Opinion Article

A Literature Review on Steel Frame-Infill Wall Structures – Research Status and Prospects

Abstract: With the rapid development of China's economy, the state pays more and more attention to the development of assembled steel structures, which makes the proportion of assembled buildings in new houses higher and higher. However, there are still many problems in the current research on steel frame-infill wall structure, such as less research on steel pipe concrete columns and less research on lightweight insulated walls. This article examines the current research status of steel-concrete frame structures both domestically and internationally, ALC wall panel structure research status and frame infill wall research status. At the same time, the problems existing in the current related research are expounded, and the corresponding summary suggestions and prospects are made.
Keywords: Steel Tube Concrete Frame Structure; ALC Wall Panel Structure; Steel Frame - Infill Wall Structure

1.Introduction

In recent years, the floor area of rural housing in China has continued to grow. However, compared with increasingly sophisticated urban housing, rural housing construction is clearly lagging behind. There is a significant gap between urban and rural residential areas in terms of seismic safety, insulation and energy conservation, construction waste disposal, and construction methods, insufficient seismic performance, high energy consumption, incomplete construction waste disposal, and extensive construction methods.

The analysis results of some experimental studies show that filling the concrete wall panels into the steel frame can properly consider the interaction between the steel frame and the concrete wall panels, and most of the vertical loads of the structure are borne by the steel frame as a boundary member, while some of the horizontal shear forces are synergistically and jointly borne by the steel frame and the concrete wall panels. In China's "Code for Seismic Design of Buildings (2016 Edition)"[1](GB50011-2010), only in the calculation of the self-resonance period of the structure by using the hypothetical vertex displacement method, a reduction factor is introduced into the calculation considering that the infill wall has a positive effect on the structural stiffness, while in other aspects, the infill wall is still only regarded as a non-structural member, and it only indicates that measures should be taken.However, in other aspects, the infill wall is still regarded as a non-structural member only, indicating only that measures should be taken to minimize the unfavorable impact on the main structure, and it is not regarded as one of the structural lateral force-resisting members. At the same time, under the strong support of national policies, the development of assembly building is faster, This article conducts a comprehensive analysis of the current research status of steel reinforced concrete frame structures, ALC (Autoclaved Lighweight Concrete) wall panel structures, and frame infill walls both domestically and internationally. In view of the many shortcomings in the existing technical system, suggestions and prospects are proposed.

2.Domestic and international research status

2.1 Current Research Status of Steel Tube Concrete Frame Structures

Concrete for steel tubes refers to the filling of concrete into steel tubes to form a structural element that allows the steel tube and the concrete inside to jointly support external loads. Concrete is strong in compression but weak in bending, while steel sections are strong in bending but prone to localized instability. By combining concrete and steel sections, the advantages of each can be realized: the steel sections restrains the internal concrete and provides support in case of lateral compression, while the steel sections remain axially compressed due to the restraining effect of the concrete. Therefore, the structure combining concrete and steel sections not only has strong load-bearing capacity, but also can effectively improve the overall stability of the structure, which is widely used in domestic and foreign practical projects.

Wang Wenda et al.[2](2006) conducted an experimental study on 12 frame specimens to investigate the seismic performance of steel-tube concrete column-steel beam planar frames, and the results showed that an increase in axial compression ratio and a decrease in steel content resulted in a decrease in the horizontal ultimate load carrying capacity of the frames as well as a decrease in displacement ductility and energy dissipation capacity; moreover, the circular cross-section column frames had an overall better seismic performance as compared to the square cross-section column frames.

Hoenderkamp JCD et al[3] (2015) investigated the seismic performance of a square steel tubular column frame assembled with precast concrete infill wall panels by means of a proposed static test.The authors then analyzed the effect of each parameter on the seismic performance and carried out numerical

Su Yisheng et al[4] (2018) conducted low circumferential repeated loading tests on square steel pipe recycled concrete column-recycled concrete beam nodes, and the results of the study showed that measures such as increasing the node plate or reinforcing rings could improve the load carrying capacity and initial stiffness of the specimens.

Han Fang[5]and Yu Jipo[6] (2019) investigated the seismic performance of steel-tube concrete column-frame-external composite wall panel structure by means of static test and finite element analysis, respectively, to study the force characteristics and damage mechanism of the specimens under horizontal load, and also carried out parametric analyses to study the influence of material and geometrical parameters on the structural force.

