
MODULAR CONSTRUCTION TECHNOLOGY

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Doi: <https://doi-doi.org/101555/ijarp.9259>**ABSTRACT**

Modular construction has emerged as a transformative approach in the building industry, offering significant advantages over traditional on-site construction methods. This review paper provides a comprehensive examination of modular construction technology, encompassing its definition, classification, structural systems, material innovations, and future prospects. The paper synthesizes recent research advancements in inter-module connections, structural systems, and the integration of computational design approaches. Through a systematic analysis of contemporary literature, this review identifies key technical developments, evaluates the performance of various modular systems, and discusses the barriers to widespread adoption. The findings indicate that modular construction can reduce construction time by up to 50% and improve economic efficiency by 20% while minimizing material waste. However, challenges persist in areas such as inter-module connection performance, regulatory constraints, logistical complexity, and higher upfront costs. The paper concludes by outlining future research directions, including the integration of artificial intelligence in design optimization and the advancement of hybrid structural systems incorporating sustainable materials.

KEYWORDS: Modular Construction, Prefabrication, Inter-Module Connections, Structural Systems, Engineered Timber, Sustainability, Building Information Modeling.

1. INTRODUCTION

The construction industry has experienced a significant paradigm shift toward modular techniques in recent years, driven by growing environmental concerns and rising labor costs in conventional on-site construction. Modular construction, as an advanced stage of

construction industrialization, involves the prefabrication of building units in controlled factory environments before transporting them to construction sites for assembly . This innovative approach exhibits numerous advantages, including improved quality, shortened construction time, reduced labor and material costs, and a stronger commitment to environmental sustainability.

Modular construction is a rapidly growing sector of the construction industry, characterized by the production of standardized components in offsite factories, which are then transported and installed onsite . This method makes it possible to shorten construction periods by minimizing work on site and enhance construction quality based on factory production. By stacking modules and connecting them together side-by-side or vertically, this overall approach addresses quality, productivity, and coordination issues faced by conventional construction methods.

Table 1.1: Key Benefits of Modular Construction.

Benefit Category	Description	Typical Improvement
Time Efficiency	Concurrent site preparation and manufacturing	Up to 50% reduction
Quality Control	Factory-controlled environment	Higher precision and consistency
Cost Savings	Reduced labor, waste, and financing costs	Up to 20% improvement
Safety	Minimized working at height and weather exposure	70-90% reduction in scaffolding
Sustainability	Reduced waste and reusability	Up to 90% waste reduction

1.1 Historical Evolution

The exploration of modular building methods can be traced back to the early 19th century. The H. Manning Company in London proposed a pioneering, fully prefabricated, and transportable building named the portable colonial cottage. The initial attempt at modularity was the 4D tower concept proposed by Buckminster Fuller in the "Dymaxion House" project in 1927. After World War II, box buildings emerged to accelerate infrastructure reconstruction, with the Soviet Union building the first 4-story box building in 1959.

Table 1.2: Historical Milestones in Modular Construction.

Year	Project/Development	Significance
Early 19th Century	Portable Colonial Cottage (H. Manning Company, London)	First fully prefabricated, transportable building
1927	Dymaxion House (Buckminster Fuller)	4D tower concept, early modularity exploration

1959	First 4-story box building (Soviet Union)	Post-WWII box building emergence
1967	Habitat 67 (Canada)	354 box components, comprehensive residential building
1999	Murray Grove (UK)	Pioneering modular residential building
2023	Clement Canopy (Singapore)	Tallest modular concrete building (140m)

Source: Compiled from historical literature

A comprehensive residential building called "Habitat 67" was built in Canada in 1967, consisting of 354 box components. The Murray Grove project, built in 1999, marked the pioneering application of modular concepts in residential buildings in the UK . With advancement in modular construction technology, high-rise modular buildings have emerged in recent years. Clement Canopy and Croydon Tower are currently the tallest modular concrete and modular steel buildings, respectively.

2. CLASSIFICATION AND STRUCTURAL SYSTEMS

2.1 Classification by Level of Prefabrication

Modular construction encompasses various levels of prefabrication, ranging from individual components to complete volumetric units. Based on the degree of prefabrication, there are three classes of prefabricated construction: 1D single element, 2D panelized system, and 3D volumetric system.

Table 2.1: Levels of Prefabrication in Modular Construction.

