Joinery-to-Structure: A Framework for Mid-Rise Modular Housing in Indian Cities

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Abstract

Modular housing is increasingly recognized as a viable strategy for addressing the growing housing demand in rapidly urbanizing cities. However, the structural feasibility of multi-storey modular buildings depends significantly on how prefabricated units are connected and integrated into a coherent structural system. Titled **Joinery-to-Structure: A Framework for Mid-Rise Modular Housing in Indian Cities**, this study examines the role of joinery as a critical mediator between modular units and overall structural behaviour. The research adopts a qualitative and comparative methodology, analysing selected modular housing precedents to evaluate inter-module connection systems, stacking logic, structural load transfer, and constructability strategies. Through this analysis, the study investigates how joinery influences stability, load continuity, and scalability in modular construction. Findings indicate that connection behaviour plays a decisive role in determining the structural reliability of mid-rise modular housing, particularly in relation to stiffness, ductility, and tolerance management. The study further identifies hybrid structural systems—combining reinforced concrete stability cores with lightweight steel volumetric modules—as a feasible approach for mid-rise modular applications. By positioning joinery as an organizing structural framework rather than a secondary technical detail, the research contributes to the discourse on modular construction and proposes a context-sensitive framework for implementing mid-rise modular housing in Indian cities.

Key Words: Modular Housing, Joinery Systems, Inter-Module Connections, Mid-Rise Construction, Structural Integration, Stacking Logic, Prefabricated Architecture.

1. INTRODUCTION

1.1 Background of the Study

Modular construction has increasingly emerged as a viable response to the growing housing demands of rapidly urbanizing cities, where conventional construction methods struggle to meet requirements of speed, efficiency, and scalability (Smith, 2010). In contrast to traditional monolithic construction systems, modular housing is based on the prefabrication of volumetric units manufactured in controlled environments and assembled on site, allowing improved quality control, reduced construction timelines, and greater precision in building production (Lawson, Ogden, & Goodier, 2014). However, the structural performance of modular buildings does not rely solely on the strength of individual modules but largely on the behaviour of inter-module connections that integrate discrete units into a stable structural system (Lacey et al., 2018).

In modular housing systems, joinery acts as the critical interface through which loads are transferred between stacked modules and through which global structural behaviour is established. Studies on modular steel construction demonstrate that connection stiffness, ductility, and load redistribution capacity significantly influence structural stability, inter-storey drift, and resilience under lateral loads (Annan, Youssef, & El-Naggar, 2009). As building height increases, the role of inter-module joinery becomes increasingly important because cumulative gravity loads and amplified lateral forces place greater demands on connection performance and alignment accuracy (Peng, Li, & Zhang, 2020).

Consequently, contemporary research in modular construction increasingly recognizes joinery not merely as a mechanical fastening detail but as an integrated structural system that governs load continuity, constructability, and scalability. Understanding joinery as a structural mediator enables modular architecture to transition from component-based prefabrication toward system-based structural integration capable of supporting mid-rise urban housing development.

1.2 Shift in Modular Construction Discourse

Early research on modular construction primarily focused on efficiency, speed of delivery, and industrialized building production (Smith, 2010). Modular systems were largely viewed as prefabricated components assembled on site to reduce construction time and improve quality control (Lawson, Ogden, & Goodier, 2014). Within this perspective, studies emphasized manufacturing processes and sustainability benefits rather than the structural behaviour of modular systems.

Recent research, however, increasingly highlights the importance of inter-module connections in determining structural performance. Studies show that connection stiffness, ductility, and alignment significantly influence load transfer, lateral stability, and seismic behaviour in multi-storey modular buildings (Lacey et al., 2018). Consequently, contemporary scholarship recognizes joinery not merely as an assembly detail but as a structural interface that integrates modular units into a coherent building system (Peng, Li, & Zhang, 2020).

1.3 Problem Context

Despite extensive global research on modular construction, limited studies address the integration of joinery systems with overall structural behaviour in the Indian context. Existing literature often focuses on construction efficiency and prefabrication technology, while the structural logic of inter-module connections in mid-rise modular housing remains underexplored (Lawson et al., 2014).