Zhou Zhongyi et al[7] (2021) conducted a study on the seismic performance and interaction mechanism of CFST (Concrete filled steel tube)frame-integral assembled infill wall, the results of the study showed that the flexible connection between infill wall panels and the frame weakened the load transmitted from the frame to the infill wall panels, and slowed down and mitigated the damage of the integral assembled infill wall panels, which showed an excellent seismic performance and safety reserve.

Xie Chuandong et al[8](2023) designed four single-span two-story frame specimens and conducted a proposed static test study on the assembled self-replacing square steel-tube concrete frame with slotted energy dissipative panels. The results showed that the frame exhibited good seismic and self-replacing performance, and the damages were mainly concentrated in the energy-dissipative panels that could be expected to be replaced.The frame could be repaired quickly by replacing the energy-dissipative panels after the earthquake.

Ai-Lin Zhang et al[9]（2022）proposed a new type of welded node for the field bolted node of steel-tube concrete columns and H-beams, the node diagram is shown in Fig. 1[9], and the effects of bolt diameter, beam flange cover, widened beam flange, and flange thickness on the seismic performance of the node were investigated through the cyclic loading test of four-bay foot-size specimens, and the new welded node was compared with the traditional welded node through tests and numerical simulations. The seismic performance of the new welded node is compared with that of the traditional welded node through tests and numerical simulations, and the simplified equations for the yield and ultimate bearing capacity of the new welded node were proposed.

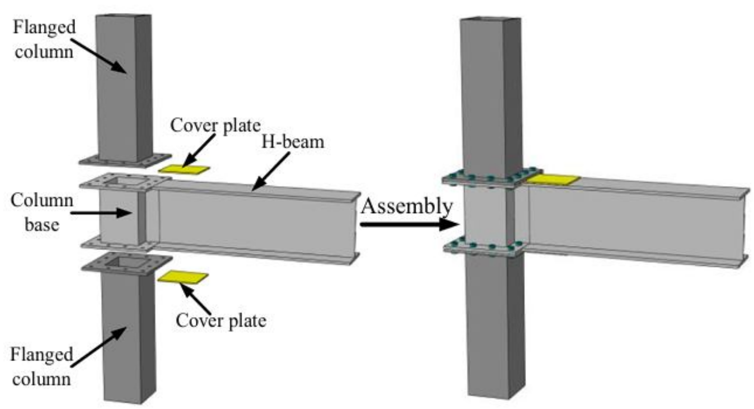
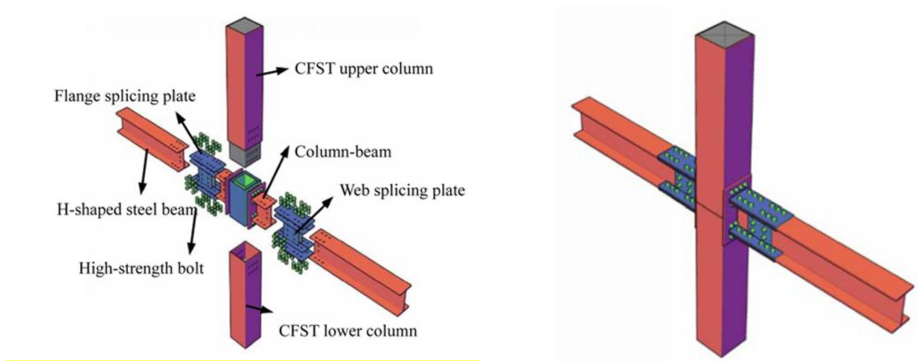


Fig. 1. Structural diagram of the joint.

Xiushu Qu et al[10]（2023）proposed a combined node of H-beam and steel-tube concrete columns, the node assembly flowchart is shown in Fig. 2.The seismic performance of this node was investigated by low weekly load test. The finite element model of the node was established by numerical analysis method. On the basis of verifying the reasonableness of the finite element model, the influence of the end plate thickness and bolt diameter on the energy dissipation performance of the node was investigated through parametric analysis to give full play to the synergistic load-bearing mechanism of the column connectors and concrete.



