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Research Status of Simplified Model of Steel Frame-filled Composite Wall

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Abstract

In order to meet the development needs of prefabricated buildings in low-rise residential buildings in villages and towns, steel frame-filled composite wall, as a new type of frame-filled wall, has received a lot of attention. Compared with steel frame, steel frame-filled composite wall has good lateral bearing capacity and stiffness. In this paper, the existing seismic model of steel-frame-filled wall and the calculation methods of some important parameters are reviewed. Finally, based on the current research situation, the existing problems and future development trend of steel-frame-filled wall are analyzed.

Keywords

Calculation Model; Baroclinic Rod; Frame-fill Wall.

1. Introduntion

With its modularity and standardization advantages, steel structure has become a form of prefabricated construction vigorously promoted in our country, and has become a hot spot in the development of prefabricated buildings in our country by virtue of its short construction period, good seismic performance, resource recycling and many other advantages [1]. With the implementation of the policy, a large number of excellent prefabricated steel structure buildings have emerged in our country, such as Hangzhou Raffles Square, Xi 'an Greenland Center and other typical cases. In addition, steel frame is the most common structural form of steel structure, generally made of steel beam and steel column at the end, with flexible structural layout, large opening, light weight, good seismic performance characteristics.

In seismic design, filled walls are usually used as non-structural elements, but actual seismic damage shows that: The filled wall is also involved in the distribution of seismic shear force of the structural system, and the shear strength of the filled wall is low, so the damage in the earthquake is also more serious. The regulations in the national norms are not the same. Researchers at home and abroad have analyzed the impact of the filled wall on the seismic performance from the materials, layout, length to height ratio, opening and other aspects of the filled wall. The design of the joint between steel frame and infill wall has always been one of the key factors limiting the prefabricated steel structure house [2], so this paper mainly describes and analyzes the research status of the joint between steel frame and infill wall and the seismic calculation model.

2. Failure Mode of the Filling Wall

Steel frames and filled walls working together to resist horizontal loads can be divided into three failure modes [3] :

2.1 Diagonal Contact Rupture

When the maximum shear stress of the filling wall occurs at the contact surface between the upper boundary frame and the filling wall, cracks soon occur on the contact surface between the frame and the filling wall, but the cracks have not yet penetrated. With the increase of lateral force, stress concentration occurs in the contact surface between the filled wall and the diagonal part of the frame, and the fracture phenomenon occurs in the diagonal part. At this time, the stress and lateral displacement of the steel frame are small, and they are still in an elastic state. The filled wall is the main component resisting side force.

2.2 Diagonal Baroclinic Failure

The maximum stress of the filled wall is mainly concentrated on the main diagonal, and most of the walls are in the state of single tension or single pressure, and the main tensile stress is relatively large in the middle and upper foot near the load end. When the stress reaches the failure criterion of the filled wall, it cracks. The cracked wall elements are mainly distributed in the baroclinic area along the main diagonal direction. Under the action of lateral force, the inclined crack area of the damaged wall elements will run through the section of the wall.

2.3 Shear Failure

The filling wall is made of mortar and block. In shear failure mode, the cracks mainly appear along the weak ash seam, and the wall will produce sliding cracks.

3. Calculation Model of Frame Filling Wall

3.1 Parallel Model of Wall and Frame

In 1997, Cao Wanlin et al. [4] proposed a simplified parallel model, as shown in Figure 1. In this model, the lateral movement of the frame and the filler wall is the same at the beam, the frame part is calculated according to the frame, and the filler wall is regarded as a cantilever rod connected to the frame by connecting rods at each layer of beams, and the stiffness and strength are superimposed by the two. This model is based on the fact that the frame at the beam and the infill wall move sideways in the same way.

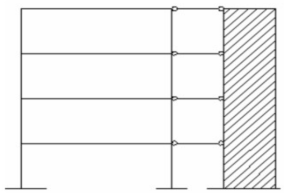

Figure 1. Parallel model

3.2 Single Pressure Rod Model

In 1956, Polyakov[5] conducted a three-layer, three-span steel framework-filled wall test and proposed the use of an equivalent diagonal compression bar to replace the filled wall. First, he proposed the concept of equivalent diagonal support, believing that the stress between the frame and the filled wall is only transmitted through the compression zone boundary of the filled wall, so the role of the filled wall is more like that of the diagonal compression bar in the truss system. Not a shear wall.

