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BUILDING THE FUTURE: A LITERATURE REVIEW ON THE ADVANCEMENTS AND INNOVATIONS IN PREFABRICATED MODULAR STRUCTURES

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Abstract:

Prefabricated modular buildings have gained significant attention in the construction industry due to their potential to revolutionize the traditional building process. This paper presents a comprehensive literature review encompassing analytical, experimental, and model studies conducted worldwide to evaluate the structural stability of low, middle, and high-rise modular steel and concrete structures. By examining relevant data from diverse sources, the study analyzes the performance of prefabricated modular buildings in terms of structural integrity and safety. The literature review encompasses studies conducted in countries, including United States, Canada, Germany, Japan, and Australia, among others. These countries have been at the forefront of researching and implementing prefabricated modular buildings, contributing valuable insights into their structural behavior and performance. Each country brings unique perspectives and experiences in terms of design methodologies, construction techniques, and regulatory frameworks, enriching the global knowledge base in this field. Furthermore, the paper explores the contributions of these structures towards sustainable development, highlighting their environmentally friendly and energy-efficient characteristics. The research reveals that prefabricated modular buildings possess inherent sustainable attributes, including reduced construction waste, enhanced resource efficiency, and improved energy performance. The modular construction approach facilitates the use of recycled materials, minimizes site disturbance, and allows for better control over energy consumption during both construction and operation phases. The findings of this literature review support the assertion that prefabricated modular buildings have immense potential to meet the demands of sustainable development while maintaining structural stability.

Keywords: module connections; living buildings; prefabricated construction; finite element analysis; resource efficiency; sustainable construction

1. Introduction

In recent years, the infrastructure industry has witnessed a growing interest in Prefabricated Modular Buildings (PMBs), owing to their potential to revolutionize the conventional building process. Prefabricated modular structures offer an innovative approach to construction, characterized by the assembly of pre-engineered components in controlled factory settings and subsequent on-site installation. This research paper presents a comprehensive literature review that explores the advancements and innovations in prefabricated modular structures, with a particular focus on their structural stability, sustainability, and performance.

Prefabricated modular buildings, also known as off-site construction or modular construction, involve the manufacturing and assembly of building components off-site, followed by their transportation to the construction site for final installation.

Joints configurations and column boundary conditions in prefabricated modular buildings play a major role in identifying their differences with conventional steel buildings. A corner-supported modular building includes up to eight discontinuous columns and sixteen beams connected by beam-to-column connections or intra-connections, in addition to inter-connections, whereas traditional buildings have a continuous column and two beams connected by beam-to-column connections. A lack of continuity in a modular structure's joints will result in differences in the structure's stiffness and dynamic properties, affecting its behaviour and performance against gravity and lateral forces. [39].

The versatility of prefabricated modular buildings allows for their application in various sectors, including residential, commercial, institutional, and industrial. The modular construction approach offers several advantages over traditional on-site construction methods, making it an appealing option for many construction projects. The worldwide modular construction market is expected to develop at a 5.7% CAGR from USD 91.0 billion in 2022 to USD 120.4 billion by 2027. [1]. This growth is being driven by a number of factors, including the need for faster, cost-effective & sustainable construction methodology.

The United States is the largest market for modular construction, followed by China, the United Kingdom, Germany, and Japan [1].

1.1 Types of Modular Buildings

Modular Buildings may be broadly classified into different types on the basis of following criteria:

1.1.1. Classification on the basis of Permanency

Modular Building Institute, USA classifies modular buildings in the following two categories [2]:

1. **Permanent modular buildings:** These are designed to be installed in one location and remain there for the long term. They are typically more durable & customizable than relocatable modular buildings.

2. **Relocatable modular buildings:** They are designed to be moved from one location to another, thereby also known as Living Buildings. These structures are less expensive and easier to transport.

Table 1 summarizes the key differences between permanent and relocatable modular buildings:

Feature	**Permanent Modular Buildings**	**Relocatable Modular Buildings**
Intended use	Long-term	Temporary
Materials	Concrete, steel, wood	Lightweight materials
Insulation	Yes	No
Weatherization	Yes	No
Transportation	Not necessary	Wheels or skids
Applications	Residential, commercial, industrial	Construction offices, disaster relief shelters, military barracks

1.1.2. Classification on the basis of Construction Methodology

According to Lusby-Taylor et al. [2004] [3], modular buildings may be classified in to the following types on the basis of the way their manufacturing conditions and the way they are handled at site:

1. **Modular (Volumetric) Construction:** This approach entails generating entire three-dimensional components or modules with great precision and efficiency in a regulated industrial setting. These components are subsequently delivered to the job site for assembly and installation.
2. **Panelized Construction:** Panelized construction entails manufacturing flat panel modules in a factory environment, including walls, floors, and roofs. These panels are then delivered to the construction site and assembled to form a three-dimensional structure.
3. **Hybrid (Semi-Volumetric) Construction:** Hybrid construction blends modular and panelized methods of building. Modular modules, sometimes known as "Pods," are commonly utilised in areas that require a high level of care and repetition, such as kitchens and baths. The rest of the structure or home is made of panels. This method enables a mix of manufacturing accuracy and on-site flexibility.
4. **OSM (Off-Site Manufacturing) Sub-assemblies and Components:** This category includes building approaches that employ factory-fabricated sub-assemblies or components inside a traditionally produced structural framework. Roof cassettes, pre-cast concrete foundation assembly, and other inventive sub-assemblies are examples. It does not include conventional features like as window sets, door sets, and roof trusses.
5. **Off-Site Manufacturing (OSM):** This category includes unique house construction techniques and structural systems that are outside of the OSM categories. It covers methodologies or systems that are not classed as modular, panelized, or using specialised off-site production procedures.

Figure 1: Modular Construction House (Left), Panelized Construction (Center) and Hybrid Construction (Right)

(Source – https://smartbid.co/the-future-of-modular-construction; https://www.landabuilders.me /blog-landbuilders/panelized-construction, https://www.base-4.com/how-bathroom-pods/)

Additionally, Gunawardena et al. [2019] [4] underlined the two key advantages of volumetric (modular) building in terms of decreased manpower and construction time when compared to other conventional and modern construction methods. Figure 2 below highlights the typical on-site labour days and typical construction period, respectively, for various types of structures including volumetric (modular) construction. It can be clearly seen that on-site labour days for volumetric construction is only 20% of that for brick & block construction while typical construction period stands at 40% only, clearly indicating that volumetric construction is both labour & cost efficient.

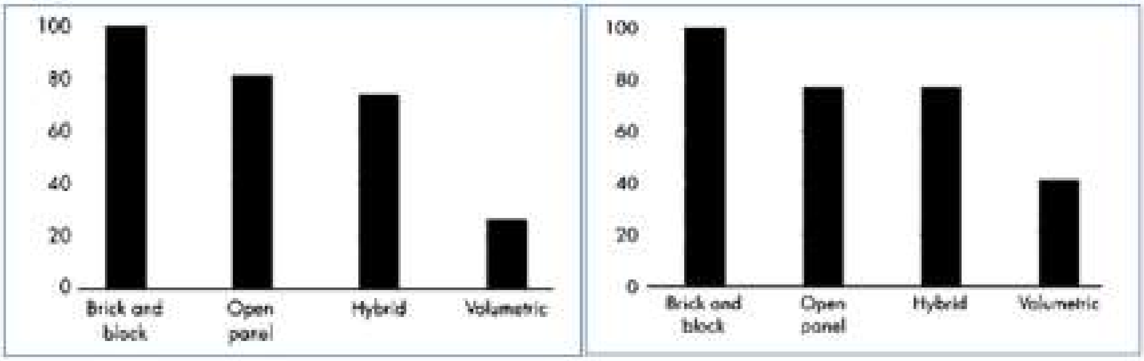


Figure 2: Typical on-site labour days as a proportion of brick & block requirements in percentage (Left) and Typical construction period as a proportion of brick & block requirements in percentage (Right) [4]

1.1.3. Classification on the basis of Structural Support provided by the Modules

According to Lawson et al. [2012] [5], there are two types of building modules classified based on their load transfer mechanisms. These classifications describe how the modules transfer loads and distribute forces within a modular structure.

1. **Corner Supported Modules:** In this classification, the modules of a modular building rely on corner supports for structural stability & strength. These corner supports, typically steel or

concrete columns, are placed at the corners of each module. The modules are then connected or stacked together to form the building structure, as can be seen from Figure 3 (left).

2. **Load-Bearing Modules:** Load-bearing modular buildings, as seen in Figure 3 (right) are designed in such a way that the individual modules themselves act as structural elements and carry the weight and loads of the building. When the modules are assembled and connected, they collectively provide the required structural support for the entire building.

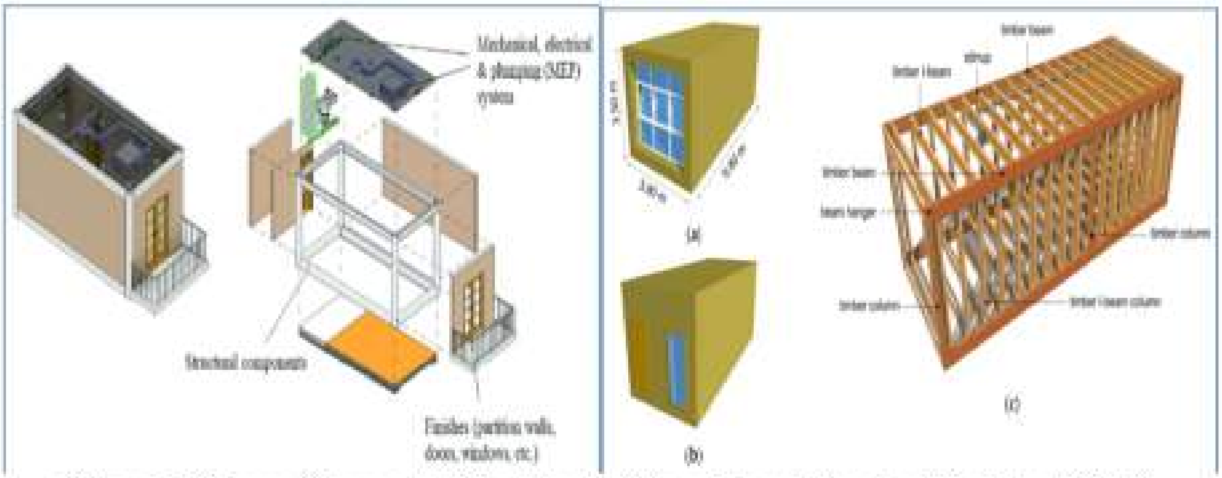


Figure 3: Corner Supported Modules (Left) and Load-Bearing Modules (Right)
(source: www.researchgate.net; https://encyclopedia.pub/)

1.1.4. Classification on the basis of Structural Systems

Gunawardena [2016] [6] classified the modular buildings in four types: Load Bearing Modules, Central RC Core & Directly Connected Modules, Central RC Core & Poured Concrete Modules and, Advanced Corner Supported Modular System with Stiff Modules. These classifications reflect different structural approaches used in modular buildings, each with its own advantages and considerations regarding height, load transfer, and reusability, as summarized in Table 2 below.