(a) Decomposition of the Joint, (b) Assembly of the Joint

Fig. 2.The Assembly Flowchart

Currently, studies on steel-tube concrete frame structures have focused on the improvement of seismic performance, load carrying capacity, energy absorption capacity, and overall structural performance. These studies have addressed the interaction mechanism between CFST frames and infill walls, the effects of different materials and configurations on the structural performance, and the response under different seismic magnitudes and loading conditions. However, there are few studies on the detailed design and fire resistance of these structures. In particular, there is a lack of research on the details of CFST frame infill wall connections, such as the connections between steel tubes and concrete infill walls, and between steel frames and infill walls, which are essential to ensure structural integrity and avoid brittle damage during earthquakes. In terms of fire resistance, although steel-tube concrete structures have good fire resistance, there is a relative lack of specific research on frame infill wall structures, such as assessment of load-bearing capacity after fire and fire-resistant design methods.

2.2 ALC wall panel structure research status

ALC board is a type of porous concrete formed board, mainly made of materials such as cement, lime, silica sand, which are cured by high-pressure steam. Compared with traditional cementitious materials, ALC board has many advantages and characteristics: firstly, due to the large number of pores, ALC board has a lighter weight, which can reduce the overall load when used in building structures, thereby reducing the self weight pressure of buildings, reducing the bearing pressure of foundations, and improving the seismic performance of buildings; secondly, due to the rich pore structure, the panels have good heat preservation and insulation properties, [11]which effectively reduces the energy consumption, improves the energy-saving performance of the building, and reduces the operating cost of the building.Moreover, the ALC panels have good sound-absorbing and sound-isolating properties, which effectively reduce the noise of the interior and exterior of the building, providing a more comfortable and quieter environment. In addition, ALC panel has good sound-absorbing and sound-insulating properties, which can effectively reduce the noise inside and outside of the building and provide a more comfortable and quiet living environment, which is conducive to the health and quality of life of the occupants; moreover, because ALC panel adopts common raw materials such as cement, lime, silica sand, etc. and adopts the high-pressure steam curing technology during the manufacturing process, the production process is relatively environmentally friendly, and it can reduce the consumption of natural resources and reduce the pollution of the environment. Therefore, as a new type of building material, ALC panel has many advantages such as light weight, heat insulation, sound absorption and insulation, environmental protection, etc. It is of great significance to study the application and construction technology of ALC lightweight wallboard in steel structure buildings. [12]It has a broad application prospect and development space, and will play an important role in the construction industry, bringing more choices and possibilities for the design and construction of buildings[13].

Li[14] (2005) conducted an experimental study on steel framed structures with externally hung and embedded ALC wall panels and analyzed the hysteretic performance of the structural system.

Tian H et al[15] (2009) investigated the shear performance of autoclaved aerated lightweight concrete (ALC) composite wall panels by means of interfacial pure shear tests.

Bulingquan et al[16] (2010) investigated the seismic performance of a steel frame with embedded honeycomb sandwich composite wall panels.

Bo Wang et al[17] (2013) carried out low circumferential repeated load tests on structural specimens of steel-tube concrete frames with pure frames and steel-tube concrete frames with ALC slats and blocks, and investigated in detail the effects of parameters such as wall panel thickness, wall panel connection form and wall panel type on the seismic performance of the specimens. J F Wang et al**Error! Reference source not found.** (2017) carried out horizontal low-cycle reciprocating load loading on ALC slab and block frame system and found that the two types of enclosing walls were connected reliably, which allowed the walls to work in concert with the frame and the structure to meet the safety requirements under seismic actions.

Hu Jingwu et al[18] (2018) implemented a shaking table test on steel frame-inserted spliced aerated concrete infill wall panel footing structure, and the frame and wall were connected through the pre-embedded parts in the wall panels. The results showed that the connection node had a certain seismic damping effect, and the model had the maximum interstorey displacement angle of 1/49 in the 8 degree rare ground shaking. Only the wall panels had localized damage while the steel frame did not have any significant damage, and the structure had a good seismic performance. The structural seismic performance is good.

Gokmen F et al[19] (2019) conducted a low weekly reciprocating load test and finite element simulation on a two-story wall panel structure in order to study the seismic performance of reinforced ALC wall panels. The test results showed that the bottom floor of the building had a greater influence on the force performance of the whole structural system during the whole test loading process, and the members had good load carrying capacity and ductility.

