Opinion Article

Research status and development of assembled lightweight steel composite structures

Abstract: Prefabricated lightweight steel composite structures are characterized by efficient load-bearing, seismic energy-saving, and eco-friendly attributes, primarily used in low-rise and multi-story buildings, adapting to the development of modern architectural industrialization. This review covers the development process, system composition, and current research status of structural seismic performance for typical prefabricated lightweight steel composite structures, including prefabricated cold-formed thin-walled steel structures, prefabricated lightweight steel-lightweight concrete structures, and prefabricated lightweight steel composite frames - lightweight steel composite shear wall structures. The analysis includes the technical features, standard systems, and current environmental applications of the aforementioned structures, raises several issues in the research of prefabricated lightweight steel composite structures, and provides a research outlook for the future development direction of prefabricated lightweight steel composite structures.

Keywords: assembled building; lightweight steel modular structure; seismic performance; technical standard; research outlook

0.Introduction

Prefabricated lightweight steel composite structures refer to lightweight steel composite components made up of cold-formed thin-walled steel or ordinary steel with thicknesses ranging from 0.8 to 10mm, combined with concrete, structural panels, and insulation materials. These components are assembled into shear walls, frame-shear wall, and frame-braced structures through connection details such as beam-column and wall panel joints, using fasteners like bolts, self-tapping screws, or pre-embedded parts. Prefabricated lightweight steel composite structures are primarily used in low-rise and multi-story buildings and represent a promising prefabricated building structural system. The main components of prefabricated lightweight steel composite structures include lightweight steel composite columns, lightweight steel composite beams, lightweight steel composite floor systems, and lightweight steel composite shear walls.

Typical lightweight steel composite structures mainly include prefabricated cold-formed thin-walled steel structures, prefabricated lightweight steel-lightweight concrete structures, and prefabricated lightweight steel composite frame-lightweight steel composite shear wall structures. 1) Prefabricated cold-formed thin-walled steel structures can be categorized into modular prefabricated cold-formed thin-walled steel wall panel structures, slab-column structures, wall-slab-column structures, etc., which means the structure is divided into column modules, wall modules, composite floor systems, and connection pieces, all of which are prefabricated in the factory and directly assembled and connected on-site; 2) Prefabricated lightweight steel-lightweight concrete structures are industrialized prefabricated structures with prefabricated lightweight steel frameworks as the structural skeleton, and lightweight concrete is poured on-site; 3) "Flexible supports" and "lightweight steel composite shear walls" serve as the first line of defense in efficient seismic-resistant units, hence the layered prefabricated lightweight steel frame-flexible support structures and prefabricated lightweight steel composite frame-lightweight steel composite shear wall structures are collectively referred to as prefabricated lightweight steel frame-high efficiency seismic-resistant unit structure systems.

Prefabricated lightweight steel composite structures have significant advantages in low and multi-story buildings: 1) The components of lightweight steel composite structures are produced in factories, leading to high assembly and construction efficiency; 2) Compared to light steel structures, there is a noticeable improvement in seismic performance, fire resistance, and corrosion resistance; 3) The use of integrated structural and insulating lightweight enclosure wall panel systems is suitable for constructing ultra-low energy consumption buildings; 4) Recycled aggregate concrete and slag can be used as eco-friendly materials, making them green and sustainable.

a) cold-formed thin-walled steel structure　b) Light steel and lightweight concrete structure　c) Light steel composite frame

Figure 1 Prefabricated light steel composite structure system

Prefabricated lightweight steel composite structures possess a broad applicability, capable of meeting the demands of both urban low-rise and multi-story buildings, as well as accommodating the construction of rural low-rise and multi-story buildings. This is crucial for accelerating the industrialization process of urban and rural construction, implementing green residential development strategies, and popularizing innovative residential forms such as lightweight steel structures in suitable areas.

