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Numerical analysis study on seismic performance of semi-rigid steel frame infilled with prefabricated composite wall panels

Abstract: The semi-rigid connected steel frame has good displacement ductility and energy dissipation capacity, and the interaction between the traditional steel frame and the filled wall is the key factor affecting its seismic performance. In this paper, for the semi-rigid steel frame, the composite wall panel is separated by foam concrete mortar and the frame, and the effective connection between the composite wall panel and the frame is realized by tension-reinforced steel. The premature brittle failure of composite wall panels can be avoided by means of friction energy dissipation between wall panels.By using ABAQUS simulation method, a semi-rigid steel frame composite wall is built, and its failure mode, hysteresis curve and skeleton curve are fitted. The reliability of the model is verified by comparing the calculated results with the experimental results. The finite element model with different number of wall panels is established to analyze its influence on the seismic performance of the structure.The results show that the frame structure realizes the effective connection between the composite wall panel and the concrete-filled steel tube frame, which jointly resists the earthquake action and reduces the damage of the earthquake action to the filled wall. With the increase of the number of composite wall panels, the ultimate load decreases gradually. The initial stiffness of the four layers of wall panels is larger and decreases rapidly. When the wall panel is three or four layers, the energy dissipation capacity of the specimen is the strongest, and the two are relatively close, stable at 24.48, and the increase is 5.15% compared with the second layer of the wall panel, and the increase is 12.72% compared with the third layer of the wall panel.

Key words: Semi-rigid steel frame; Foam concrete; Seismic performance; ABAQUS;

1Introduction

Semi-rigid connected steel frames have remarkable displacement ductility and energy consumption ability[1-3], However, the lateral stiffness and strength of the frame will decrease under the action of earthquake[4-6]。In order to improve the stiffness and strength of the structure, many scholars have proposed various acceptable methods for strengthening the system, Such as enhancing the stiffness of connectors[7], improving the stiffness of supporting members[8], and enhancing the stiffness of steel plate filling walls[9]。At the same time, on the one hand, the masonry filled wall provides a large lateral stiffness of the structure, reduces the interstory displacement of the structure, absorbs part of the seismic shear force, dissipates the seismic energy, and plays a favorable role in the seismic resistance of the structure. On the other hand, due to the excessive weight, stiffness and brittleness of the masonry filled wall itself, the energy absorbed by the whole structure is also increased, and the filled wall is more prone to failure, and this energy is unfavorable to the seismic performance of the whole frame structure after failure [10-13].

At present, researchers at home and abroad have carried out many studies on the earthquake resistance of filled walls and frames.Mohammadi et al. [14] designed a friction-slip fuse placed in the center of the infill wall to limit or eliminate damage to the infill wall and frame. During an earthquake, the upper and lower walls can slide relative to each other to avoid structural damage and dissipate energy; Alex Brodsky et al. [15] conducted two sets of scaled model tests to study the interaction principle between the steel frame and the filled wall in the steel frame system of masonry filled wall. The results show that the contact area between the filler wall and the frame changes constantly during the horizontal loading process, and the contact area depends on the geometric size of the frame and the filler wall and the material properties.

As a new type of building material, foamed concrete has attracted wide attention due to its lighter weight compared with traditional filling wall materials, and its advantages such as thermal insulation, fire and sound insulation, and simple installation.J F Wang [16] carried out horizontal low-cycle reciprocating loads on ALC plate and block frame system, and found that the connection of the two types of enclosure walls was reliable, which enabled the walls and frame to work together, and the structure met the safety requirements under earthquake action; Seyed[17] studied the influence of the height-width ratio of sandwich composite wallboard on the seismic performance of steel frame, and calculated the horizontal bearing capacity of wall-filled steel frame. The results show that with the decrease of the height-width ratio of composite wallboard, the bearing capacity and energy dissipation capacity of specimens have increased.