Yinggang Zhang[20] (2021) constructed a hysteretic performance assessment model for steel frame-ALC wall panel structure by using ABAQUS software, and investigated the role of several factors such as mortar fill, span-height ratio, axial-compression ratio, wall panel dimensions (width and thickness), and strength of the ALC wall panels on the seismic capacity of the structure.

In order to investigate the cracking resistance of ALC panels with different connection methods in steel frames under horizontal loads and the cracking resistance of different finishes, Ruihua Huang et al. [21]（2022）designed and carried out low-cycle reciprocating load tests on three bays of full-size two-story single-span steel frames with embedded ALC wall panels. The results show that: the main damage mode of embedded ALC wall panels is cracking at the wall panel joints; the cracking resistance of wall panels with built-in anchors is better than that of the hook-and-bolt and sliding-bolt joints; the location of the wall panel joints with the steel frames is the weakest location for cracking resistance of the finish; the location of the wall panel joints is good for cracking resistance of the finish; and the cracking resistance of the caulked joints of the two-component sealant is better than that of the one-component sealant.

In order to study the effect of mortar fullness on the hysteretic properties of the external ALC panel-steel frame system and the crack resistance of ALC wall panels, Chen J et al. [22](2023) established a finite element model based on the ABAQUS software and the Crack Expansion Finite Element Method (XFEM), as shown in Fig. 3. The authors analyzed the effects of the parameters of the ALC wall panel strength, wall panel thickness, wall panel width, axial compression ratio, and span-to-height ratio on the strength, thickness, width, axial compression ratio, and span-to-height ratio of ALC wall panels. The results show that: in terms of hysteretic performance, the ALC wall panels have a very good performance. The results show that, in terms of hysteretic performance, the bearing capacity and stiffness of the external ALC panel-steel span system decreased with the increase of axial compression ratio, while other parameters such as mortar fullness had less influence.

Li Zhihua and others [23]（2020）analyzed the causes and control of cracks in ALC energy-saving wall panels. ALC wall panels in the process of practical application, has good application characteristics. Although the state has introduced relevant standards and atlases, but the actual application of the process due to the structure of the building and the system is different, need to be constructed according to the actual situation, control the quality of the panels.

At present, there are two main connection methods for ALC wall panels: external ALC wall panels are often attached to the frame as a load,[24] which is a burden to the overall structure; when ALC wall panels are embedded, there is continuous interaction between the wall and the frame under seismic action, and the wall has a great influence on the self-resonance period, lateral stiffness[25], load carrying capacity, energy dissipation characteristics of the frame, etc. If the wall is only regarded as a load in mechanical analysis, it will cause serious discrepancies between the calculation results and the actual forces on the structure. If the wall is only regarded as a load in the mechanical analysis, the calculation results will not be consistent with the actual stresses of the structure, and there are few studies on this aspect.