At the same time, rapid urbanization in Indian cities has increased the demand for faster and more efficient housing solutions. Although modular housing offers significant potential, the absence of clear frameworks linking joinery design with structural performance creates uncertainty in implementation and regulatory approval.

1.4 Purpose of the Study

This research investigates how joinery systems influence structural behaviour in mid-rise modular housing. Through qualitative and comparative analysis of selected case studies, the study evaluates parameters such as inter-module connections, stacking logic, and structural load transfer.

The objective is to understand how joinery functions as a structural mediator that enables stability, constructability, and scalability in modular buildings. Based on these insights, the research proposes a joinery-to-structure framework suitable for mid-rise modular housing in Indian cities.

1.5 Structure of the Paper

The paper is organized into five sections. Section 2 reviews theoretical and empirical literature on modular construction and connection systems (Lawson et al., 2014; Lacey et al., 2018). Section 3 outlines the qualitative comparative methodology used in the study. Section 4 presents case study analysis of selected modular housing projects. Section 5 discusses findings, limitations, and implications for modular housing development in Indian cities.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Conceptual Foundations of Modular Construction

Modular construction is increasingly understood as an industrialized building approach in which structures are assembled from prefabricated volumetric units manufactured in controlled factory environments and connected on site (Smith, 2010). Unlike conventional monolithic construction systems, modular buildings rely on discrete structural units that must be integrated through engineered connections to function as a cohesive structural system (Lawson, Ogden, & Goodier, 2014). As a result, the performance of modular buildings depends significantly on how individual modules are joined and stacked.

In modular housing, joinery systems act as the structural interface between modules and the overall building framework. Inter-module connections govern vertical load transfer, lateral stability, and alignment accuracy, ensuring that stacked modules function collectively as a stable structural assembly (Lacey et al., 2018). Research on modular steel buildings demonstrates that connection behaviour—particularly stiffness, ductility, and tolerance management—directly influences structural reliability and scalability in multi-storey modular systems (Peng, Li, & Zhang, 2020).

As building height increases, the importance of joinery systems becomes more pronounced. Mid-rise modular buildings require calibrated connection strategies to manage cumulative gravity loads, lateral forces, and tolerance deviations during assembly. Consequently, contemporary modular construction increasingly treats joinery not merely as a fastening detail but as a structural mechanism that integrates architectural design, structural behaviour, and construction processes.

2.2 Theoretical Models of Modular Structural Integration

Several theoretical frameworks explain how modular buildings achieve structural stability through connection systems and stacking strategies. These models emphasize the relationship between connection behaviour, structural load paths, and construction efficiency.

One key framework is the Structural Load Transfer Model, which explains how gravity and lateral forces are transmitted through stacked modules and their connection interfaces (Lawson et al., 2014). In modular systems, load paths are established through connection nodes rather than continuous structural frames. Properly designed joinery ensures efficient load transfer and prevents stress concentration across module interfaces.

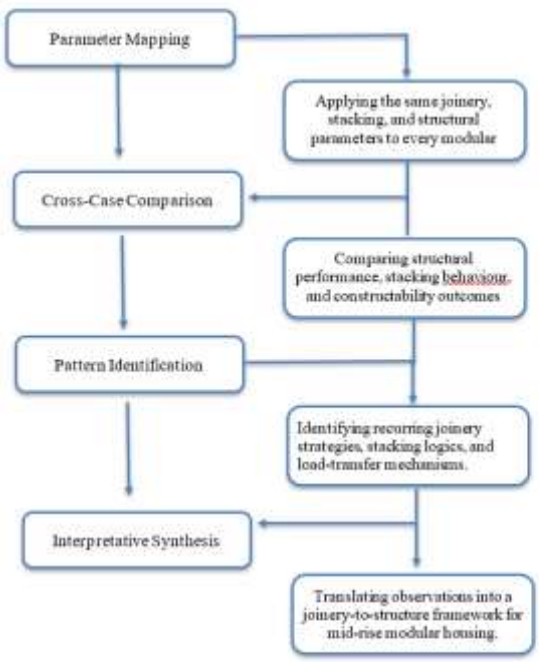
Category	**Parameters & Focal Points**
Joinery	Connection type, detailing, stiffness, and load transfer
Structure	Vertical and lateral load paths, stability mechanisms
Stacking Logic	Module arrangement, alignment, and tolerance management
Constructability	Assembly sequence, speed, and site feasibility
Adaptability	Disassembly, expansion, and system flexibility