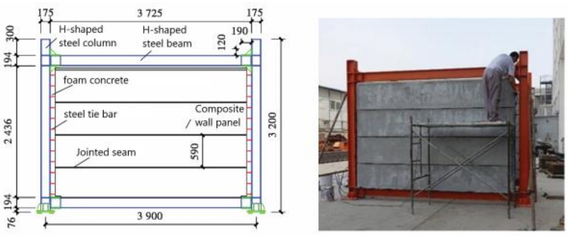
In order to overcome these problems, a new steel frame system is proposed in this paper: semi-rigid steel frame infilled with prefabricated composite wall panels, the composite wall panel is divided into multiple layers, and separated from the surrounding frame, there is a horizontal sliding joint between the wall panels, and with the aid of foam concrete mortar bonded into a whole. The frame system can not only give full play to the good ductility of the semi-rigid steel frame, but also improve the seismic performance of the composite wall through the sliding damping mechanism, and avoid the premature shear failure of the composite wall panel due to the bad interaction between the frame and the composite wall.

In this paper, ABAQUS finite element analysis software is used to conduct separate numerical modeling of semi-rigid connected steel frame and composite wall panel. The applicability of the numerical model and the accuracy of parameter selection are verified by comparative test results, and the bearing capacity and deformation law of semi-rigid connected steel frame and wall layer number under horizontal earthquake are studied.

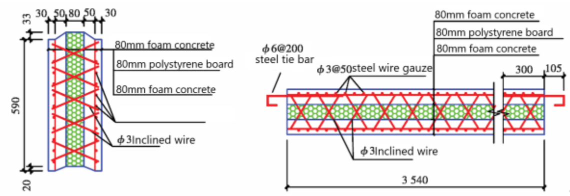
2Construction of FEM model

2.1 Introduction to test model

The seismic performance of semi-rigid steel frame infilled with prefabricated composite wall panels is studied by low cyclic load test. The test structure is single-span and single-span. In this paper, the numerical simulation will be carried out, and the variable parameter analysis of the number of wall panels will be carried out.Fig. 1 shows the detailed dimensions and reinforcement of the semi-rigid steel frame infilled with prefabricated composite wall panels. The cube compressive strength of the foam concrete wall panel is 3.8MPa. The vertical load with the size of 499.5kN is applied to each concrete-filled steel tube column and kept constant. The horizontal load is applied through the beam axis direction, and the whole displacement is controlled. The test loading direction is positive when pushed out by jack and negative when pulled back. When the test specimen has a large deformation and loses its bearing capacity, the test load is stopped.



（a）Geometric dimension （b）test picture



（c）longitudinal section（d）transverse section

Fig. 1The detailed dimensions and reinforcement

2.2 Cell types and interactions

2.2.1 Main body frame

Solid element C3D8R (i.e., three-dimensional solid reduction integral element) is used for the concrete filled steel tube column, H-beam, connecting plate and bolt. Compared with the ordinary complete integral element, the 8-node reduction integral element uses one less integral point in each direction, reducing the calculation amount of the model and improving the accuracy of the model calculation. The deformation and stress of the foundation beam are not considered, so the rigid body element is used for simulation.

The friction coefficient is 0.4 between the concrete column and the steel pipe. The left and right ends of the upper H-shaped steel beam are anchored with 12 M12 high-strength bolts and the connecting plate, and the pre-tightening force of the bolts is set to 32kN. The lower H-shaped steel beam and the connecting plate are bound to the steel pipe through Tie, and the lower end of the steel pipe is bound to the foundation rigid beam.

2.2.2 Steel bar element

Due to the slender material characteristics of the steel bar, it can only withstand the tensile and compression action but not the transverse shear action, which is consistent with the truss element, so the T3D2 element (two-node linear three-dimensional truss element) is used to simulate the steel bar.

In the numerical analysis, the adhesive slip between the foamed concrete and the steel mesh is not considered, and it is Embedded into the wall panel, and connected to the main frame by the tie bar.