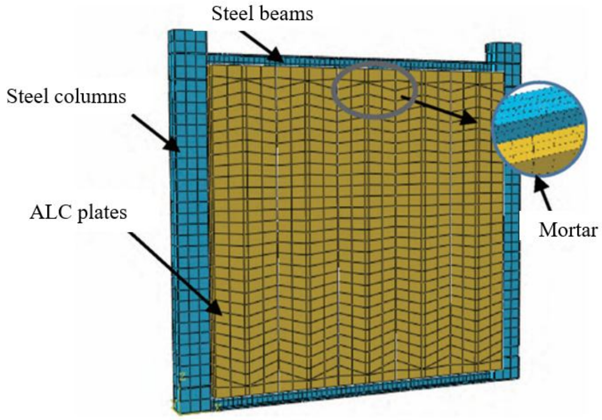


Fig 3.Finite element model of external ALC wall panel-steel frame system

2.3 Current status of frame infill wall research

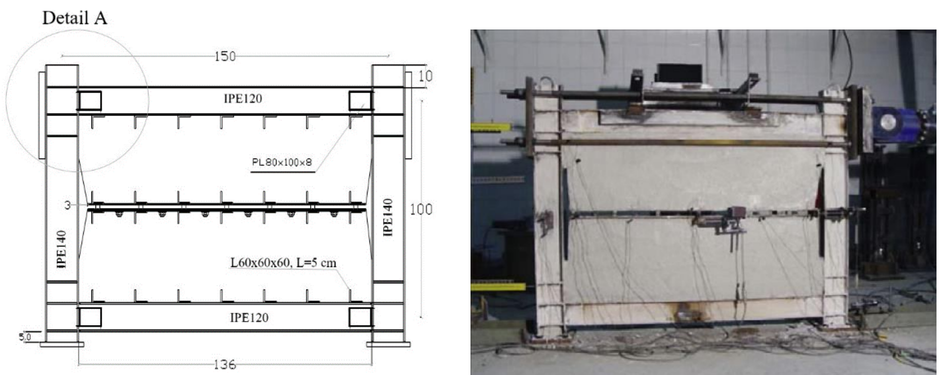
China's "Code for Seismic Design of Buildings (2016 Edition)"[1](GB 50011-2010) stipulates that the infill wall and partition wall should give priority to the use of lightweight wall materials, and try to take measures to minimize the adverse impact on the main structure, and should be set up with tie reinforcement, horizontal tie beams, ring beams, structural columns, etc. The main structure of the reliable tie.The wall should be reliable tie with the main structure. Reliable ties should be provided between the walls and the main structure, which can adapt to the interstory displacement in different directions of the main structure. In the process of structural design, the infill wall is designed as a non-structural member, and the empirical formula method is adopted to calculate the basic cycle of the frame structure. The influence of the infill wall on the overall stiffness is considered through the introduction of the reduction factor.The cycle reduction factor of the frame structure can be taken to be 0.6~0.7.

In the U.S. FEMA-356 specification[26], the calculation method of infill walls in frame structures is clearly defined, and it is recommended to use the diagonal brace model to analyze the influence of infill walls on the stiffness and strength of frame structures, which is a simplified method to facilitate the numerical modeling and subsequent analysis and calculation of frame-infill wall structures.

In Eurocode[27], all types of infill walls are considered as non-structural elements, and dynamic elastic-plastic analyses can be used to evaluate the seismic performance of frame-infill wall structures, and to study the interaction between infill walls and reinforced concrete frames and the effects on their mechanical properties.

In the other view, the infill wall is considered as a nonstructural element with a greater impact on the frame structure, and therefore the influence of the infill wall on the overall seismic performance should be considered when the structure enters the elastic-plastic stage. However, it is difficult to determine the factors affecting the interaction between the infill wall and the frame structure, such as the material of the infill wall, the connection method, the stiffness of the wall, and so on, which leads to the complexity of the research and analysis. Therefore, further in-depth studies and research are needed to develop more scientific and reasonable design codes and engineering practice guidelines to ensure the coordination and safety between infill walls and framed structures.

Mohammadi et al. [28](2010) designed a friction sliding fuse placed in the center of an infill wall, as shown in Fig4, to limit or eliminate damage to the infill wall and frame,during an earthquake.This device allows for the upper and lower walls to slide relative to each other, thus avoiding structural damage and dissipating energy. Tests confirmed the hysteresis and ductility of the device to be superior to that of conventional infill wall framing



(a) Typical specimen construction (b) Typical specimen photo

Fig. 4 Steel frames-infill walls with sliding surfaces

Morelli F et al [29] (2019) developed a new energy-consuming structure (SRCW), as shown in Fig. 5, which is connected between a hybrid structural frame and a reinforced concrete infill wall by means of bolts.The effect of the number and distribution of bolts on the seismic performance of this structure was investigated through experiments, and the experimental results were verified by using a finite element analysis method. A method for evaluating the structural performance and energy dissipation capacity of bolted connections was ultimately proposed.

Ghobadi M S et al[30] (2019) investigated the effect of masonry infill walls on the structural performance of steel frames and the effectiveness of repair measures taken on damaged masonry infill walls by conducting three different experiments. The experimental results showed that these repair methods were effective in restoring the load carrying capacity, stiffness and ductility of the damaged infill walls.

LIU.Y et al[31] (2012) conducted a proposed static test on one steel frame specimen and ten steel frame-concrete masonry infill wall specimens with different parameters to study the effects of shear-to-span ratio, grouting range, opening rate, and wall-to-frame stiffness ratio on the mechanical properties and damage characteristics of the specimens and evaluated the reliability of the calculation method for frame-masonry infill wall structures in the current design codes of Canada and the United States on the basis of the test results. The reliability of the calculation methods in the current Canadian and US design codes was evaluated.