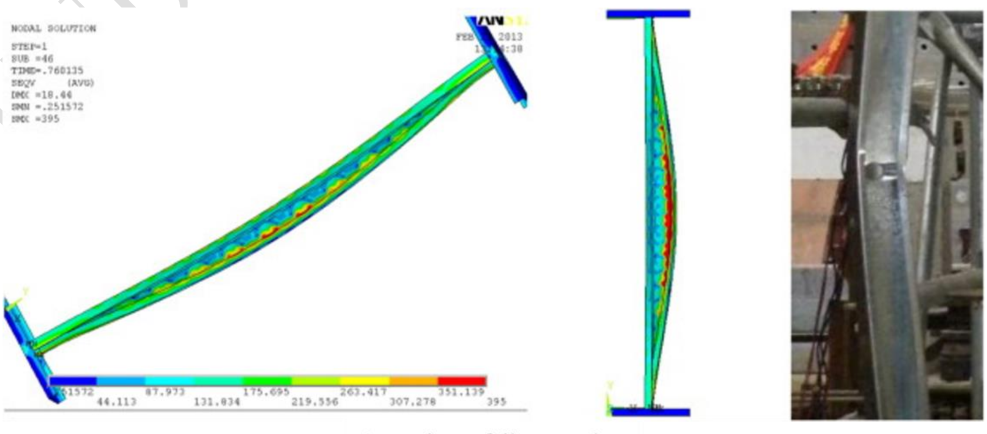
1 Research Status

1.1 Prefabricated cold-formed thin-walled steel structure.

Low-rise cold-formed thin-walled steel residential structures utilize light steel framing as the main load-bearing elements. The cold-formed thin-walled steel is connected to the wall panels with self-tapping screws, and the wall panels restrain the buckling of the light steel framing under compression. The resulting composite walls serve both as load-bearing elements and as lateral force-resisting components. Standardized connectors are used to assemble cold-formed thin-walled steel joists into structural panel composite flooring systems or composite flooring systems consisting of light steel beams, profiled steel sheets, and in-situ concrete layers.

Manikandan P and Aruna G et al.[1] conducted an axial compression performance analysis on four cold-formed thin-walled channel sections with different edge stiffening types, and then simulated the behavior using the ANSYS finite element software, discussing the effects of section thickness, yield strength, and slenderness ratio on the ultimate load-bearing capacity and buckling modes of the members. They compared the accuracy of three direct strength method formulas[2] and proposed a new suggested formula for the direct strength method. Liu Zhanke et al.[3] conducted an in-depth analysis of the performance of lightweight steel members under various loading states such as axial compression and bending, systematically organized and summarized the theories and methods in the current design standards of China, the United States, and Europe, and further explored the impact of initial geometric imperfections on the stability of cold-formed thin-walled steel, proposing corresponding design methods based on this research. Xiang Yi et al.[4] carried out axial compression performance tests on complex flanged cold-formed thin-walled steel columns, analyzed the impact of different cross-sectional dimensions and column lengths on the load-bearing capacity of the specimens, and verified the test results using finite element software, demonstrating that the flange width-to-thickness ratio and web height-to-thickness ratio are key factors affecting the axial compression load-bearing capacity.

POST [5] evaluated the axial compression performance of cold-formed thin-walled steel composite walls through experiments and finite element simulation, and calculated the axial load-bearing capacity of the composite walls using the direct strength method and finite strip method. YE et al. [6] conducted experimental studies on the axial compression performance of cold-formed thin-walled steel composite walls, exploring the failure characteristics and load-bearing capacity of the wall panels. The results indicated that when the light steel keel columns used composite sections, the axial compression load-bearing capacity of the walls was significantly enhanced, as shown in Figure 3 for some of the tests. Shen Zuyan et al.[7], Li Yuanqi[8][9], and LI et al. [10]conducted low-cycle reciprocating tests and full-scale model shaking table tests on the seismic performance of cold-formed thin-walled steel structural systems, as well as finite element simulations. They studied the working mechanism of cold-formed thin-walled steel structures, established models for calculating load-bearing capacity, and proposed practical design methods.