Table 2: Comparison of Four Types of Structural Systems

System	Load-Bearing	Central RC Core and Directly Connected Modules	Central RC Core and Poured Concrete Floors	Advanced Corner Supported Modular System with Stiff Modules
Height	1-2 stories	8-10 stories	25-30 stories	No limit
Structural system	Load-bearing modules	Corner-supported modules with central RC core	Stacked modules with poured concrete diaphragm	Stiff modules with reduced dependency on central core
Lateral load resistance	No lateral load resistance	Lateral load resistance provided by central RC core	Lateral load resistance provided by central RC core and poured concrete diaphragm	Lateral load resistance provided by stiff modules
Reusability of modules	High	Medium	Low	High
Concrete usage	Low	High	High	Low
Cost	Low	Medium	High	High
Flexibility	Low	Medium	Low	High

1.1.5. Classification on the basis of Purpose

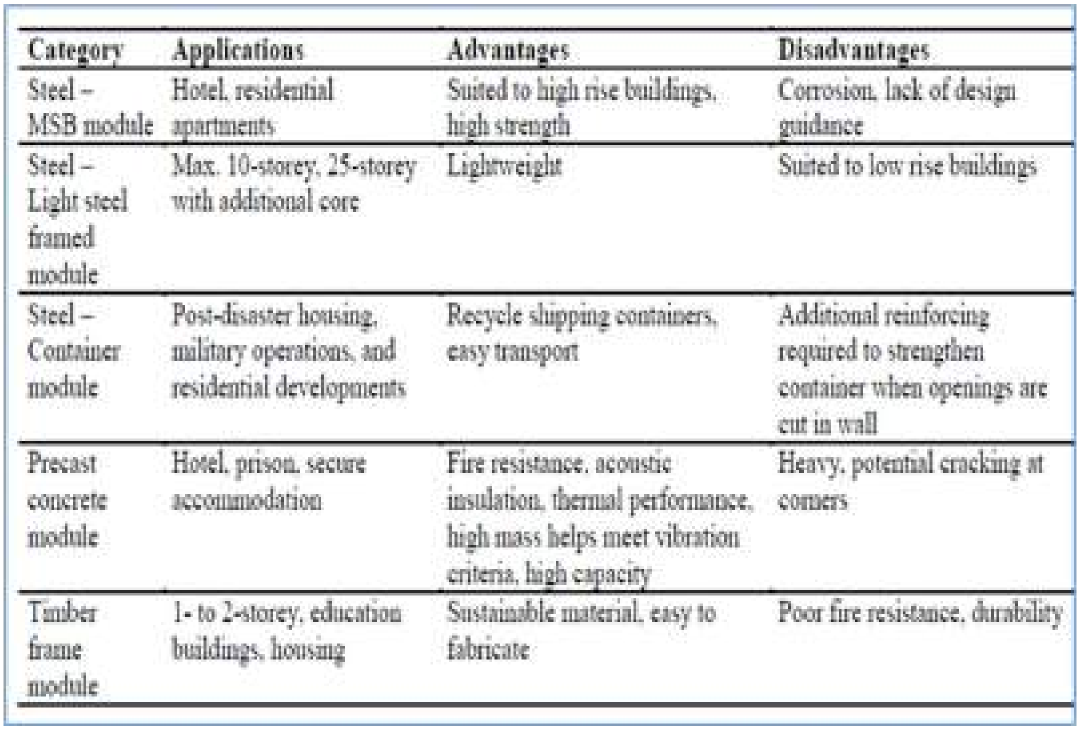
PMBs may further be classified on the basis of their use:

1. **Residential Modular Buildings:** These modular structures are designed for residential purposes, such as single-family homes, apartments, or dormitories.
2. **Commercial Modular Buildings:** These buildings are constructed for commercial purposes, including office buildings, retail stores, educational institutions, healthcare facilities, and hotels.

1.1.6. Classification on the basis of Construction Materials

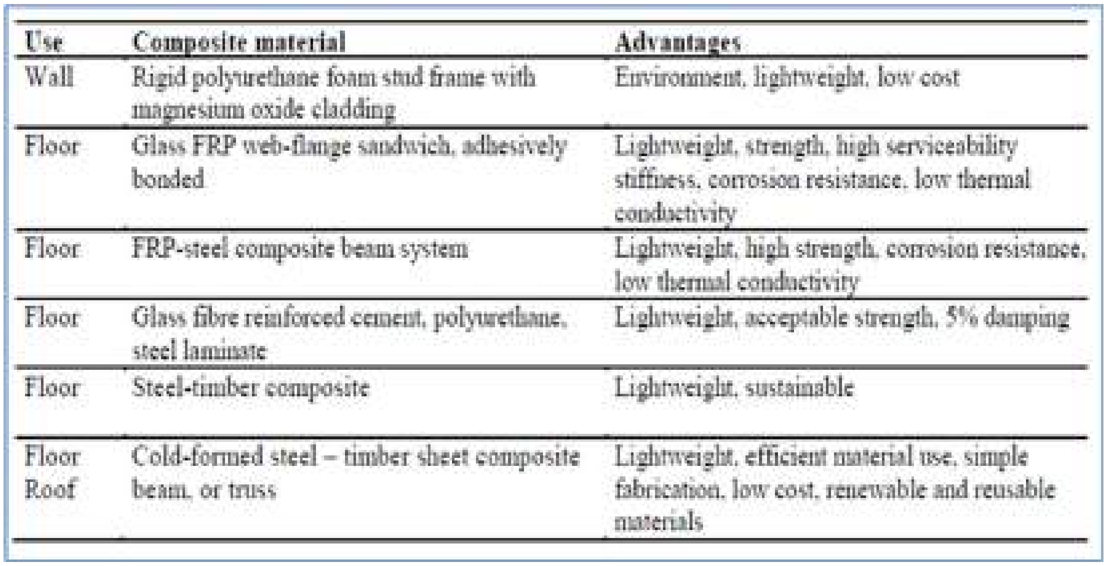
The selection of construction materials depends on factors such as structural requirements, local building codes, project budget, and desired architectural aesthetics. Lacey et al. [2017] [7] classifies modules on the basis of construction materials, as shown in Table 3. Further, the authors give some applications of various composite materials that may be used in modular construction, as can be seen from Table 4 below.

Table 3: Module Classification on the Basis of Construction Materials



Category	Applications	Advantages	Disadvantages
Steel – MSB module	Hotel, residential apartments	Suited to high rise buildings, high strength	Corrosion, lack of design guidance
Steel – Light steel framed module	Max. 10-storey, 25-storey with additional core	Lightweight	Suited to low rise buildings
Steel – Container module	Post-disaster housing, military operations, and residential developments	Recycle shipping containers, easy transport	Additional reinforcing required to strengthen container when openings are cut in wall
Precast concrete module	Hotel, prison, secure accommodation	Fire resistance, acoustic insulation, thermal performance, high mass helps meet vibration criteria, high capacity	Heavy, potential cracking at corners
Timber frame module	1- to 2-storey, education buildings, housing	Sustainable material, easy to fabricate	Poor fire resistance, durability

Table 4: Composite Materials used in Modular Construction



Use	Composite material	Advantages
Wall	Rigid polyurethane foam stud frame with magnesium oxide cladding	Environment, lightweight, low cost
Floor	Glass FRP web-flange sandwich, adhesively bonded	Lightweight, strength, high serviceability stiffness, corrosion resistance, low thermal conductivity
Floor	FRP-steel composite beam system	Lightweight, high strength, corrosion resistance, low thermal conductivity
Floor	Glass fibre reinforced cement, polyurethane, steel laminate	Lightweight, acceptable strength, 5% damping
Floor	Steel-timber composite	Lightweight, sustainable
Floor Roof	Cold-formed steel – timber sheet composite beam, or truss	Lightweight, efficient material use, simple fabrication, low cost, renewable and reusable materials

1.2 Construction Methodology

The construction methodology of a modular structure is summarized as follows [8]:

1. Design & Manufacturing: The design phase is the first step in the construction of a modular building. In this phase, the architect or designer will create the plans for the building, including the layout, materials, and finishes. Once the design is complete, the modules will be manufactured in a factory, so as to maintain high quality standards.
2. Transportation to Site: Once the modules are manufactured, they will be delivered to the construction site, by truck or rail, and they are then craned into place. The delivery phase ensures that the modules arrive at the site on time and in good condition.
3. Site Assembly: Once the modules are delivered, they will be assembled on the construction site, using steel beams or connectors.
4. Grid Connection: The assembly phase is important because it ensures that the modules are properly connected at the joints and that the building is structurally sound.

The construction methodology & stages have been depicted in Figure 4.

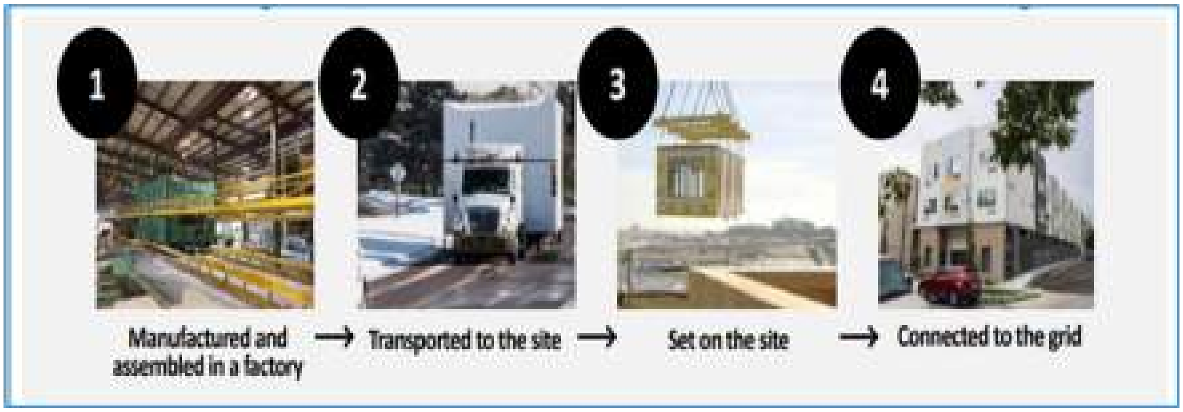


Figure 4: Four Stages of Industrialized Construction of Modular Buildings [8]

1.3 Advantages of Prefabricated Modular Buildings

PMBs are made up of prefabricated modules that are assembled/ connected on-site, to significantly reduce construction time and cost. According to a report by the Modular Building Institute, USA, modular building projects can be completed 30% to 50% sooner than traditional construction [2], as depicted in Figure 5.

