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Review Article

A Review Study on Modular Buildings Construction

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Abstract *- Prefabricated modular steel construction offers a rapid and cost-effective solution for addressing the demand for low-cost housing, gaining popularity in multi-to-high-rise buildings due to its mechanical strength, eco-friendliness, and construction efficiency. While it significantly reduces onsite construction time, multi-story modular steel buildings (MSBs) can be vulnerable to failure during large earthquakes due to the intricate detailing and assembly required for these systems. Using a complete analysis of current research, this study addresses modular steel construction's environmental advantages, cost efficiency, and obstacles, such as seismic performance, connection details, and logistical complications. Furthermore, the research emphasizes modular construction's potential to transform the construction industry by lowering waste, increasing onsite efficiency, and providing flexibility for future adjustments. However, technical skills and competent management have been highlighted as crucial to overcome structural variability and assembly accuracy constraints. This assessment serves as a platform for future research on modular steel construction system optimization, with an emphasis on enhancing resilience, scalability, and overall performance in a variety of building applications.*

Keywords *- Modular steel construction, Prefabricated modular construction, Modular steel connections, Seismic Performance, Sustainability.*

1. Introduction

Modular buildings are transforming the construction industry by offering a faster, more sustainable, cost-effective alternative to traditional construction methods. Modular steel construction is a way of creating structures using prefabricated steel modules. These modules, commonly made of steel frames, are built offsite in a controlled environment and then delivered to the building site for final assembly [1].

Modular building methods are increasingly being employed across the globe. The applications span from low-rise to high-rise structures. Modern modular buildings include energy-saving systems [20]. Rapid construction and minimal onsite work make them ideal for disaster relief, emergency shelters, and temporary structures [2].

Rajanayagam et al. assess the feasibility of flat-pack modular systems in construction, focusing on design flexibility, structural integrity, and operational benefits. These systems have a high load-bearing capability, resilience to earthquakes and adverse environmental circumstances, and a longer lifespan.

The deployable and removable parts used in building structures, such as walls, roofs, and floors, change to adapt to evolving demands and constraints of space [3]. Other pertinent aspects include the fact that MSBs are designed to be easily adaptable for the future, making it simpler to disassemble modules for their relocation or repurpose toward achieving the goals of circular construction and sustainability in the building industry.

Modular Steel Construction (MSC) blends modularity with steel's inherent strength, durability, and recyclability. This combination is becoming increasingly common for multi-story and high-rise structures due to steel's capacity to withstand huge loads, resist environmental stresses, and retain long-term structural integrity.

MSC also promotes ideas of sustainable construction, as steel modules are recyclable and reusable, while offsite fabrication reduces waste and environmental impact.

However, problems still abound, most importantly with module connections, structural component variability, and logistical complexity in transportation and onsite assembly. To understand the capacity and seismic vulnerabilities of modular construction, the behaviour of the structure in seismic action must be studied.

Unlike other research, this assessment offers a more thorough and orderly examination of modular building construction. This review paper explores modular steel buildings' current applications, benefits, and limitations, examining advancements in structural design, sustainability, cost efficiency, and seismic performance.

The aspects that this paper deals with are (i) materials, (ii) connections, (iii) advantages over traditional construction methods, (iv) seismic performance, (v) challenges and limitations, (vi) Sustainability and environmental impact, and (vii) applications whereas several case studies were also presented here.

1.1. Research Methodology

This literature study on modular steel buildings (MSBs) was conducted using a systematic analysis of previous research on the subject, as well as industry reports and case studies pertaining to steel structures, modular construction, and their applications. Google Scholar is the primary source of the paper, and the important keywords include modular construction, modular steel structure, various types of connections in modular construction, Seismic evaluation of modular steel building, sustainability and environmental impacts of modular buildings, case studies on modular structure, etc. Screening is done based on title and abstract, after which recent year and indexed publications journals were considered.

Key issues identified during the study process include the mechanical characteristics of steel in modular systems, environmental sustainability, cost-effectiveness, speed of construction, and logistical and seismic risk. The methodology attempts to emphasize the developments, constraints, and future possibilities of MSBs in the construction sector by combining information from multiple sources, offering a thorough grasp of both theoretical and practical elements.

