Asia Pacific Science Press

Journal of Advances in Engineering and Technology
ISSN(O):3005-7507
ISSN(P):3005-7493
Vol. 2 No.4 (2025)

A Review of Research on the Development and Application of Modular Steel Structures

Chunyang Hu, Siqi Li, Yibing Wang, Zijing Song, Chunhao Wang*

The College of Architecture and Civil Engineering, Beijing University of Technology, Beijing, 100124

Corresponding Author: Chunhao Wang, wangchunhao@emails.bjut.edu.cn

Abstract: Modular steel structures combine the advantages of industrialized production and green construction, emerging as a key driver for the transformation of the construction industry. This paper focuses on summarizing existing research on inter-module connection technologies, primarily covering three aspects. It introduces the concept and characteristics of modular steel structures, analyzing their research and application status both domestically and internationally. This research emphasizes the current state of research on connection nodes between modules in modular steel structures, summarizing the technical features and existing issues of the two mainstream connection methods: bolted connections and plug-in connections. It analyzes the development trends and challenges facing modular steel structures in areas such as assembly devices, connection technologies, and intelligent management systems.

Keywords: Modular Steel Structures; Connection Nodes; Intelligent Management and Control

Published: Oct 26, 2025

DOI: https://doi.org/10.62177/jaet.v2i4.844

1.Overview of the development and application of modular steel structures

Modular steel structures represent an advanced construction system evolved through prefabrication technology in the building industry. Leveraging steel's lightweight, high-strength, and easy-to-assemble properties, this approach deconstructs functional spaces into standardized modular units. Structural fabrication, MEP integration, and interior pre-installation are completed in factories before transporting these units to sites for on-site assembly into complete buildings. Modular steel structures offer dual advantages of industrialized production and green construction. Their distinct benefits—enhancing project quality, shortening construction cycles, enabling recyclability, and reducing construction pollution—align with global trends toward new building industrialization and sustainable architecture. They have become a key driver in transforming the construction industry(Zhu et al., 2022; Wang et al., 2020; Hou & Liu, 2021). Existing engineering practices demonstrate that modular steel structures can reduce on-site labor by over 60%, cut construction waste by more than 90%, lower carbon emissions by 50% to 60% compared to traditional cast-in-place buildings, and shorten construction cycles by 30% to 50%(Wang et al., 2020; Peng et al., 2020). Since its inception, the concept of modular steel structures has evolved through years of research and application, crystallizing into three critical components: standardized design of modular units, development of reliable inter-module connection nodes, and end-to-end intelligent process control. In recent years, driven by the advancement of prefabricated building policies and the continuous upgrading of industrialized construction demands, its application scenarios have expanded from early-stage temporary structures and low-rise residential buildings to high-rise residential buildings, large public buildings, commercial complexes, and other fields. This has formed a diversified landscape covering low-rise to high-rise structures, temporary to permanent buildings, and single-function to multi-functional facilities(Hou & Liu, 2021; Yang et al., 2016). Currently, despite multidimensional research and practical achievements domestically and internationally, modular steel structures still face technical challenges such as optimizing lateral stiffness for super-high-rise buildings and ensuring joint performance under extreme conditions. Additionally, industrial issues like insufficient cross-enterprise standard coordination and difficulties in controlling full-lifecycle costs require technological innovation and industrial collaboration to drive high-quality development(Ding et al., 2019).

1.1 Current status of domestic research and development

The development of modular steel structures in China can be divided into four stages: technology introduction, independent R&D, engineering demonstration, and large-scale promotion. Dual drivers of policy guidance and market demand have been the core forces propelling industry breakthroughs(Wang et al., 2020; Hou & Liu, 2021). In the early 21st century, domestic modular construction practices primarily relied on technology imports, with applications concentrated in temporary buildings and small-scale low-rise projects. For instance, temporary office buildings employed simple steel structural module assembly schemes. While achieving rapid delivery, these approaches revealed technical shortcomings such as insufficient module connection rigidity and low functional integration(Huang et al., 2022). Following the 2016 issuance of the "Guiding Opinions on Vigorously Developing Prefabricated Buildings," the industry entered a phase of standardized development. Policies explicitly designated modular steel structures as a key development direction for prefabricated construction, setting a target for modular buildings to account for no less than 15% of total prefabricated construction by 2025(Wang et al., 2020).