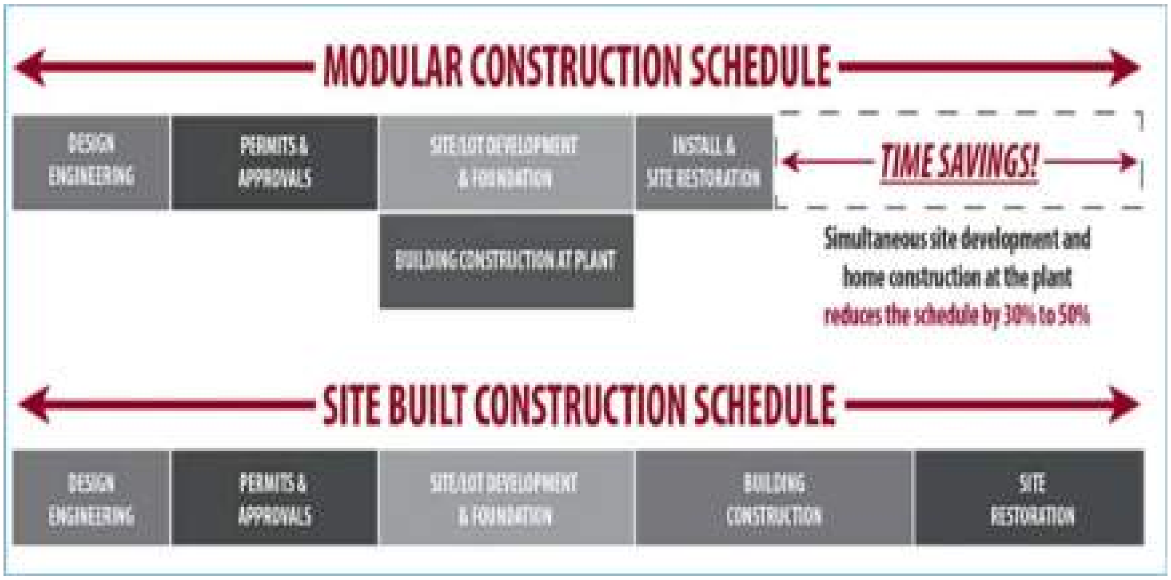


Figure 5: Time Comparison of Project Schedule [2]

PMBs are also more sustainable than traditional buildings. They can be made from recycled materials and they can be designed to be energy efficient. For example, a study by the U.S. Department of Energy aims to achieve 50% reduction in US Greenhouse Gas Emissions by 2030 [8]. Some of the highlighted advantages of PMBs are stated below:

a. Increased Speed and Efficiency
b. Enhanced Quality Control
c. Cost Savings
d. Sustainability and Environmental Benefits

1.4 Limitations of Prefabricated Modular Buildings

Despite the numerous highlighted advantages of PMBs, there are also some challenges. One challenge is that it is usually more difficult to obtain financing for PMBs than traditional buildings as reliability on these structures for various loading conditions & site criteria needs to be assessed. Additionally, PMBs may not be suitable for all types of projects because of the following reasons:

a. Design Limitations due to the need for module transportation and assembly constraints can affect architectural freedom and customization options to some extent.

b. Transporting large modules from the factory to the construction site requires careful planning and coordination. Access to the construction site, route selection, and logistical challenges must be considered to ensure smooth transportation.

c.

d. While prefabricated modular buildings offer long-term cost savings, the initial investment required for factory setup and specialized equipment is higher.

Various theoretical studies conducted on Prefabricated Modular Buildings (PMBs) serve several purposes and provide valuable insights for researchers, designers, and industry professionals. These include Performance Evaluation, Design Optimization, Code Development & Compliance, Innovation & Advancement and Cost & Time Optimization.

Experimental studies on modular structures are carried out to evaluate their structural performance, test materials and components, validate computational models, ensure compliance with building codes, and drive innovation.

Computational studies involve subjecting modular systems to controlled tests to measure parameters such as load-carrying capacity, stiffness, and response to dynamic forces. They help researchers understand the structural behavior of modular structures, identify weaknesses, and refine design approaches.

The chronological literature review presented in this paper encompasses a wide range of analytical, experimental, and model studies conducted worldwide to evaluate the structural stability, performance, and sustainability of prefabricated modular buildings. The research includes studies conducted in countries at the forefront of modular construction, such as the United States, Canada, Germany, Japan, and Australia, among others. These countries have made significant contributions to the knowledge base in this field, offering diverse perspectives and experiences in design methodologies, construction techniques, and regulatory frameworks. Ultimately, it highlights the importance of adopting modular construction practices for a more sustainable and resilient built environment.

1.5 Literature Review

One of the earliest cited experimental studies of PMBs was by Harrison [2003] [25] who discussed the need for blast resistant yet portable buildings (Refer Figure 6 below) within explosively hazardous areas. The author predicted that these buildings will become increasingly common in the petroleum and chemical processing industries as the need for safety continues to grow.

Figure 6: Representative Blast Resistant Portable Structure [25]

Hart et al. [2005] [9] introduced the approach of Living Buildings in the structural design of buildings. The study provided reliable estimates of building performance during future severe winds and earthquakes. This data is analyzed on the basis of the building Medical Data Center, California, that was constructed just prior to the 1994 Northridge earthquake. The base shear model of the building is studied.

Annan et al. [2009] [43] investigated the seismic performance of 2-, 4-, and 6-story MSB-braced frames in Vancouver, by subjecting their nonlinear analytical models to an ensemble of 20 earthquake ground motions of different intensities. The results showed that the spectral acceleration was a more consistent intensity measure for the MSB-braced frame system. Figure 7 below compares the experimental results of a study on the seismic behavior of MSB-braced frames to the analytical predictions made using a specific modeling technique.

The comparison suggests that the modeling technique is capable of accurately predicting the seismic behavior of MSB-braced frames.

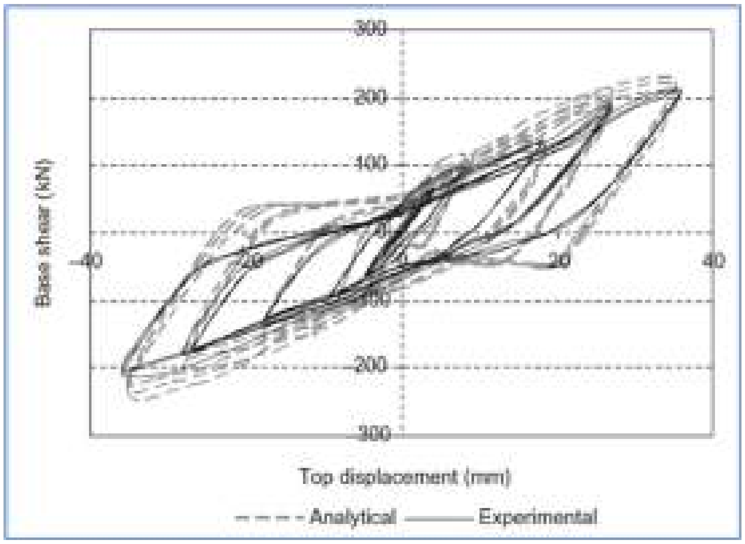
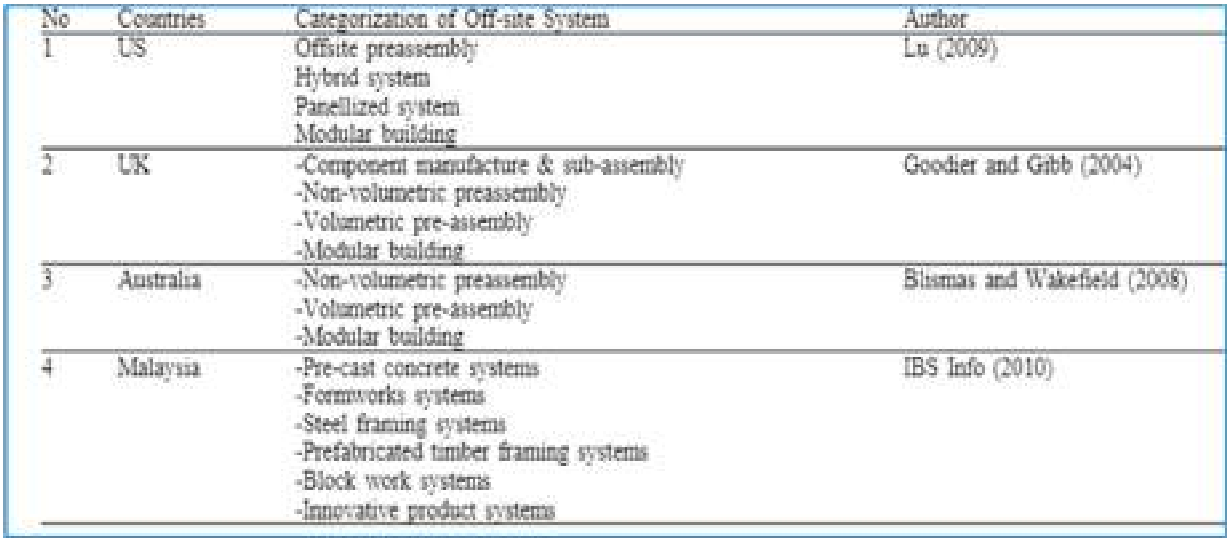


Figure 7: Comparison of experimental and analytical load-displacement curves of MSB-braced specimen [43]

Azman et al. [2010] [10] explored the challenges that were faced by the construction industry in integrating modern off-site construction methods based on the experiences different countries. Figure 8 presents the categorization of off-site system in various countries, as suggested by Azman et al.



No	Countries	Categorization of Off-site System	Author
1	US	Offsite preassembly Hybrid system Panellized system Modular building	Lu (2009)
2	UK	-Component manufacture & sub-assembly -Non-volumetric preassembly -Volumetric pre-assembly -Modular building	Goodier and Gibb (2004)
3	Australia	-Non-volumetric preassembly -Volumetric pre-assembly -Modular building	Blismas and Wakefield (2008)
4	Malaysia	-Pre-cast concrete systems -Formworks systems -Steel framing systems -Prefabricated timber framing systems -Block work systems -Innovative product systems	IBS Info (2010)

Figure 8: Categorization of Off-site System in various countries [10]

Kim et al. [2011] [44] investigated the potential of modular mega-frame structures to resist progressive collapse. The authors used finite element software code MIDAS (2009) to simulate the collapse of a column in a modular mega-frame structure. The results showed that the structure was not able to resist progressive collapse if only four corner columns were present. However, the structure was able to resist progressive collapse if additional floor trusses, moment-resisting frames, or vertical mega-bracing were added. The authors concluded that the story-wise arrangement of the floor beams was also important in preventing symmetrical failure modes.

Further, Lawson et al. [2012] [11] demonstrated how the basic cellular concept in modular construction may be applied to a different buildings of varying forms & heights. Two modular spatial configurations were proposed: a) A cluster of modules accessed from the core or from lobbies next to the core; and b) A corridor layout with modules accessed from corridors on each side of the core, as depicted in Figure 9 below.

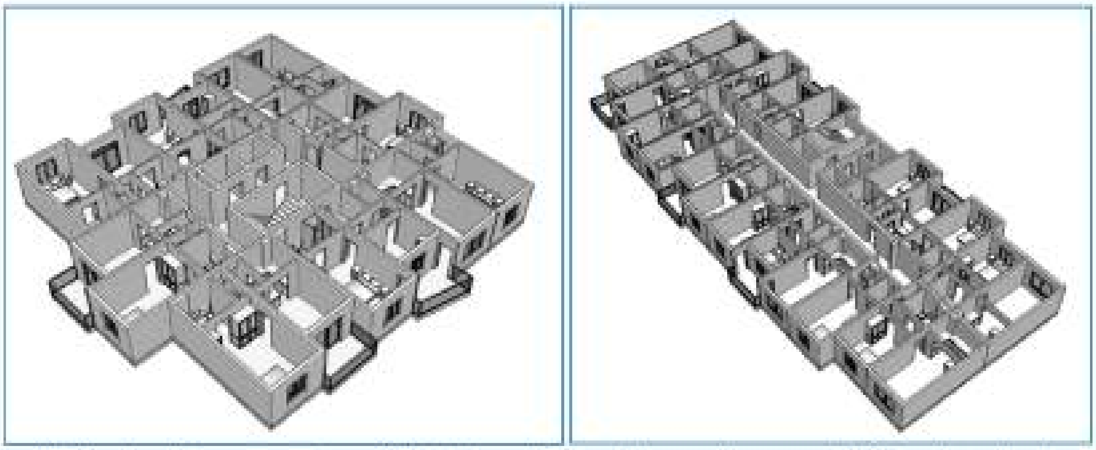


Figure 9: Typical Construction of Modules clustered around a core (left) and typical corridor arrangement of modules (right) [11]

Aye et al. [2012] [12] compared traditional concrete construction to modular steel and wood building technologies. Figure 10 depicts a summary of the findings of this study. The graph shows that modular steel and timber constructions save significantly more energy in terms of volume, mass, and embodied energy than standard concrete structures.