Table 1 Analytical variables and spatial parameters of the study

Another important perspective is the Constructability and Assembly Model, which focuses on dimensional coordination, tolerance management, and construction sequencing in modular building systems. Since modular units are fabricated in controlled factory environments and transported to site for installation, small dimensional deviations can occur during manufacturing, transportation, or lifting. These deviations must be accommodated during on-site assembly without compromising structural stability or alignment accuracy. As a result, connection systems in modular buildings must be designed with tolerance-adjusting mechanisms that allow modules to be positioned precisely while maintaining effective load transfer. Research highlights that adjustable connection plates, slotted bolt holes, and calibrated joinery systems are commonly used to address these challenges, enabling efficient alignment and rapid assembly on site (Lacey et al., 2018). Proper tolerance management not only ensures structural continuity but also improves construction speed and reduces installation errors, which is a key advantage of modular construction.

A third framework is the Connection Performance Model, which examines the mechanical behaviour of inter-module joints under various loading conditions, including gravity loads, wind forces, and seismic actions. In multi-storey modular buildings, connections act as critical structural nodes that transfer loads between stacked modules and distribute forces throughout the building system. Studies show that connection stiffness, strength, and ductility significantly influence global structural behaviour, particularly in terms of inter-storey drift, lateral stability, and progressive collapse resistance (Peng et al., 2020). Semi-rigid and ductile connection systems are often preferred because they allow controlled deformation and energy dissipation under dynamic loading conditions. This flexibility improves structural resilience by reducing stress concentration at connection points and enabling the building to respond more effectively to environmental forces such as earthquakes and wind loads.

Together, these theoretical models demonstrate that the performance of modular construction is determined not only by the efficiency of prefabrication processes but also by the effectiveness of structural integration achieved through joinery systems. Inter-module connections play a critical role in linking individual modular units into a coherent structural system capable of supporting multi-storey construction. Therefore, understanding connection behaviour, tolerance management, and load transfer mechanisms becomes essential for designing reliable and scalable mid-rise modular housing systems.



2.3 Evolution of Modular Construction Systems

Modular construction has evolved significantly over the past century, transitioning from experimental prefabrication techniques to advanced structural systems capable of supporting multi-storey buildings. Early forms of modular construction emerged during the early twentieth century when prefabricated housing was developed to address rapid housing shortages and post-war reconstruction demands (Smith, 2010). These early modular structures primarily focused on rapid assembly and cost efficiency rather than structural sophistication.

As prefabrication technologies advanced, modular construction began to incorporate more complex structural systems. During the late twentieth century, improvements in steel fabrication, transportation logistics, and digital design tools enabled the development of volumetric modular units that could be manufactured off-site and assembled into larger building systems (Lawson, Ogden, & Goodier, 2014). These developments expanded the scope of modular construction beyond low-rise housing to include mid-rise and high-rise buildings.

In recent decades, modular construction has reached a new level of technological maturity, particularly in regions such as Europe, North America, and East Asia. Contemporary modular buildings increasingly rely on engineered connection systems and hybrid structural frameworks that combine steel modular units with reinforced concrete cores or frames (Lacey et al., 2018). These systems improve structural stability, seismic performance, and scalability in multi-storey modular buildings.

The evolution of modular construction also reflects a shift from purely manufacturing-driven approaches toward integrated architectural and structural design strategies. Inter-module connections have become critical structural elements responsible for load transfer, alignment, and lateral stability within modular systems (Peng, Li, & Zhang, 2020). As a result, joinery is increasingly recognized as a fundamental component that determines the feasibility and structural reliability of mid-rise modular housing.

This evolution demonstrates how modular construction continues to adapt to technological advancements, urban housing demands, and structural engineering innovations while maintaining the core principle of prefabricated building assembly.

2.4 Comparative Case Study Analysis

To understand how joinery systems influence structural performance in modular construction, this research analyses selected international modular housing case studies. These projects represent significant developments in modular architecture and demonstrate different approaches to structural integration and connection design.