Against this policy backdrop, domestic research institutions and enterprises have undertaken systematic research on core modular steel structure technologies. Regarding structural system innovation, Hou et al. proposed that module dimensions should follow the 3M modular system through standardized design of fully prefabricated modules and compatibility analysis with lateral force resistance systems, enabling the development of multiple composite load-bearing systems(Hou et al., 2023). The modular steel frame and core tube composite system, validated through a 15-story test building, demonstrated a 40% reduction in lateral displacement under horizontal loads compared to purely modular systems, with mechanical performance meeting the requirements of JGJ 3-2010 "Technical Specifications for Steel Structures of High-Rise Civil Buildings"(Wang et al., 2020). Additionally, Liu Xuechun's team proposed a box-type modular prefabricated steel structure system. By optimizing beam-column joint parameters, the system enhances joint load-bearing capacity and seismic performance, achieving a ductility coefficient exceeding 3.31. This meets current seismic design requirements(Liu et al., 2018), providing core technological support for advancing China's modular steel structures from low-rise temporary buildings to mid-to-high-rise permanent structures.

In terms of node technology breakthroughs, limitations of traditional welded nodes have been overcome through the development of novel connection forms such as self-positioning grout sleeve nodes, semi-rigid bolted nodes, and prefabricated diagonal brace nodes. Among these, the semi-rigid bolted node has been validated through 2 million fatigue cycles, achieving a fatigue strength of 120 MPa, thereby meeting the structural demands of high-rise and long-span modular buildings(Ding et al., 2019). Wang Yongrui's novel in-column bolted node (IBC node) demonstrated excellent load-bearing capacity under gravity loads through full-scale testing. Failure primarily occurred at beam or module internal nodes, with no significant damage observed at inter-module nodes. Diagonal bracing significantly enhanced node stiffness and load-carrying capacity(Wang, 2020). The cross-plate-end-plate connection node proposed by Wang Qinglin et al. exhibited a failure mode characterized by plastic hinges forming at beam ends during testing. Increasing the height of roof beams and floor beams significantly enhances the node's flexural capacity, initial stiffness, and ductility coefficient(Wang et al., 2020). This ensures the structural integrity and safety of modular steel structures in high-rise, long-span, and seismic-resistant regions, providing critical technical support for the engineering implementation and application expansion of modular steel structures.

In the integration of smart construction, a full lifecycle management platform is established by combining BIM (Building Information Modeling), IoT, and digital twin technologies. For modular housing projects, BIM models enable digital prefabrication of components, construction progress simulation, and on-site installation guidance, effectively reducing wet operations at the construction site while enhancing design efficiency and construction precision. Pan et al. applied BIM technology to the design and construction of prefabricated steel structures. Through BIM modeling, they achieved digital prefabrication of components, simulated construction progress, and provided on-site installation guidance. This approach effectively reduced wet operations at the construction site while improving design efficiency and construction precision(Pan et al., 2023).

In engineering practice, China has established a multi-scenario application framework covering residential, public, and commercial buildings. In the residential sector, Yang Xiaojie et al. designed a box-type steel modular residential building exceeding 15 stories using standardized steel frame modules. Structural, MEP, and interior finishes were prefabricated as integrated units in the factory. On-site assembly was completed via bolted connections, reducing the main structure construction period to just 18 months—a 45% reduction compared to traditional methods. The structure met seismic design requirements for a 7-degree intensity(Yang et al., 2016), validating the feasibility of high-rise modular steel structures in residential buildings. The standardized module design provides a technical reference for future large-scale implementation. The Shenzhen Huazhang New Construction affordable housing project further enhanced module integration by fully pre-installing kitchens and bathrooms within modules. Post-delivery, only basic soft furnishings are required for occupancy, realizing turnkey modular housing. Li leveraged BIM technology to develop a novel composite exterior wall panel system. This design features a fully three-dimensional adjustable connection system that reduces installation complexity. Simultaneously, ANSYS software optimized the thermal performance of the wall panels, while Fuzor-Construction software enabled virtual construction, visually demonstrating the entire process from factory production to installation(Li, 2019). This work laid a practical foundation for the technical maturity and large-scale application of modular steel structures in residential construction.

In the public building sector, the Kaili Hotel project within the Xiong'an Civic Service Center employed large-scale steel structural modules. Through modular assembly, it achieved multifunctional spatial layouts encompassing guest rooms, conference halls, and restaurants, with an assembly rate reaching 92%. The project progressed from groundbreaking to operation in just 120 days, setting a record for the fastest modular construction of a large-scale public building(Wen et al., 2021) and providing a solution for flexible spatial planning in multifunctional public structures. Beijing's Xicheng District Emergency School Capacity Project employed lightweight steel modules to construct three teaching buildings within three months without disrupting surrounding traffic or residents' lives, effectively alleviating regional school capacity shortages(Wen et al., 2021). Wuhan Leishenshan Hospital stands as a quintessential example of prefabricated steel modular construction. Through standardized design, industrialized production, and assembly-based construction, this infectious disease hospital was completed in just 12 days. Its design and construction integrated advanced concepts across structural systems, exterior envelope systems, mechanical/electrical/plumbing systems, and interior finishing systems(Peng et al., 2020), enabling rapid response in emergencies and establishing a paradigm for similar emergency projects.