a) specimen failure mode

Fig. 2 Seismic test of cold-formed thin-walled steel wall

Shi Yu et al. [11] conducted bending performance tests on cold-formed thin-walled steel roof trusses of different construction forms and thoroughly explored their working mechanisms and failure modes. The study found that the strength of the steel, the section form, and the thickness of the steel have a significant impact on the load-bearing capacity of the trusses. CHEN et al. [12], CELIS-IMBAJOA et al. [13], and LIU et al. [14] conducted research on composite floor slabs made of profiled steel sheets and steel-wood composite floor slabs, discovering that compared to traditional on-site poured concrete floor slabs, lightweight steel structure floor slabs have distinct advantages in terms of weight and ease of installation. Shi Yu et al.[15] and Guan Yu et al.[16] researched the bending and dynamic performance of cold-formed thin-walled steel beams combined with OSB (Oriented Strand Board) panels and cold-formed thin-walled steel combined with gypsum self-leveling mortar floor slabs. The results indicated that the cold-formed thin-walled steel beam-structural panel composite floor slabs have good load-bearing performance, which can reduce the difficulty of assembly construction for cold-formed thin-walled steel structures.

1.2 prefabricated lightweight steel-concrete structure

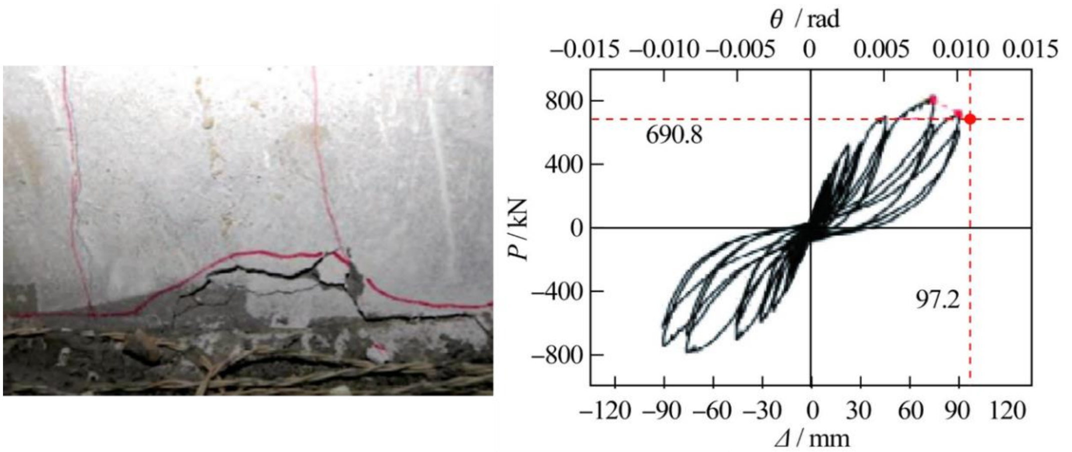
The primary materials of the lightweight steel-lightweight concrete structure are thin-walled lightweight steel, non-removable formwork, and new-type lightweight concrete. By combining thin-walled lightweight steel with non-removable formwork, a lightweight steel composite frame is formed. On the basis of the lightweight steel composite frame, lightweight concrete is poured to create non-removable formwork lightweight steel-lightweight concrete walls. The characteristic of this structure is the synergistic work of the lightweight steel frame and lightweight concrete, resulting in good structural performance[17].

The application of lightweight concrete materials in lightweight steel composite structures is currently a hot topic of research. Prabha et al. [18] conducted axial compression tests and theoretical studies on composite walls filled with lightweight foamed concrete and enclosed by thin-walled steel plates, finding that the thin-walled steel enclosure contributes little to the vertical load-bearing capacity of the wall, primarily serving to restrict the deformation of the foamed concrete and thereby increase its strength, and proposed a calculation formula for the axial compression load-bearing capacity of this new type of wall. Francesco M et al. [19] proposed a novel dissipative structure (SRCW) that uses bolted connections between hybrid structural frames and reinforced concrete infill walls, as shown in Figure 3. They experimentally investigated the influence of the number and distribution of bolts on the seismic performance of the structure and validated the experimental results using finite element analysis, finally proposing an assessment method for the structural performance and energy dissipation capacity based on bolted connections. Ghobadi M S et al. [20] conducted three different experimental studies on the impact of masonry infill walls on the performance of steel frame structures and the effectiveness of repair measures for damaged masonry infill walls. The experimental results showed that these repair methods can effectively restore the load-bearing capacity, stiffness, and ductility of damaged infill walls. Salgar P B and Patil P S[21] performed axial compression tests on square steel tubes, rectangular steel tubes, and circular steel tubes filled with lightweight concrete, comparing their buckling performance and load-bearing capacity at different slenderness ratios and thickness ratios, and compared the load-bearing capacities calculated according to AISC and EC4 specifications with the experimental results. The experimental results indicated that compared to ordinary concrete columns, the self-weight of lightweight concrete columns was reduced by 25.3%, and when the slenderness ratio is constant, the load-bearing capacity of the members increases as the ratio of depth to thickness (D/t) decreases.