2.2.3 Foam concrete wall panels

The foamed concrete wall panel is regarded as a continuous homogeneous material, and the model is easy to converge under cyclic load by using the quadratic reduction integral element C3D8R.

Table 1 shows the contact parameters between the four-layer foamed concrete composite wall panel and the wall panel and the frame. The sliding friction between the adhesion of mortar and the composite wall panel is simulated by the cohesion + Coulomb friction criterion.

Table 1 Contact interface parameters

contact surface	rigidity (MPa/mm)			peak stress（MPa）			G_f^I	μ
	K_{nn}	K_{ss}	K_{tt}	t_n^0	t_s^0	t_t^0	(N/ mm)	
Wall to wall	82	36	36	0.55	0.5	0.5	0.04	0.2
Wall to frame	82	36	36	0.275	0.25	0.25	0.02	0.4

2.3 Constitutive model of materials

2.3.1 Constitutive relation of steel

Since the loading mode of the model is low-cycle reciprocating loading, the steel is adopted as a double-broken line model. Before the steel reaches the yield point, the steel is regarded as a linear elastic material, and the slope of the broken line is Young's model Es at this time. After the yield point is reached, the steel is regarded as a plastic material. Table 2 shows the parameters of the steel.

Table 2 Mechanical properties of steel

Type of steel	f_y/MPa	f_y/MPa	E/GPa
steel tie bar	405.0	581.0	206.9
steel fabric	662.0	718.0	190.8
square steel	373.0	444.3	218.2
steel beam	296.0	453.0	202.2
connecting	318.0	468.0	202.9

2.3.2 Constitutive relation of concrete

The stress-strain curve of concrete under uniaxial tension can be calculated as follows:

$$\sigma = (1 - d_t)E_c\varepsilon$$

$$d_t = \begin{cases} 1 - \rho_t[1.2 - 0.2x^5] x \le 1 \\ 1 - \dfrac{\rho_t}{a_t(x-1)^{17} + x} x > 1 \end{cases}$$

$$\boldsymbol{x} = \frac{\boldsymbol{\varepsilon}}{\boldsymbol{\varepsilon}_{t,r}} \rho_t = \frac{f_{t,r}}{E_c\varepsilon_{t,r}}$$

Here$a_t$is the parameter value of the descending section of the uniaxial tensile stress-strain curve of concrete. $f_{t,r}$ represents the uniaxial tensile strength of concrete. $\boldsymbol{\varepsilon}_{t,r}$is the peak tensile strain of concrete corresponding to the representative value of uniaxial tensile strength. d_t is the evolution coefficient of concrete uniaxial tensile damage.

The stress-strain curve of concrete under uniaxial compression can be determined by following the formula:

$$\sigma = (1 - d_c)E_c\varepsilon$$

$$d_c = \begin{cases} 1 - \dfrac{\rho_c n}{n - 1 + x^n} & x \le 1 \\ 1 - \dfrac{\rho_c}{\alpha_c (x-1)^2 + x} & x > 1 \end{cases}$$

$$\eta = \frac{E_c \varepsilon_{c,r}}{E_c \varepsilon_{c,r} - f_{c,r}} \quad \rho_c = \frac{f_{c,r}}{E_c \varepsilon_{c,r}}$$

Hereα_c is the parameter value of the descending section of the stress-strain curve of concrete under uniaxial compression; $f_{c,r}$ represents the uniaxial compressive strength of concrete; $\varepsilon_{c,r}$ is the peak tensile strain of concrete corresponding to the representative value of uniaxial compressive strength; d_c is the evolution coefficient of concrete uniaxial compression damage.