Holmes and Stafford-Smith also put forward a similar concept when studying similar problems, and pointed out that: in the steel frame-filled wall structure, regardless of the axial deformation of the steel member, an equivalent diagonal pressure bar with two ends articulated and an effective width of 1/3 diagonal length of the filled wall is used to replace the filled wall, namely: $b_w = 1/3d$ [6]. In the model, the length of the equivalent pressure rod is taken as the diagonal length of the wall, and the thickness and elastic modulus are the same as that of the wall material. The width of the equivalent pressure rod is simply defined as a function of the diagonal length of the filling wall, as suggested by Paulay[7] $b_w = 0.25d$, Penelis[8] suggested it $b_w = 0.2d$ and PI Shuping [9] $b_w = 0.3\sin(2\theta)d$.

In addition, in order to comprehensively consider the material characteristics of the steel frame and the filler material as well as the cracking and degradation of the filler wall during the increase of horizontal load, Stafford-Smith[10] further modified the equivalent diagonal support when studying the filler frame by using the finite difference method. The relationship between the contact length of the filled wall and the frame members is established by the energy and static equilibrium methods, and the bearing capacity of the whole structure is evaluated by calculating the bearing capacity of the filled wall and the frame respectively. An expression of the equivalent pressure rod width related to the characteristics of the frame and the filled wall is proposed (1) and (2).

$$\lambda h = (\frac{E_c t h^3 \sin 2\theta}{4E_s I})^{1/4} \tag{1}$$

$$b_W = \frac{2\Pi}{\lambda} \tag{2}$$

Where: is the stiffness ratio between the filling wall and the steel frame; t is the thickness of the filling wall; E_c is the elastic modulus of the filling material; E_s is the elastic modulus of the frame material; θ is the Angle between the diagonal and the horizontal line of the filling wall; I is the moment of inertia of frame column section; b_w is the width of the equivalent pressure bar.

According to ASCE41-06[11] and FEMA356[12] and other specifications, it is pointed out that the interaction between the filled wall and the frame should be considered, and the equivalent baroclinic rod model is proposed to model the frame structure. The filled wall is regarded as a diagonal strut with the same thickness as the wall and a similar width hinged on the frame plane, and the diagonal rod is only subjected to pressure. In this way, the joint lateral force resistance of the steel frame and the filled wall is formed. The formula for calculating the width of the equivalent pressure rod is given in the specification, as shown in equations (3) and (4), and the central pressure rod model, eccentric pressure rod model and multi-pressure rod model of the filled filler wall frame are proposed.

$$\alpha = 0.175\left(\lambda h_{col}\right)-0.\ 4\mathrm{r}_{\mathrm{inf}} \tag{3}$$

$$\lambda = \left[\frac{E_{me} t_{\mathrm{inf}} \sin 2\theta}{4E_{fe} I_{col} h_{\mathrm{inf}}}\right]^{1/4} \tag{4}$$

Table 1. Calculation formula of equivalent pressure bar width

Researcher	Expression
Mainstone[13]	$b_w = 0.175 d(\lambda h)^{-0.4}$ $\lambda h < 5$
	$b_w = 0.16 d(\lambda h)^{-0.3}$ $\lambda h > 5$
Gao Rundong [14]	$b_w = 0.18 d(\lambda h)^{-0.35}$
Sun Lijian [15]	$b_w = \frac{0.86 h \cos\theta}{\sqrt{\lambda_h}}$
Liauw[16]	$b_w = \frac{0.95 h \cos\theta}{\sqrt{\lambda_h}}$
Smith B S[17]	$b_w = \frac{0.85 h \cos\theta}{\sqrt{\lambda_h}}$
CharlesJ.Tucker[18]	$b_w = 0.25 d(\lambda h)^{-1.15}$

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Formula: α is the equivalent pressure bar width; E_{me} is the elastic modulus of the filled wall; E_{fe} is the elastic modulus of the frame; $t_{\inf}$ is the thickness of the filling wall; I_{col} is the moment of inertia of the column; λ is the equivalent width coefficient; h_{col} is the height of the column between the center line of the beam; $h_{\inf}$ is the height of the filling wall; $r_{\inf}$ is the diagonal length of the filling wall; θ the tangent value is the ratio of height to width of the filled wall.