Level	Description	Examples	Prefabrication Extent
1D: Single Elements	Individual components	Beams, columns, wall panels	Lowest
2D: Panelized Systems	Pre-assembled panels	Floor panels, wall panels, roof panels	Moderate
3D: Volumetric Systems	Complete room units	Bathroom pods, entire rooms, stacked modules	Highest (70-95%)

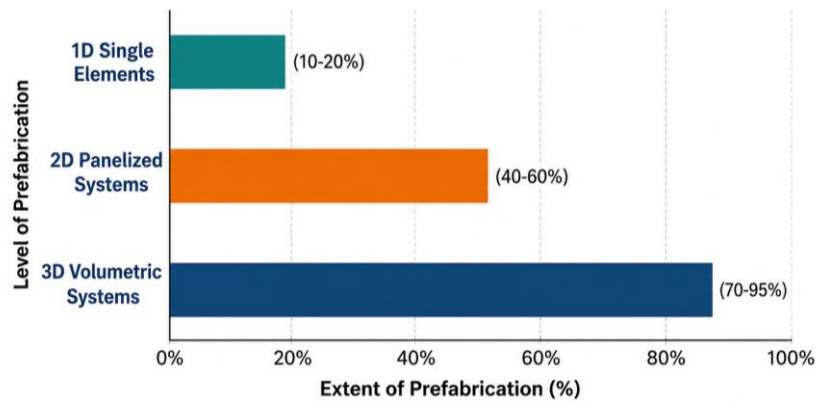


Figure 2.1: Levels of Prefabrication in Modular Construction.

Panelized and volumetric construction, also known as modular construction, is the most efficient class of prefabricated construction since it allows for 70% to 95% of a building to be prefabricated in a factory before transporting it for onsite assembly.

2.2 Structural Systems for Modular Buildings

Modular buildings employ various structural systems depending on the material, building height, and performance requirements. There are three main construction approaches for stacking modular units: core-based, podium-based, and infilled frame systems.

Table 2.2: Structural Systems for Modular Buildings.

System Type	Description	Applications
Core-Based	Modules clustered around stability cores	High-rise buildings
Podium-Based	Modules placed on top of podium structure	Mixed-use buildings
Infilled Frame	Modules placed between beams and columns	Specific architectural requirements

*Source: *

In the core-based approach, all modules are clustered around one or more stability cores. The modular unit is designed to resist only vertical gravity loads, whilst the lateral forces from wind and earthquake actions are separately resisted by the cores. In the podium-based method, the modular unit is placed on the top of a podium or platform structure which is designed as a traditional steel, concrete or hybrid steel–concrete structure. This method is particularly suitable for mixed-use buildings. In the infilled frame method, modular units are placed between the beams and columns of a primary framing structure.

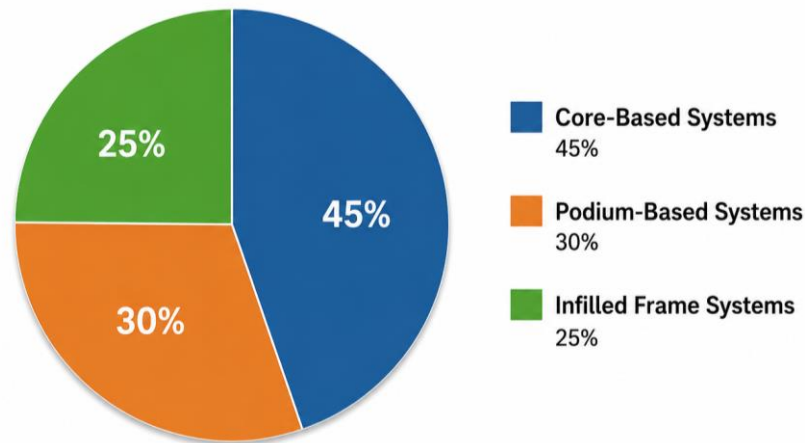


Figure 2.2: Structural Systems Distribution in Modular Buildings.

Current applications of modular construction for high-rise buildings are limited due to the lack of strong structural systems and joining techniques to ensure structural integrity, overall stability, and robustness. Less than 1% of modular high-rise buildings have been constructed recently using the panelised method or volumetric method based on wet joining techniques.

2.3 Inter-Module Connections

Inter-module connections (IMCs) play a critical role in ensuring the overall structural integrity and stability of multi-story modular buildings. Recent research has proposed various IMCs to enhance the safety and efficiency of modular construction . Connection systems serve as the critical interface between modular units, ensuring the safe and efficient transfer of forces and the overall stability of the building.

Table 2.3: Classification of Inter-Module Connections.