The research is categorized into materials like steel, concrete and lightweight composite materials, connections, structural performance in seismic actions, and sustainability factors. By synthesizing findings from various sources, the methodology aims to highlight the advantages over traditional construction methods, limitations, and future potential of MSBs in the construction industry, providing a thorough comprehension of both theoretical and practical aspects.

A total of 25 papers were selected for in-depth analysis of different literature and review of the academic papers.

2. Materials

There are various types of materials used for modular construction, and these are described below:

2.1. Lightweight Composite Materials

Steel modular systems provide advantages over concrete systems, such as lower weight and better design flexibility, but they confront durability and fire resistance difficulties. Liew et al. [4] provide a unique steel-concrete composite technology that addresses these concerns in high-rise modular construction.

This study models a 40-story modular building and analyses its lateral stability, inter-module connections, and lateral force resistance. The proposed lightweight composite system is believed to improve durability and flexibility while reducing overall weight, combining the merits of both steel and concrete for better performance.

2.2. Steel

Steel's strength, resistance, and versatility make it a good candidate for various modular systems, particularly in commercial and industrial domains. This project designs five unconventional modular designs for high-rise modular steel construction (MSC) modules that include staggered layouts as part of the assessment of the seismic response.

Each design is worked out within the set parameters of plans and structural parts so that an account of overall seismic stresses is elected and retrofitted. Particular layouts have different impacts on the lateral resistance and the deformation that occurs, which is significantly large.

Further, it is noted that there is a positive change towards the performance of the MCSs when there is a diffusion from parallel stacking arrangements to staggered arrangements done over time [5]. Steel modular building systems surpassed concrete systems in terms of construction speed, onsite worker productivity, reduction of waste, air pollution, and delivery trips, resulting in a considerable 62% reduction [6]. Steel modular systems are easy to remove and reassemble and, therefore, can be used for emergency purposes, like in China at the time of the COVID-19 pandemic [2]. Steel modular modules are approximately 20-35% lighter than concrete modular units [4].

2.3. Concrete

The concrete modular system was shown to be more cost-effective, productive, and energy-efficient than the steel system [6]. Despite being lighter than concrete, steel modular construction is rarely used in high-rise residential structures because of corrosion and fire safety concerns [4].

3. Connections

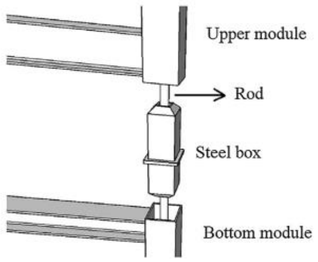
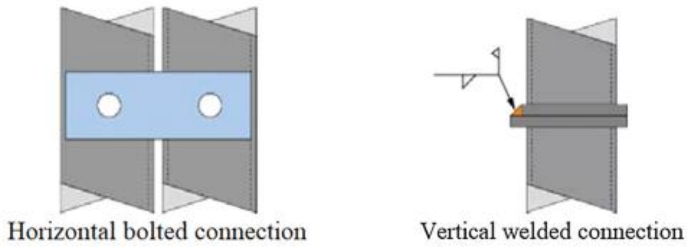
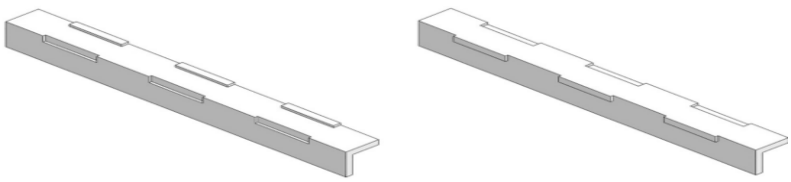
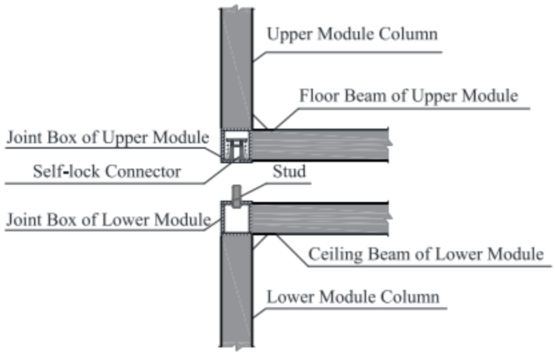
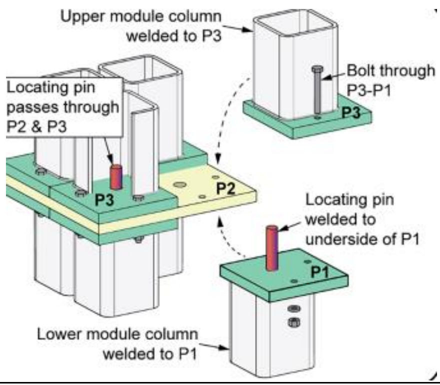
Connections in Modular Steel Construction (MSC) are critical components that link individual modules together to form a unified, stable structure. These connections are essential for maintaining the building's integrity, safety, and performance of the building, especially in high-rise and multi-story constructions.