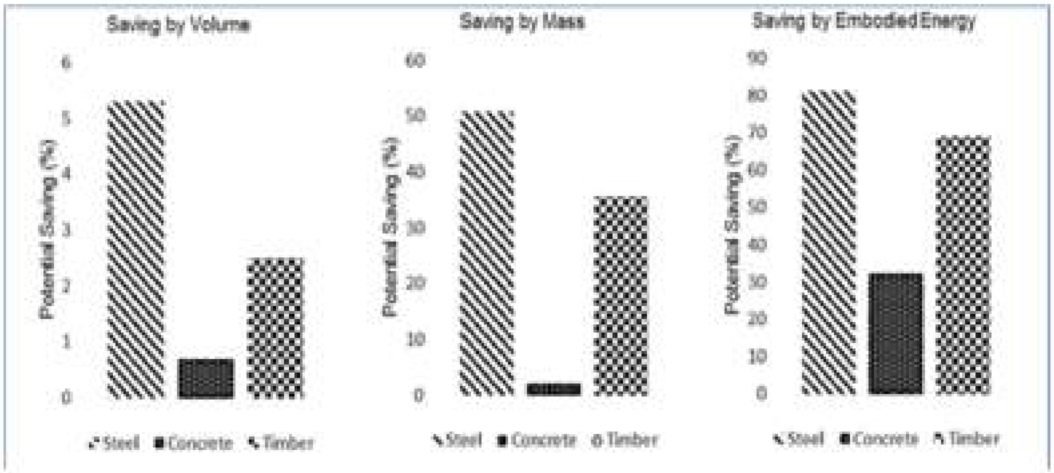


Figure 10: Total Volume, Mass & Embodied Energy of Concrete & Pre-fabricated Steel & Timber Building Scenarios with potential of percentage savings achieved from reuse of materials through Modular Construction [12]

Tawil et al. [2014] [13] summarized the advancements in computational structural simulation for progressive collapse modeling between 2003 and 2014. Hong et al. [2014] [26] studied 12-story modular system joints and connections, choosing the best system based on structural and economic efficiency. The study tested the connection's rotation behavior and quasi-static cyclic loading, finding that a 12mm block joint provided adequate structural performance.

Further ahead, Generalova et al. [2016] [14] reiterated the above stated drawbacks and highlighted the need for more research and development to improve the performance of modular buildings so that they can be widely adopted. Fathieh et al. [2016] [45] conducted a study on the seismic performance of modular steel buildings in accordance with Canada's National Building Code. The study aimed to understand the seismic behavior of modular steel buildings, especially in seismically active regions. The research has some limitations, such as using a single building model, which may limit generalization to all modular steel buildings. Additionally, wind loading effects were not considered in the study. Nonetheless, the findings provided valuable insights into the seismic performance of modular steel buildings.

Lacey et al. [2017] [7] discussed various aspects such as the advantages of modular construction, the types of modules used in modular buildings (steel or concrete), and the joint connections between these modules – Inter-modular, Intra-modular & Module to Foundation Connections (Refer Figure 11) in addition to their advantages & disadvantages (Table 5). They highlight the need for investigating the behaviour of mid- to high-rise modular buildings subject to blast loading and and loading.

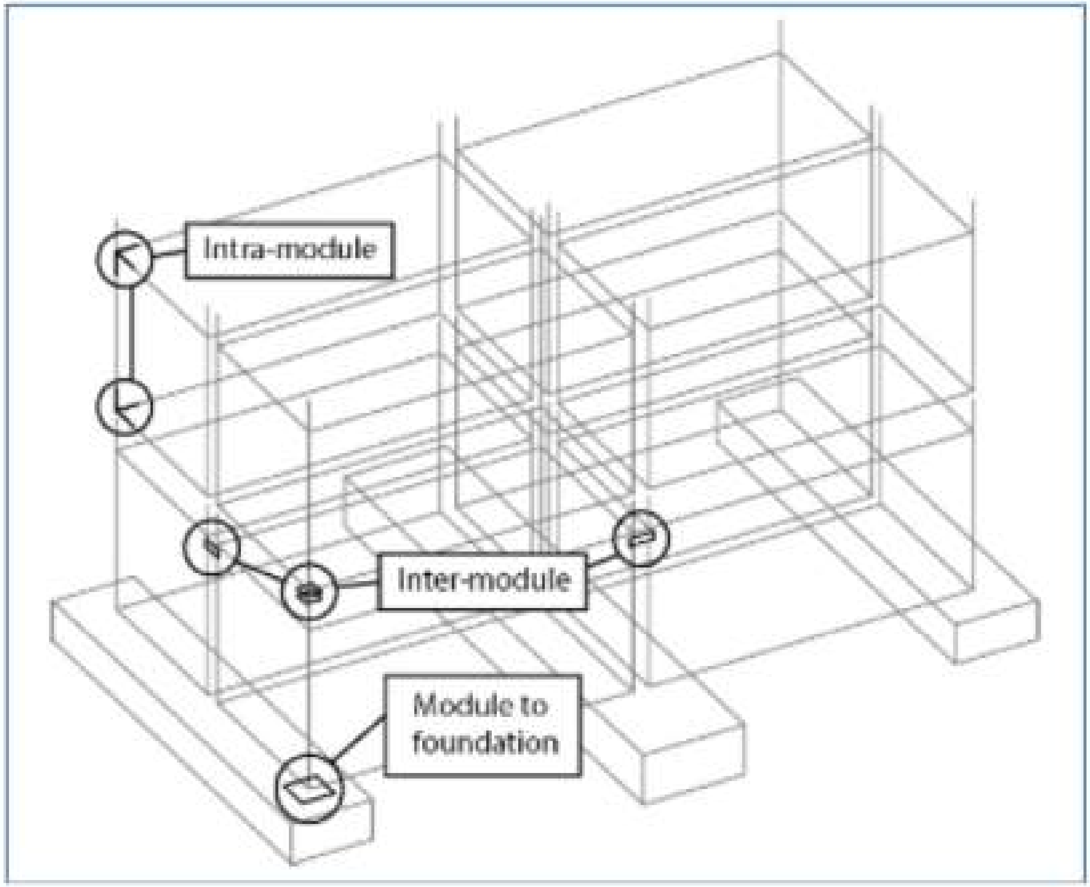
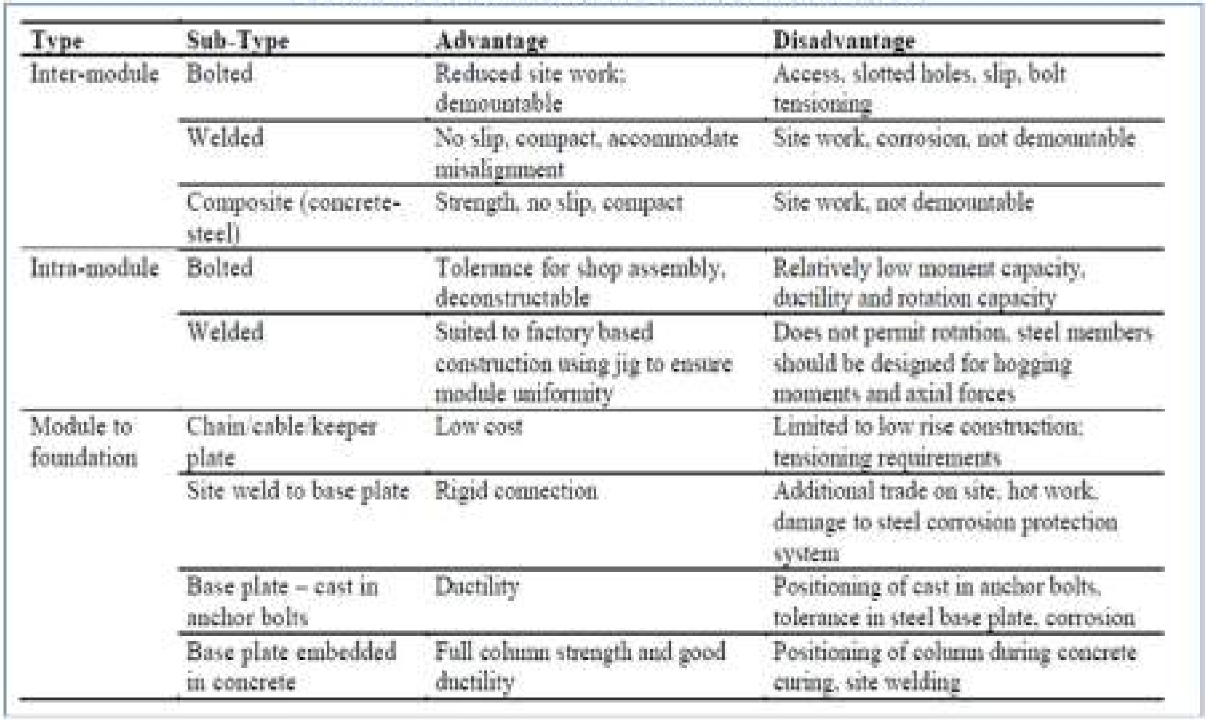


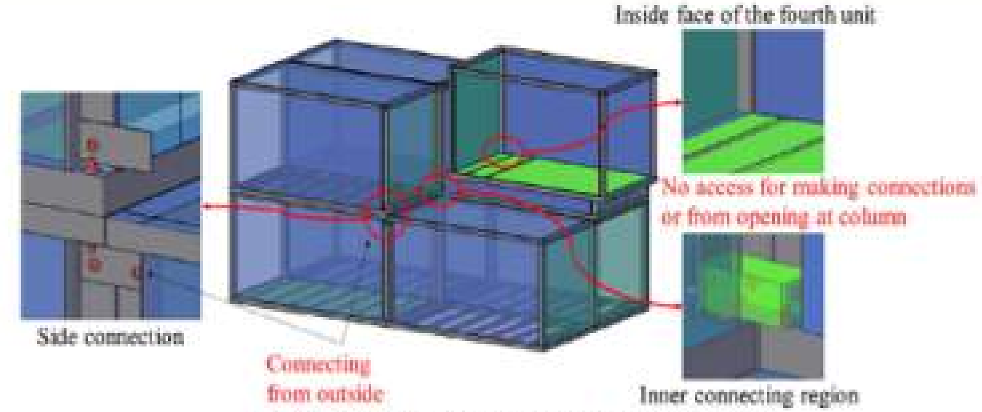
Figure 11: Types of Modular Joints [7]

Table 5: A Summary of Modular Joints [7]