2.3.3 Constitutive model of foam concrete

As a new type of building material, autoclaved aerated block is rarely studied in the academic field on the constitutive relationship of autoclaved aerated block. In this paper, the constitutive model of light filling wall material is adopted, and the expression of compressive stress-strain relationship is as follows:

$$y = \begin{cases} x & x \le 0.5 \\ 2x - 1.1x^2 - 1.7x^3 + 3.8x^4 - 2x^5 & 0.5 < x \le 1.0 \\ \dfrac{5.2 + 3.7x}{1 + 7.9x} & 1.0 < x \le 4.0 \end{cases}$$

Here $x = \varepsilon/\varepsilon_{pr}$, $y = \sigma/\sigma_0$; ε_{pr} is the compressive strain value corresponding to the peak stress, which is 3.8MPa measured by the test. σ_0 is the peak compressive stress.

The expression of the descending section of the uniaxial tensile stress-strain curve of foamed concrete is as follows:

$$y = \begin{cases} x & x \le 1.0 \\ \dfrac{x}{\alpha_t (x-1)^{1.7} + x} & x \ge 1.0 \end{cases}$$

Here$x = \varepsilon/\varepsilon_{pt}$, $y = f/f_{pr}$; ε_{pt} is the tensile strain value corresponding to the peak stress;f_{pr} is the peak tensile stress,$\alpha_t = 0.312 f_t^2$。

Fig. 2 shows the finite element model of the frame composite wall established according to the above steps.

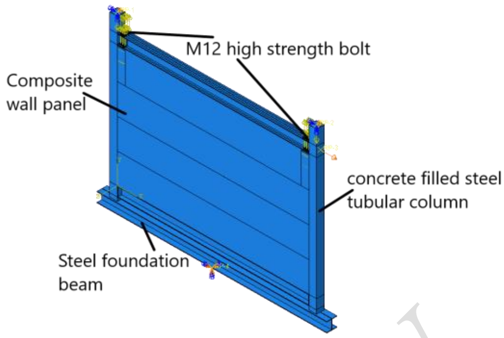
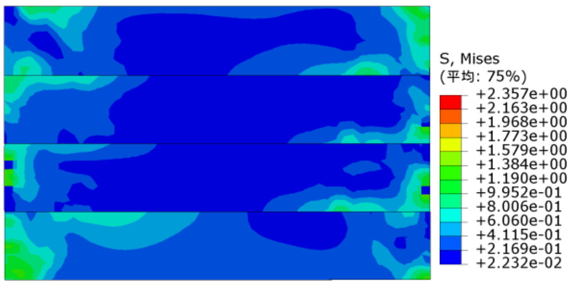


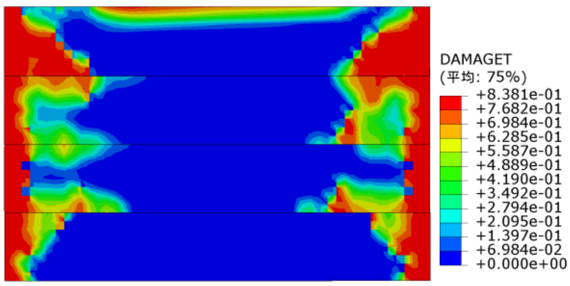
Fig. 2 Numerical model diagram

3Numerical results verification

Fig. 3 shows the stress comparison and concrete damage of the finite element model analysis results. The stress transmitted by the concrete-filled steel tube column is small and located at the four corners of the whole wall panel. The foamed concrete composite wall panels move each other in the process of lateral force, resulting in discontinuity of stress between the wall panels, so the composite wall panels are less damaged by compression. According to the damage of the composite wall panel, it can be seen that because there are only tension reinforcement bars at the joint of the composite wall panel and the frame column, the tensile damage of the edge of the concrete wall panel is more serious, and the crack trend is consistent with the test.



