “he” are usually adopted to appraise the energy consumption performance of the structure, shown in
Figure 9. See Formula (1) and Formula (2) for calculation of the energy consumption coefficient $E$ and equivalent viscous damping coefficient $h_e$:

\[ E = \frac{S_{(ABC+CDA)}}{S_{(\Delta OBE+\Delta ODF)}} \]  

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

Whereas: $S_{(ABC+CDA)}$ --- area enclosed by the hysteresis circle;  
$S_{(\Delta OBE+\Delta ODF)}$ --- area of the triangle enclosed by the hysteresis circle peak value, coordinate origin and horizontal coordinate axis;  
According to Formula (1) and Formula (2), the area of the hysteresis circle of the envelope system at the yielding load and limit load are calculated to obtain the energy consumption coefficient $E$.  
It is concluded from Table 1: 1) In the yielding load, the equivalent viscous damping coefficient $h_e$ and the energy consumption coefficient $E$ of the envelope system W2 are the maximum; 2) In the limit load, the total energy consumption and equivalent viscous damping coefficient of the envelope system W3 are the maximum; 3) W2 among the three envelope systems has the maximum total energy consumption.

**Table 2 Energy Consumption Coefficient E and Equivalent Viscous Damping Coefficient he of the Specimens**

| Envelope System | Wall Panel Name | Connection Name | Total Energy Consumption $W$(N.m) | Yielding Load $E$ | $h_e$ | Limit Load $E$ | $h_e$ |
|-----------------|-----------------|-----------------|----------------------------------|------------------|------|----------------|------|
| W1              | Y1              | YZ1             | 1164.639                         | 0.992            | 0.158| 1.382          | 0.220|
| W2              | G1              | GZ1             | 2402.133                         | 1.0              | 0.159| 1.10           | 0.175|
| W3              | G2              | GZ2             | 1750.688                         | 0.851            | 0.136| 1.759          | 0.280|

Ductility is an index reflecting the deformation capacity of the structure and member. It refers to the performance that the structure or member will not be destroyed when the external load is continuously acted on the structure or member and the deformation continues increasing in the plastic phase. As to the seismic capacity of the structure is concerned, ductility is more important than the bearing capacity. The ductility of the structure or member is usually expressed by the ductility coefficient. In this paper, the displacement ductility coefficient $\mu$ and displacement angle $\theta$ is taken to reflect the deformation capacity and the seismic capacity of the structure. It is calculated by taking Formula (3) and Formula (4) according to the Specification of Test Methods for Earthquake Resistant Buildings (JGJ101) [5]:

\[ \mu = \frac{x_y}{x_x} \]  

\[ \theta = \arctan \frac{x}{H} \]  

Whereas, $x_y, x_x$ ---- displacement value of the structure or member in the yielding load and limit load, respectively;  
$H$----Height of the structure or member  
According to the test data of the loading process of each envelope system, the displacement ductility coefficients and displacement angles in all the phases are available in accordance with (3) and (4).  
It can be seen from Table 2: The three envelope systems of cracking load are about 20 kN, roughly equivalent to load of non-structural members under 8 degree earthquake action. At this time, the crack displacement angles are in 1/600–1/1000, less than the limit value of 1/300 of the displacement.
angle between the elastic layers on the effect of small earthquakes on the multi-layer and high steel structures in the specification; Under the seismic action of the maximum deformation of the main structure equivalent to 8 degree earthquake, the envelope system has not yet yielded; When the envelope system is destroyed, the ultimate displacement angle in 1/90~1/150, is less than the standard of many high-rise steel structure elastic-plastic displacement angle limit of 1/50 requirements under the big earthquake. It will not affect the main structure. In addition, it can be seen that the three envelope systems have good ductility, of which the envelope system W1 has the best ductility.

### Table 3 Displacement Angles $\theta$ and Ductility Coefficients of the building envelope systems

| Envelope System | Crack Displacement (mm) $x_c$ | Yielding Displacement (mm) $x_y$ | Yielding Displacement (mm) $x_u$ | Crack Displacement Angle $\theta_c$ | Yielding Displacement Angle $\theta_y$ | Limit Displacement Angle $\theta_u$ | Ductility Coefficient $\mu$ |
|-----------------|-------------------------------|-------------------------------|-------------------------------|---------------------------------|---------------------------------|-----------------------------|--------------------------|
| W1              | 2.06                          | 5.36                          | 10.672                        | 1/632                           | 1/243                           | 1/122                       | 1.990                    |
| W2              | 1.21                          | 7.19                          | 14.032                        | 1/1078                          | 1/181                           | 1/93                        | 1.952                    |
| W3              | 1.36                          | 6.47                          | 9.784                         | 1/960                           | 1/201                           | 1/133                       | 1.512                    |

### 6. Conclusion
With the experimental research on the seismic capacity of the three envelope systems consisting of 3 stuffed composite wall panels and 2 connection modes in the paper, the conclusion can be obtained as follows: 1) no serious destruction or separation occurs to the stuffed composite wall panels after the connections are destroyed. The wall panel is good as a whole and the test purpose of the project is achieved—the node is destroyed earlier than the whole; 2) the three envelope systems designed in the test meet the seismic capacity requirements of the structure in the bearing capacity, energy consumption and ductility in the specification. The seismic capacity is high and the differences between the comprehensive evaluation of the three systems in the capacity are small, all of which can be applied in the actual engineering; 3) 2 kinds of connection modes are the flexible connections, which prevent the common welding connection mode at present and achieve the structural requirement that no effect of the light wall panel on the principal rigidity of the frame structure; 4) in the case of meeting the local energy conservation requirements, the thickness of the G wall panel is smaller than that of the Y wall panel, which increases the using area of the building.

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