The following is the formula for calculating the equivalent pressure rod width of steel frame-filled wall given by researchers in recent years.

In addition, Papia et al. [19,20] concluded that the equivalent compression bar width was not only related to the lateral stiffness of the frame, but also to the axial deformation of the steel column, so the calculation formula was proposed:

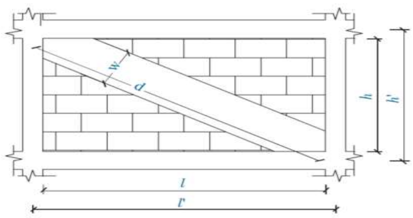

Figure 2. Papia equivalent pressure rod width calculation diagram

$$\frac{b_w}{d} = k \cdot \frac{c}{z} \cdot \frac{1}{(\lambda^*)^{\beta}} \tag{5}$$

$$\lambda^* = \frac{E_d t h'}{E_f A_c}\left[(\frac{h'}{l'}) + \frac{1}{4} \cdot \frac{A_c l'}{A_b h'} \right] \tag{6}$$

$$\varepsilon_v = \frac{F_v}{2 A_c F_f} \tag{7}$$

$$k = 1 + (18\lambda^* + 200) \cdot \varepsilon_v \tag{8}$$

$$z = 1 + 0.25 \cdot (\frac{l}{h} - 1) \tag{9}$$

$$c = 0.249 - 0.0116\upsilon + 0.576\upsilon^2 \tag{10}$$

$$\beta = 0.146 + 0.0073\upsilon + 0.126\upsilon^2 \tag{11}$$

E_d and E_f are the elastic modulus of the filled wall and steel, respectively; υ is Poisson's ratio of the filling wall; A_c and A_b are the section areas of the frame column and beam respectively; t is wall thickness for the filling wall; F_v is Vertical load; h and l are respectively the height and width of the filling wall; h' and l' is center line distance of frame beam and column respectively; h' and l' are the center line distances of the frame beam and column, respectively.

According to Uva[21] 's sensitivity analysis of the compression rod model, the results show that under the same structure and mechanical properties, the peak load of the filled wall structure simulated by using a wide compression rod is larger, while the ductility of the low-value structure is better.

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Through the above analysis, it can be seen that the width of the equivalent barooblique bar is the key factor in the calculation model, and the determination group of the width of the equivalent barooblique bar should comprehensively consider the material characteristics of the frame and the filling wall and the cracking and degradation factors of the filling wall under the horizontal load. With the increase of the horizontal load, the structure has a strong nonlinear, and the above formulas can not well simulate the stiffness change caused by this.

3.3 Three-pressure Rod Model

Although the single pressure rod model can well reflect the influence of the filling wall on the overall stiffness and bearing capacity of the structure, EI-Dakhakhni,Wael.W[22] believe that the equivalent use of the single pressure rod model cannot effectively reflect the influence of the contact length between the steel frame and the filling wall on the overall structure. In order to better simulate the high stress generated between the packed wall and the frame column and the column in the wide contact length range, and the real internal force distribution of the beam and the column under the restraint of the packed wall. For the simulation of the wall, in addition to a diagonal support along the main diagonal direction, two diagonal supports should be added at the position of the beam and column with larger bending moment to form the equivalent diagonal support of the three-pressure bar.

The filling wall is equivalent to three supporting rods, the contact length between the filler wall and the steel frame is proposed h_c , l_b and the calculation formula of the total section area of equivalent diagonal support, as shown in Figure 3 below, it is assumed that the main diagonal compression section area is $A/2$, the cross-sectional areas of the two diagonal supports are respectively $A/4$, the simplified calculation model is shown in Figure 3.

