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Behavior and sustainability benefits of modular steel buildings

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ABSTRACT

Modular steel buildings have gained significant attention in recent years due to their potential to offer efficient construction methods, improved performance, and enhanced sustainability in the built environment. Accordingly, this study aims to first perform a bibliometric analysis of current literature to identify key trends in the field, then discuss the existing findings in the literature, and finally conduct a critical sustainability assessment to place modular steel buildings within the context of the United Nations Sustainable Development Goals. It focuses on examining structural integrity, durability, and resistance to external forces, as well as evaluating the environmental impacts of modular construction compared to traditional building methods. The motivation behind this research comes from the increasing demand for sustainable construction practices, as well as the need for more efficient and cost-effective solutions in the construction industry. The findings of this study are expected to be of significant importance to both industry professionals and researchers, helping to drive further innovation in modular construction and support the adoption of more sustainable building practices.

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KEYWORDS
Modular construction; steel buildings; structural behaviour; sustainability; building performance

1. Introduction

The construction industry plays a pivotal role in shaping the built environment (Chen et al. 2024; Iwuanyanwu et al. 2024; Joensuu, Edelman, and Saari 2020; Li, Greenwood, and Kassem 2019). As a result, it has been undergoing a significant transformation towards more sustainable, efficient, and innovative building solutions (Abarkan et al. 2024; Ferdous et al. 2019; Rabi et al. 2024; Rabi, Abarkan, and Shamass 2024). Building construction significantly impacts natural resource consumption and environmental emissions (Elzokra et al. 2020; Yu et al. 2021). Traditionally, construction emphasises time, cost, and quality, but modern approaches prioritise reducing emissions and conserving resources (Kibert 2016; Rabi et al. 2023). In North America, buildings are major contributors to CO_2 emissions, leading to a growing interest in sustainable construction methods like hybrid cold-formed steel structures (Ferdous et al. 2019). Despite the advantages of hybrid cold-formed steel structural systems, such as their lightweight design and flexibility, they are still underutilised due to limited awareness of their potential benefits (Usefi et al. 2021). Modular construction, particularly using steel, has emerged as a promising approach to meet the increasing demand for efficient and sustainable building practices (Jammi and Sanjeevi 2021; Maxineasa et al. 2021; Youssef et al. 2016). Modular steel buildings are prefabricated offsite in controlled environments, which presents several environmental, economic, and social benefits, establishing it as an effective alternative to traditional on-site methods by means of allowing for faster construction times, reducing waste, and enhancing precision (Z. Chen, Liu, and Yu 2017; Kamali and Hewage 2016; Khan et al. 2023). Munmulla et al. (2022) emphasised the importance of event control, direct design, and indirect design approaches to ensure the robustness of modular buildings, with non-linear analyses revealing that interior column removal poses the most critical scenario due to high force redistribution and demand capacity ratios, while corner column removal generally caused the least disruption. Emamikoupaei et al. (2025) highlighted that modular building systems, constructed using prefabricated volumetric units, offer advantages such as faster assembly, reduced environmental impact, and improved quality control, with their stability heavily reliant on robust inter-module connections to resist gravitational, seismic, and extreme loads, as demonstrated through numerical and experimental analyses. Aye et al. (2012) revealed that a prefabricated steel system reduced material consumption by up to 78% compared to conventional concrete construction as well as offered up to 81% savings in embodied energy and 51% in materials. As a result, prefabricated steel systems have been recognised as an attractive option for addressing environmental concerns and the need for rapid urbanisation (Ferdous et al. 2019). The modular construction market is anticipated to grow at a compound annual growth rate of 5.69%, reaching a market value of $154.8 million by the end of 2023, driven by the increasing need for efficient construction methods and a shift from traditional stick-built processes (Abdul Nabi and El-Adaway 2020). In general, modular construction, particularly steel-based systems, is known for its ability to reduce construction time

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significantly while maintaining high levels of structural performance (Liew, Chua, and Dai 2019). The offsite fabrication process allows for better quality control and minimises on-site disturbances, making it an ideal solution for urban environments where construction activities can be disruptive (Ferdous et al. 2019). Additionally, steel's inherent properties, such as its high strength-to-weight ratio, recyclability, and durability, make it a preferred material in modular construction systems (Kamali and Hewage 2016). Previously, several studies have explored the structural performance of modular steel buildings, particularly in terms of their behaviour under different loading conditions. For instance, Chen, Liu, and Yu (2017) conducted an experimental study on interior connections in modular steel buildings and found that connection design plays a crucial role in the overall structural performance. Similarly, Fathieh and Mercan (2016) evaluated the seismic performance of modular steel buildings and highlighted the importance of connection detailing in enhancing the buildings' resilience to seismic loads. Annan (2008) and Annan, Youssef, and El Naggar (2009) further emphasised the need for comprehensive seismic vulnerability assessments of modular steel buildings, as traditional design procedures may not be entirely applicable to modular systems. Shi, Yin, and Hu (2018) investigated the performance of the prefabricated steel frame and concluded that it demonstrated excellent seismic performance, horizontal load-carrying capacity, and ductility during the full-scale cyclic loading tests. The frame maintained its strength without significant degradation, even at a large overall drift ratio of 7.69%. Lacey et al. (2019) reviewed the bolted inter-module connections in modular steel buildings and identified several areas where improvements could be made to enhance the structural response of modular buildings. Chua, Liew, and Pang (2020) developed models for connections and lateral behaviour in high-rise modular steel buildings, emphasising the need for robust connection designs to ensure the structural integrity of modular buildings under extreme loading conditions. The robustness of inter-module connections is also critical in scenarios where a column is lost, as demonstrated by Chua et al. (2022), who assessed the resilience of steel modular buildings under column loss scenarios. Another area of concern is the seismic performance of modular steel buildings. Nadeem et al. (2021) investigated the structural behaviour of intermodular connections (IMCs) in modular steel construction and pointed out the complexity of such systems, which depends on the connection types and rigidity. Alembagheri et al. (2020) further explored the collapse capacity of modular steel buildings under module loss scenarios and highlighted the critical role of inter-module connections in maintaining structural integrity during such events. In addition to structural performance, the sustainability of modular steel buildings has also attracted significant attention in recent years. Life cycle assessments are now widely utilised to measure environmental impacts, although they face challenges due to limited data availability (Cavalieri et al. 2023; Eckelman et al. 2018). Maxineasa et al. (2021) explored the environmental performances of cubic modular steel structures and found that modular construction can significantly reduce material waste and energy consumption, contributing to more sustainable building practices. Similarly, Kamali and Hewage (2016) conducted a critical review of the life cycle performance of modular buildings and highlighted the potential of modular construction to reduce greenhouse gas emissions and energy use, particularly in comparison to traditional construction methods. The recyclability of steel and the potential for reuse of modular components further enhance the sustainability profile of modular steel buildings (Liew, Chua, and Dai 2019). Accordingly, the ability of modular steel systems to reduce material waste, enhance energy efficiency, and promote resource-efficient construction practices aligns with the global push for more sustainable and resilient infrastructure (Iuorio et al. 2019). Currently, while the structural behaviour of modular steel buildings has been extensively studied, there is still a need for a comprehensive research on their sustainability benefits, particularly in relation to the United Nations Sustainable Development Goals (SDGs). Therefore, this study aims to conduct a bibliometric analysis of the existing literature sources to highlight major trends in this field, provide a discussion of the existing literature, and perform a critical sustainability assessment to place modular steel buildings in the context of the United Nations SDGs. By systematically analysing the sustainability and structural efficiency of modular steel systems, with a focus on high-strength steel applications, this research underscores the importance of robust inter-module connection designs and evaluates the life cycle performance of modular systems to advance understanding and promote the adoption of sustainable modular construction practices.

2. Bibliometric analysis

The bibliometric analysis of modular steel buildings was conducted using VOSviewer to provide an in-depth review of the research trends in this field. A total of 894 articles were identified from the Scopus database, providing a broad base of literature for analysis. These publications primarily focus on modular construction and its various aspects, such as structural performance, stiffness, and the application of the finite element method in design processes. The keyword occurrence analysis revealed several major themes that dominate the literature on modular steel buildings, as illustrated in Figure 1. Commonly used keywords include 'modular construction', 'modulars', 'modular buildings', 'steel structures', 'stiffness', 'structural design', and 'finite element method'. This analysis demonstrates the diverse yet interconnected nature of research in this area, with significant emphasis on the engineering and structural aspects of modular steel buildings. These keywords indicate that researchers are particularly interested in exploring how modular methods can be integrated into steel structures and how they can enhance construction efficiency, structural integrity, and sustainability. In terms of document sources, Figure 2 highlights the major journals that frequently publish research on modular steel buildings. Notable journals in this field include *Engineering Structures*, *Journal of Constructional Steel Research*, *Journal of Building Engineering*, and *Buildings*. Conference papers from platforms such as