In the commercial sector, the Shenzhen Bay International Convention and Exhibition Center's supporting hotel project adopted the ME-House modular system. Modules integrated photovoltaic panels and high-efficiency insulation layers, achieving an 83% building energy savings rate and reducing annual carbon emissions by approximately 500 tons, establishing it as a benchmark for green modular construction(Wen et al., 2021).

Current development of modular steel structures in China still faces three challenges: 1) Insufficient industry standardization, with significant variations in module dimensions and interface formats across different enterprises(Zhai et al., 2022); 2) Significant cost control difficulties, as initial investment in modular construction exceeds traditional methods primarily due to additional expenditures on mold development and high-precision manufacturing, necessitating cost reduction through scaled production and technological optimization; 3) Incomplete design theoretical frameworks, with existing codes lacking targeted provisions for calculating thermal stresses and overall stability in modular steel structures(Ding et al., 2019).

1.2 Current status of international research and development

The development of modular steel structures began relatively early overseas. Countries and regions such as the United States, Japan, and Europe have established mature technical systems, standards, and industrial ecosystems, exhibiting differentiated development characteristics based on regional demand variations(Huang et al., 2022; Ye & Yu, 2019). The United States has pursued a development path centered on market-driven forces and standardized construction, with innovations in modular structural design technology providing critical support for this approach. Zhang et al. proposed an evolutionary optimization method to enhance the design efficiency and standardization of modular structures composed of predefined building blocks, thereby better aligning with market expansion requirements(Zhang et al., 2025).

In the United States, modular steel structures find their most extensive application in the residential sector. The Brooklyn Modular Apartments project in New York utilized cold-formed thin-walled steel modular units, achieving rapid on-site assembly through fully bolted connections. The project comprised 280 apartments with a total construction period of only 8 months—a 60% reduction compared to traditional methods. Construction waste decreased by 85%, and the building's seismic performance met the requirements of ASCE 7-16 Seismic Design Code for Buildings at Seismic Intensity 9, providing technical support for accelerated construction. In commercial construction, the United States leads in modular building digitalization. Its developed digital module platform enables data coordination across module design, production, and construction. The module production process is monitored in real-time via the Internet of Things, achieving a product qualification rate of 99.5%(Huang et al., 2022). This provides a critical practical reference for global technical standardization and cross-scenario promotion of modular steel structures.

Japan focuses on technical refinement and seismic performance optimization. Influenced by its earthquake-prone environment, it invests heavily in R&D for seismic design and node innovation in modular steel structures. Its research direction aligns closely with international advanced seismic technologies. The novel swing-type connection node developed by Sharafi et al., specifically designed for high-performance prefabricated modular building systems, significantly enhances structural seismic performance, providing a technical reference for Japan's node innovation(Sharafi et al., 2025). The 1972 Bank of Japan Capsule Building, designed by Kisho Kurokawa, stands as the world's first box-type steel modular structure. It employs detachable steel capsule modules connected via flexible bolted joints, allowing relative displacement between modules to dissipate seismic energy during earthquakes. After over 50 years of service, the structure maintains excellent performance(Huang et al., 2022), with its flexible joint design offering seismic resistance insights for modular buildings in earthquake-prone regions.

Europe prioritizes green and sustainable development. The EU funds modular building technology R&D through Horizon 2020 and Horizon Europe programs, focusing on breakthroughs in energy-efficient modules, recyclable modules, and low-carbon construction techniques. Jin J Y et al.'s exploration of EPS-module steel structure energy-saving systems in industrial construction also provides references for energy-saving technology development in this field(Jin et al., 2013). The Munich Modular School project in Germany employs a steel-framed modular system where each unit integrates photovoltaic panels, high-efficiency insulation, and fresh air systems. Building energy consumption is reduced by 70% compared to conventional structures, with annual electricity generation meeting 30% of the building's demand. Modules are bolted together, achieving an 80% recycling rate after dismantling and enabling full lifecycle circularity(Huang et al., 2022), offering a reference for greening educational buildings. The Rotterdam Modular Apartments project in the Netherlands employs removable steel modules with no on-site welding—all connections are bolted. This facilitates future layout adjustments or demolition/reconstruction while minimizing construction waste(Huang et al., 2022). It achieves low-carbon, eco-friendly, and resource-efficient utilization throughout the modular steel structure's lifecycle, offering a technical pathway and engineering paradigm for the green transformation of global modular buildings in education, housing, and other sectors.