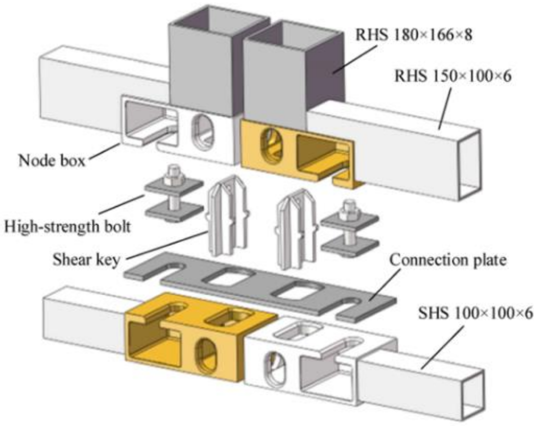
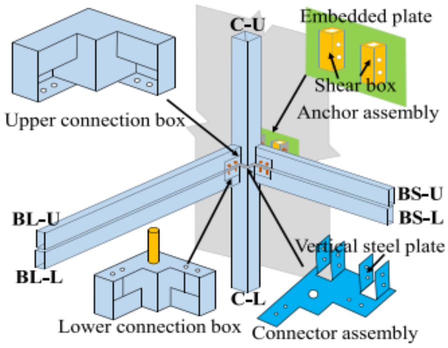
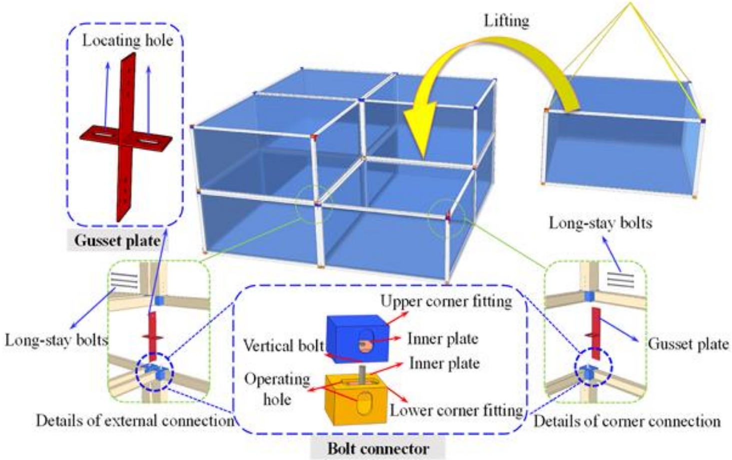
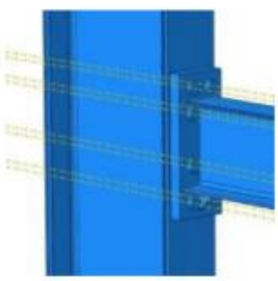
Proper connections ensure that the entire modular structure behaves as a single unit, particularly in resisting loads, such as wind or seismic forces. Connections are responsible for transferring loads between modules, including vertical, horizontal, and lateral forces.

One of the most prevalent types, bolted connections, provides convenience in assembly and disassembly. They are commonly applied for vertical and horizontal module-to-module connections, creating solid, long-lasting joints. A few modular systems involve interlocking systems, where modules are made to interlock precisely to provide stability and alignment. These systems have the potential to streamline the building process and enhance assembly accuracy.