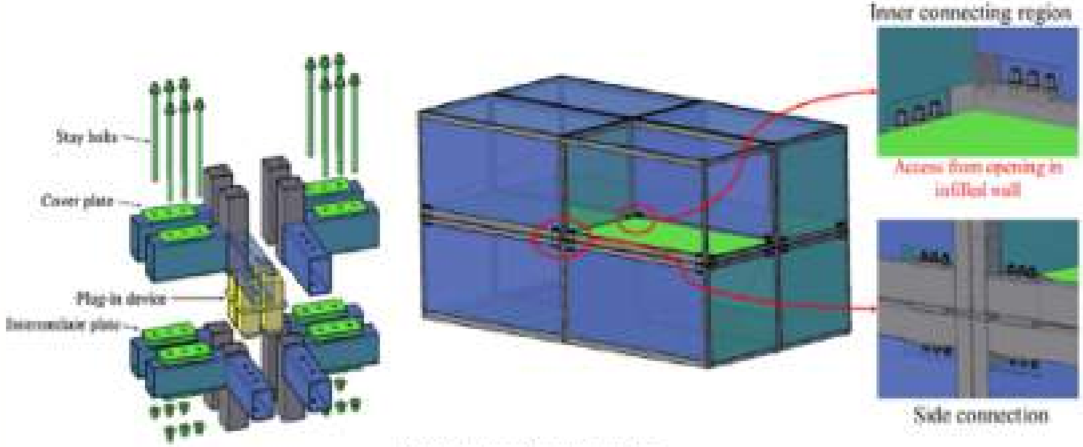


Type	Sub-Type	Advantage	Disadvantage
Inter-module	Bolted	Reduced site work; demountable	Access, slotted holes, slip, bolt tensioning
	Welded	No slip, compact, accommodate misalignment	Site work, corrosion, not demountable
	Composite (concrete-steel)	Strength, no slip, compact	Site work, not demountable
Intra-module	Bolted	Tolerance for shop assembly, deconstructable	Relatively low moment capacity, ductility and rotation capacity
	Welded	Suited to factory based construction using jig to ensure module uniformity	Does not permit rotation, steel members should be designed for hogging moments and axial forces
Module to foundation	Chain/cable/keeper plate	Low cost	Limited to low rise construction; tensioning requirements
	Site weld to base plate	Rigid connection	Additional trade on site, hot work, damage to steel corrosion protection system
	Base plate – cast in anchor bolts	Ductility	Positioning of cast in anchor bolts, tolerance in steel base plate, corrosion
	Base plate embedded in concrete	Full column strength and good ductility	Positioning of column during concrete curing, site welding

Chen et al. [2017] [27] focussed on conducting an experimental study & finite element analysis on interior connections in modular steel buildings (MSBs) to indicate that the gaps formed between upper and bottom columns due to the construction between two unit joints, influence deformation patterns and bending load distribution at each joint. Stiffeners were shown to effectively increase stiffness and load-bearing capacity but could potentially reduce ductility performance.



(a) Conventional plate and single bolt connection



(b) Proposed connection

Figure 12: Construction of inner connecting region in the proposed MSB connection [27]

In another study, Chen et al. [2017] [28] proposed an innovative connection design for modular steel buildings (MSBs) using an intermediate plug-in device and beam-to-beam bolt system. The design aims to eliminate on-site welding and improve load transfer capacity and seismic behavior. Static and quasi-static tests showed gaps between columns affect deformation patterns and bending demand distribution.

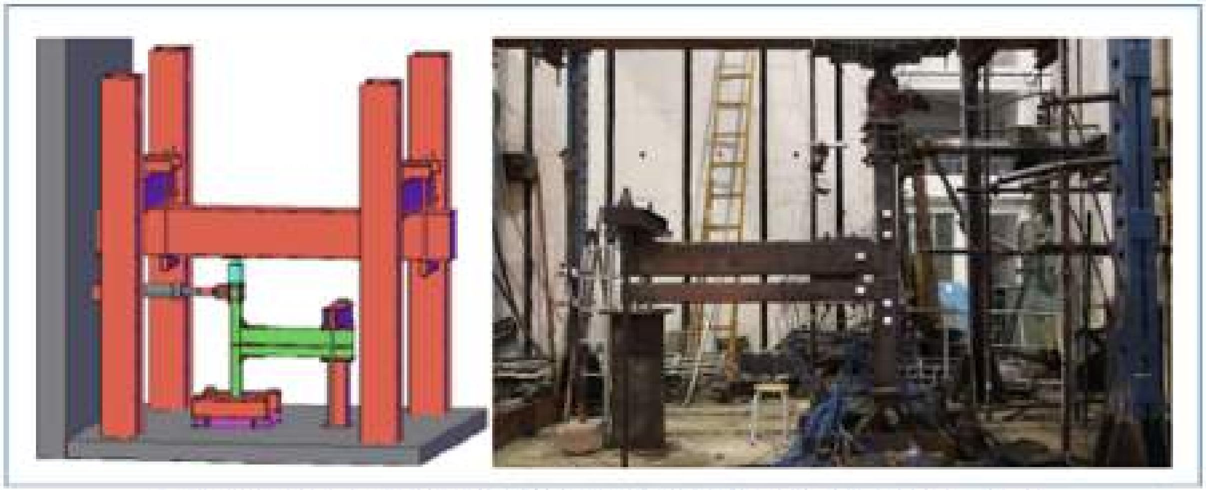
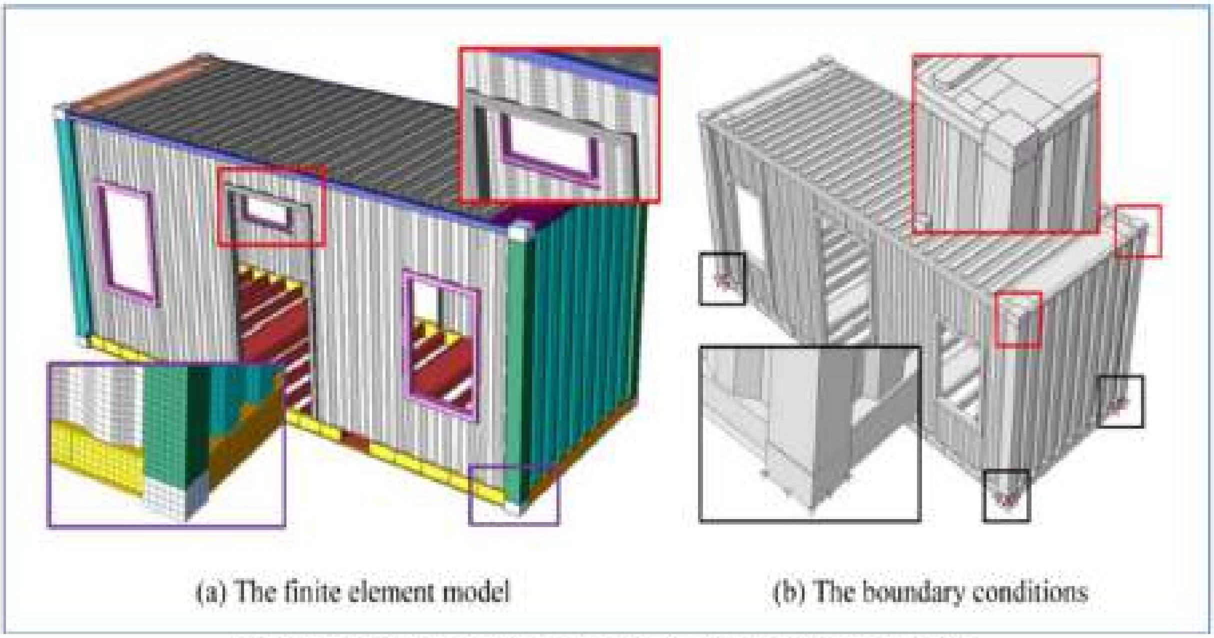


Figure 13: Test-Set up for T-shaped MSB Cnnection [28]

Sener et al. [2017] [29] investigated a novel fabrication technology for modular steel-concrete construction. The technology was able to produce high-quality modules that were strong, durable and easy to assemble on-site. Zuo et al. [2017] [46] studied the stiffness of container buildings with holes using finite element simulation and experimental verification.



(a) The finite element model

(b) The boundary conditions

Figure 14: Container model establishment [46]

Pasnur-Patil [2018] [15] explored the advancement of contemporary modular construction techniques aimed at offering the population affordable, comfortable, and sustainable housing. Landolfo et al. [2018] [30], studied the seismic performance of modular lightweight steel buildings, part of the ELISSA project, and found that these buildings performed well under seismic loading with minimal damage. The study also found that their dynamic properties were comparable to traditional concrete buildings, suggesting that modular lightweight steel buildings could be a viable alternative to traditional concrete in seismically active regions.

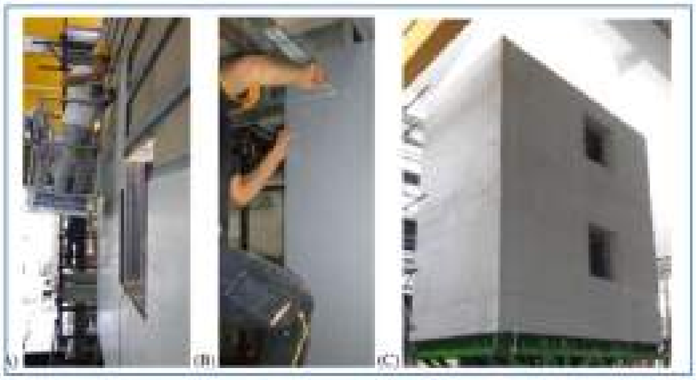


Figure 15: Completed building: external wall panel fixing, interior wall panel fixing, and final building view under ELISSA Project [30]

Khan et al. [2019] [16], Gunawardena et al. [2019] [17] and Ferdous et al. [2019] [18] further emphasized the use of modular construction over traditional construction methods. Dai et al. [2019] [31] proposed a plug-in self-lock joint to address the challenges of modular steel construction joints. The study explained its working mechanism, conducted pull-out tests, and tested eight full-scale joint specimens under quasi-static load. The findings validated a simplified mechanical model for the joint's behavior in the elastic stage, and provided design recommendations for future construction.