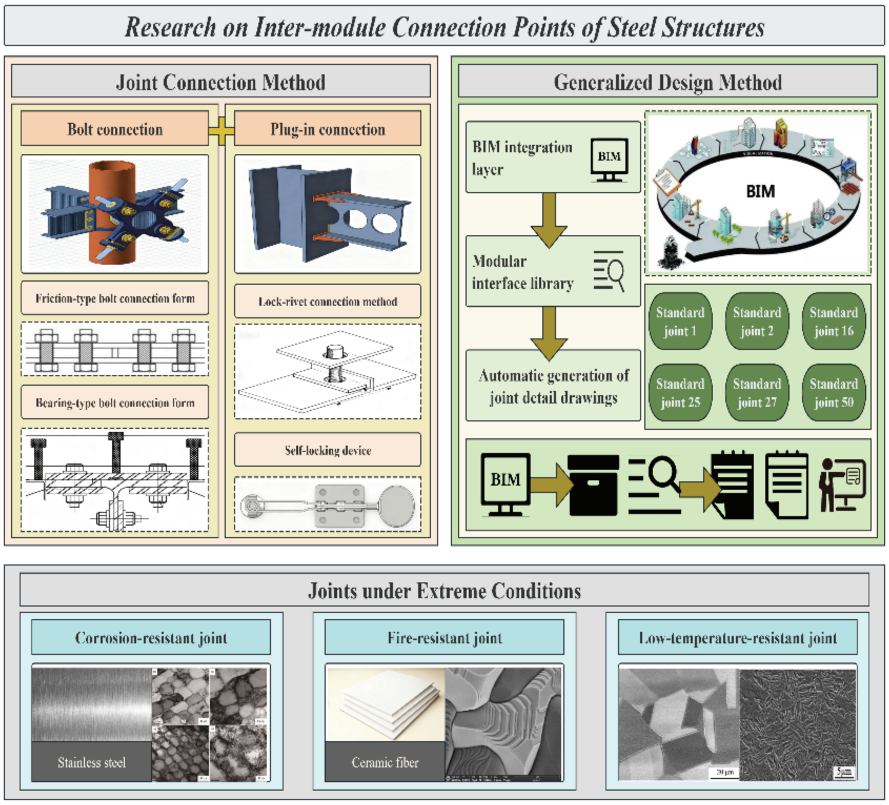
The UK excels in intelligent and digital aspects of modular construction. Xiong et al. investigated the seismic performance of fully assembled bolted concrete modular structures through full-scale shake table tests, providing structural safety references for modular buildings(Ref 20). Furthermore, Ly et al. developed a life-cycle assessment-based framework for allocating module impacts during adaptive reuse of modular buildings. This framework can integrate with technologies like BIM and digital twins, incorporating them into the digital management system for the entire life cycle of modular buildings, thereby further enriching the UK's technical practices in this field(Ly et al., 2025).

Currently, numerous foreign countries have transitioned from specialized industrialized systems to large-scale universal systems. Centered on standardized, serialized, and universal building components and parts, these systems leverage specialized production of steel structures as the carrier for modern building systems and modern portable buildings in many nations. They draw upon the industrialization of steel structures and modular construction to achieve the modernization of the housing industry through production and commercialized supply(Li, 2019; Ye & Yu, 2019). The shared advantages of modularization represent the construction approach sought by countries worldwide.

2.Research status on connection nodes between modules in modular steel structures

The connection nodes between modular steel building components are critical to the overall structural safety and stability. Their core function is to achieve effective force transfer between modules, rapid installation, and coordinated structural performance through a universal design approach. This chapter primarily focuses on connection methods, universal design methodologies, and node performance under extreme conditions, as illustrated in Figure 1.

Fig. 1 Study on connection points between steel structure modules



2.1 Node connection methods

In the field of modular steel structures, the method of connecting nodes between modules is critical, as it directly impacts the performance of the entire building structure and the efficiency of the construction process. Among the numerous connection methods currently available, the mainstream approaches fall into two categories: bolted connections and plug-in connections. Different connection methods cater to distinct application scenarios and requirements.