Connections intra-modular are usually addressed connections within a module, similar to the case of traditional connection features. Intra-modular connections of MBSs apply welded and bolted connections.

Table 1. Connections

References	Connections	Experimental Setup
[7]	a. Vertical post-tensioned connection; b. Intermodular horizontal and vertical connections for MSBs	 a.  b.
[8]	Integrating connection strips	
[9]	Plug-in self-lock joint	
[10]	Interlocking inter-module connection	

[11]	Inter-module connection	
[12]	Module-to-core wall connection	
[13]	Fully prefabricated liftable connection (FPLC)	
[21]	Extended-Haunched end-plate connection	

4. Advantages Over Traditional Construction Methods

Conventional and modular construction life cycles consist of four stages. The production, transportation, and onsite installation of modules characterize the construction phase of modular buildings. Modular buildings offer chances to minimize energy and material usage compared to traditional techniques, even if certain activities are identical [14].

By using prefabricated components known as “modules” that are assembled onsite, the modular building approach provides a quicker alternative to conventional onsite construction. This methodology has an array of benefits over traditional building methods, including quicker build times, greater effectiveness, and enhanced sustainability. Scheduled work conducted in industries is also far more probable and represents less likelihood of the project’s deadline [22].

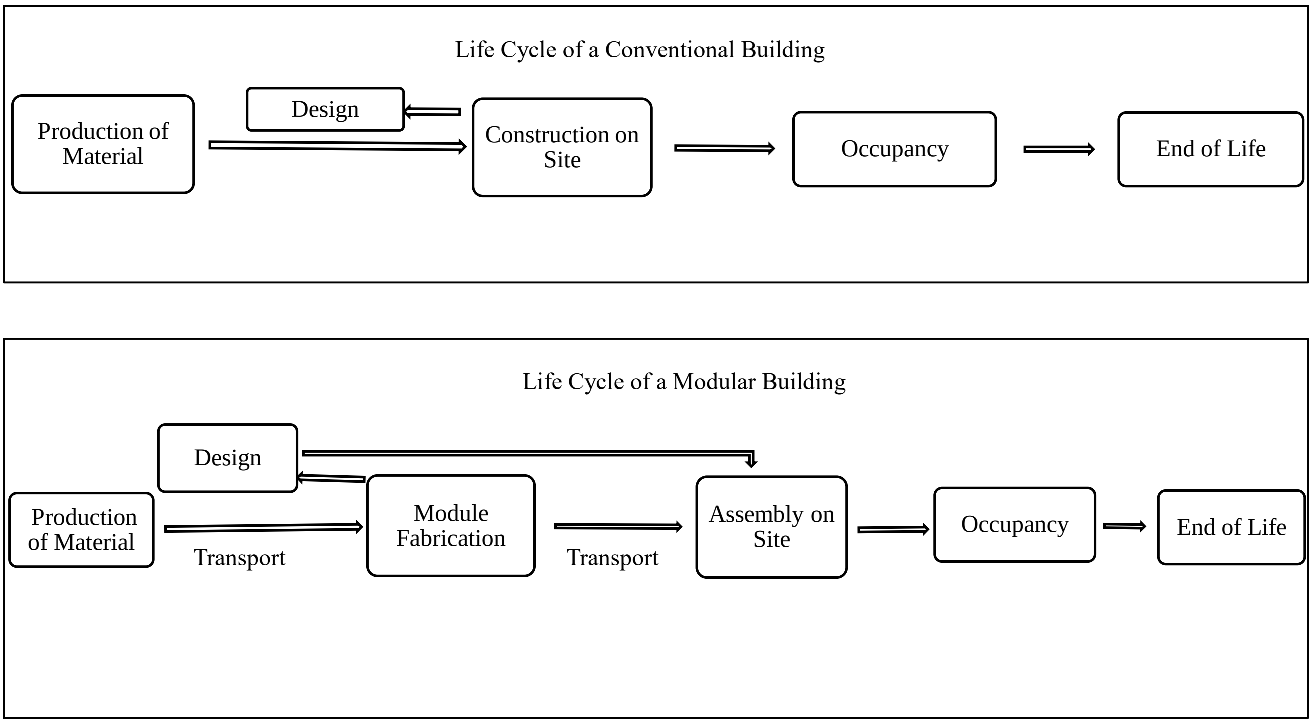


Fig. 1 Life cycle of modular versus traditional structures [14]