Classification Criteria	Types
Connected Members	Corner joints, perimeter joints, internal joints
Connecting Methods	Bolt connections, tie-rod connections, bracket connections, rotary-type connections, self-locking designs
Material	Steel modular connections, concrete modular connections, hybrid connections

*Source: *

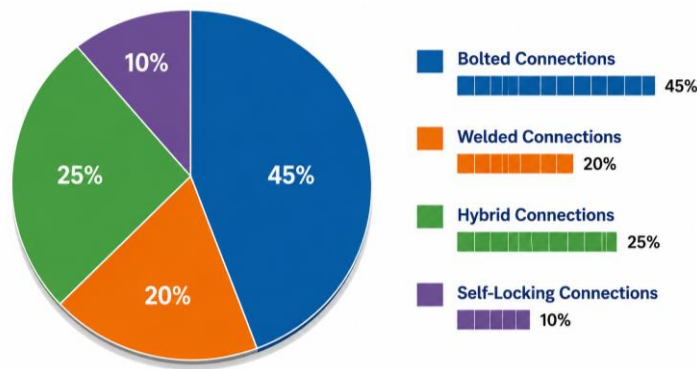


Figure 2.3: Types of Inter-Module Connections Distribution.

Bolted connections offer ease of installation but lower energy dissipation, while welded connections provide high structural integrity. Hybrid bolted-welded connections balance strength and adaptability, making them suitable for various applications. Key characteristics of successful IMC designs include self-alignment, adjustment capability, and tolerance allowance. Research has demonstrated that the stiffness of IMCs significantly influences the fundamental period of modular buildings and consequently greatly impacts overall seismic performance.

3. MATERIALS AND TECHNOLOGICAL INNOVATIONS

3.1 Emerging Materials: Engineered Timber

Engineered timber products have increasingly been recognized for their favorable strength-to-weight performance, reduced embodied emissions, and compatibility with off-site prefabrication. The lightweight nature of timber presents significant advantages for modular construction, reducing the self-weight of modules and enabling easier handling, transportation, and on-site assembly.

Table 3.1: Engineered Timber Products in Modular Construction.

Material	Properties	Applications
Cross-Laminated Timber (CLT)	Versatile, high strength-to-weight ratio	Mid to high-rise modular applications
Laminated Veneer Lumber (LVL)	Structural optimization	Hybrid systems
Glue-Laminated Timber (Glulam)	Strength and durability	Structural optimization
Structural Insulated Panels (SIPs)	Rapid assembly, improved thermal efficiency	Wall and roof systems

*Source: *

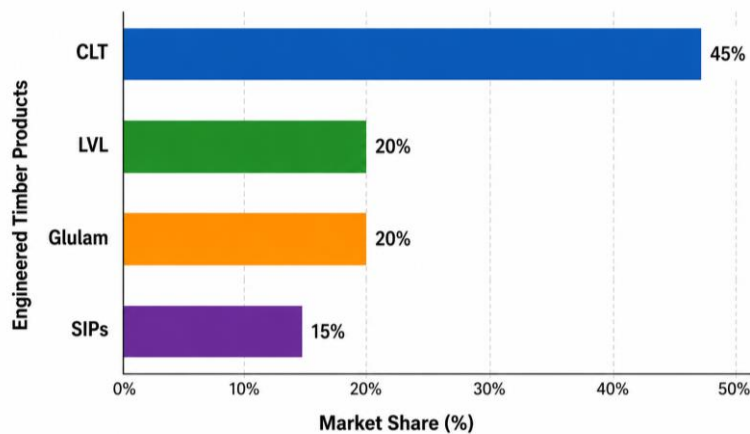


Figure 3.1: Market Share of Engineered Timber Products

CLT dominates current research owing to its versatility in mid to high-rise modular applications, while LVL and glulam contribute to structural optimization in hybrid systems, and SIPs support rapid assembly and improved thermal efficiency. Despite these advantages, adoption barriers persist, including regulatory constraints, logistical complexity, and higher upfront costs.

3.2 Digital Technologies and Computational Design

Computational design approaches have been increasingly adopted to support and automate modular design generation. The integration of digital technologies with modular construction methods extends to circular and bioclimatic efforts, renewable energy sources, and passive building design strategies.

Two predominant modularization workflows have been identified: the module-composition method (bottom-up) and the decomposition-to-modules method (top-down). The concept of "modularization lock-in point" has been proposed to analyze the impact of design decisions on production strategy, dominant cognitive mode, and the role of computational design tools. The integration of technologies such as artificial intelligence (AI) and Building Information Modeling (BIM) makes modular construction technology more competitive and applicable.