Figure 16: Healthcare Facility (left) and Railways Station Components (right) constructed in Melbourne, Australia in 2018 [17]

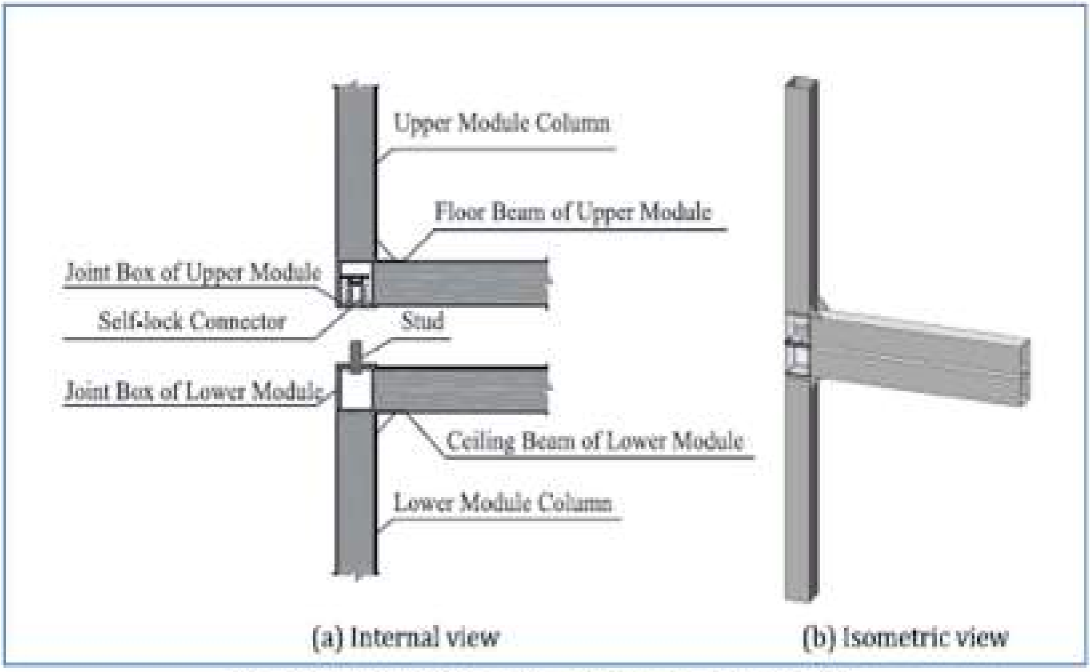


Figure 17: Plug-in self lock joint [31]

Ormarsson et al. [2019] [32] conducted research on modular-based timber buildings using numerical and experimental methods. They developed a three-dimensional finite-element model to study its performance and reliability under mechanical and moisture loading.

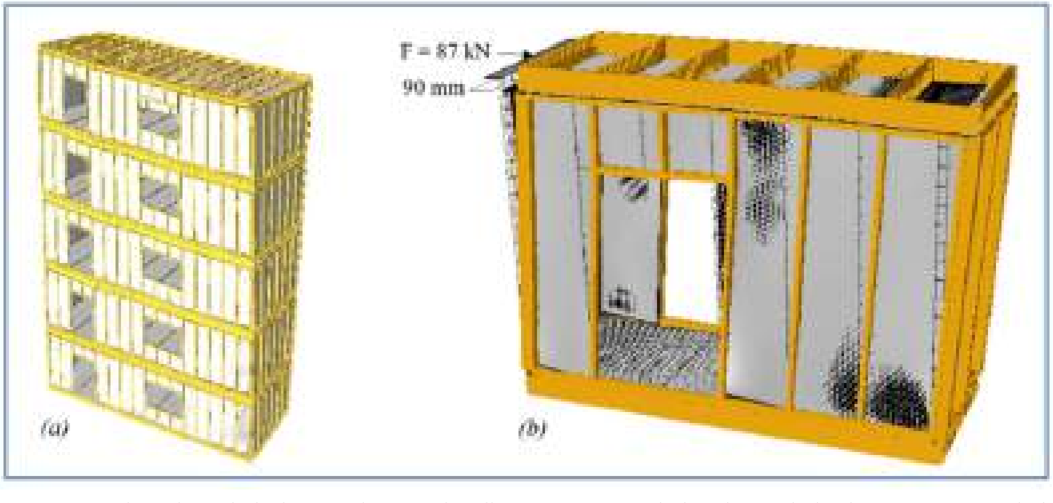


Figure 18: Simulated deformations of a five story modular-based timber tower and the testmodule

studied, (a) structure loaded in biaxial bending, (b) structure forced to horizontaldisplacement of 90 mm at the left top side of the module (deformations sized by factor of 2) [32]

Wang et al. [2019] [33] introduced a modular connection solution using bolts in columns to address defects in existing connections. The study found that specimens with smaller diagonal stiffeners lost bearing capacity due to welding seam failure, while specimens with large diagonal stiffeners experienced beam buckling.

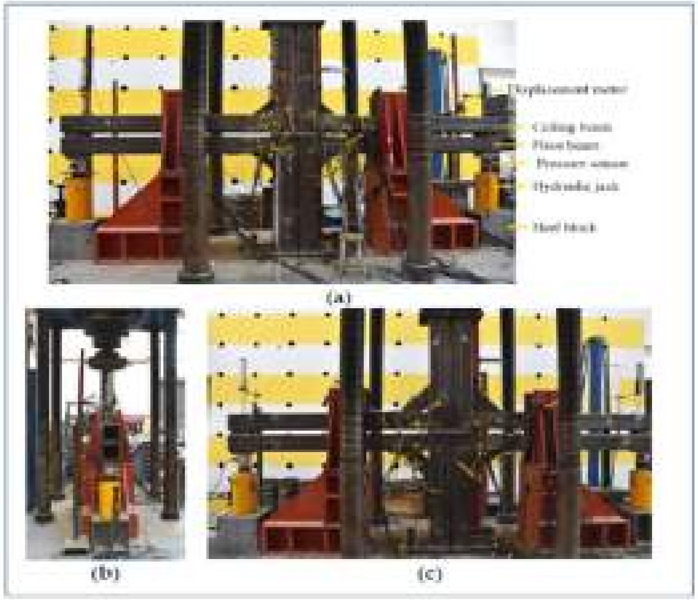


Figure 19: Testing site. (a) Front view of S1 (b) side view of S1 (c) front view of S2 Top of Form [33]

Luo et al. [2019] [47] investigated the structural robustness of steel-framed modular buildings using alternative load path method and LS-DYNA software. The findings indicated that increasing the number of modules per floor, the number and capacity of supporting posts, the rotational stiffness and capacity of inter-module connections, and the use of longitudinal wall bracing could improve the collapse resistance of steel modular buildings. The study also discovered that taking into account floor slabs offered a more accurate description of collapse processes, and that the structure was more sensitive to the removal of modules (or posts) near a building's end corner.

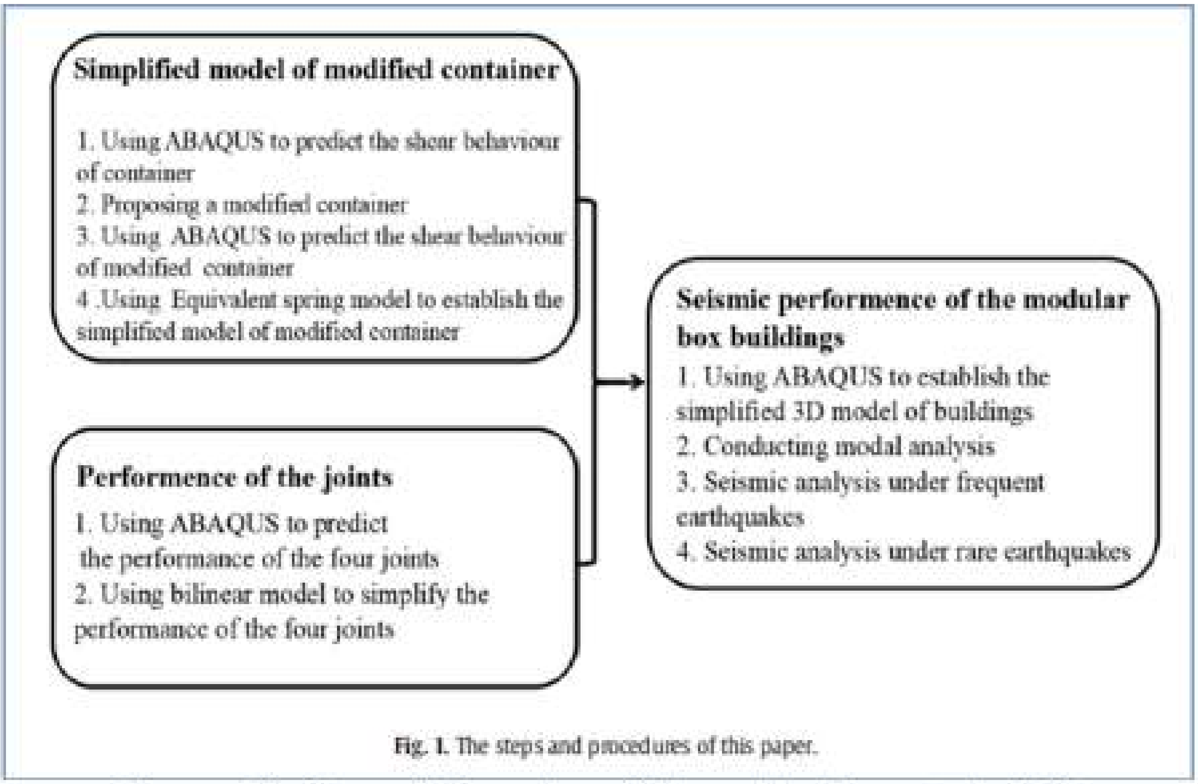


Figure 20: Steps & Procedure followed by Feng et al. [50]

Thai et al. [2020] [19] provided a critical analysis of current advancements in high-rise building modular construction technology with a focus on offering potential solutions for future study. Future research was also suggested for some potential solutions to these problems, such as (i) creating composite modules with lighter and stronger structural members, (ii) creating smart joining techniques with higher strength and stiffness and ease of installation, (iii) creating a computationally efficient computer tool for advanced analysis and routine design of modular tall buildings, and (iv) developing new materials with higher strength and stiffness (v) establishing design standards to hasten the adoption of modular building in the actual world.

Through a comprehensive three-step research process involving bibliometric, quantitative, and qualitative analyses, the literature on Modular integrated construction (MiC) was extensively examined by Abdelmageed – Zayed [2020] [20]. The analysis identified ongoing research trends, highlighted current gaps, and recommended future research directions. Future research directions involved stakeholder analysis, contractual relationships, cost comparisons, and curriculum integration. A similar study was carried out by Young-Seidu [2020] [21].

Sendanayake et al. [2020] [34] conducted an experimental study on inter-modular connections for modular buildings, focusing on their seismic performance. They found that using unique energy-absorbing connections improved seismic performance, shifting primary failure locations from columns to connection areas. However, limitations included laboratory conditions and lack of practical application cost considerations.

Zhang et al. [2020] [35] presented the results of an experimental study on the seismic performance of the connection for Assembled-Type Light Steel (ATLS) Modular House. It was found that the connection can withstand significant cyclic loading without significant damage. The study also found that the axial load significantly impacted the connection's performance, with better results when applied. The findings suggest that the ATLS modular house connection is a viable option for seismically active regions, demonstrating its ability to withstand significant cyclic loading.

(a)Failure mode of column (b)Bucking of column

(c)Broken of corner fitting (d)Necking of bolt B1

Figure 21: Typical experiment phenomenon of specimen under 40 KN axial cyclic loading [35]

Yang et al. [2020] [36] investigated the seismic behavior of a two-story modular structure by subjecting a full-scale model to a series of simulated earthquakes. The structure performed well under seismic loading, withstanding significant forces without collapse. Only minor cracking was observed in the joints between the modular units. Alembagheri et al. [2020] [48] discussed the results of a parametric analysis on the progressive collapse responseof typical corner supported modular steel buildings. The impact of inter-modular connection design on anti-collapse resistance of these buildings was the main topic of discussion. The findings highlighted the translational behavior of connections, particularly in shear, as having a substantial impact. When the modules were made to individually function as full rigid moment frames, it was observed that the rotational stiffness did not significantly contribute to maintaining overall stability. In another research, Alembagheri et al. [2020] [49] analysed how inter-module connections affect a building's ability to withstand scenarios of gradual collapse brought on by gravity and involving the removal of individual or combinations of complete modules from the ground floor. The final capacity for collapse of the modular buildings as well as their collapse mechanism and failure modes were determined. It was demonstrated that the modular buildings are far more resilient and capable of withstanding collapse than their conventional equivalents.