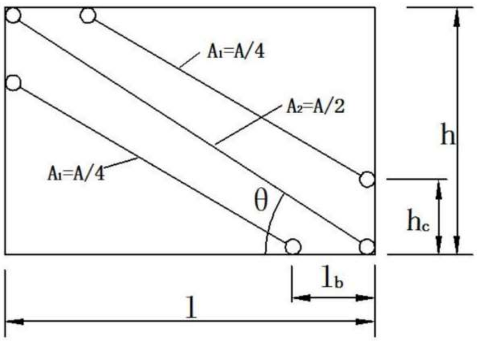

Figure 3. Simplified calculation model of three-pressure rod

$$h_c = \alpha_c h = \sqrt{\frac{2(M_{pj} + 0.2M_{pc})}{tf'_{m-0}}} \le 0.4hl \tag{12}$$

$$l_b = \alpha_b l = \sqrt{\frac{2(M_{pj} + 0.2M_{pb})}{tf'_{m-90}}} \le 0.4l \tag{13}$$

$$A = \frac{(1-\alpha_c)\alpha_c th}{\cos\theta} \tag{14}$$

Formula: h_c is the contact length of the column; l_b is the contact length of the beam; h is column height, l is the beam length; M_{pc} is the yield bending moment of column section; M_{pj} is minimum yield bending moment of beam, column and joint; M_{pb} is the yield bending moment of the beam section;is the thickness of the filling wall; f'_{m-90} is the vertical compressive strength of the filling wall; f'_{m-0} is the horizontal compressive strength of the filling wall; θ is the Angle between the main diagonal support and the bottom of the beam.

As a simplified calculation model, several assumptions need to be made in the process of finite element modeling and calculation:

First, the contact length of the wall, frame column and frame beam is fixed as the length of the steel frame when it enters the yield stage after calculating according to equations (12) and (13), ignoring the fact that the contact length is constantly changing with the continuous increase of load. Secondly, when the steel frame enters the plastic stage, the filled wall has played all the strength of the material along the diagonal brace direction, and the compressive strength of the composite wall at this time is used as the calculated compressive strength of the three-pole material. Finally, it is assumed that the material properties of the three pillars are isotropic.

Here are some things to note: When the structure enters the elastoplastic stage, the three struts are gradually removed from the work due to the low strength of the material, and the internal force redistribution occurs in the steel frame and the three struts and the steel frame. At this time, the steel frame mainly bears the external shear force until it enters the failure stage. Due to the different internal forces in the three inclined struts, Therefore, the work will not be quit at the same time, and the overall stiffness of the steel frames-three struts is slightly higher than the experimental value, which is related to the above hypothesis [23].

It is worth noting that during the whole process of loading, the contact length and corner brace area of the filling wall are not a constant, and the corner brace area and contact length should gradually decrease with the increase of horizontal force. Therefore, the three-bar model of EI-Dakhakhni is inconsistent with the actual situation. In order to solve this problem, Zhai Changhai [24] proposed an improved three-bar model. He believed that the width of the middle pressure bar remained the same throughout the process of loading, and the width of the other two pressure bars was gradually reduced.

In addition, in actual projects, filled walls often open doors and Windows, which often need to consider the reduction of the equivalent diagonal rod area, in order to solve this problem, Gao Rundong for the frame filled walls with window holes and window holes in the center by multiplying this factor to reduce the area of the equivalent pressure rod to consider the impact of opening holes. The reduction factor is the ratio of the remaining area of the wall after opening the hole to the area without opening the hole. Based on the three-pressure rod model, Thiruvengadam[25] proposed that the impact of the opening could be considered by removing and redistributing the pressure rod that passes through the opening area, and studied the factors affecting the contact length between the filling wall and the frame.

3.4 Equivalent Oblique Plate Calculation Model

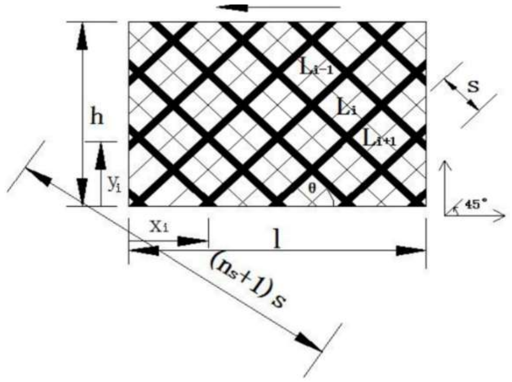

Figure 4. Calculation model of equivalent oblique strip

In 2010, Dr. Sun Guohua[26] from Beijing University of Technology, based on the test results, established a symmetrical oblique plate and strip model based on the truss model used in the calculation formula of the shear bearing capacity of concrete beams in the Architectural Society of