Fig3 Failure mode of SRCW specimen

J.Y. Richard Liew et al.[22] have explored the latest research on Steel-Concrete-Steel (SCS) sandwich composite structures, where novel J-hook connectors, high-strength steel plates, and new types of lightweight cement composite materials have been considered for the development of SCS sandwich products to enhance their strength-to-weight performance. Wang Jingfeng et al. [23][24] conducted research on the axial compression performance of light steel structure walls filled with light polymer and the shear resistance of light steel composite wall panels filled with light-quality slurry, providing a basis for the design and calculation of light steel walls filled with polymer. Tian Le et al.[25]experimentally studied the mechanical properties of light steel and foam concrete composite walls, finding that parameters such as the density of foam concrete and steel content have no effect on the failure mode of the composite walls but significantly affect the shear bearing capacity. Hu Xibing et al. [26]proposed a type of light steel foam concrete wall panel composed of foam concrete, light steel, and steel mesh, which possesses good overall stiffness and elastoplastic deformation ability.

Huang Qiang et al. [27] carried out quasi-static tests on a three-story full-scale specimen of light steel-lightweight concrete structures, analyzing the structural failure mode, hysteresis characteristics, and deformation capacity, etc. The results indicated good seismic performance of the structure. Some failure phenomena of light steel-lightweight concrete structures and measured hysteresis curves are shown in Figure 4.



a) specimen failure phenomenon b) hysteretic curve

Fig. 4 Seismic performance test of light steel and light concrete structure

1.3 Prefabricated lightweight steel composite frame - lightweight steel composite shear wall structure.

Dall'Asta A et al. [28] proposed a seismic design method for the design of steel frame-shear wall structures and validated the rationality of this method through experimental and numerical simulation methods. Sun L et al. [29] focused on the influence of the stiffness of the beam-column joints and the infill recycled concrete wall panels on the seismic performance of steel frames, conducting parametric analyses on the wall panel hanging points, recycled concrete strength, wall panel thickness, shear span ratio, and axial compression ratio. Hashemi S J et al.[30] conducted experimental research and numerical simulation on the seismic performance of steel frames with embedded "sandwich" wall panels, studying the effects of the shear span ratio and "sandwich" wall panels on the steel frames. Varela-Rivera J et al. [31] conducted low-cycle reciprocating tests on AAC masonry walls to study the effects of axial compression ratio and shear span ratio on their seismic performance, and provided the lateral load-bearing capacity of the walls under shear and flexural-shear failure modes.

Li et al. [32] conducted full-scale shaking table tests on steel frame structures with aerated concrete exterior wall panels, comparing the differences in seismic response between embedded and attached assembly methods through experiments, and comparing the hysteretic performance of steel frame structures with aerated concrete exterior wall panels using the two assembly methods through pseudo-static tests[33]. They concluded that the embedded walls with simple connections significantly enhance the stiffness and load-bearing capacity of the steel frames compared to attached walls, which should be considered in structural design. Wang Bo et al.[34] implemented low-cycle repeated load tests on steel tube concrete pure frame structures and steel tube concrete frame structures with ALC slabs and blocks, studying in detail the effects of wall panel thickness, wall panel connection forms, and wall panel types on the seismic performance of the specimens. Hu Jingwu et al.[35] conducted shaking table tests on full-scale steel frame structures with embedded aerated concrete infill wall panels, where the frames and walls were connected through embedded components in the wall panels. The results showed that the connection nodes had certain seismic damping effects; the model had a maximum story drift angle of 1/49 during an 8-degree rare earthquake, with only local damage to the wall panels and no significant damage to the steel frames, indicating good seismic performance of the structure.