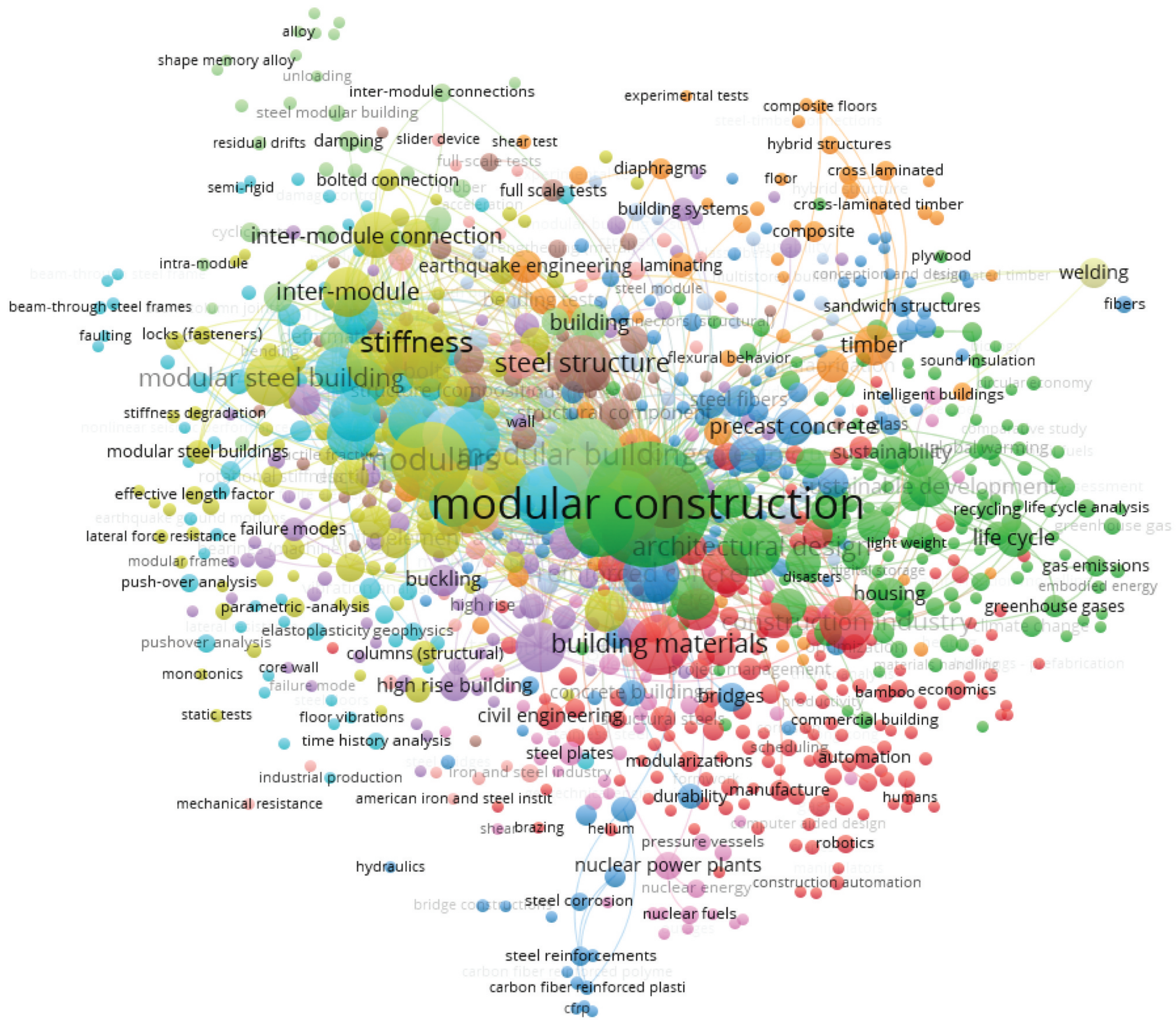

Figure 1. Keyword occurrence analysis of publications on modular steel buildings.

Lecture Notes in Civil Engineering also contribute significantly to the field, suggesting that this topic is a focal point of academic conferences as well as journal publications. This wide range of publishing outlets points to the interdisciplinary nature of modular steel building research, which spans both theoretical investigations and practical applications.

Figure 3 illustrates the geographical distribution of publications on modular steel buildings. The majority of research output comes from countries such as China, the United States, Australia, the United Kingdom, and Portugal. These nations are at the forefront of innovations in modular construction techniques, particularly in the context of steel buildings. The prevalence of research from these countries indicates a global interest in the topic, with these regions likely driving much of the technological advancement and practical implementation of modular steel building methods.

The trend analysis presented in Figure 4 reveals a steady increase in publications over the years, with a noticeable surge in recent years. From only two publications in 2000, the number of articles grew to 112 in 2023. This upward trajectory reflects the growing recognition of modular steel buildings as a promising solution for sustainable construction, as well as the increasing demand for more efficient and resilient building methods.

Lastly, Figure 5 categorises the types of documents published on modular steel buildings. Research papers account for the largest share, with 535 publications, followed by conference papers with 246. The significant number of conference papers emphasises the dynamic and evolving nature of research in this field. Other document types, such as reviews and book chapters, also contribute to the ongoing discussion of modular steel buildings, providing comprehensive overviews and future directions for research. The bibliometric analysis highlights modular steel buildings as a rapidly growing research field focused on enhancing construction efficiency, sustainability, and resilience through themes like modular construction, steel structures, and structural design. Led by countries such as China and the United States, the field has seen significant growth, with publications rising from 2 in 2000 to 112 in 2023, primarily in research papers and conferences. This

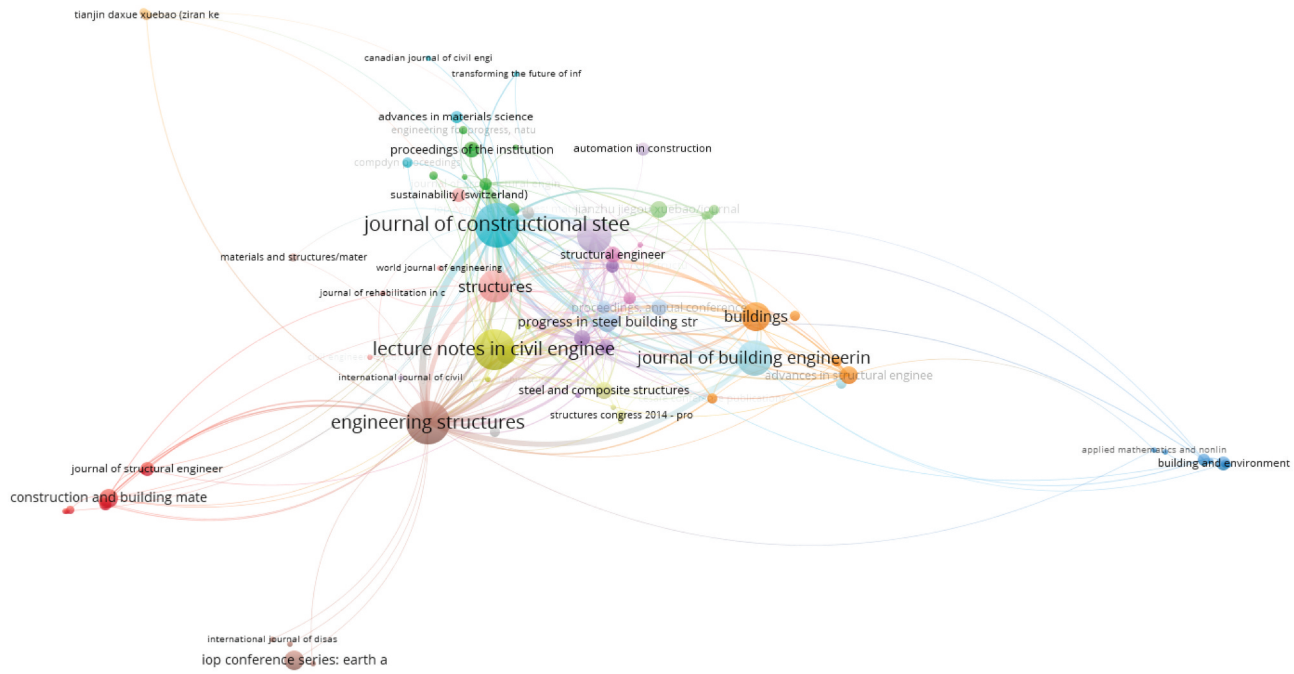

Figure 2. Document source analysis of publications on modular steel buildings.