5. Seismic Performance

A four-story, nine-span MSC was subjected to nonlinear dynamic research in order to establish its mechanical reaction under different failure scenarios. The inquiry was to understand how the structure would respond to unanticipated failures, thus providing insight into its resilience towards slow collapse. The experiment proved that the MSC structures retain their integrity even in different failure conditions, where load redistribution takes place mainly inside the damaged spans [11]. The seismic performance of a four-story modular steel building (MSB) is assessed using incremental dynamic analysis (IDA) and nonlinear static pushover in 2D and 3D models. MSB constructions have a comparatively high maximum base shear resistance due to the extra columns [1]. The prefabricated elements are found to be efficient for various loading conditions, such as seismic, static, cyclic, dynamic, explosion, fire, and long-term [15].

6. Challenges and Limitations

Lately, the inadequate technical knowledge in handling modular steel buildings has restricted their implementation. It is causing incorrect design and assembly. For instance, there may be misalignments or structural weaknesses due to inconsistency in modules, possibly resulting from an inappropriate control of variability over construction components. Logistics are further complicated by improper handling and storage of prefabricated modules on site, which raises the possibility of damage or installation delays [16]. Modular design is constrained by delivery and building procedures since big, heavy components need sophisticated installation and heavy machinery [22]. When the tower crane’s lifting capacity exceeds 20 t, the cost rises by up to 60% [4]. Currently, modular buildings are constructed according to classic limit state criteria that favour stability, strength, and serviceability. There are quite a few design rules for prefabricated modular houses [15].

7. Sustainability and Environmental Impact

Offsite manufacturers’ financial sustainability is still in its early stages, and depending on the project type and market conditions, it may save anywhere from 30 to 50 percent of the time. While 10–20% cost reductions are possible for large-scale off-site manufacturing projects, smaller initiatives sometimes depend on using repeatable designs to gain economies of scale [17]. The overall amount of energy used and the environmental effect of modular building can be reduced [14]. A targeted sampling approach was used to select two representative modular undertakings in Hong Kong, one using concrete and the other using steel modules. Concrete and steel modular systems exceed their traditional equivalents in terms of environmental sustainability (66-70% reduced water use, 46-87% decreased waste disposal, and 25-50% reduced air pollution), social harmony (no accidents documented), and cost savings of over 25% [6]. Flat plate Modular Building Systems possess significant potential to transform the construction industry by providing efficient solutions, sustainable and flexible [3].

8. Applications

- Residential: Apartments, townhouses and modular homes.
- Commercial: Office buildings, retail stores and schools.
- Healthcare: Hospitals, clinics and medical facilities.
- Industrial: Warehouses, factories and large-scale storage solutions.

Modular construction is frequently employed for low-rise structures in several nations, including the United Kingdom and North America. Recent improvements have permitted the construction of some modular high-rise structures, although they are still restricted internationally.

Singapore: Singapore has promoted modular building for local projects to improve efficiency and save construction time and personnel. Modular construction projects in Singapore include (i) NTU North Hill Residence Hall and (ii) Crowne Plaza Hotel Extension, Changi Airport. A 40-storey building in Hong Kong has been developed with the help of prefabricated elements [4].

China: In China, at the time of emergency due to the COVID-19 pandemic, an affordable steel-framed modular construction was carried out for hospital purposes [2]. Seismic research was conducted for high-rise structures using several module configurations located in Beijing. Chinese code GB 50,011–2010 Code is used.

UK: The UK has taken a significant lead in developing modular construction technology for tall buildings. In all European countries, EN 1993-1 Eurocode is used to design steel structures and Eurocode 8-Part 3 for seismic assessment of existing steel structures. A 29-storey Apex House, Scape Wembley, was constructed from modules.