The case studies examined include:

- Habitat 67, Montreal
- 461 Dean Street, New York
- Nakagin Capsule Tower, Tokyo

These projects illustrate different stages in the evolution of modular construction and highlight varying strategies for module stacking, structural load transfer, and connection detailing (Lawson et al., 2014).

Habitat 67 in Montreal represents one of the earliest experimental modular housing projects. Designed using prefabricated concrete modules, the project explored complex stacking arrangements and direct load-bearing modular systems. The structural stability of the building relies on post-tensioned connections that integrate individual modules into a unified structural system (Smith, 2010).

Similarly, the Nakagin Capsule Tower in Tokyo demonstrates an early exploration of modular plug-in architecture. The building consists of prefabricated capsule units attached to a central reinforced concrete core using high-tolerance bolted connections. This system allowed individual capsules to be theoretically replaced or reconfigured, illustrating the potential adaptability of modular joinery systems (Kurokawa, 1977).

More recent modular developments such as 461 Dean Street in New York demonstrate the application of volumetric modular construction in high-rise residential buildings. The project utilizes steel-framed modules stacked within a hybrid structural framework supported by a reinforced concrete core. Bolted inter-module connections play a critical role in transferring loads and ensuring structural alignment across multiple storeys (Lacey et al., 2018).

While these projects employ different structural strategies, they share a common emphasis on connection performance as a determinant of structural reliability and constructability. Early experimental modular projects often relied on rigid stacking strategies, whereas contemporary systems increasingly incorporate calibrated joinery designed to manage structural loads, tolerances, and assembly efficiency.

Through this comparative analysis, the study identifies recurring structural principles related to joinery behaviour, stacking logic, and structural load paths. These observations provide insights that inform the development of a joinery-to-structure framework suitable for mid-rise modular housing applications.

Figure 1 Habitat 67 — Montreal

Figure 2 Image of stacking a modular

2.5 Structural Parameters of Modular Joinery Systems

This research identifies several key structural parameters that influence the performance and feasibility of mid-rise modular housing systems. These parameters help explain how joinery systems integrate individual modular units into a stable and efficient structural framework.

Inter-Module Joinery

Inter-module joinery forms the primary interface through which individual modules are connected and structurally integrated. In modular construction, these connections are responsible for transferring loads between stacked modules while maintaining alignment and stability (Lawson, Ogden, & Goodier, 2014). Studies indicate that the stiffness and detailing of joinery systems directly influence the structural performance and reliability of multi-storey modular buildings (Lacey et al., 2018).

Structural Load Transfer

Efficient load transfer is a critical parameter in modular construction. Vertical loads from upper modules must be transferred through connection nodes to lower modules and eventually to the foundation system (Peng, Li, & Zhang, 2020). Unlike conventional frame structures, modular systems rely on discrete connection points to establish continuous load paths. Properly designed joinery systems therefore ensure structural continuity and prevent stress concentration at module interfaces.

Stacking Logic and Alignment

Stacking logic refers to the arrangement and alignment of modular units within the building system. Vertically aligned modules promote direct load transfer and structural efficiency, while irregular or offset stacking can introduce additional stresses within connection systems (Lawson et al., 2014). Accurate alignment between modules is therefore essential to maintain structural stability and minimize tolerance-related issues during construction.

Constructability and Assembly

Constructability is an important consideration in modular construction because modules are fabricated off-site and assembled on-site. Joinery systems must allow rapid and accurate installation while accommodating minor dimensional variations that occur during manufacturing and transportation (Lacey et al., 2018). Adjustable connections, slotted bolt systems, and tolerance-absorbing interfaces are commonly used to ensure efficient assembly and structural reliability.

Structural Robustness and Adaptability

Finally, joinery systems contribute to the overall robustness and adaptability of modular buildings. Well-designed connection systems allow modular structures to redistribute loads effectively and resist progressive collapse under extreme conditions (Peng et al., 2020). In addition, demountable or semi-rigid joinery systems enable future modification, expansion, or replacement of modules, improving the long-term flexibility of modular housing.