Bian Jinliang et al. [36]and BIAN et al. [37] proposed a node with double L-shaped members welded to steel tube concrete columns and bolted to H-shaped steel beams, which significantly increases the node area of light steel beam-column connections, especially the increase in section height can rapidly enhance the node's stiffness. They conducted comparative seismic performance tests on 38 different constructed double L-shaped members with diagonal stiffening ribs nodes and ordinary nodes, analyzing the failure characteristics, hysteretic properties, and energy dissipation capabilities of each specimen. The results indicated that the double L-shaped members with diagonal stiffening ribs nodes have simple construction, low steel consumption, fewer bolts used, and superior seismic performance. The comparison of the double L-shaped members with stiffening ribs nodes construction and partial measured hysteresis curves with the current ordinary nodes hysteresis curves is shown in Figure 5.

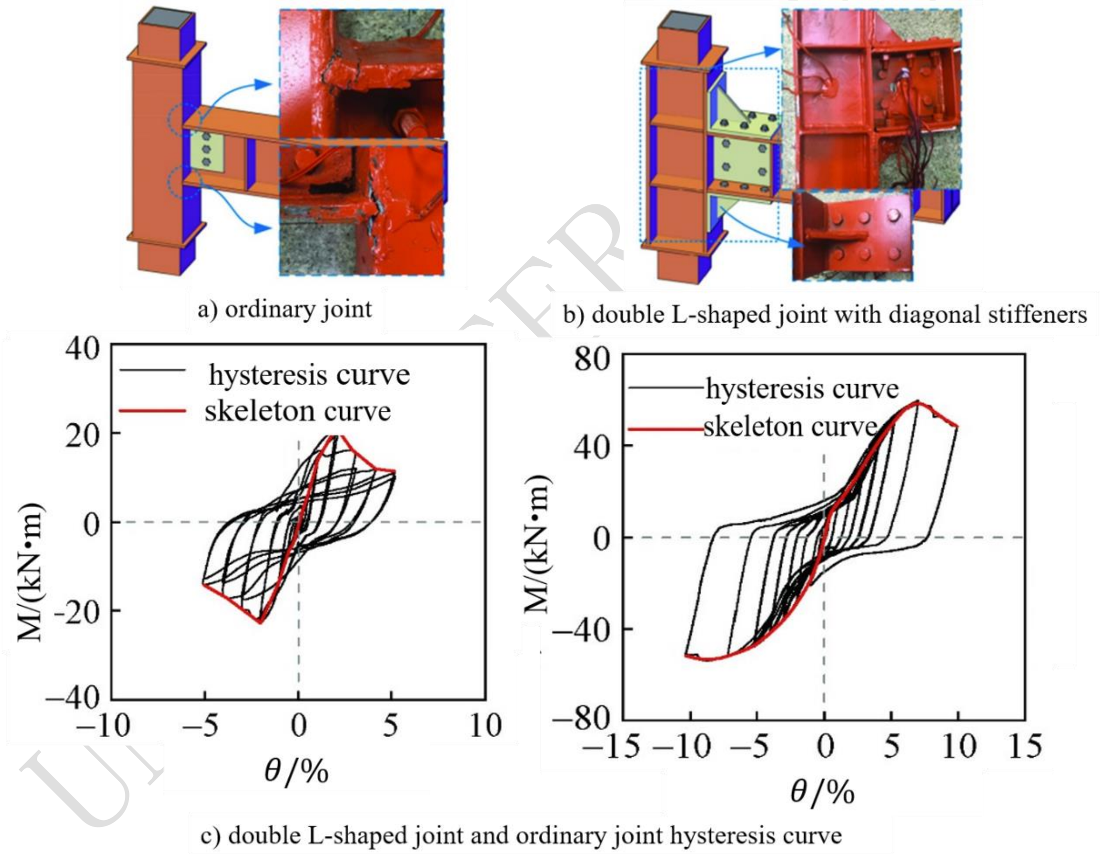


Figure 5 Comparison between ordinary joints and double L-shaped joints with diagonal stiffeners