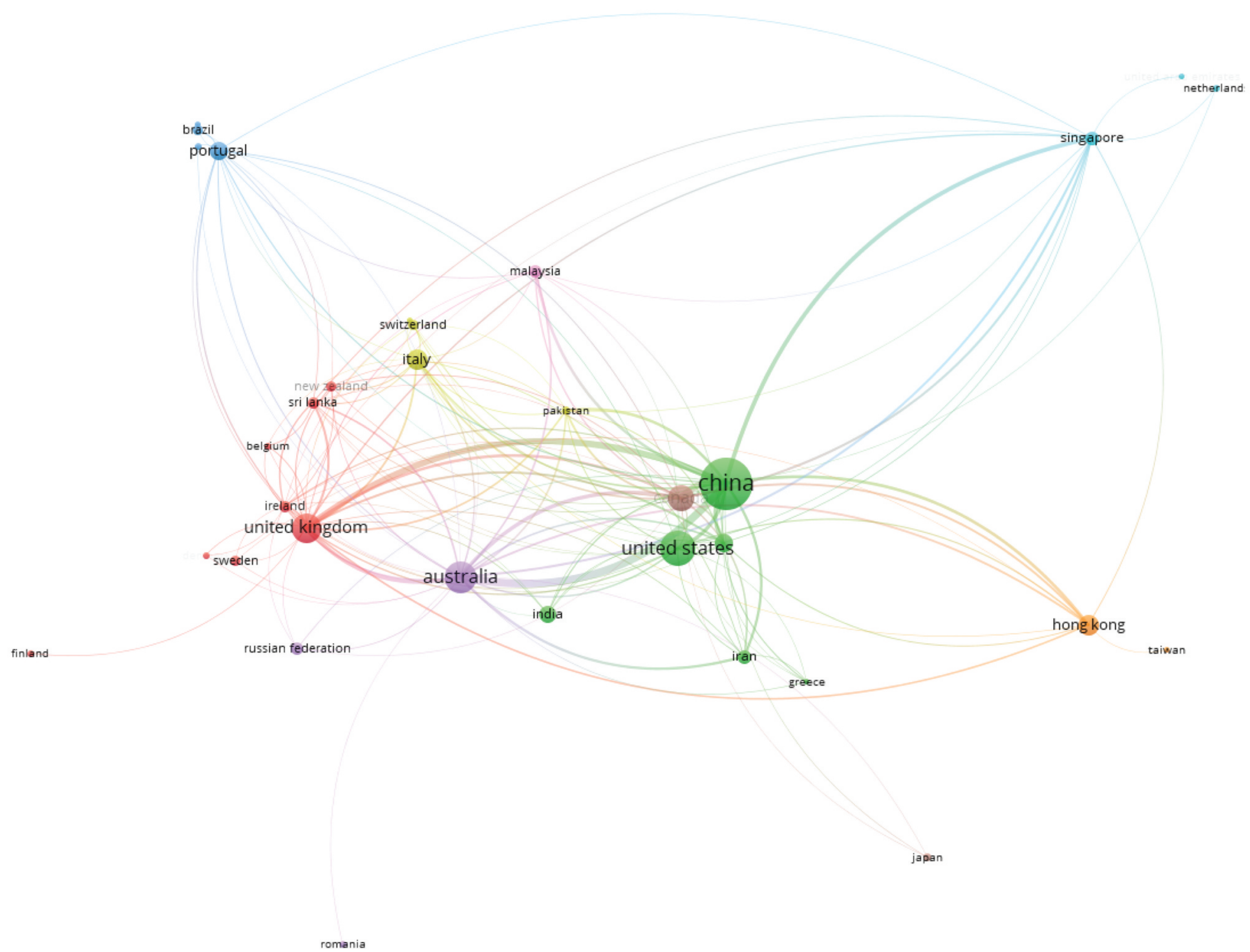

Figure 3. Source origin analysis of publications on modular steel buildings.

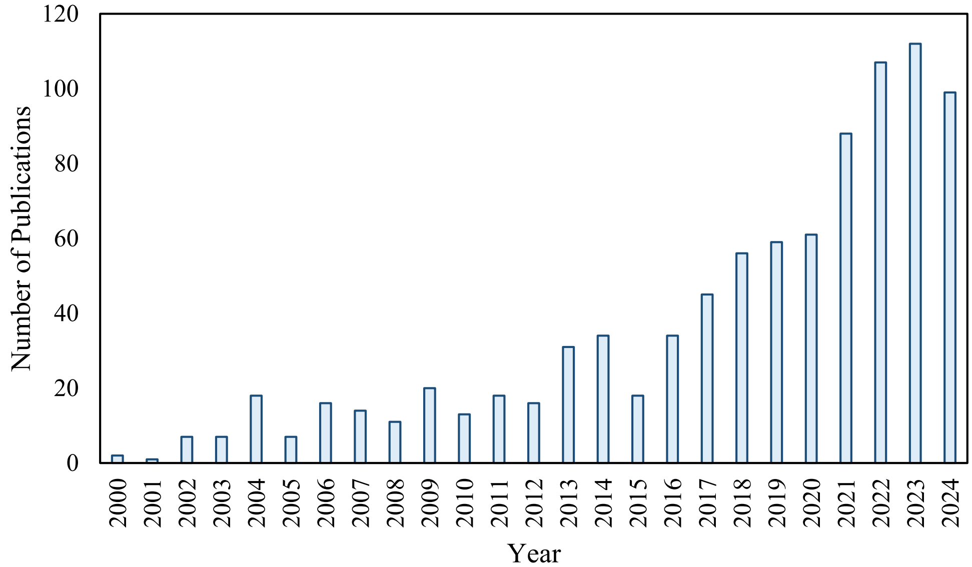

Figure 4. Yearly increase in the number of publications on modular steel buildings.

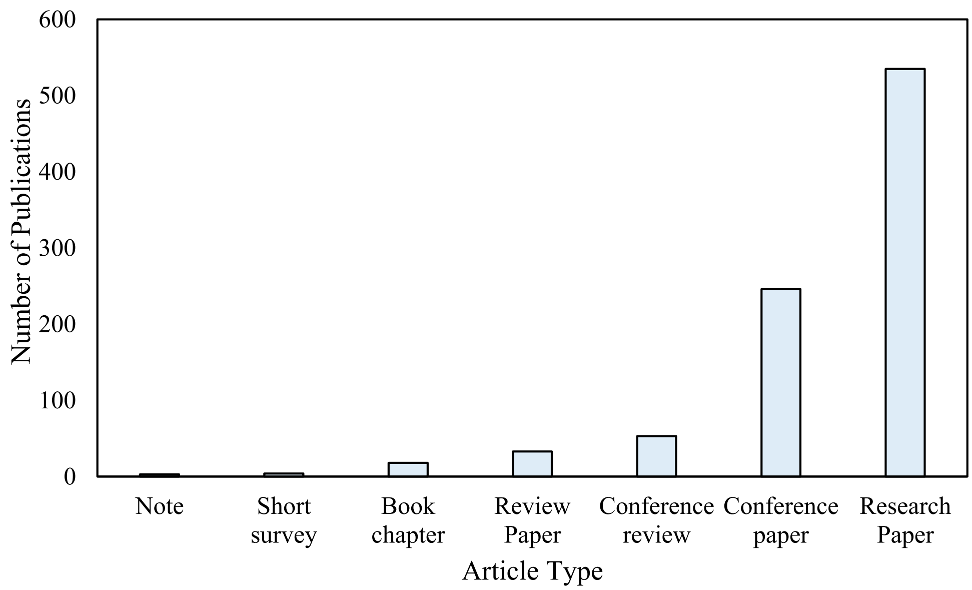

Figure 5. Type and number of documents published on modular steel buildings.

underscores the global interest and innovation driving advancements in modular construction techniques.

3. Modular steel building: concepts and definitions

3.1. Definition and types of modular construction

Modular construction, Figure 6, as a method for erecting buildings, has gained considerable traction in recent years due to its efficiency, sustainability, and adaptability to various structural requirements. The process involves prefabricating building components in a factory-controlled setting and subsequently assembling these modules on-site (Jagtap and Dhawade 2015). This method is distinct from conventional construction processes, where buildings are constructed piece by piece on-site, which often results in longer project durations and increased waste generation (Lawson, Ogden, and Goodier 2014).

Modular construction, Figure 7, is characterised by its versatility in application and scalability, making it suitable for projects ranging from low-rise residential buildings to high-rise commercial structures (Lawson, Ogden, and Popo-Ola 2011; Thai, Ngo, and Uy 2020). This flexibility has allowed modular construction to adapt to the growing demand for efficient and sustainable building methods, especially in urban areas, compared to traditional construction, Figure 8. Bertram et al. (2019) discusses the potential of modular construction to transform traditional building approaches by shifting from project-based methods to a more product-oriented model, thereby increasing efficiency and scalability in the construction industry. There are several types of modular construction systems, Table 1, each distinguished by the materials used and the extent of prefabrication. Permanent modular construction (PMC) refers to buildings that are designed for permanent

Figure 6. Prefabricated modules in factories (Adopted from Thirunavukkarasu et al. 2021).

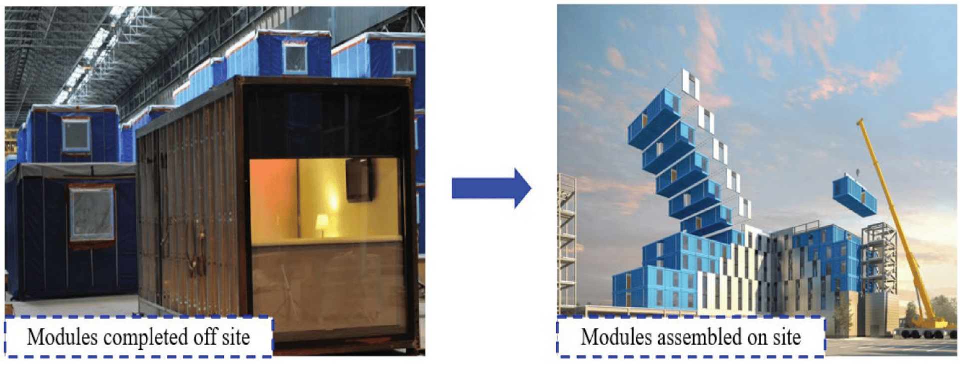

Figure 7. Construction of modular steel (Adopted from Yang et al. 2023).

use. In PMC, modules are fabricated in a factory, transported to the site, and then assembled, forming a permanent structure. These buildings offer long-term durability and are comparable to traditionally constructed buildings in terms of structural performance (Smith and Rice 2017).