2.1.1 Bolted connection

In steel structural connection systems, bolted connections serve as the primary joint configuration for nodes, with their connection mechanisms directly influencing the overall structural performance(Liu, 2025). From a force-bearing perspective, bolted connections are primarily categorized into friction-type and bearing-type. Friction-type bolted connections primarily rely on the friction force generated by bolt preload to resist shear loads, making them suitable for structural scenarios with frequently fluctuating loads. Bearing-type bolted connections permit minor slippage at the connection interface, with the bolt shank itself directly bearing shear or axial forces. When node constraints are less stringent, this type offers greater advantages in terms of economy and construction flexibility. Chen et al. (Chen et al., 2024) summarized existing friction surface treatment methods for friction-type bolted connections, which involve first removing the oxide film from the steel surface and then enhancing the slip resistance coefficient by increasing surface roughness or modifying the material properties of the friction pair. Chen et al. (Chen et al., 2004) conducted slip resistance coefficient studies on high-strength bolted connections where contact surfaces were coated with either alkyd iron oxide paint or polyurethane zinc-rich paint, proposing corresponding slip resistance coefficient values for these primers. Liu et al. (Liu et al., 2009) achieved a slip resistance coefficient of 0.413 on friction surfaces treated with sandblasting. Wang et al. (Wang et al., 2005) analyzed slip resistance coefficients for high-strength bolted connections treated with zinc coating followed by paint application. Their results indicated a slip resistance coefficient of 0.45 for such zinc-coated surfaces. Chen et al. (Chen et al., 2021) conducted tests on high-strength steel bolt connections with arc-sprayed aluminum contact surfaces. Results indicated that load-induced preload loss in Grade 10.9 high-strength bolts could exceed 10%. The slip resistance coefficient of contact surfaces treated with arc-sprayed aluminum reached 0.71. Currently, there is limited literature on bearing-type bolt connection configurations. In practical engineering applications, different types of bolted connections are typically selected flexibly. This choice is based on factors such as the specific function of the structure, the characteristics of the load, and the specific conditions of construction, to ensure that the structural logic and mechanical performance achieve a coordinated and consistent effect.

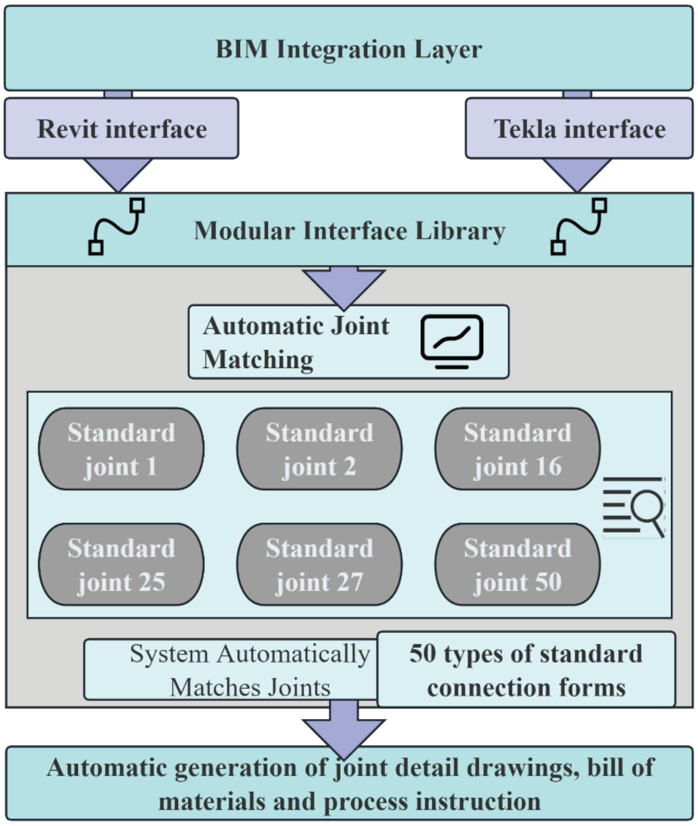
2.1.2 Plug-in connection

Plug-in connections employ a modular interface design, enabling rapid assembly and module fixation through lock-rivet connections or self-locking mechanisms. Liu (Liu, 2020) proposed utilizing light steel plug-in construction for rapid erection of new temporary structures. Song et al. (Song et al., 2020) introduced lock rivet connections for component assembly, demonstrating superior bending capacity, stiffness, and ductility compared to self-tapping screw connections, with particularly notable advantages in bending stiffness. Xu et al. (Xu et al., 2024) proposed a novel fully assembled modular steel structure insert connection node with additional energy dissipation to promote the application of integrated steel modules in high-rise buildings and seismic-resistant zones. The node employs T-shaped connectors instead of traditional welded connections to achieve full assembly of module units, with relative sliding between the connectors and friction plates providing additional energy dissipation. Dai (Dai, 2021) developed a modular steel structure insert self-locking node. The team designed an insert connector with self-locking and unlocking functionality, enabling rigid connection between upper and lower module columns. Wang (Wang, 2023) designed a novel self-locking modular steel structural node with an internal insert. The connection between upper and lower module columns primarily relies on the self-locking action between the insert and the fixed ring plate. The team investigated the node’s tensile and bending resistance, performed stiffness classification for this novel self-locking node, and derived its moment-rotation relationship formula using the approximation method.