2 Structural Characteristics and Technical Standards

2.1 Structural characteristics

Prefabricated cold-formed thin-walled steel structures, where the walls serve as the primary vertical load-bearing elements and lateral force-resisting elements, exhibit the distinct characteristics of shear wall structures and have a high degree of prefabrication. Prefab cold-formed thin-walled steel structures: full-scale structural shaking table tests demonstrate that the main structure remains undamaged during an 8-degree earthquake; they possess good thermal insulation properties that meet building energy-saving standards; the wall thickness is about half that of traditional structures, increasing the net interior area by more than 10%, with a self-weight of approximately one-third that of traditional brick-concrete structures; most materials are recyclable and can be reused in a circular economy; the construction process is environmentally friendly and energy-saving, with low noise, dry construction methods, and only 10% of the water usage required for traditional construction methods.

Prefabricated lightweight steel-lightweight concrete structures, belonging to the category of lightweight steel-lightweight concrete composite shear wall structures, feature the assembly of light steel frames and non-removable formwork, with in-situ casting of polystyrene particle concrete for the walls, resulting in good overall wall integrity. Prefab lightweight steel-lightweight concrete structures: full-scale seismic tests on the structures show that the main structure remains undamaged during an 8-degree earthquake; the steel usage is only 25-35 kg/m²; compared to conventional reinforced concrete construction, they save 30% on labor, 25% on water usage, 35% on electricity, reduce the construction period by 30%, and cut down on wood consumption and construction waste by more than 50%.

2.2 Technical Standards

Prefabricated cold-formed thin-walled steel structures: 1) Abroad: The American Iron and Steel Institute (AISI) has developed a series of standards for the design and construction of cold-formed thin-walled steel structures, such as the Specification for the Design of Cold-Formed Steel Structural Members (AISI S100-16)[37], North American Standard for Seismic Design of Cold-Formed Steel Frame Structures (AISI S213-07)[38], Design and Construction of Load-Bearing Cold-Formed Steel Structural Framing (AISI S240-15)[39], and Specification for the Design of Cold-Formed Steel Structural Members for Seismic Applications (AISI S400-15)[40]. These series of standards provide systematic regulations on steel material, section selection, force on plates and bars, structural assembly, and connection details, and have partially revised and updated the design of component stability, fatigue performance, and seismic structural systems. The design methods integrate the Allowable Stress Design, Limit State Design, and Load Resistance Factor Design methods, explaining the seismic design requirements for new types of cold-formed thin-walled steel-structural panel composite wall panels and cold-formed steel frames, and regulating the seismic performance test methods for new structural components.

Prefabricated lightweight steel-lightweight concrete structures: The national industry standard "Technical Specification for Lightweight Steel-Lightweight Concrete Structures" (JGJ 383-2015)[41] has been established, stipulating that this structural system is mainly applicable to areas with a seismic fortification intensity of 8 degrees (0.2g) and below, not exceeding 6 stories and not more than 20m in height for standard fortification class buildings. It also provides technical regulations on the use of materials, structural design, and construction acceptance for lightweight steel-lightweight concrete structures, and puts forward technical requirements for the structural measures of shear walls, floor slabs, and beams and columns.

Prefabricated lightweight steel composite frame-lightweight steel composite shear wall structures: The Beijing local standard "Technical Standard for Prefabricated Low-Rise Residential Light Steel Frame-Composite Wall Structures" (DB11/T 1873-2021)[42] has been established, stipulating that this structural system is mainly applicable to areas with a seismic fortification intensity of 8 degrees and below, with a story height not exceeding 4m and an eave height not exceeding 10m for 1-3 story prefabricated low-rise residential buildings. It also provides technical regulations on materials, structural design, construction, and quality acceptance, and defines terms such as composite walls, short-leg composite walls, light steel truss lightweight concrete shear wall panels, and light steel frame concrete thin-slab sandwiched polystyrene shear wall panels.

3 Current Status of Prefabricated Light Steel Structure Applications

Due to the inherent technical advantages of lightweight steel structures and prefabricated steel structures, they positively impact projects in both the design-construction phase and the building's service life, particularly in environmental protection, cost control, and enhancement of structural safety performance. Therefore, in the future development of steel structure construction, lightweight, prefabricated, and energy-saving principles are gradually becoming the main directions. At the same time, these technologies will continue to be optimized and improved to fully leverage their technical advantages and address existing technical application issues. Additionally, the Chinese government has provided ample and favorable policy support for the development of lightweight steel structures and prefabricated steel structures, with related technical specifications and standards continuously being refined and improved. As a result, the application field of steel structure technology in China is also in a process of constant improvement. The regulation of technical management and technical standards has also played a role in promoting the healthy development of related industries.