In contrast, relocatable modular construction involves buildings that are designed for temporary use. These structures can be disassembled, relocated, and reassembled at different sites, making them ideal for temporary housing or emergency facilities (Smith 2016). Another approach is volumetric modular construction, where entire volumetric units, such as rooms or apartments, are prefabricated and transported to the site (Chen et al. 2021). This method allows for rapid assembly and minimal on-site labour, making it particularly beneficial for large-scale projects like hospitals or schools (Loizou et al. 2021). Hybrid modular construction combines 3D modular components with 2D panel construction systems to reduce the cost and optimise the space (Lawson and Ogden 2008; Salama, Salah, and Moselhi 2017). This method is typically used for projects that require complex designs or structural elements that cannot be entirely modularised, such as building cores or large atriums (Thai, Ngo, and Uy 2020). The adaptability of these different modular construction types enables the method to meet the specific needs of diverse construction projects while enhancing efficiency and reducing environmental impact.

3.2. Steel as a primary material in modular systems

Steel is widely recognised as a fundamental material in modular construction due to its inherent properties that contribute to the overall strength, durability, and sustainability of building structures (Brunesi et al. 2015; Chourasia et al. 2023; Habib and Yildirim ,2023b; Gardner 2023; Shrif et al. 2024). Its high strength-to-weight ratio, recyclability, and ability to withstand extreme loads make it particularly suitable for multistorey and high-rise buildings, where structural integrity is paramount (Baharudin and Isa 2022). In the context of modular construction, steel is often used for both the framework of the building modules and the connections between them, ensuring that the assembled structure performs reliably under various conditions. The use of steel in modular construction not only enhances the structural capabilities of buildings but also allows for more efficient prefabrication processes, as steel components can be easily fabricated and assembled in factory-controlled environments (Nadeem et al. 2021). One of the key advantages of using steel in modular systems is its ability

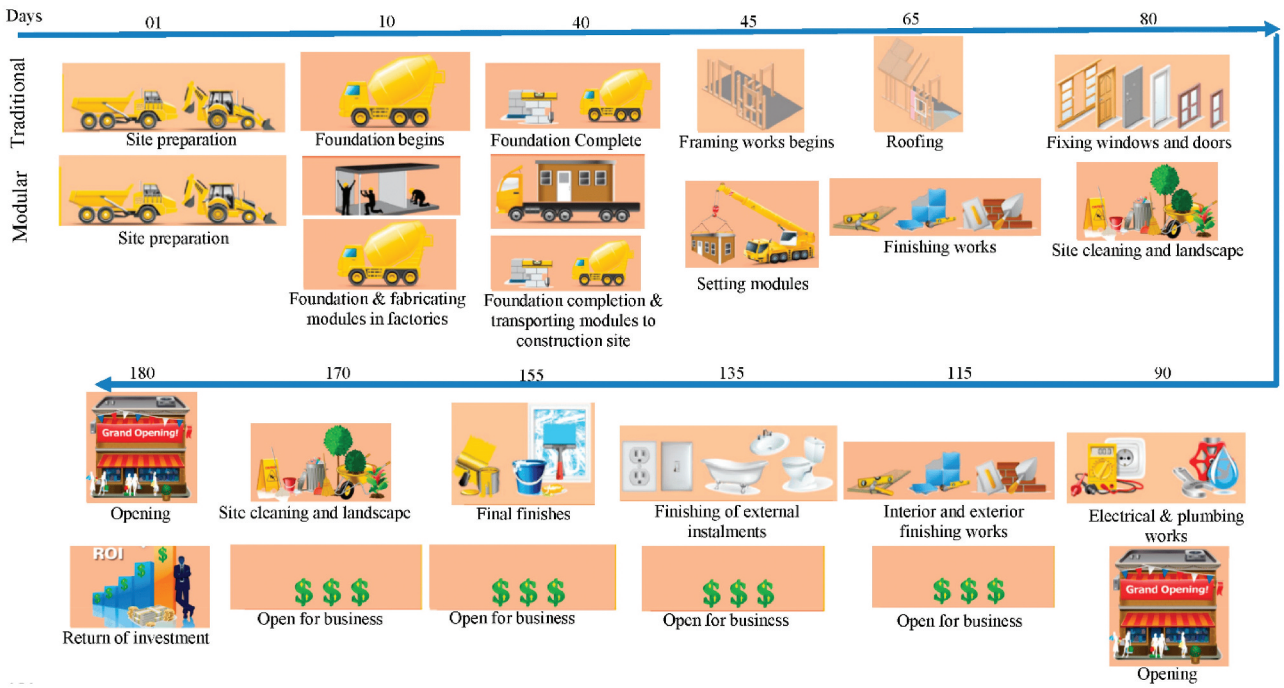

Figure 8. Modular construction vs traditional construction (Adopted from Thirunavukkarasu et al. 2021).

Table 1. Definitions and key features of various types of modular construction.

Type of Modular Construction	Definition	Key Features	Examples of Use
Permanent Modular Construction	PMC refers to modular buildings that are designed for permanent use. The modules are prefabricated in a factory and assembled on-site to form a permanent structure with long-term durability comparable to traditionally constructed buildings.	Permanent use, factory-controlled prefabrication, comparable to traditional construction, long-term durability.	Permanent residential or commercial buildings, high-rise projects.
Relocatable Modular Construction	Relocatable modular construction involves temporary buildings that can be disassembled, relocated, and reassembled at different sites. These are typically used for emergency housing or temporary structures and can be reused multiple times.	Temporary, relocatable, flexible for multiple uses, ideal for emergency or temporary facilities.	Emergency housing, mobile offices, disaster recovery units.
Volumetric Modular Construction	Volumetric modular construction involves prefabricating entire volumetric units, such as rooms or apartments, in a factory and transporting them to the site for assembly. This allows for rapid assembly and minimal on-site labor.	Prefabrication of entire volumetric units, rapid on-site assembly, minimal labor required, ideal for large-scale projects.	Hospitals, schools, apartments, large-scale housing developments.
Hybrid Modular Construction	Hybrid modular construction combines modular components with traditional construction techniques. This method is used for complex projects where certain structural elements, such as building cores, require traditional construction, while modular components are used for the rest.	Combination of modular and traditional construction, adaptable to complex designs, used for structures with complex elements like cores.	Complex buildings with structural cores or large atriums, mixed-use developments.

to support innovative connection designs, which are crucial for ensuring the stability and robustness of modular buildings. Furthermore, the seismic performance of curved hunched connections in modularised prefabricated steel structures is that these connections significantly enhance the flexural resistance of the columns and control plastic hinge formation in beams, aligning with the seismic design principle of strong column and weak beam. Longer haunches were found to provide superior strength, stiffness, and ductility by distributing loads more uniformly along the beams, preventing high stress concentrations, and thus enhancing energy dissipation capacity during seismic events (Feng et al. 2020). Inter-module connections play a critical role in determining the overall performance of modular steel buildings, especially in terms of their resistance to seismic and wind loads (Corfar and Tsavdaridis 2022). Yang et al. (2023) highlight that the mechanical behaviour of these connections, including their rotational stiffness and load-bearing capacity, is essential for maintaining the integrity of the modular structure under dynamic loading conditions. Similarly, Yang (2020) concluded that semi-rigid connections significantly affect the overall performance, including bending properties, lateral stiffness, and rotational behaviour, of high-rise steel structures. Moreover, steel frame structures with semi-rigid connections exhibit higher stiffness and more significant structural integrity compared to modular structures. The innovative rotary inter-module connection design eliminates the need for opening holes in beams or columns, thereby preserving the architectural integrity of modular units, as well as, it simplifies the assembly process by avoiding on-site welding, while still providing effective resistance against tensile and shear forces, ensuring structural safety and efficiency (Chen et al. 2019). Additionally, Li, Tsavdaridis, and Gardner (2021) emphasises that advancements in additively manufactured steel connections have further optimised the efficiency of these systems, allowing for more complex and resilient modular designs. The seismic performance of modular steel buildings has been a significant area of research, particularly for mid-to-high-rise structures that are subjected to lateral forces during earthquakes. Several studies have investigated the behaviour of modular steel buildings under seismic conditions. In this regard, Jasmin and Basheer (2021) reviewed the seismic performance analysis of high-rise modular steel building construction. These studies demonstrate the importance of developing reliable connection systems that enhance the seismic resilience of modular steel buildings, particularly in earthquake-prone regions. Steel's versatility also extends to its ability to be combined with other materials, such as concrete, to form composite systems that enhance the overall performance of modular buildings, Figure 9. For example, steel-concrete composite systems have been widely used in high-rise modular construction due to their ability to combine the best properties of both materials. These systems offer acceptable load-bearing capacity, fire resistance, and seismic performance (Yu 2023). Ping, Pan, and Mou (2022) explored innovative module-to-core wall connections in high-rise steel modular buildings and found that these composite systems significantly improve the building's lateral stability, making them ideal for use in tall structures. Furthermore, a review conducted by Poudel, Lee, and Choi (2022) highlighted that the connection methods used for steel module-to-concrete core systems in high-rise modular buildings are similar to those used in conventional steel-framed buildings, particularly the connection of steel beams to concrete walls using bolted and welded methods. Despite the many advantages of steel in modular construction, challenges remain in terms of optimising connection designs and ensuring the long-term durability of the system. Additionally, the impact of environmental factors, such as floods, must be considered when designing steel modular systems to ensure their longevity (Di Sarno and Forgione 2024). However, with ongoing research and technological advancements, the use of steel in modular construction continues to evolve, offering increasingly efficient and sustainable solutions for the built environment (Prabowo 2019).