Feng et al. [2020] [50] used numerical simulation to explore the seismic behaviour of multi-story modular box structures. The study performed modal analysis and construction analysis under frequent and infrequent earthquakes. The buildings' finite element (FE) models were made up of modified containers and four different types of joints. The FE approach was used to forecast the performance of the redesigned container and four types of joints, which were then simplified into a bilinear model. The analogous spring model was used to represent the simplified performance of the redesigned container, and spring components were used to simulate the simplified performance of four types of joints in ABAQUS. The steps and procedures of this paper are shown in figure below. The results of the study showed that multi-story modular box buildings with the current joints do not satisfy the Chinese code. New connections and structural systems are required for further application.

Hořínková [2021] [22] provided an overview of the advantages and disadvantages of modular construction. Chen et al. [2021] [37] presented the results of an experimental study on a novel self-locking inter-module connection to enhance the seismic performance of modular steel buildings. The study included four cyclic tests on full-scale specimens, followed by the development and validation of detailed and simplified finite element models. The connection withstood lateral loads without major damage and showed good ductility. However, the study's limitations include a small number of tested specimens and did not consider wind loading, materials, or long-term corrosion. Modular construction offers advantages like integrity, speed, and emission reduction. However, the effect of laminated double beams on lateral force resistance is not fully understood. A study by Xu et al. [2021] [38] found that corner plug-in junctions strengthen sub-frame components and superimposed bending action reinforces structural integrity. This analytical procedure aids in modular construction design.

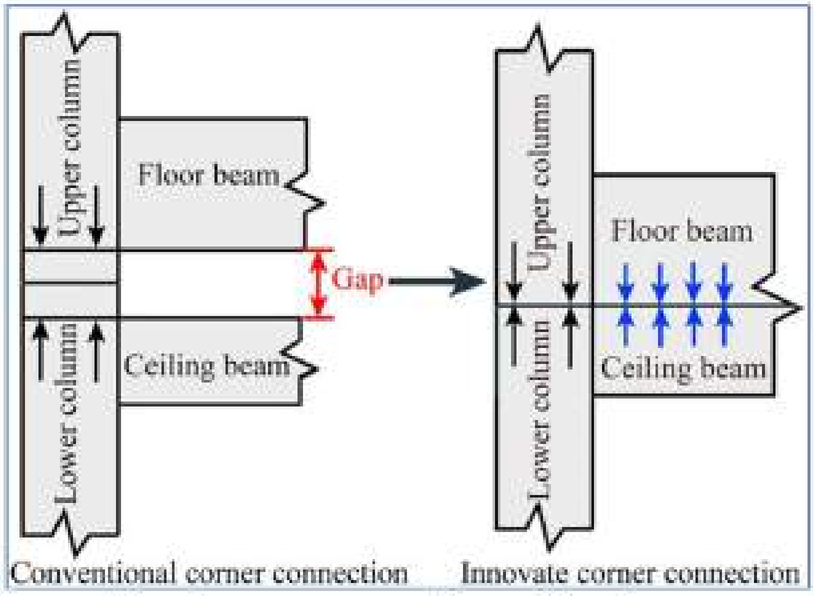


Figure 22: Conventional corner connection vs Novel corner connection [38]

Can He et al. [2021] [51] examined the structural resilience of corner-supported modular steel buildings with an emphasis on various inter-module connections. They used high fidelity finite element analysis to examine a sub-structure taken from a five-story modular building in a corner column removal scenario. They found that the inter-module connection types would influence the beam-column joint characteristics, which rule the resistance of MiC structures to progressive collapse.

Gatheeshgar et al. [2021] [52] presented a novel approach to the design and construction of modular buildings that were specifically suited for emergency situations. They proposed a number of innovative features that improved the performance of modular buildings in terms of healthcare, structural, fire, and lightweight performance. They conducted a comprehensive assessment of the proposed design using numerical models. The results showed that the proposed design could achieve significant improvements in performance over traditional modular buildings.

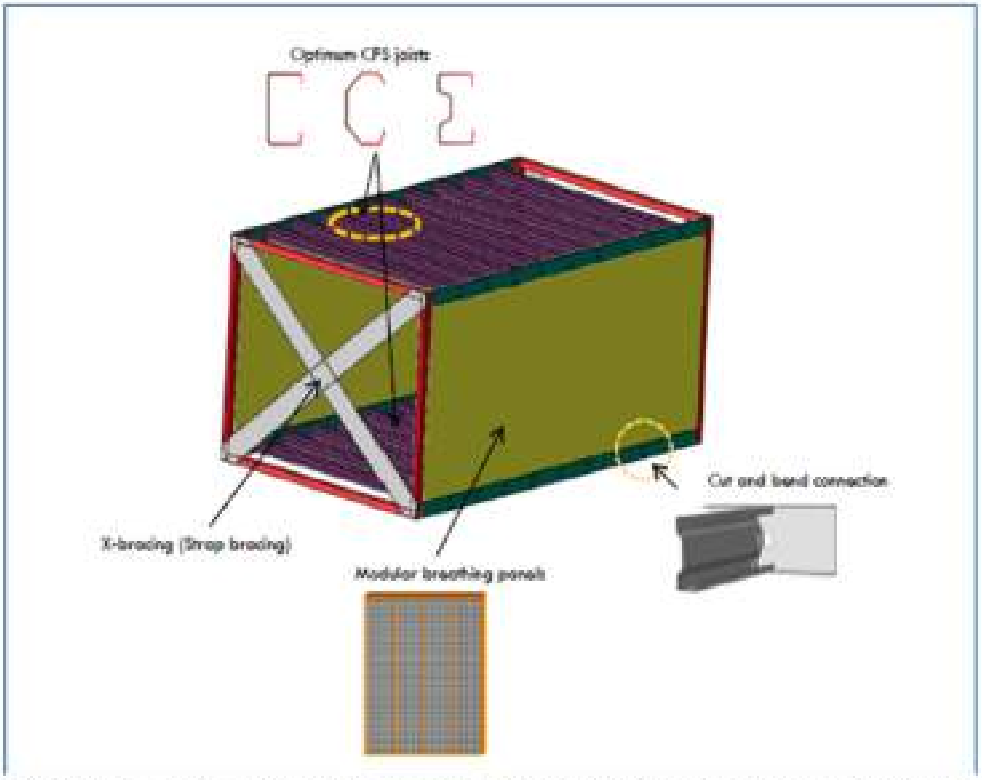


Figure 23: Proposed corner post modular unit for various applications [52]

Peng et al. [2021] [53] proposed a newly designed composite modular system for multi-storey applications and presented a system-level numerical study on its structural performance. They found that the structural performance of modular structures was significantly enhanced by the suggested composite modular system. The suggested composite modular system's multi-story modular buildings were observed to have sufficient load carrying capability for lateral wind loads, however they fell short of the requirement for deflection control in service conditions.

Sanches et al. [2021] [54] assessed the seismic design factors and the seismic performances of 3D models of 6-, 12-, and 32- story MSBs located in Vancouver and designed for moderate ductility according to the Canadian code by means of pushover analyses and bi-directional nonlinear time history analyses in ETABS Ultimate. They found that the existing Canadian code overestimates the ductility of mid- to high-rise MSBs while underestimating their excessive strength. Additionally, when building height rises, these characteristics tend to decline. The code does not address this correlation. Additionally, it was found that, for the same amount of hazard intensity, the building's height tends to cause more damage.

Sharafi et al. [2021] [55] discussed how, compared to conventional buildings, multistory modular buildings require special consideration when designing interconnections because of the various load distribution mechanisms, level of redundancy, integration strategies, and stability requirements, particularly under accidental load conditions. They studied the resilience of corner-supported modular steel buildings, subject to various unexpected loss situations, by examining the collapse resisting capacities and likely gravity-induced progressive collapse mechanisms for structures with various heights and configurations.

Thirunavukkarasu et al. [2021] [56] proposed the development of a modular building system (MBS) using built-up sections to improve its sustainability performance. A literature review was conducted on the sustainability benefits of MBSs in terms of economic, environmental, and social aspects. Numerical analysis was also performed to investigate the flexural capacity of built-up sections with different screw arrangements. The results showed that the flexural capacity of built-up sections could be improved by up to 156% compared to single sections. This suggested that built-up sections could be used to improve the sustainability of modular construction.

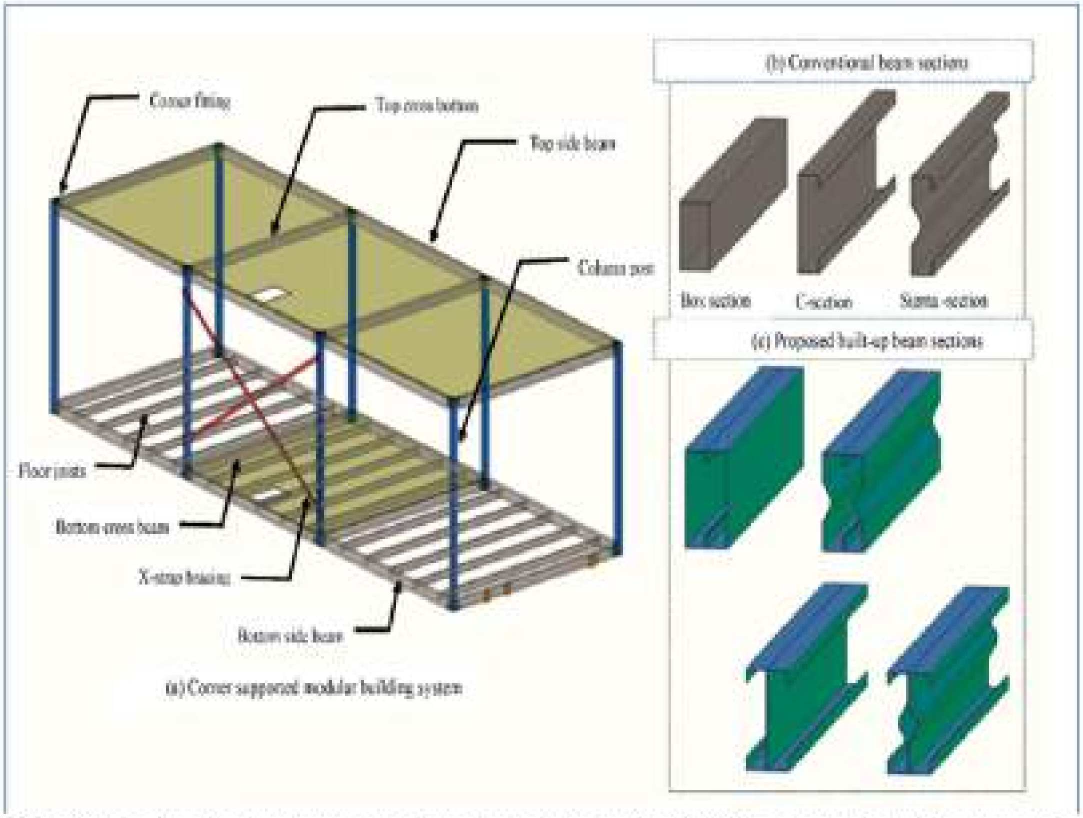


Figure 24: Typical (a) corner supported steel modular unit with (b) conventional beam sections and (c) proposed cold-formed steel built-up sections [56]

Rocha et al. [2022] [23] reviewed the potential of prefabrication in the construction industry, particularly in light of the goals set for 2050 and the impact of the COVID-19 pandemic. As seen in Figure 25, the cost of manpower was the one that grew the most among all construction costs from 2010 to 2016. Therefore, it can be safely accepted that prefabrication will lead to control of economic aspects, not only through the reduction of general costs and impacts, but also, in the case of labour control, through worker qualification and the improvement of safety and working conditions.