(a)

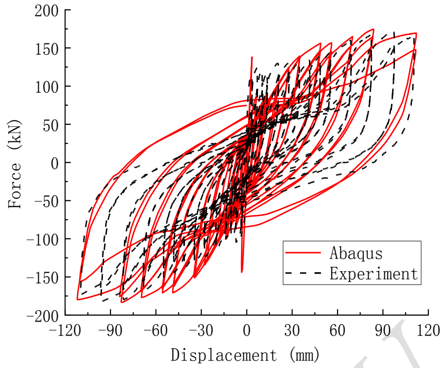


(b)

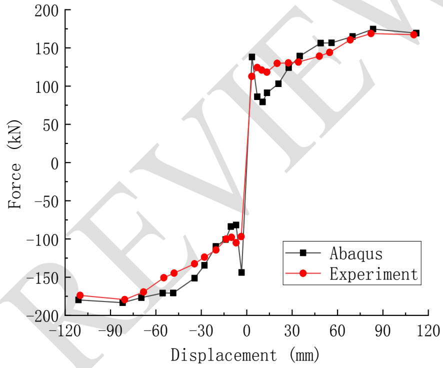
(c)

Fig 3Stress nephogram(a), damage nephogram(b) and crack trend(c) of composite wall panel (unit: MPa).

Fig. 4 shows the simulation and test hysteresis curve and skeleton curve of the semi-rigid steel frame infilled with prefabricated composite wall panels. The overall hysteretic curve shows an inverse S-shape, and the pinch effect appears in the middle. This is because the four layers of wall panels are bonded by foamed concrete, and the composite wall panels first appear horizontal cracks at the joint, and then mismove. When the horizontal load transferred to the composite wall panels exceeds the sum of the bonding force and friction of foamed concrete at the joint, the horizontal joint cracks. There is relative horizontal sliding between wall panels, which is simulated by the cohesive force + Coulomb friction model in finite element simulation. In addition, due to the cracking of the tensile zone of concrete and the sliding of steel bars in the test, and only the embedding command is used to simplify the processing in the finite element model, the middle position of the simulated curve is relatively "full", and the sliding phenomenon is more obvious in the test. The skeleton curve in the early stage is different from the simulation because of the viscous action of mortar. However, with the loading of horizontal displacement, the viscous effect gradually disappeared, and the interaction between wall panels gradually changed into frictional contact, and the skeleton curves of simulation and test results gradually agreed.



(a)



(b)

Fig.4Contrast between hysteretic curve(a) and skeleton curve(b)

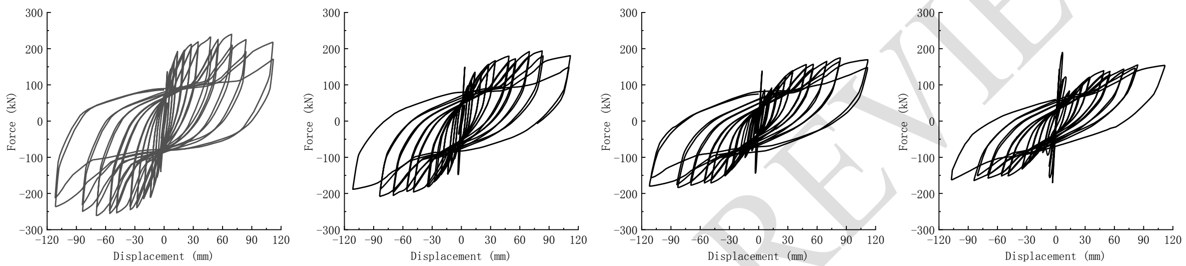
The whole loading process of the semi-rigid steel frame infilled with prefabricated composite wall panelsis simulated by the distributed modeling, and the reliability of the model is verified. The crack development, hysteretic curve and skeleton curve of the test model of semi-rigid steel frame composite wall are fitted. The stress nephogram, compression damage and displacement distance of foamed concrete composite wall panel are analyzed, and the results are satisfactory, which verifies the feasibility of the model established in this paper and the correctness of parameter selection.