Fig. 5 Failure mode of SRCW specimen

In the 1970s, Yin Zhiqian[32]took the lead in the study of the effect of clay brick infill walls on the bearing capacity of frame structures under horizontal loads, and found that the distribution of stiffness between infill walls and frames affects the conclusions of the horizontal loads that can be support by both of them, which opened the prelude to experimental research on infill wall frame structures in China.

Fang Mingji et al.[33] (2005) conducted full scale shaking table tests on steel frame-lightweight sand aerated concrete exterior wall panel structure and steel frame-block infill wall structure, focusing on the differences in the effects of lightweight sand wall panels and block walls on the seismic performance of steel frame structures, comparing the force mechanisms and weak points of the two, and proposing design recommendations for this type of structure.

Zhao Yuliang[34] (2009) conducted shaking table tests on a scaled model of a steel frame-external prefabricated dense-ribbed wall panel structure. The results showed that the structural stiffness of the wall panels was increased, the amplification coefficient of the acceleration at the top level was lower than that of the bare frame specimen, and the connection with a rubber gasket had a certain seismic isolation and energy-consuming effect.

Gao Liang[35] (2015) used ABAQUS finite element software to investigate the effects of compressive strength of recycled concrete, yield strength of frame column sections, axial compression ratio, wall block strength, and wall aspect ratio on the seismic performance of profile recycled concrete frame-recycled block infill walls.

Guo Hongchao et al.[36] (2017) conducted a proposed static test on steel frame-embedded recycled concrete wall structure, which mainly explored the distribution of internal forces between the wall and the frame under the horizontal load.The test results revealed that the stiffness of the beam-column nodes has a limited effect on the structural capacity, and in comparison with the concrete material properties of the embedded wall, the stiffness of the beam-column nodes has a limited effect on the structural capacity and the seismic performance. The test results revealed that the stiffness of beam-column nodes had a limited effect on the load carrying capacity of the structure, whereas the concrete material properties of the embedded walls had a significant effect on the load carrying capacity and stiffness.

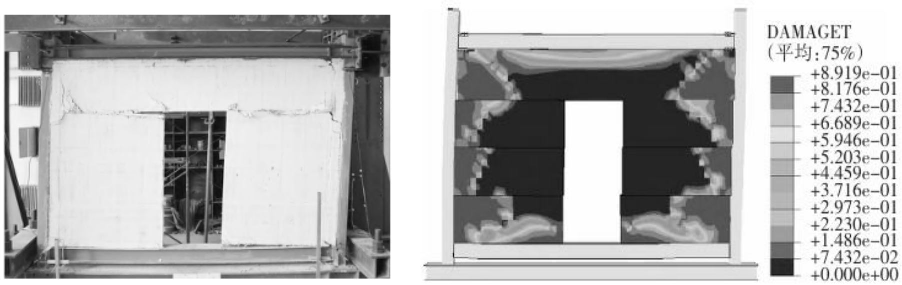
Dong Hongying et al.[38][38](2019) conducted a two-story, single-span steel frame-external microcrystalline foamed wall panel foot-scale structural shaking table test to investigate the dynamic characteristic changes and seismic response of the structure. The results showed that the structure meets the code requirements for seismic resistance. The wall can reduce the interstory displacement of the structure to a certain extent.The preexisting joints between adjacent walls need to be added with flexible materials to mitigate the phenomena of mutual impacts and compression. Flexible materials need to be added to the joints between neighboring walls to reduce mutual impact and compression.

In order to investigate the effects of different types of regenerated infill wall on the load carrying capacity, deformation capacity, ductility and energy dissipation capacity of the specimens, Yuchou Wang et al.[39] (2020) conducted low-cycle repeated loading tests on 5-bay frame-reclaimed infill wall specimens (including 1-bay bare frame and 1-bay wall specimens), which showed that the composition of wall materials of regenerated infill wall had a greater effect on the seismic performance of the frame structures. The test results show that the wall material composition of reclaimed infill wall has a greater influence on the seismic performance of frame structures, and the performance of frame-reclaimed infill wall structures degrades faster after ultimate loads than that of frame-ordinary infill wall structures.