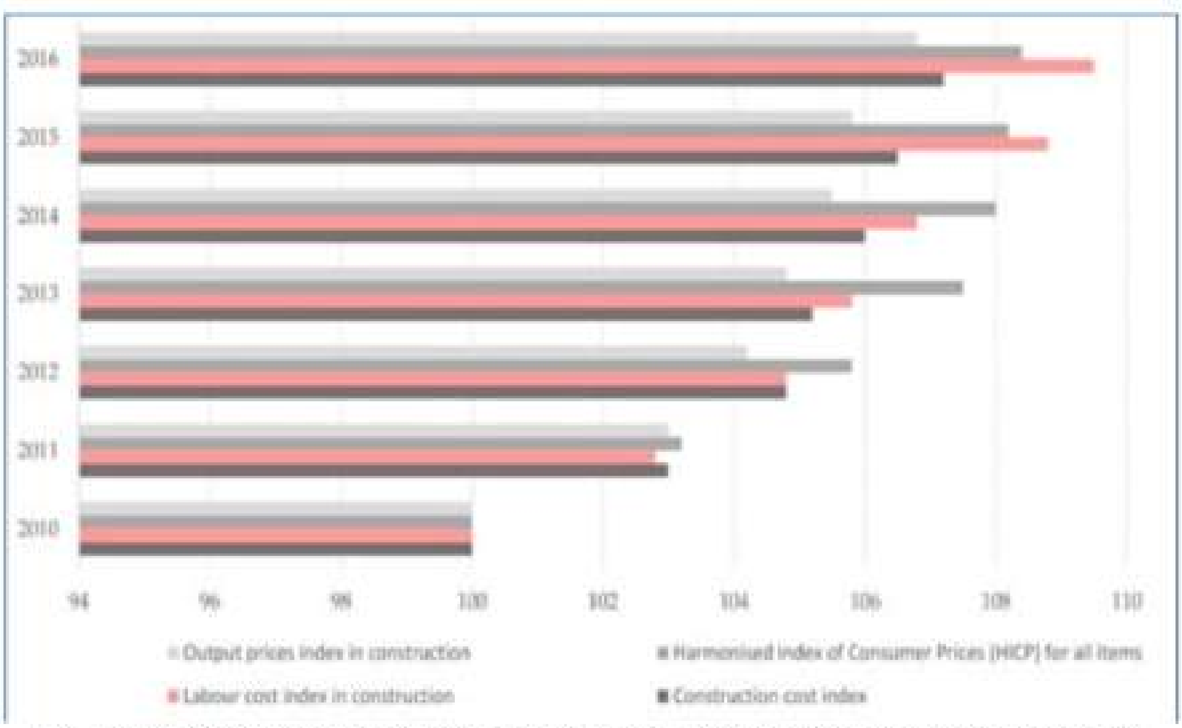


Figure 25: Comparative Study of Construction Costs from 2010 to 2016 [23]

One of the latest comprehensive reviews on prefabricated modular structural systems, general concepts, joint connections for steel and concrete modules, and their structural behavior has been cited by Chourasia et al. [2022] [24]. Furthermore, the impediments in previous Prefabricated Volumetric Modular Construction (PVMC) systems were outlined, and technical challenges that restricted their widespread acceptance were discussed. Farajian et al. [2022] [39] conducted an investigation at Western Sydney University to explore the dynamic characteristics of corner-supported modular structures with inter-connections. They tested a three-storey building under various vibrations and used operational modal analysis techniques to understand the impact of inter-connections on structural behavior. The findings could inform future research on multi-storey modular building design.

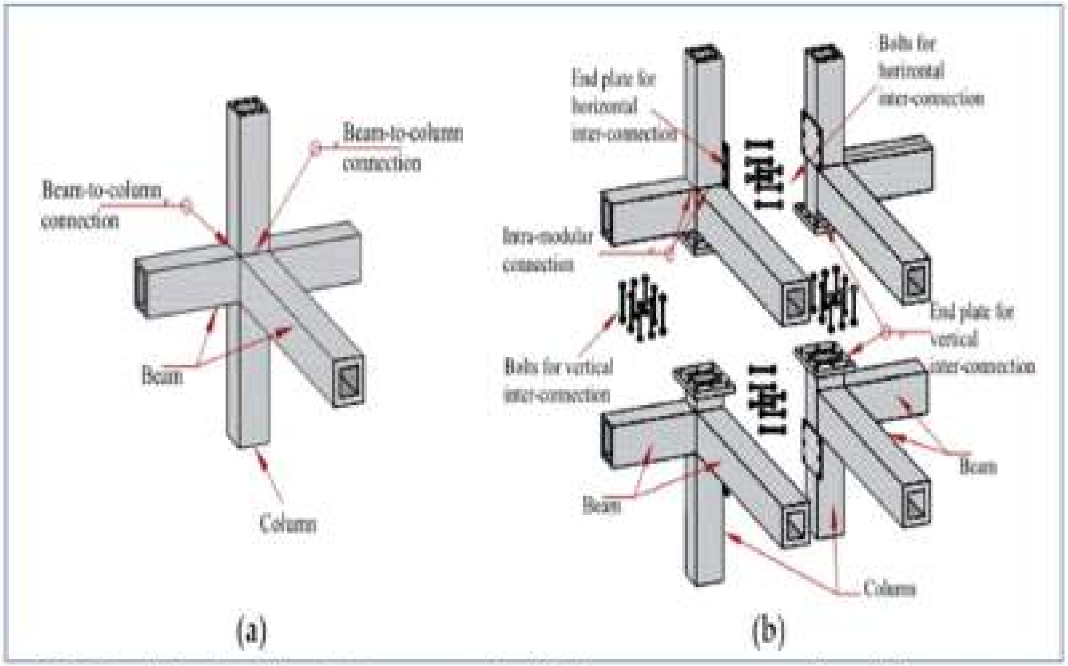


Figure 26: Details of a joint in (a) conventional (b) corner-supported modular structures [39]

Rajanayagam et al. [2022] [40] presented the results of an experimental study on three different connection designs. The connections were tested in shear, and their load-deformation behavior was studied. The results of the experiments showed that the connections were all slip-critical, meaning that they tended to fail by slipping even at a small lateral load. The study suggests that inter-modular connections should resist both forces and consider shear slip behavior when designing modular buildings.

Ping et al. [2022] [41] proposed a module to core (M2C) connection for modular buildings, designed for high-rise use. The connection, consisting of a steel plate, anchor rods, and connector plate, was strong but failed in monotonic sliding due to anchor rod shear failure. A simplified finite element model for modular steel structure building wallboard was developed by Cong et al. [2022] [57] based on experimental research and finite element analysis. The model was able to accurately predict the behavior of the wallboard under different loading conditions, including the stiffness, strength, and failure mode. The model was also able to identify the key factors that affect the behavior of the wallboard, such as the thickness of the wallboard, the type of steel used, and the type of connection between the wallboard and the steel frame. The model can be used to design and analyze modular steel structure building wallboard, and to study the effects of different design parameters on the behavior of the wallboard.

Figure 27: Experimental Lab Set-up by Cong et al. [57]

The study by Nikolaidis Th. et al. [2022] [58] investigated the structural robustness of steel-framed modular buildings using numerical (alternative load path method) and experimental methods (LS-DYNA software). The study found that the collapse resistance of steel modular buildings could be improved by increasing the number of modules per floor, the number and capacity of supporting posts, the rotational stiffness and capacity of inter-module connections, and the use of longitudinal wall bracing. The study also found that considering floor slabs provides a more realistic description of collapse mechanisms.

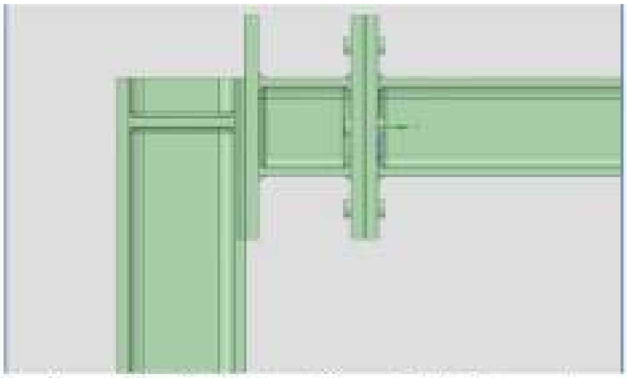


Figure 28: Schematic view of the initial configured JL-6 beam to column steel joist [58]

Khan et al. [2023] [42] introduced a self-locking automatic connection for inter-modular connections, offering easy installation, complete connectivity, and reliable performance without welding. These connections improved in-plane rigidity, load transfer, safe handling, and optimal utilization of modular components' strength, contributing to the advancement of modular steel buildings.

1.6 Conclusion

The broad investigation of modular building revealed a dynamic and growing landscape in the construction industry through a chronological analysis of research findings. Early studies, such as those conducted by Harrison [2003] and Hart et al. [2005], emphasised the need of blast-resistant moveable buildings and established the notion of Living Buildings. Researchers explored into seismic performance, energy efficiency, and creative design ideas for modular buildings as time passed.

Seismic studies conducted by Annan et al. [2009], Fathieh et al. [2016], and Gunawardena et al. [17] provided insight on the structural integrity of modular structures, particularly in earthquake-prone areas. The findings emphasised the significance of proper modelling methodologies and elements like as construction materials and load predictions. Aye et al. [2012] also investigated energy efficiency, discovering that modular steel and timber buildings offer considerable volume, mass, and embodied energy reductions when compared to standard concrete structures.

As indicated by research from Chen et al. [2017], Dai et al. [2019], and Feng et al. [2020], the growth of modular construction was distinguished by breakthroughs in joint connections. Innovative solutions, such as plug-in self-lock joints, were proposed in these works to improve load transfer capacity, seismic behaviour, and simplicity of construction. Furthermore, Gatheeshgar et al. [2021] and Peng et al. [2021] presented unique ways for emergency scenarios and composite modular systems, respectively, demonstrating an expanding potential for modular building applications.

Recent research by Yang et al. [2020], Thirunavukkarasu et al. [2021], and Chourasia et al. [2022] focused on the seismic performance of modular buildings. These studies shed information on the structural resilience of modular structures under seismic stresses and emphasised the possible sustainability benefits of built-up parts.

Sendanayake et al. [2020], Zhang et al. [2020], and Rocha et al. [2022] investigated the seismic performance of inter-modular connections, highlighting the significance of unique energy-absorbing connections and resilient designs.

Khan et al. [2023] and Nikolaidis Th. et al. [2022] make recent additions that introduce self-locking automated connections and structural robustness concerns, respectively. These studies demonstrate the continued search of technologies to improve modular steel building connection, stiffness, and load transfer capability.

Declaration of Conflicting Interests

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