9. Case Studies and Real-World Applications

A comparison of 2D and 3D models of a four-story MSB structure is made using Incremental Dynamic Analysis (IDA) and pushover analysis, where the 3D model shows weaker structural capability against collapse than the 2D model, primarily due to the latter's failure to account for torsional effects [1]. Shi et al. prepared five different module arrangements for MSCs of high-rise modular steel constructions, with staggered arrangements, to check the seismic performance. Each of the plans is modelled with dimensions and detailing exactly defined so that its behavior under seismic loads can be checked exhaustively. The data indicate that alternative layouts significantly impact lateral resistance and deformation. The dynamic time history study demonstrates that staggered arrangements boost seismic performance compared to parallel stacked modules [5]. Several case studies of 12, 17 and 25-storey buildings in the UK.

Advanced analytical techniques are essential for the appropriate evaluation of steel structures since they typically display nonlinear behavior prior to reaching their maximum load. The research introduces the 'Practical Advanced Analysis Program (PAAP)', which improves predictions of inelastic seismic responses and refines the plastic hinge model, therefore outperforming current software. Three numerical examples and a case study of a large suspension bridge under two seismic scenarios are used to show the program's accuracy and usefulness. The quick results demonstrate how well PAAP anticipates the nonlinear behavior of steel structures, offering a quicker and more affordable solution than commercial design tools [18]. Palmiotta et al. considered an ideal case study in which structural response is evaluated through time history analyses. This research aims to develop seismic-resistance modules with minimal seismic impairment in seismic-prone locations, ensuring the integrity of elements and components (e.g. partitions, amenities) [23].

10. Conclusion

This paper thoroughly analyses modular steel structures and connections, looking at their structural behavior, contemporary developments, and difficulties in the building sector. This paper deals with all the aspects required in the modular construction of the building.

- The modular building saves time and money and reduces environmental impact compared to typical onsite construction methods.
- According to the review, the current innovative modular connections, on average, only modestly meet the functional, structural, and construction performance requirements. Thus, more innovation through research and development is required to enhance modular connections, particularly for multi-story buildings, to increase the industry's acceptance and implementation of offsite construction solutions.
- This study reviews current breakthroughs in modular technologies, focusing on structural features such as systems, different types of connections, analysis, and design.
- Inter-modular connections outperformed standard steel connections in terms of lateral load performance, load transfer mechanism, and robustness under progressive collapse, according to studies.

10.1. Future Scope

Several limitations should be addressed in future studies for deep knowledge and development of techniques supporting modular constructions. These are as follows:

- Modular construction is preferable for various applications due to its enhanced precision, quality, and waste reduction, yet there have been few investigations on the earthquake-related behavior of modular steel structures (MSBs).
- Future research suggests developing a computationally efficient software tool for advanced analysis and everyday design of modular tall structures.
- With the integration of smart technologies, modular buildings will feature systems for monitoring energy use, temperature, and other conditions, making them more efficient and adaptable.
- As of right now, modular building is not subject to any particular design codes or regulations. As a result, the designers' sole option is to use the standard steel connection rules when creating modular connections. Guidelines for the structural design of modular structures are currently lacking.
- Previous analytical and practical research has clearly demonstrated the limitations of guidelines in the context of modular construction design. In order to arrive at an agreement about the standard design principles for modular construction, additional experimental and theoretical investigations are required in numerous aspects of the study.
- There is no research discussing dynamic or cyclonic wind loads for modular structures. More work is required to study the dynamic tremorous response of modular structures to wind loads.
- Particularly in multi-story applications, modular structures' fire resistance calls for further study and better laws.