4. Structural Behavior of modular steel buildings

4.1. General structural Behavior of modular steel buildings

The general structural behaviour of modular steel buildings hinges on the performance of individual modules and the connections between them. These prefabricated structures typically consist of steel modules assembled on-site, forming a composite system that behaves differently from traditional monolithic structures. In general, the behaviour of modular steel buildings is influenced by various factors (Table 2) including the geometry of the modules, the arrangement of structural components, and the load paths through the connections (Alembagheri et al. 2020; Lawson, Ogden, and Bergin 2012; Nadeem et al. 2021). The modular nature of these buildings introduces discontinuities at the module boundaries, which can affect the load transfer and overall stiffness. Liu et al. (2015) demonstrated that prefabricated modular steel structures could achieve comparable or superior structural performance to conventional steel buildings, provided the design carefully accounts for the unique load paths in modular systems. This is especially critical in multistorey buildings, where the cumulative effects of vertical and lateral loads are more pronounced. Additionally, Baharudin and Isa (2022) emphasised that modular construction using steel frameworks offers significant benefits in terms of speed and efficiency without compromising the structural integrity of the building. They noted that the ability to fabricate and assemble modules offsite reduces the impact of external variables, such as weather conditions, that often hinder traditional construction. The dynamic behaviour of these buildings under various loads also plays a crucial role in ensuring stability. Liu et al. (2017) highlighted that modular steel structures, especially those in high-rise configurations, need to account for wind and seismic loads. The inherent flexibility of steel as a material helps in absorbing some of these dynamic forces, but careful design is required to prevent excessive deflection and potential resonance issues.

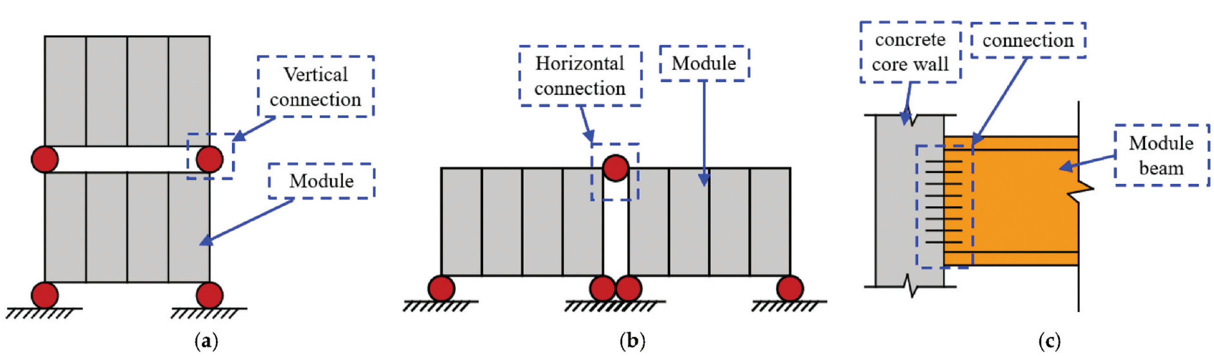

Figure 9. Connections on modular steel building. (a) Vertical connection; (b) horizontal connection; (c) modular-to-concrete core connection (Adopted from Yang et al. 2023).

Table 2. Major factors influencing the structural behaviour of modular steel buildings.

Factor	Description	Impact on Structural Behavior	Design Implications	Suggested Strategies for Optimization
Module Geometry and Size	The dimensions and shape of individual modules	Affects load distribution and stiffness, with larger modules increasing load complexity	Standardise module dimensions for predictable load behavior	Use smaller, uniformly sized modules to reduce load concentration
Connection Rigidity	The stiffness and flexibility of inter-module connections	More rigid connections improve lateral stiffness but reduce flexibility	Balance connection rigidity with flexibility to accommodate load variations	Use hybrid semi-rigid connections for balanced performance
Load Transfer Mechanisms	How vertical and lateral loads are transferred through the structure	Direct impact on overall stability and resilience, especially in multistory buildings	Carefully map load paths from upper stories to the foundation	Use reinforced corner and edge connections to improve load-bearing capacity
Dynamic Load Behavior	Building's response to wind, seismic, and other dynamic loads	Can lead to significant deflections, stress concentrations, or even collapse	Design for lateral stability under wind and seismic events	Use bracing systems, core structures, or shear walls for improved dynamic performance
Material Properties of Steel	The inherent strength, flexibility, and ductility of steel used in the modules	Steel's flexibility allows for energy dissipation but requires careful connection design	Leverage steel's ductility to absorb seismic energy	Choose high-strength steel for areas with high load concentration and seismic activity
Prefabrication Precision	The accuracy of manufacturing and assembly processes in controlled environments	Enhances predictability in performance, minimizing construction errors	Ensure quality control during prefabrication for optimized module-to-module fit	Implement stricter QA/QC processes in factory production for consistency in performance

4.2. Lateral stability and stiffness in modular steel buildings

Lateral stability and stiffness are critical factors for built structures including modular steel buildings, especially in high-rise applications where wind and seismic forces play a more significant role (M. Habib et al. 2024). Zhai et al. (2023) investigated the initial lateral stiffness of plate-type modular steel frame structures with semi-rigid corner connections. The stiffness of the system is primarily governed by the rigidity of the connections between modules, which often act as weak points in the structure. Lacey et al. (2018) provided an overview of the structural response of modular buildings, emphasising that the lateral stiffness of a building is highly dependent on the design of the inter-module connections. They found that bolted connections, commonly used in modular construction, can lead to reduced stiffness compared to welded connections used in traditional buildings. However, bolted connections offer greater flexibility and ease of disassembly, which aligns with the sustainability goals of modular construction. Several studies have focused on improving the lateral stiffness of modular steel buildings by optimising connection designs. For instance, Liu et al. (2017) explored the performance of H-section beams connected to hollow structural section (HSS) columns in prefabricated modular structures and found that these connections could significantly enhance the lateral stiffness of the building. He, Zhang, and Shang (2023) investigated the dynamic characteristic and parameter analysis of a modular building with suspended floors, including its lateral stiffness as shown in Figure 10. Similarly, Zhai et al. (2023) emphasised the importance of corner connections in maintaining lateral stability, especially in taller buildings. Their research indicated that even semi-rigid connections could provide sufficient stiffness if designed and implemented correctly.

In high-rise modular steel buildings, the cumulative effect of wind loads on lateral stability becomes more pronounced. Ye et al. (2021) conducted a comprehensive review of structural stability in multistorey modular buildings. This research suggests that while modular steel buildings offer many advantages in terms of speed and efficiency, the lateral stability of these structures requires careful consideration, particularly in regions prone to high winds or seismic activity.

4.3. Seismic performance and dynamic load response in modular steel buildings

Seismic performance is a critical aspect of the structural behaviour of buildings, particularly in earthquake-prone regions

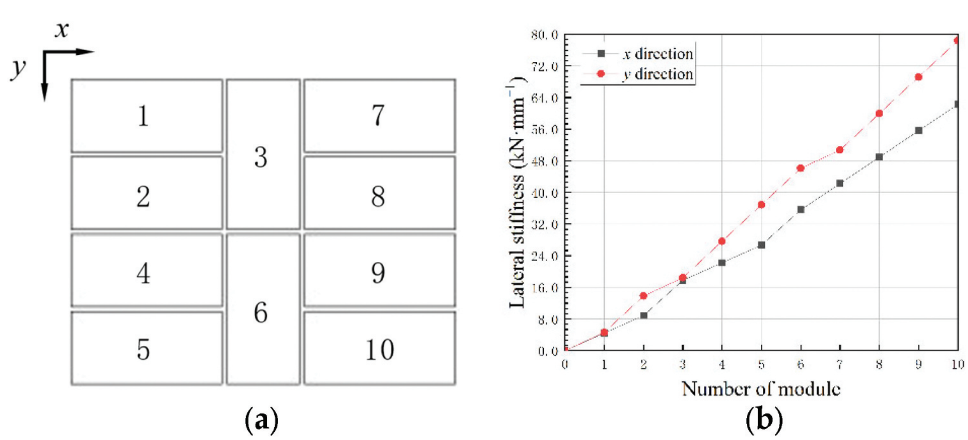

Figure 10. (a) a standard scheme of horizontal assembly; (b) lateral stiffness of the structure (Adopted from He, Zhang, and Shang 2023).