2.2 Generalized design methodology

The modular steel structure universal design methodology adheres to principles of function-oriented design with dimensional normalization, component reuse and standardization, and unified interfaces with compatibility. It focuses on standardizing module units, universalizing core components, standardizing interfaces and piping systems, and optimizing production and transportation compatibility. Through BIM simulation, pilot testing, and standardized documentation output for validation and refinement, this approach ultimately enables module sharing and rapid assembly across diverse projects. Modular projects face significant node performance variability due to differing steel strengths and load requirements. Generic design addresses this by standardizing node construction and employing parametric adaptation techniques, enabling a single node to serve multiple scenarios. Core strategies include strength-graded design, establishing a modular interface library, and performance-adjustable techniques. First, strength grading is established according to GB 50017-2017 “Code for Design of Steel Structures”(Ministry & Urban-Rural, 2017), such as classifying nodes into five categories (A to E) based on seismic resistance levels, with each category corresponding to different bolt quantities, plate thicknesses, and weld grades. A seismic resistance system for nodes is established based on the code. Subsequently, a modular interface library encompassing 50 standard connection types is developed. This library enables automatic matching of project parameters with Revit and Tekla interfaces via the BIM platform. Finally, node detail drawings, material lists, and fabrication instructions are automatically generated, as shown in Figure 2.

Fig. 2 Node matching diagram



2.3 Performance research under extreme conditions

The reliability of modular steel structure joints under extreme loads is a key factor limiting their widespread adoption. Recent research has focused on the following areas: First, regarding corrosion resistance, Wang et al. (Wang et al., 2025) proposed a stainless steel ring-groove rivet. This rivet combines the superior properties of stainless steel, such as high corrosion resistance, with the advantage of high structural reliability. It holds broad application prospects in corrosion-resistant structural connections for aluminum alloys and stainless steel, as well as in large-span spaces, building facades, and scientific installations. Regarding fire resistance, the high-temperature softening of steel poses a significant challenge. The European standard EN 1993-1-2 requires a fire resistance rating of ≥90 minutes for joints. The development of ceramic fiber-wrapped joints(Wang et al., 2022; Kong, 2013; Liu, 2012; Yao, 2006) has become the primary method for enhancing joint fire resistance. Some ceramic fiber-wrapped joints can increase load-bearing capacity retention from 35% to 70% under 600°C conditions. Low-temperature toughness of joints is equally critical. It directly determines the safety threshold of steel structural joints in cold regions or low-temperature environments and serves as a core indicator for preventing brittle fracture. Since steel modular buildings are less commonly applied in low-temperature and cold regions, research on the low-temperature toughness of steel joints remains limited. This represents one of the key areas requiring future research investment.

3.Issues and analysis regarding connections between existing modules

Modular steel structures offer significant advantages in industrialized construction and efficient building processes. However, the connections between modules remain a critical bottleneck constraining overall performance and widespread adoption. Current research and engineering practice reveal widespread issues such as low on-site module assembly efficiency, insufficient installation precision, poor recyclability of joints, and the absence of health monitoring systems. These problems not only impact construction progress and safety but also hinder the sustainable development of buildings throughout their entire lifecycle. To address these bottlenecks, a systematic analysis across multiple dimensions—including assembly techniques, node design, material recycling, and intelligent monitoring—is required. This approach will provide the theoretical foundation and technical support for subsequent optimization of assembly devices and research into green connection technologies.

3.1 Challenges of on-site splicing

Modular steel structures face numerous technical and management challenges during on-site assembly. Due to the large dimensions of individual modules, complex interfaces, and variable construction environments, on-site assembly efficiency is generally low. Ensuring high-precision alignment between modules is difficult, leading to installation deviations and cumulative errors that compromise overall structural stability and safety. Furthermore, on-site assembly is often constrained by limited lifting space, equipment precision, and the technical proficiency of construction personnel, resulting in complex operations and high coordination difficulties. Enhancing assembly speed while maintaining installation accuracy has become a critical bottleneck hindering the widespread adoption of modular steel structures. Consequently, research and practice are increasingly focused on developing efficient auxiliary assembly devices, intelligent positioning technologies, and standardized assembly systems to improve construction efficiency and quality.