4. ADVANTAGES AND CHALLENGES

4.1 Advantages of Modular Construction

Volumetric-modular construction offers a range of significant advantages that make it an attractive alternative to traditional methods. The factory-based production of modules is considerably quicker than traditional methods due to a controlled manufacturing setting, opportunities for process automation, and repetitive tasks. This approach enables

simultaneous module production alongside foundation work at the construction site, contrasting with the sequential nature of traditional construction .

Cost savings are realized by significantly lowering the requirements for formwork (up to 75%), scaffolding (75-90%), and wet concrete (90%). Additionally, lower costs stem from the high readiness level of modules at the factory, incorporating both exterior and interior finishes, which reduces the need for on-site labor. As much as 80% of all tasks can be shifted to the manufacturing location, facilitating the employment of more skilled workers and decreasing labor expenses .

4.2 Challenges and Limitations

Despite its significant potential, modular construction encounters systemic challenges . The lack of national standards for design and a large amount of initial investment in production hinders the introduction of new technologies in construction .

The existing terminological ambiguity and the absence of a comprehensive, universally accepted classification of volumetric-modular systems pose a significant barrier to standardization, regulatory development, and consequently, to the widespread adoption and investment in this technology . The lack of harmonized standards results in inconsistencies in design practices and complicates research findings comparability.

5. APPLICATIONS AND FUTURE SCOPE

5.1 Applications and Case Studies

Modular construction has been widely adopted for residential buildings, ranging from single-family homes to multi-story apartment complexes. The Murray Grove project in the UK (1999) marked the pioneering application of modular concepts in residential buildings . The use of modular construction technologies can reduce construction time by 50% and save cost by 20% based on a case study of recent projects.

Table 5.1: Notable High-Rise Modular Buildings.

Building	Location	Height	Material	Significance
Clement Canopy	Singapore	140m	Concrete	Tallest modular concrete building
Croydon Tower	UK	135m	Steel	Tallest modular steel building
HuaZhangXinZhu	China	-	Concrete	China's first high-rise modular concrete

*Source: *

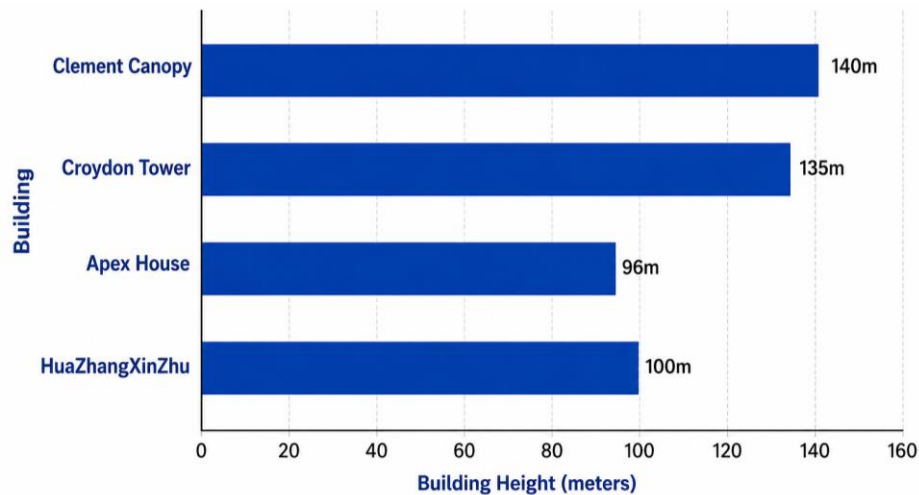


Figure 5.1: Height Comparison of Notable Modular Buildings.

5.2 Future Scope

Future research should focus on developing advanced fairness-aware deep learning architectures capable of adapting to changing societal conditions. The integration of artificial intelligence and machine learning techniques into modular construction can enhance design optimization, predictive maintenance, and quality control.

6. CONCLUSION

Modular construction has emerged as a transformative approach to addressing global housing and infrastructure challenges by offering efficiency, sustainability, and resilience . This review has examined the historical evolution, types, structural systems, material innovations, and future directions of modular construction technology.

The findings indicate that modular construction significantly reduces construction time, enhances quality control, and minimizes material waste. Engineered timber products, including CLT, LVL, glulam, and SIPs, are increasingly recognized for their favorable strength-to-weight performance, reduced embodied emissions, and compatibility with off-site prefabrication . However, challenges persist in areas such as inter-module connection performance, regulatory constraints, logistical complexity, and higher upfront costs .

The integration of digital technologies, including BIM, digital twins, and artificial intelligence, is crucial for advancing modular construction and achieving global sustainability goals. A synergistic approach combining robust regulatory frameworks, industry-academic collaboration, and targeted financial incentives is needed to unlock the full potential of modular systems for sustainable urban development .

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