Yanqing Zhang[40](2022) conducted low-cycle reciprocating loading tests by designing a 1-bay recycled concrete frame and a 2-bay recycled masonry infill wall-profile steel recycled concrete frame with the aim of investigating the seismic performance of recycled masonry infill wall-profile steel recycled concrete frame structures, and the results of the tests showed that the frames with infill walls had better energy dissipation capacity than the pure frame specimens at the beginning of loading, but inferior to the pure frame specimens at the later stage due to the destruction of infill walls. The test results show that the frame with infill wall has better energy dissipation capacity than the pure frame specimen at the beginning of loading, but worse than the pure frame specimen at the end of loading due to the damage of infill wall.

Jinliang Bian et al[41](2022)proposed an assembled structure (CFST frame-ESP combination wall) consisting of a lightweight steel-tube concrete frame and embedded steel plate (ESP) combination wall. In order to investigate the seismic performance of the prefabricated structure, six full-size specimens were tested with low reverse cyclic loading to compare the damage characteristics, hysteresis characteristics, load carrying capacity, stiffness degradation, and energy dissipation capacity of the specimens.

In order to study the seismic performance of concrete-filled steel tube frame-ALC wall panel structure, Wu Tao et al [42](2024) established a finite element model of the structure with ABAQUS software and applied low cycle reciprocating load for analysis, as shown in Fig. 6.The influence of key factors such as the size and location of the openings on the seismic performance of concrete-filled steel tube frame-ALC wallboard structure was discussed. Compared with the experimental results, the validity of the modeling and analysis results was verified.



(a)Photographs of test wall panels (b) Numerical simulation of damage cloud

Fig. 6 Test wall photo and numerical simulation diagram

3. Problems with existing research

From the above literature, combined with the previous researches in recent decades, it can be seen that there are many researches on steel frame-fill wall structures, but there are still some problems that need to be further investigated:

(1) Most of the steel frames used are H-type steel columns or steel beams, and there are fewer studies on steel pipe concrete columns.

(2) At present, the research on structural damage after fire mainly focuses on concrete structures and steel structures, while the research on concrete-filled steel tube structures is less.

(3) There are few studies on the fire resistance of ALC plate in steel frame structure.

(4) The research on the frame-filled wall mainly focuses on the joint form of the reinforced steel frame and the connection method with the wall panel. Few people study the collaborative deformation of the wall panel and the frame.

(5) The main wall panels of the frame structure are mostly filled with masonry walls, and there are few studies on light insulation walls.

4. Conclusion and future Prospect

The research on steel-concrete frame structures mainly focuses on improving their seismic performance, bearing capacity, energy absorption capacity, and overall structural performance through experiments and finite element analysis. Steel reinforced concrete structures have good seismic performance. In recent decades, there has been significant progress in the research of steel-concrete structures worldwide, and at the same time, various countries have also introduced design specifications for steel-concrete structures. Although steel-concrete structures have a development history of decades, compared with the ubiquitous reinforced concrete and steel structures in daily life, steel-concrete structures are undoubtedly an emerging type of structure. However, as people gradually recognize the excellent performance of steel reinforced concrete, it has attracted more and more researchers to invest in the research of this structure. With the deepening and improvement of scientific research, steel reinforced concrete will appear more and more frequently in people's vision in the future.

The research on steel frame infill wall structure and ALC wall panel structure mainly focuses on their seismic performance. The extensive application of ALC board in engineering reflects its excellent performance and simple construction technology.[43] ALC wall panels are mainly divided into embedded ALC panels and external ALC panels. The main research focuses on the hysteresis performance, displacement ductility, and bearing capacity of assembled steel frames filled with ALC wall panels under the combined action of earthquake response. The results indicate that ALC panels and connecting nodes have good seismic performance. Wall panels can work together with steel frames and play a significant role. In the future, it is necessary to conduct research on the fire resistance performance of ALC wall panels and conduct certain experimental studies. Reveal the damage mode, damage mechanism, and temporal variation of bearing capacity under fire. Further research is needed on steel frame lightweight insulation walls to achieve integration of insulation and structure, reduce building energy consumption, minimize construction noise and waste concrete pollution, save a lot of time, and improve construction efficiency while ensuring their good seismic performance. We also need to study the collaborative deformation between infill walls and frames, in order to reduce wall damage by improving their ductility. By coordinating the deformation between the wall and the steel-concrete frame, excessive shear forces on the frame columns can be avoided. The slight displacement between the wall panels can also dissipate some seismic energy and reduce the seismic response of the upper structure.

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