3.1.1 On-site splicing efficiency is low

Modular steel structures commonly suffer from low construction efficiency during on-site assembly, primarily due to: 1) insufficient standardization of modules leading to poor interface compatibility; 2) complex coordination of on-site work sequences; 3) high dependence on specialized equipment; and 4) environmental constraints affecting lifting and positioning accuracy(Li et al., 2017). Furthermore, the absence of systematic assembly processes and collaborative management prolongs construction cycles and increases rework rates. Research indicates that establishing standardized and serialized modular systems, coupled with the integration of BIM technology and laser scanning positioning equipment during construction, can significantly enhance assembly precision and reduce construction cycles by approximately 20%–50%(McKinsey & Company, 2019). Simultaneously, adopting dry or bolted connection methods reduces welding operations, improving on-site operational safety and repeatability(Chong et al., 2016). Looking ahead, integrating digital twin technology with 5G communication to enable real-time monitoring and data feedback during modular construction will become a key direction for enhancing assembly efficiency and resource utilization(Lu et al., 2021). Therefore, improving the efficiency of steel structure modular assembly requires coordinated advancement across three dimensions: standardized design, intelligent equipment, and lean construction.

3.1.2 Difficulties in performing combined operations across multiple modules

During multi-module collaborative installation, cumulative errors are the primary factors affecting the overall stability and assembly accuracy of steel modular buildings. Such errors typically originate from dimensional deviations and orientation errors during module manufacturing, transportation, and on-site hoisting. Their cumulative effect is amplified during installation, leading to structural misalignment, uneven load distribution at connections, and localized stress concentration(Wang et al., 2019). To minimize error propagation, strict control of component machining accuracy is required during manufacturing. Anti-deformation reinforcement measures should be implemented during transportation, and high-precision measurement and positioning verification must be conducted prior to assembly(Zhao et al., 2019). On-site, integrating laser scanning, total stations, and BIM 3D models enables millimeter-level alignment control, significantly enhancing assembly precision and installation efficiency(Tang et al., 2010). Furthermore, real-time monitoring and data analysis systems enable automatic identification and correction of installation deviations, thereby enhancing safety and reliability during multi-module assembly. With the advancement of artificial intelligence, the Internet of Things, and digital twin technologies, future modular steel structure installations will achieve intelligent precision control and full-process traceability, providing technological support for the high-quality development of prefabricated buildings(Lu et al., 2021).

3.2 Recyclability issues

Modular construction of steel structures should adhere to principles of environmental protection, health, safety, and energy conservation. Through systematic material selection and design, it aims to reduce environmental pollution, enhance structural safety, and lower energy consumption. However, research on the recyclability of connection nodes between modules currently lags significantly behind the overall development of structural systems. The constraints primarily manifest in three aspects:

irreversible material damage, structural failure thresholds, and technical-economic compatibility(Gorgolewski, 2008). Regarding materials, welded and bolted connections under cyclic loading are prone to crack propagation and localized tearing, leading to rapid degradation of node load-bearing capacity(Ding et al., 2016). Structurally, hole aspect ratio, plate thickness, and bolt arrangement significantly impact node durability; improper design reduces connection performance after repeated assembly and disassembly(Li et al., 2020). Technically and economically, the absence of performance evaluation systems and cost standards for reusable joints also hinders the development of sustainable construction systems. Future research should focus on the mechanical degradation patterns of demountable joints, strength recovery mechanisms of recycled materials, and life cycle assessment methodologies to provide theoretical support for greening and recycling in modular steel structures(Zhao et al., 2018).

3.3 Lack of health monitoring

The health monitoring system for modular steel structure joints remains in its infancy, facing critical bottlenecks such as high data dependency, environmental noise interference, and difficulties in identifying multiple damage types(Farrar & Worden, 2013). While existing research has made some progress along different technical pathways, overall issues of fragmentation and insufficient applicability persist. Acoustic-based methods enable early damage detection by analyzing the time-frequency characteristics of bolt loosening sounds. However, they heavily rely on manual feature extraction and noise filtering, making stable quantitative diagnosis challenging(Zhang et al., 2021). Structure-response-based monitoring methods (e.g., acceleration and strain signals) can utilize convolutional neural networks to extract damage features, but their performance is constrained by sample size and operational diversity(Teng et al., 2022). Computer vision technologies like YOLO and Mask R-CNN demonstrate strong automatic recognition capabilities in bolt condition detection, yet false detection rates remain high due to factors like lighting, weather, and occlusion(Ref 54). In summary, there is currently a lack of integrated monitoring systems that fuse multi-source sensor data while offering environmental robustness and low data dependency. Future research should focus on developing multimodal sensor fusion and digital twin-driven self-learning diagnostic models to achieve adaptive structural health monitoring and full-lifecycle management under complex operating conditions.