(Habib, Yildirim, and Eren 2021). Several studies have focused on evaluating the seismic performance of these buildings, with a particular emphasis on the behaviour of connections and the overall dynamic response of the structure. Peres et al. (2024) conducted a comprehensive review of the seismic design of modular steel buildings and emphasised the need for more robust design procedures to ensure the resilience of these structures in earthquake-prone regions. The discontinuities between modules, particularly at the connections, can lead to stress concentrations and potential failure points. Deng et al. (2020) conducted a critical review of the seismic performance of mid-to-high-rise modular steel buildings and found that while these structures generally perform well under seismic loads, the design of the connections between modules plays a pivotal role in their overall seismic resilience. Their study emphasised the importance of designing connections that can accommodate the relative motion between modules during an earthquake, as rigid connections may lead to brittle failure. Jasmin and Basheer (2021) conducted a review on the seismic performance of high-rise modular steel buildings, highlighting that the flexibility of steel, combined with the modular nature of these buildings, can provide inherent seismic resilience. However, they also noted that traditional seismic design methodologies might not be entirely applicable to modular structures, as the load transfer mechanisms in modular buildings differ significantly from those in monolithic structures. The dynamic behaviour of modular steel buildings under seismic loads has also been extensively studied through experimental and numerical approaches. Liu et al. (2018) developed and validated a new design approach for modular-prefabricated high-rise steel frame structures with diagonal braces, it was shown that using an elastic-plastic time-history analysis for rare earthquakes to account for high-order vibrational modes, is crucial for ensuring the structural integrity of such prefabricated buildings. The findings emphasise that the elastic-plastic time-history analysis cannot be replaced by simpler pushover analysis, as it helps prevent the collapse of the entire structure due to damaged connections. Moreover, the study develops design formulas for critical joints, including the column-column flange connection, truss-column connection, and diagonal brace-truss connection, ensuring the structure's safety and compliance with seismic design codes. These design methods have been compiled into technical specifications, providing an essential reference for future developments in modular prefabricated steel structures. Zhang et al. (2021), who conducted shaking table tests on prefabricated steel frame structures with all-bolted connections, demonstrating the importance of connection design in achieving satisfactory seismic performance. This finding was corroborated by Zhai, Zha, and Chen (2023) who investigated the shaking table tests on plate-type modular steel and composite structures with semi-rigid corner connections, demonstrating it is significantly higher, eight to nine times greater, than that of traditional steel frame structures, primarily due to the effective skin action of the wall panels. However, this stiffness can decrease by approximately 50% during severe seismic events due to damage and loosening of corner connections, highlighting the critical need for robust connection design to ensure structural integrity under seismic loads. Additionally, several studies have focused on optimising the seismic performance of modular steel buildings through innovative connection designs. For example, Zhang et al. (2023) explored the use of self-tapping bolts in modular steel structures, finding that these connections provided enhanced seismic resilience compared to traditional bolted connections. Fan et al. (2022) investigated the seismic behaviour of novel self-tightening one-side bolted joints, concluding that these connections could significantly improve the seismic performance of modular steel buildings by reducing stress concentrations at the joints. Gong et al. (2022) investigated the seismic performance of modular structures with novel steel frame that offer light gauge slotted steel stud walls and simplified joints.

4.4. Connection design in modular steel buildings

The design of connections in modular steel buildings is a critical factor that influences the overall structural behaviour of these buildings. Connections serve as the interface between individual modules, and their performance under various loads directly impacts the building's stability, stiffness, and seismic resilience. Currently, several types of connections exist for modular construction, as shown in Figure 11 and Table 3. Nadeem et al. (2021) provided a detailed review of connection designs in modular steel construction, emphasising that bolted connections are the most commonly used due to their ease of assembly and disassembly. However, they noted that bolted connections tend to be less rigid than welded connections, which can lead to reduced stiffness and increased deformation under load. Lacey et al. (2019) reviewed bolted inter-module connections in modular steel buildings, highlighting that while bolted connections offer significant advantages in terms of flexibility and ease of construction, they can also require access, tolerance by slotted holes, slip, and bolt tensioning. Their review suggested that bolted connections need to be carefully designed to ensure that they can accommodate both vertical and lateral loads without compromising the building's structural integrity. Additionally, a study conducted by Srisangeerthanan et al. (2018) identified two key challenges hindering the widespread adoption of multistorey modular buildings (MSMBs) which are the lack of efficient lateral load resistance systems that limits the structural stability of these buildings, especially under wind or seismic forces and the second challenge is the absence of high-performance inter-module connections impedes both vertical and horizontal load transfer, affecting overall building integrity. Zhang et al. (2019) investigated designing prefabricated beam-column joints with enhanced seismic resilience, particularly those incorporating cantilever beams. The findings of this research reveal that replaceable flange cover plates, slotted steel dampers, and modular components offer significant promise in effectively dissipating seismic energy, mitigating brittle failures, and facilitating swift post-earthquake recovery. Both experimental and numerical studies underscore the superior performance of these joints, showcasing enhanced ductility, improved energy dissipation, and greater rotational capacity, all while ensuring exceptional assembly efficiency. Corfar and Tsavdaridis (2022) conducted a comprehensive review and classification of inter-module connections for hot-rolled steel modular building

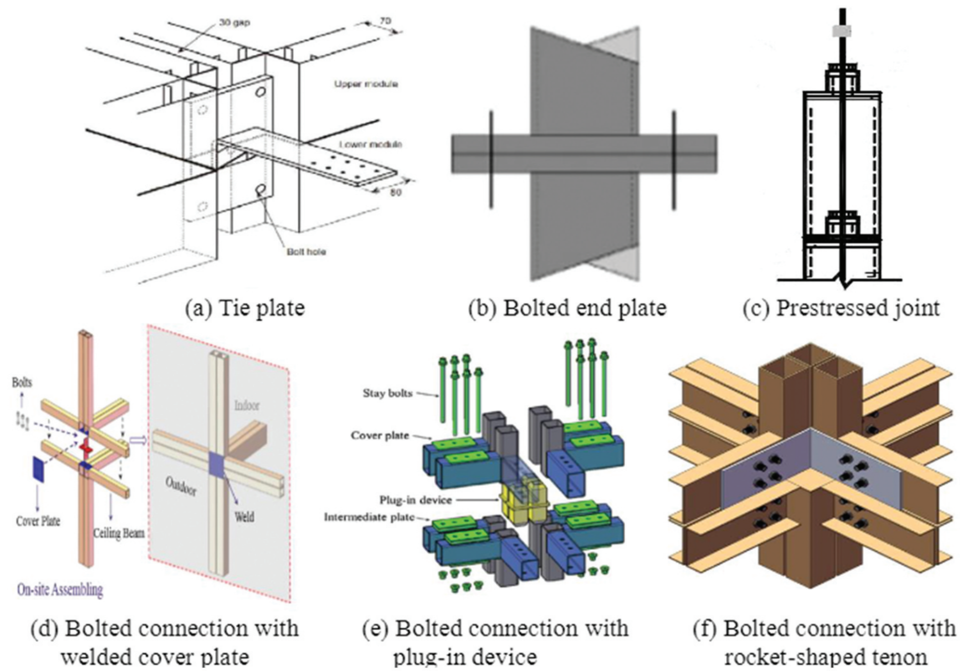

Figure 11. Schematic diagram of existing joints (Adopted from Wang et al. 2019).

Table 3. Connection design and structural implications in modular steel buildings.

Connection Type	Description	Advantages	Disadvantages	Best Use Scenarios
Bolted Connections	Modules are connected using bolts, which allow for ease of assembly and disassembly	Flexibility for absorbing dynamic loads and ease of maintenance	Lower stiffness, more prone to deformation under high loads	Suitable for low-rise buildings or where flexibility is required, and maintenance access is prioritized
Welded Connections	Permanent joints are created by welding modules together	High stiffness and strength, ensuring structural integrity	Time-consuming and difficult to disassemble, prone to stress concentration	Ideal for high-rise structures or in cases where lateral stiffness is essential, but disassembly is not needed
Hybrid Bolted-Welded	Combination of bolting and welding, balancing flexibility and stiffness	Balances ease of assembly with increased rigidity	Complex design and installation processes	Best used for mid-to-high rise buildings that require a combination of flexibility and lateral stiffness
Semi-Rigid Connections	Connections that allow limited movement while maintaining some rigidity	Offers a balance between load-bearing capacity and flexibility	Moderate in stiffness and may require reinforcement under heavy loads	Suitable for multistory buildings where both flexibility and rigidity are required
Self-tightening Bolted Connections	A novel type of bolted connection that tightens under load	Increased resistance to loosening, performs well under dynamic loads	Still in development, requires more research	Ideal for seismic regions where bolted connections need to maintain integrity under cyclic loading