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References

[1] Amirahmad Fathieh, and Oya Mercan, "Seismic Evaluation of Modular Steel Buildings" *Engineering Structures*, vol. 122, pp. 83-92, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[2] Perampalam Gatheeshgar et al., "Development of Affordable Steel-framed Modular Buildings for Emergency Situations (Covid-19)," *Structures*, vol. 31, pp. 862-875, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[3] Heshachanaa Rajanayagam et al., "A-State-Of-The-Art Review on Modular Building Connections," *Structures*, vol. 34, pp. 1903-1922, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[4] J.Y.R. Liew, Y.S. Chua, and Z. Dai, "Steel Concrete Composite Systems for Modular Construction of High-Rise Buildings," *Structures*, vol. 21, pp. 135-149, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[5] Fengwei Shi et al., "Seismic Behavior of High-Rise Modular Steel Constructions with various Module Layouts," *Journal of Building Engineering*, vol. 31, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[6] Wei Pan, and Zhiqian Zhang, "Benchmarking the Sustainability of Concrete and Steel Modular Construction for Buildings in Urban Developments," *Sustainable Cities and Society*, vol. 90, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[7] Rafaela Sanches, Oya Mercan, and Brent Roberts, "Experimental Investigations of Vertical Post-Tensioned Connection for Modular Steel Structures," *Engineering Structures*, vol. 175, pp. 776-789, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[8] Pezhman Sharafi et al., "Interlocking System for Enhancing the Integrity of Multi-storey Modular Buildings," *Automation in Construction*, vol. 85, pp. 263-272, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[9] Xiao-Meng Dai et al., "Experimental Study on Seismic Behavior of a Novel Plug-In Self-Lock Joint for Modular Steel Construction," *Engineering Structures*, vol. 181, pp. 143-164, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[10] Andrew William Lacey et al., "New Interlocking Inter-Module Connection for Modular Steel Buildings: Experimental and Numerical Studies," *Engineering Structures*, vol. 198, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[11] Liang Zong et al., "Progressive Collapse Analysis on Modular Steel Construction Based on a Simplified Joint Model," *Thin-Walled Structures*, vol. 198, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[12] Sidi Shan, and Ben Mou, "Development of an Innovative Module-To-Core Wall Connection for Steel-Framed Modular High-Rise Buildings," *Journal of Constructional Steel Research*, vol. 214, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[13] En-Feng Deng et al., "Seismic Behavior of a Novel Liftable Connection for Modular Steel Buildings: Experimental and Numerical Studies," *Thin-Walled Structures*, vol. 197, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[14] Mohammad Kamali, Kasun Hewage, and Rehan Sadiq, "Conventional Versus Modular Construction Methods: A Comparative Cradle-To-Gate Lca for Residential Buildings," *Energy and Buildings*, vol. 204, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[15] Wahid Ferdous et al., "New Advancements, Challenges and Opportunities of Multi-Storey Modular Buildings – A State-Of-The-Art Review," *Engineering Structures*, vol. 183, pp. 883-893, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[16] Yaik-Wah Lim et al., "Planning and Coordination of Modular Construction," *Automation in Construction*, vol. 141, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[17] R.M. Lawson, and R.G. Ogden, "'Hybrid' Light Steel Panel and Modular Systems," *Thin-Walled Structures*, vol. 46, no. 7-9, pp. 720-730, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[18] Huu-Tai Thai, and Seung-Eock Kim, "Practical Advanced Analysis Software for Nonlinear Inelastic Dynamic Analysis of Steel Structures," *Journal of Constructional Steel Research*, vol. 67, no. 3, pp. 453-461, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[19] Huu-Tai Thai, Tuan Ngo, and Brian Uy, "A Review on Modular Construction for High-rise Buildings," *Structures*, vol. 28, pp. 1265-1290, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[20] Elena M. Generalova, Viktor P. Generalov, and Anna A. Kuznetsova, "Modular Buildings in Modern Construction," *Procedia Engineering*, vol. 153, pp. 167-172, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[21] B.P.R.V.S. Priyatham et al., "Seismic Analysis and Design of Steel Beam-Column Connections in Indian Standard Code Framework," *Materials Today: Proceedings*, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[22] Jeffrey Molavi, and Drew L. Barral, "A Construction Procurement Method to Achieve Sustainability in Modular Construction," *Procedia Engineering*, vol. 145, pp. 1362-1369, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[23] Annarita Palmiotta et al., "Seismic Behaviour of Steel Modular Buildings: Numerical Analysis and Comparisons between Different Design Solutions," *Procedia Structural Integrity*, vol. 44, pp. 1156-1163, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[24] "*Eurocode 3: Design of Steel Structures - Part 1-1: General Rules and Rules for Buildings*," European Standard En Norme Europeenne Europaische Norm, Report, pp. 1-93, 2005. [Google Scholar] [Publisher Link]

[25] EN 1993-1-8 (2005) (English): Eurocode 3: Design of Steel Structures - Part 1-8: Design of Joints, European Standard En Norme Europeenne Europaische Norm, Report, pp. 1-135, 2005. [Google Scholar] [Publisher Link]