4The influence of the number of wall panels

On the premise of determining the size of the semi-rigid steel frame infilled with prefabricated composite wall panel, the number of layers of the composite wall panels is modified. Because the damage of the whole foamed concrete wall panel is relatively serious during the loading process of the whole wall panel simulation calculation, only the influence of double, three, four and five layers on the seismic performance of the wall panels is analyzed.

4.1 Hysteretic curves

Fig. 5 shows the hysteresis curves of specimens SJ1 to SJ4. When the composite wallboard of the specimen is composed of two layers, the hysteresis curves show a "Z" shape, and the middle of the curve is relatively gentle, indicating that a large amount of slip occurs during loading;When the composite wall panels are three or four layers, the hysteresis curve is "S", and slip occurs during the loading process. At the initial stage of loading, due to the viscous action of mortar between each layer of wall panels, the load is large, and then the viscous action disappears, and the viscous action between wall panels changes to Coulomb friction. When the composite wall board is five layers, the hysteresis curve is fill-shaped and not full, and compared with the previous several specimens, the mortar has a greater viscous effect and lasts longer before it turns into coulomb friction.



(a)(b) (c) (d)

Fig. 5. Hysteretic curves of specimens (a)SJ1, (b)SJ2,(c)SJ3,(d)SJ4

4.2 Skeleton curve

Fig. 6 shows the skeleton curves of the four specimens. It can be seen that SJ1 has a significantly stronger bearing capacity than other specimens, and enters the yield stage at the earliest. With the increase of the number of wall panels, the peak load decreases gradually.

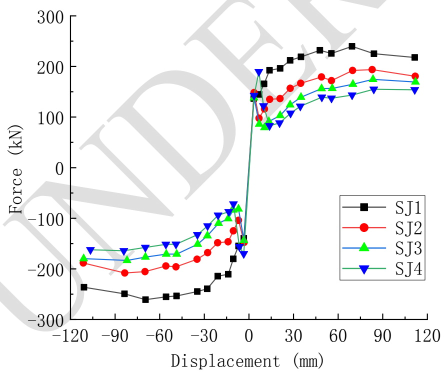


Fig. 6Skeleton curve of specimens

4.3 Stiffness degradation

Stiffness degradation refers to the phenomenon that the displacement of peak point increases with the increase of the number of cycles when the same peak load is maintained under cyclic repeated loads. In this paper, the circular stiffness is used to describe the stiffness degradation of the specimen. The loop stiffness is expressed as follows:

$$K_j = \frac{\sum_{i=1}^{n}\left|P_j^i\right|}{\sum_{i=1}^{n}\mu_j^i}$$

Here， K_j is the stiffness under the J-class load, Pji is the load under the I-cycle of the J-class load, andμ_j^i is the displacement under the I-cycle of the J-class load. The stiffness degradation diagram of each wall panel is compared and analyzed, and the following conclusions are drawn:

At the initial stage of loading, due to the viscous action of mortar between the wall panels, the composite wall is bonded as a whole, and the stiffness is stable at 42.94kN/mm, and the error is not more than 5%. With the increase of horizontal displacement, the viscosity of each specimen gradually disappeared. The viscosity of specimen SJ4 disappeared the latest due to the number of layers, and the stiffness gradually degraded from the maximum to the minimum. The final stiffness degradation of specimen SJ1 was the largest and stabilized at 2.042 kN/mm, while the rest of the specimens stabilized at 1.556 kN/mm.

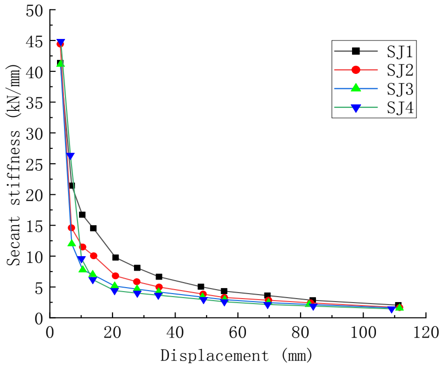


Fig. 7. Stiffness degradation curves of specimens.