The development of prefabricated lightweight steel composite structure systems largely depends on the advancement of industrial construction technologies. China has numerous industrialized production bases for prefabricated lightweight steel composite structure components, such as Beijing New House Co., Ltd., Hefei Guorui Integrated Building Technology Co., Ltd., Tangshan Ji dong Development Integrated Housing Co., Ltd., and Hebei Jing tong Building Technology Co., Ltd.

4 Future Research Prospects

4.1 Challenges Faced

This paper synthesizes recent domestic and international literature on the research of lightweight steel composite structure systems, categorizing them into three types based on their structural composition: cold-formed thin-walled structures, lightweight steel-lightweight concrete structures, and lightweight steel composite frames-lightweight steel composite shear wall structures, and elaborates on the structural characteristics and technical standards of each system.

With the continuous deepening of research worldwide, many connection methods with good load-bearing and force-transfer performance, as well as structural systems that meet architectural demands, have been developed. However, research on prefabricated construction for mid-to-high-rise buildings is still not comprehensive and faces challenges.

(1) Structural Systems: Expand the prefabricated lightweight steel composite structure systems and develop prefabricated lightweight steel hybrid structures by rationally matching light steel components, light steel composite components, and reinforced concrete components. For example, the development of prefabricated light steel composite frames - concrete shear wall structures can break through the limitation of light steel composite structures being mainly applicable to buildings of 6 stories and below, extending their application to buildings of up to 9 stories.

(2) joint Connections: Some scholars have proposed prefabricated light steel composite frame joints with double L-shaped members and diagonal stiffening ribs, and π-shaped joints, which have superior seismic performance compared to traditional joints. Further research and development of new high-performance light steel composite structure component connections are still needed.

(3) Ecological Components: The rational application of ecological and environmentally friendly building materials such as recycled concrete, slag, plant fiber panels, bamboo, and small-diameter timber in the production of independent foundations, foundation connecting beams, floor slabs, external wall panels, and internal infill wall panels of prefabricated light steel composite structures, and the study of their performance, are demands of green building development.

(4) Green Construction: Prefab lightweight steel composite structures should possess the core characteristics of architectural industrialization, namely, standardization of building design, factory production of components, assembly construction, integrated decoration, and information-based management. The integration of structural systems, external envelope systems, equipment and pipeline systems, and internal fitting systems should be gradually realized. Currently, the production bases for prefabricated light steel composite structure components are still few and large enterprises, with overall insufficient investment in research and development, leaving considerable room for development.

(5) Overcoming Drawbacks: Cost issues are a concern as users often compare the cost of light steel composite structures with brick-concrete structures without comparing their thermal performance and seismic performance. The hollow sound when knocking on light steel keel composite wall panels leads some users to mistakenly believe they are unsafe. Improving wall panel construction and optimizing the structural system to make the cost-performance ratio more reasonable requires further in-depth research.

4.1 Outlook

Prefabricated light steel structure residences possess numerous advantages, but their practical application must be improved to meet the needs of rural residents. Currently, low- and multi-story buildings are primarily located in rural towns, accounting for approximately 50% of the national construction area. Over 90% of rural town houses have extremely poor seismic performance, poor energy efficiency, and severe resource waste and environmental pollution during construction. This situation is highly incompatible with the development goals of achieving "national urban-rural integration" and "beautiful rural construction" strategies. It involves significant livelihood and resource issues related to architectural disaster prevention and mitigation, energy saving and emission reduction, environmental protection, and sustainable development. The research and development of prefabricated light steel composite structure seismic energy-saving systems and industrialized technology meet the demands of ultra-low energy consumption and green construction. They are instrumental in leading the technological development of low- and multi-story prefabricated buildings and offer significant social, economic, environmental, and ecological benefits, with vast application potential and promotion value.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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