systems. They classified connections based on their rigidity, load-bearing capacity, and ease of installation, and concluded that while fully rigid connections provide the best structural performance, they are often impractical in modular construction due to the need for flexibility during assembly. Instead, semi-rigid connections, which offer a balance between strength and flexibility, are often preferred in modular steel buildings. Yang et al. (2023) explored the mechanical behaviour of inter-module connections and assembled joints in modular steel buildings, finding that the performance of these connections is highly dependent on the type of joint used and the load-transferring path. In addition to bolted and welded connections, several studies have focused on developing innovative connection designs to improve the structural performance of modular steel buildings. Liu et al. (2018) investigated the performance of slipping bolted truss-to-column connections in modular steel structures, finding that these connections provided enhanced ductility and energy dissipation capacity without significantly reducing the ultimate bearing capacity during seismic events. Moreover, Liu et al. (2018) concluded that the flange thickness significantly affects the performance of bolted-flange connections used in prefabricated multistorey and high-rise steel structures, particularly under coexisting axial compression, bending moments, and shearing. The study found that flange thickness had a considerable impact on the stiffness and strength of the connections, while bolt edge distance and flange edge width had lesser effects. This research also successfully developed a finite element analysis (FEA) model that aligned with the experimental results, providing critical insights that were not obtainable through physical testing alone. Another study conducted by Yin and Shi (2018) developed an accurate and efficient finite element model (FEM) to simulate the cyclic behaviour of fully prefabricated steel frames with bolted end-plate joints, flexible braces, and composite slabs. This model addresses the limitations of existing modelling approaches by achieving high accuracy and stabilisation while reducing computational costs. The FEM was validated against a full-scale cyclic test of a three-story steel frame, effectively simulating seismic performance aspects such as deformation capacity, cyclic behaviour, energy dissipation, and stiffness degradation. Additionally, new formulas for yield-bearing capacity based on yield line theory and T-stub analogies were proposed and validated. Similarly, Azizi Naserabad et al. (2018) evaluated the behaviour of a new bolted connection design called bolted beam-to-column connections (BBCC), which ensures better seismic performance by forming plastic hinges in the beams while preventing bolt failure, making it a superior option for use in high-rigidity applications. Lastly, Liu et al. (2017) proposed newly site-bolted beam-to-column connection for modularised prefabricated steel structures demonstrates excellent seismic performance. The study showed that these connections, when subjected to cyclic loading, exhibited good ductility, energy dissipation capacity, and plastic deformation ability. The results from both experimental testing and FEA indicated that the connection could undergo significant plastic deformation, achieving an ultimate rotation angle of 0.09 radians. It effectively dissipated energy through slippage in smaller earthquakes and through a combination of slippage and plastic deformation in more severe earthquakes. Accordingly, recent studies suggest that factors such as rotational stiffness, assembly and disassembly complexity, and overall cost must be thoroughly evaluated when selecting the most suitable connection for a specific modular steel building. For instance, while bolted connections are praised for flexibility and ease of maintenance, welded connections offer greater stiffness but necessitate more intensive labour and complicate future alterations. Hybrid connections aim to strike a balance between these design extremes, yet careful evaluation of site conditions, building height, and seismic requirements remains essential for achieving optimal structural performance. This highlights the need for ongoing research focusing on integrated design approaches that allow precise comparisons of various connection types under critical factors such as cyclic loading, assembly speed, and long-term serviceability. Therefore, the findings across multiple studies converge on the conclusion that more nuanced comparisons and performance-based design methods for modular connection systems are key to developing safe, cost-effective, and adaptable solutions for different building scenarios.

5. Sustainability assessment

5.1. Environmental benefits

One of the primary environmental benefits of modular steel building construction is the significant reduction in material wastage. In traditional construction, a large proportion of materials can go unused due to inefficient on-site practices, resulting in waste that must be disposed of in landfills. Modular construction, however, takes place in a controlled factory setting, allowing for more precise measurements and the ability to reuse leftover materials, minimising the overall weight of waste up to 83.2%, corresponding to a 47.9% reduction in the cost of waste for mega projects (Loizou et al. 2021). This precision reduces waste generation considerably compared to traditional methods, making it a more environmentally responsible choice (Kamali and Hewage 2016). Mirshekarlou et al. (2021) developed a knowledge-based tool for waste management specifically designed for prefabricated steel structure projects. This tool integrates three essential mechanisms: waste estimation, waste monitoring, and waste analysis. The tool's ability to capture and store waste-related knowledge from previous projects is key for reducing waste and improving efficiency in future projects. It also incorporates a similarity assessment method to estimate material waste by comparing ongoing projects with past ones, which aids in monitoring performance and making adjustments. The reduced waste not only minimises the environmental burden but also decreases the cost of materials, further contributing to the economic sustainability of modular construction. Energy savings during both the construction and operational phases are another key advantage of modular steel buildings. Traditional construction is energy-intensive, particularly in terms of transportation of materials and on-site processes such as welding, cutting, and other forms of manual labour. In contrast, modular steel building construction consolidates many of these energy-intensive processes within a factory, where energy consumption can be optimised and renewable energy sources can be incorporated into the production process (Tumminia et al. 2018). Moreover, the use of energy-efficient materials and designs in modular buildings can result in significant energy savings during the operational phase, reducing the building's overall carbon footprint by at least 40%-50% (Ferdous et al. 2019). Modular steel building construction also contributes to a reduction in the carbon footprint of buildings. A study by Jin, Hong, and Zuo (2020) and Teng et al. (2018) demonstrated that modular construction results in 15.6% of embodied and 3.2% of operational CO_2 emissions compared to conventional construction methods. This reduction is primarily due to the optimised material use, shorter construction timelines, and reduced transportation needs, In addition to that, Cabaleiro et al. (2023) proposed a new connection called clamp-based connections that offers a highly promising solution for creating fully demountable and reconfigurable steel structures. These connections align with circular economy principles by enabling repeated reuse and adaptability of steel components, thereby promoting sustainability. However, their practical application is currently limited due to challenges such as lower rigidity compared to traditional bolted connections, higher costs, and a lack of comprehensive studies on their mechanical behaviour. Further research is needed to optimise and standardise these connections for widespread industrial use. Additionally, modular steel buildings can potentially be disassembled and repurposed (Yuan and Wang 2021). This capacity for disassembly and reuse further enhances the environmental benefits of modular steel building construction, aligning it with circular economy principles and contributing to long-term sustainability.

5.2. Social benefits

In addition to the environmental advantages, modular steel building construction offers numerous social benefits, particularly in terms of health and safety. The offsite nature of modular construction significantly reduces the hazards typically associated with traditional construction sites. MC typically involves a smaller on-site workforce, which leads to fewer commuting vehicles, less idling machinery, and reduced on-site equipment. Much of the work is done offsite, such as cutting materials, minimising waste and the need for heavy tools like saws and grinders on-site. This also decreases energy consumption and the transportation of waste, further lowering greenhouse gas emissions (Sajid et al. 2024). This controlled environment leads to safer working conditions, lower accident rates, and improved worker welfare. Furthermore, the repetitive nature of modular construction allows workers to specialise in specific tasks, improving their skill levels and increasing productivity. The impact on local communities is another crucial social benefit of modular steel building construction. Traditional construction projects often cause significant disruption to local communities, particularly in urban environments, due to noise, dust, and heavy machinery. Modular construction, however, reduces on-site activity, as much of the building process is completed offsite. This not only minimises disruption but also shortens construction timelines, allowing buildings to be completed faster and reducing the duration of any negative impacts on surrounding areas (Jayawardana et al. 2023). Additionally, modular construction creates job opportunities both within the factory setting and on-site, providing a steady source of employment and contributing to the local economy. Modular steel buildings also have the potential to address the global need for affordable housing. With growing urban populations, the demand for cost-effective and sustainable housing solutions is more pressing than ever. Modular construction offers an efficient way to deliver high-quality, affordable housing at scale, as the speed and cost savings associated with this method can be passed on to residents (Kamali and Hewage 2016). By reducing construction costs and timelines, modular construction can help address housing shortages in both developed and developing countries, contributing to social equity and improved quality of life for underserved populations (Patel and Kaushal 2024).

5.3. Economic benefits

The economic benefits of modular steel building construction are evident in the significant cost savings that arise from its efficient building process. One of the primary economic advantages is the shorter construction time. Traditional construction projects can be subject to delays due to weather, material shortages, or logistical issues, which can significantly increase costs. In contrast, modular construction is far less dependent on external factors, as the majority of the construction process takes place indoors in a factory-controlled environment. This not only speeds up the construction process but also reduces the likelihood of costly delays (Aghasizadeh et al. 2022). Faster construction times translate into lower labour costs and allow buildings to become operational more quickly, generating revenue sooner. Financial viability over the life cycle of modular buildings is another important economic benefit. Although the initial costs of modular steel building construction may be higher due to the need for specialised design and manufacturing processes, these costs are offset by the reduced time on-site, lower material wastage, and energy savings during the operational phase (Marrone, Imperadori, and Sesana 2023). Additionally, the durability of steel, combined with its ability to be reused or repurposed at the end of a building's life cycle, enhances the long-term financial benefits of modular steel building construction (Cabaleiro et al. 2023). Buildings constructed using modular steel systems also tend to have lower maintenance costs over time, as the prefabricated modules are designed to high tolerances and quality standards in controlled environments, reducing the need for repairs and upkeep (Liew, Chua, and Dai 2019). When compared to traditional construction, modular steel systems demonstrate a favourable cost-to-return ratio. While traditional construction projects often require significant upfront capital and ongoing maintenance costs, modular construction offers a more environmentally friendly and cost-effective approach (Zhenquan 2021). The ability to complete projects faster, reduce material wastage, and lower energy consumption makes modular steel building construction an attractive option for developers and investors alike. Furthermore, as sustainability becomes an increasingly important consideration in real estate, buildings that offer long-term environmental and economic benefits are likely to see higher returns on investment over time (Ferdous et al. 2019).