Japan's Guide to the Seismic Design of Reinforced Concrete Buildings to Ensure ductility, as shown in Figure 4. The inclined plate strip model is to divide the inner partition wall into a series of inclined plates with equal spacing at a certain Angle. In order to ensure accuracy, there should be a sufficient number of inclined plates. This paper mainly discusses the mechanical performance of plate strips when the forward loading is 45°, analyzes the number and width of equivalent inclined plates strips, and gives the calculation formula of inclined plates strips when the forward loading is carried out.

As can be seen from Figure 4:

$$(n_s + 1) \cdot S = l \cdot \sin\theta + h \cdot \cos\theta \tag{15}$$

The geometric length of the strip connected with the beam and column is:

$$L_{i-c} = \frac{x_i}{\cos\theta} \text{ or } \frac{y_i}{\sin\theta} \tag{16}$$

The geometric length of the strip connected to the beam and beam is:

$$L_{i-b} = \frac{h}{\sin\theta} \tag{17}$$

h is the height of the inner partition wall; l is the width of the inner partition wall; S is the width of the strip; L_i is the length of the strip; θ is the strip Angle; n_s is the indicates the number of boards and tapes; x_i is the vertical coordinates of the first diagonal plate belt connected to the upper steel beam-column; y_i Is the vertical coordinates of the first diagonal strip connected to the lower steel beam-column.

In addition, for the convenience of modeling, relevant assumptions should be made for the equivalent oblique plate and strip model:

1) The bolting effect of the steel bars distributed by the inner partition wall is not considered;

2) The shear slip of the interfacial shear connector is not considered;

3) The connection between the two ends of the equivalent inclined plate belt and the surrounding steel frame is hinged;

4) The horizontal load transmitted from the loading corner to the far side of the inclined plate strip attenuates in the form of a curve, and the shape of the curve is related to the strength of the filled concrete wall;

5) The axial force-displacement relationship of the inclined plate strip is given according to the unidirectional stress-strain relationship curve of the filled concrete;

4. Existing Problems

1) The study of filling wall openings considered in the model is not comprehensive enough. The size and position of the openings directly affect the position and width of the pressure rod, and have a direct impact on the internal forces and failure forms of the components, so systematic research should be conducted. The existing models of single pressure rod and multi-pressure rod fail to comprehensively consider the influences of many factors on the form and width of pressure rod, such as the material of filling wall, the size ratio of filling wall, the size and position of door and window openings, and the relative strength of frame and filling wall.

2) The study lacks systematic research on the interaction mechanism between the filled wall and the steel frame, and does not reveal the influence of the filled wall on the forces in the core area of the

surrounding frame beams, columns and joints under various influencing factors. The influence should be quantified so that measures can be taken to ensure the realization of the ductile failure mechanism in the design.

3) The stiffness ratio between the filled wall and the steel frame and the performance state of the filled wall affect the shear distribution of the two. In the actual work, the stiffness and strength of the filled wall are in a dynamic change, so the determination of the most adverse internal forces of the filled wall and the steel frame needs to be further studied.

5. Conclusion

1) Under the general trend of wall material innovation, solid clay brick filling wall materials are gradually being replaced by some new gas or wall panel materials. Therefore, the research on the design method of the new type of steel frame structure can provide a basis for the design of the new type of steel frame structure in the future, which is helpful to the wall reform, energy saving policy and the promotion and application of new materials.

2) In future tests, various opening forms of the filled wall should be reflected, including opening location and starting size, and finite element analysis should be carried out in combination with the in-plane and out-of-plane seismic performance of the multi-layer multi-span model, so as to comprehensively study the influence of the filled wall on the seismic performance of the structure and the influence on the internal force of the surrounding members.

3) According to the experimental results of steel frame-filled wall structure, a reasonable calculation model is proposed, in which comprehensive factors such as the size and position of the opening and the strength ratio between the filler wall and the surrounding frame should be considered. Based on the summarized model, reasonable suggestions are put forward for the design of beams and column joints in the design of steel frame-filled wall.

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