4.Future research trends and outlook

Driven by China's intensifying policies for prefabricated construction and the "dual carbon" goals, the market for modular steel structures will achieve steady growth with continuously optimized application frameworks. As a vital component of prefabricated building development, modular steel structures urgently require advanced technologies and methodologies to achieve modernization. Looking ahead to future green construction demands, and considering current research, application status, and development trends both domestically and internationally, the following areas warrant focused attention in research and application advancement. Progress in modular steel structure construction can be gradually enhanced through the development of auxiliary joining devices, upgraded connection techniques, and the creation of intelligent management systems.

4.1 Auxiliary joining devices for module connections

Traditional steel structures face challenges during assembly, including difficulties in achieving stable fixation, susceptibility to assembly errors, and inherent risks in the joining process. Existing auxiliary devices are bulky, making them impractical for on-site operations with small steel structures. Their cumbersome mobility results in low splicing efficiency and operational difficulties for small steel components. Therefore, researching auxiliary splicing devices for small steel structures represents a crucial trend in modular steel construction, holding significant scientific and engineering value.

4.2 Green connection technologies between modules

4.2.1 Demountable design

Current modular steel structure joints predominantly employ permanent connection methods. Disassembly often causes component damage, hindering material recycling. Traditional welded joints undergo high-temperature cutting during demolition, altering the metallographic structure of steel and degrading its mechanical properties. Some bolted joints experience low bolt reuse rates post-disassembly due to long-term corrosion or preload decay. Additionally, existing removable joint designs suffer from complex construction and high costs. Furthermore, the absence of unified evaluation standards for demountable joints leads to significant variations in disassembly efficiency and material recovery rates across projects, hindering the green and circular development of modular steel structures. Therefore, developing low-cost, easily fabricatable, and reliable demountable joints while establishing a comprehensive recycling evaluation system represents a critical direction for advancing the sustainability of modular steel construction.

4.2.2 Low-carbon materials

Currently, modular steel structural nodes primarily rely on virgin steel, whose production process generates high carbon emissions, whereas recycled steel exhibits significantly lower carbon emissions. However, recycled steel has notable shortcomings in node applications: bolted joints made from recycled steel exhibit low tensile strength and reduced fatigue life. Concurrently, existing low-carbon materials lack sufficient adaptability for node connections. Furthermore, design codes and construction techniques for low-carbon material joints remain underdeveloped, with a lack of joint calculation models tailored to the mechanical properties of these materials, creating safety hazards in engineering applications. Therefore, enhancing recycled steel performance, developing novel low-carbon composite materials, and establishing design standards for low-carbon material joints are core pathways to reduce the carbon footprint of modular steel structures. How to utilize recycled steel in modular steel structure joints and fully replace virgin steel represents an urgent and promising future research direction.

4.3 Intelligent management of modular steel structures

Currently, intelligent management across the entire lifecycle—design, construction, and operation—remains inadequate, with significant data fragmentation. During design, BIM models struggle to integrate with other specialized software. In construction, while IoT monitoring devices are deployed, data processing efficiency is low, requiring manual analysis before adjustments can be made—failing to meet dynamic construction demands. During operation and maintenance, there is a lack of full lifecycle data tracking, resulting in low accuracy for node damage early warning. Furthermore, intelligent management systems exhibit poor compatibility, making it difficult for equipment and software from different manufacturers to work together. Therefore, establishing a cross-platform data interaction system, developing real-time intelligent analysis algorithms, and creating a full lifecycle data traceability system are key breakthrough points for achieving intelligent management of modular steel structures.

5.Conclusion

This study examines the current status, challenges, and development trends in the research and application of modular steel structures. Modular steel construction is emerging as a future trend in the building industry, yet the field still faces significant challenges. These include designing auxiliary joining devices suitable for small-scale steel modularization, developing new environmentally friendly and low-carbon steel materials, and advancing intelligent modular steel construction technologies. Therefore, we must advance steel modular construction into a new phase characterized by “future-oriented, fully renewable, and achieving negative carbon emissions” through the integration of material innovation and intelligent construction technologies.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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