5.4. Comparative assessment with traditional construction methods

This section compares the environmental, social, and economic benefits of modular steel building construction against traditional construction methods. In general, the comparative assessment between modular steel building construction and traditional construction methods reveals significant sustainability advantages associated with modular approaches. One of the most prominent benefits of modular construction is the substantial reduction in material wastage due to the precision of prefabrication. In contrast, traditional construction often results in higher material waste due to inefficient on-site processes. This distinction is evident in the environmental impact of both methods, with modular construction not only minimising waste but also proving more energy-efficient during the construction phase. Factory-controlled processes used in modular building projects ensure that energy use is optimised, whereas traditional methods are more energy-intensive and less controlled, leading to increased energy consumption. In terms of the carbon footprint, modular steel building construction demonstrates lower emissions, owing to its efficient use of materials and energy. Traditional construction, on the other hand, tends to have a higher carbon footprint, exacerbated by longer construction timelines and more extensive transportation needs. Additionally, the recyclability of materials in modular construction is much higher, as steel is a highly reusable resource, unlike traditional construction methods that often generate more waste and have limited recyclability. These factors collectively contribute to a shorter construction time in modular projects, while traditional methods are prone to delays due to on-site work and potential weather conditions (Table 4). Socially, modular steel building construction offers

Table 4. Sustainable benefits comparison between modular steel building construction and traditional construction methods.

Sustainability Aspect	Major Factors	Modular Steel Building Construction	Traditional Building Construction
Environmental	Material wastage	Significantly reduced due to precise prefabrication	Higher due to inefficient on-site processes
	Energy use during construction	More efficient with factory-controlled processes	More energy-intensive, less controlled on-site processes
	Carbon footprint	Lower due to material, construction, and energy efficiency	Higher due to longer construction times and transportation
	Recyclability	Higher as steel is highly recyclable and reusable	Limited recyclability, leading to higher waste generation
	Construction time	Shorter with faster assembly on-site	Longer due to on-site work and potential weather delays
Social	Worker health and safety	Safer with controlled factory conditions	Higher risk of accidents in open construction sites
	Community disruption	Minimal due to reduced on-site activities	High due to noise, dust, and extended construction timelines
	Job creation	Jobs created in factories and for on-site assembly	Primarily focused on labor-intensive on-site jobs
	Affordable housing potential	Faster and more cost-effective construction	Slower with higher costs
	Specialization of labor	Higher due to repetitive factory work enabling specialization	Lower as diverse tasks are performed on-site
Economical	Worker health and safety	Reduced due to shorter construction times and less waste	Higher due to longer timelines and increased material waste
	Community disruption	Lower due to reduced maintenance and energy-efficient design	Higher due to ongoing maintenance and higher energy usage
	Job creation	Higher with faster project completion and lower operational costs	Lower due to longer construction times and higher maintenance
	Affordable housing potential	Significantly reduced due to precise prefabrication	Higher due to inefficient on-site processes
	Specialization of labor	More efficient with factory-controlled processes	More energy-intensive, less controlled on-site processes

improved worker safety and less disruption to local communities because much of the construction takes place offsite. The economic benefits are equally compelling, with modular construction leading to cost savings through faster project completion and lower life cycle costs, while traditional methods often incur higher costs due to extended timelines and increased maintenance requirements. The comparative analysis shows that modular construction provides a more sustainable, efficient, and cost-effective approach to building.

Table 5. Alignment analysis of modular steel buildings with the United Nations SDGs.

United Nations SDGs	Goal Description	Modular Steel Building Construction Contribution	Details of Contribution
SDG 9: Inustry, Innovation, and Infrastructure	Promote resilient infrastructure, sustainable industrialization, and foster innovation	Resilience and innovation in building infrastructure	Modular steel structures are durable and resilient, especially in extreme weather conditions and seismic events (Kamali and Hewage 2016). Prefabrication enables precision and quality control, enhancing innovation (Ferdous et al. 2019).
		Sustainable industrialization through prefabrication	The controlled factory environment improves resource efficiency, reduces wastage, and lowers energy use (Loizou et al. 2021). This method also minimizes on-site environmental disruption (Ferdous et al. 2019).
		Scalable innovation for large-scale infrastructure projects	Modular steel building construction facilitates faster, cost-effective infrastructure projects, such as schools and hospitals, helping to meet urban demands (Mandala and Nayaka 2023).
SDG 11: Sustainable Cities and Communities	Make cities and human settlements inclusive, safe, resilient, and sustainable	Contribution to sustainable urban growth	Modular steel buildings are energy-efficient and adaptable, contributing to urban sustainability by reducing energy use and environmental disruption in cities (Marrone, Imperadori, and Sesana 2023; Sajid et al. 2024).
		Increased housing affordability and inclusivity	Modular steel systems enable rapid construction of affordable housing, addressing urban housing shortages (Kamali and Hewage 2016). These systems are useful in disaster-stricken regions for temporary housing (Sajid et al. 2024).
		Resilience in disaster-prone urban areas	The strength of steel and precision of modular construction ensures resilience in high-risk urban areas prone to earthquakes and other disasters (Sajid et al. 2024).
SDG 12: Responsible Consumption and Production	Ensure sustainable consumption and production patterns	Reduction of construction waste through prefabrication	Modular construction allows precise material usage, limiting waste during prefabrication. Reusable and recyclable materials such as steel reduce the environmental impact (Yuan and Wang 2021).
		Promotion of recyclable and reusable building materials	Steel is a recyclable material, and modular steel structures can be disassembled, reused, or reconfigured, extending their life cycle and minimizing new raw material use (Cabaleiro et al. 2023).
		Energy-efficient production and operational phases	Modular steel building construction uses less energy during the production and operation phases, with optimized insulation and energy-efficient design (Marrone, Imperadori, and Sesana 2023).

5.5. Alignment with United Nations sustainable Development goals

Modular steel building construction aligns with several of the United Nations SDGs, Table 5, which aim to promote sustainability, resilience, and equality on a global scale. Specifically, modular construction supports Industry, Innovation, and Infrastructure (SDG 9), Sustainable Cities and Communities (SDG 11), and Responsible Consumption and Production (SDG 12). SDG 9 emphasises the need for resilient infrastructure, inclusive and sustainable industrialisation, and innovation. Modular steel building construction promotes resilient infrastructure by offering a building method that is adaptable, durable, and capable of withstanding extreme environmental conditions. The steel used in modular construction is not only strong and long-lasting but also flexible enough to be repurposed or reused, contributing to the longevity of buildings and reducing the need for new construction (Kamali and Hewage 2016). Furthermore, the innovative nature of modular construction, particularly in its ability to incorporate cutting-edge design and manufacturing techniques, aligns with the goal of fostering innovation within the construction industry (Garusinghe, Perera, and Weerapperuma 2023). SDG 11 focuses on making cities and human settlements inclusive, safe, resilient, and sustainable. Modular steel buildings contribute to sustainable urban development by reducing resource consumption, minimising waste, and lowering the overall environmental impact of construction (Yuan and Wang 2021). As urbanisation continues to accelerate, modular construction offers a scalable solution that can deliver high-quality housing and infrastructure quickly and efficiently. Additionally, the reduced on-site disruption associated with modular construction makes it a more socially sustainable option (Mandala and Nayaka 2023). SDG 12 calls for responsible consumption and production patterns, with a focus on reducing waste and promoting the sustainable use of materials. Modular steel building construction supports this goal by significantly reducing material waste through the use of prefabrication and precise manufacturing processes. The controlled factory environment allows for better resource management, while the ability to reuse and recycle steel modules at the end of a building's life cycle contributes to a circular economy (Cabaleiro et al. 2023). By promoting the use of sustainable materials and reducing the environmental impact of construction, modular steel buildings help to ensure that the industry moves towards more responsible production practices (Sajid et al. 2024).

6. Conclusion

This study emphasises the growing significance of modular steel buildings in modern sustainable construction due to their ability to offer numerous benefits in terms of efficiency, reduced waste, and enhanced environmental performance. Modular steel buildings reduce construction time, improve structural integrity, and align with global sustainability goals, particularly the United Nations SDGs related to infrastructure, sustainable cities, and responsible consumption. On the basis of the above statements, the following conclusions are made:

- Modular steel buildings provide acceptable structural resilience, particularly in high-risk regions, due to advanced connection designs that meet the performance criteria under dynamic and seismic loads.
- Modular steel buildings offer material efficiency and recyclability. They have the potential to lower the overall environmental footprint by cutting down on waste and emissions while enabling the reuse of steel components.
- Using energy-efficient materials and designs in modular buildings can cut energy use by 40%-50%, significantly reducing the carbon footprint.
- Previous studies have indicated that prefabricated steel system can reduce material consumption by up to 78% compared to conventional concrete construction as well as offer up to 81% savings in embodied energy and 51% in materials.
- The faster assembly process, combined with reduced material and labour costs, makes modular steel construction financially appealing, with the added benefit of minimal long-term maintenance requirements.
- Modular steel buildings align with SGD 9, 11, and 12 by promoting sustainable infrastructure, reducing waste, and promoting resource efficiency, which ultimately contribute to more resilient and sustainable urban environments globally.

Finally, future trends should focus on incorporating technological innovations, such as advanced connection designs, 3D printing, and automation, further improving the efficiency and cost-effectiveness of modular steel buildings.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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