4.4 Equivalent viscous damping ratio

As shown in the fig. 8, the energy dissipation capacity can be measured by equivalent viscous damping ratio h_e. The equivalent viscous damping ratio is characterized by:

$$h_e = \frac{1}{2\pi}\frac{S_{ABC} + S_{CDA}}{S_{OBE} + S_{ODF}}$$

where $S_{ABC} + S_{CDA}$ is the area surrounded by the hysteresis loop; $S_{OBE} + S_{ODF}$ is the area surrounded by the triangles OBE and ODF.

Fig.9 shows the equivalent viscous dampingcoefficients of the four groups of specimens. It can be seen that the energy dissipation stage can be divided into three stages: First, due to the viscous action of mortar between wall panels, the energy dissipation effect increases rapidly; With the continuous loading, the concrete steel tube column gradually yields, and the energy dissipation capacity decreases as a whole; After that, due to the dislocation of the composite wall panels, friction energy consumption, the energy consumption capacity of the components increased rapidly. As the wall panel of specimen SJ1 is badly damaged, the friction energy consumption in the later period is reduced. SJ4 has the worst energy dissipation capacity because of the lowest ultimate bearing capacity, the most stratified wall panels and less relative slip. The energy dissipation capacity of SJ2 and SJ3 samples is the strongest, and they are close to each other, stable at 24.48, and increased by 5.15% compared with SJ1 and 12.72% compared with SJ4.

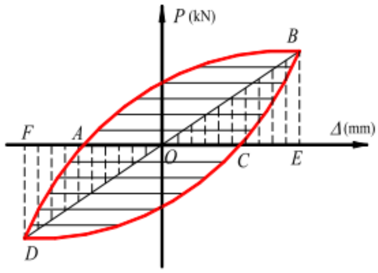


Fig. 8. Calculation of equivalent viscous damping coefficient.

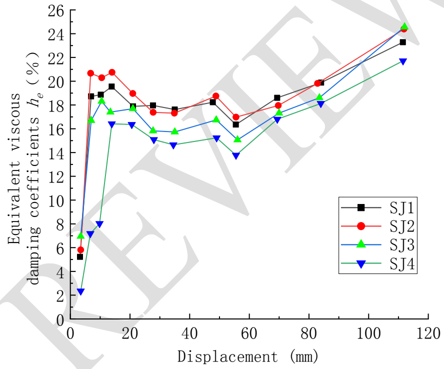


Fig. 9. Equivalent viscous damping coefficients.

5 Conclusions

（1）During the loading process, the composite wall panel and the semi-rigid connected steel frame are effectively connected through the tensioned steel reinforcement to jointly resist the earthquake action. Moreover, due to the misalignment of the wall panel, on the one hand, the stiffness of the semi-rigid steel frame infilled with prefabricated composite wall panels is reduced, and the stress between the wall panels is not coherent, which reduces the damage of the composite wall panel caused by the earthquake action. On the other hand, due to the friction of the four-layer composite wall plate under the reciprocating load, the energy dissipation capacity of the frame structure gradually increases after the yielding of the tensioned steel bars.

（2）By comparing and analyzing the hysteretic curve and skeleton curve of four different layers of composite wall panels, it is found that the ultimate load decreases gradually with the increase of the number of layers of composite wall panels, and when the wall panels are two layers, the damage of composite wall panels is more serious, and the composite wall panels enter the descending stage at the earliest. When the wall plate is five layers, the bearing capacity is obviously weaker than that of other specimens.

（3）Due to the viscous action of foamed concrete mortar between composite wall panels in the early stage of loading, the initial stiffness of the four groups of frame walls is relatively close, stable at 42.94Kn/mm, and the error is not more than 5%. According to the equivalent viscous damping coefficient, it can be judged that the energy dissipation capacity of the frame structure is the strongest when the number of wallboard layers is three or four.

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