Together, these structural parameters demonstrate that the performance of modular housing systems depends not only on prefabrication efficiency but also on the effectiveness of joinery systems in integrating modules into a coherent structural framework.

2.6 Synthesis of Findings

The comparative analysis highlights a significant shift in the understanding of modular construction systems. Early modular housing projects primarily focused on prefabrication efficiency and rapid construction as the main advantages of modular building systems (Smith, 2010). In these early models, modular units were treated largely as independent components assembled on site, with limited emphasis on the structural behaviour of inter-module connections (Lawson, Ogden, & Goodier, 2014).

Contemporary modular construction, however, increasingly emphasizes the structural role of joinery systems in determining overall building performance. Recent studies demonstrate that connection stiffness, ductility, and tolerance management significantly influence load transfer, lateral stability, and global structural behaviour in multi-storey modular buildings (Lacey et al., 2018). Rather than functioning merely as mechanical fasteners, inter-module connections are now understood as structural interfaces that integrate individual modules into a unified building system (Peng, Li, & Zhang, 2020).

This shift reflects broader transformations in the construction industry, including increased urban density, demand for faster housing delivery, and advancements in prefabrication technologies (Lawson et al., 2014). Despite these changes, contemporary modular construction continues to rely on fundamental structural principles such as load continuity, alignment, and hierarchical structural support systems (Smith, 2010).

Therefore, modular construction can be understood as an evolving structural methodology in which joinery systems play a central role in enabling scalable and reliable multi-storey modular housing.

3. CONCLUSIONS

3.1 Summary of Research Findings

This research examined how joinery systems influence structural performance in mid-rise modular housing. Through a qualitative and comparative analysis of selected modular housing precedents, the study evaluated inter-module connections, stacking logic, load transfer mechanisms, and constructability as key parameters affecting modular building performance.

The findings confirm that early modular housing projects often relied on rigid stacking strategies or experimental connection systems that prioritized prefabrication efficiency over structural integration (Smith, 2010). In these systems, the structural behaviour of modular buildings was largely dependent on the strength of individual modules rather than on coordinated connection frameworks (Lawson et al., 2014).

In contrast, contemporary modular construction increasingly employs engineered connection systems designed to manage structural loads, tolerances, and lateral stability. Modern modular buildings frequently integrate hybrid structural systems combining reinforced concrete stability cores with steel volumetric modules connected through calibrated joinery systems (Lacey et al., 2018). These connections enable effective load transfer and improved structural resilience in multi-storey modular buildings (Peng et al., 2020).

The comparative analysis therefore demonstrates that the structural viability of mid-rise modular housing is largely determined by the performance of inter-module joinery systems.

3.2 Interpretation of Structural Transformation

The study indicates that the transformation in modular construction is driven primarily by technological advancement and changing urban construction demands. Rapid urbanization and increasing housing shortages require construction systems that are faster, more efficient, and adaptable to dense urban conditions (Smith, 2010).

Traditional construction systems based on cast-in-situ concrete structures are often labour-intensive and time-consuming, making them less suitable for large-scale housing delivery in rapidly growing cities (Lawson et al., 2014). Modular construction provides an alternative approach by shifting much of the construction process to controlled factory environments.

However, the structural reliability of modular buildings depends heavily on how modules are connected. Advances in connection engineering and digital fabrication have enabled more precise joinery systems capable of accommodating tolerance deviations and dynamic structural loads (Lacey et al., 2018).

Consequently, modern modular housing increasingly prioritizes calibrated connection systems that enable structural continuity, adaptability, and efficient construction sequencing (Peng et al., 2020).

3.3 Contribution to Architectural Theory

This research contributes to architectural discourse by reframing joinery as a primary structural mediator in modular construction rather than a secondary assembly detail. By emphasizing the relationship between connection design, structural behaviour, and stacking logic, the study highlights the importance of system-level thinking in modular architecture (Lawson et al., 2014).

The research also establishes a comparative analytical framework based on parameters such as inter-module joinery, structural load transfer, stacking alignment, constructability, and structural robustness. This framework enables modular housing systems to be analysed systematically across different case studies and construction approaches (Lacey et al., 2018).

Furthermore, the study demonstrates that the feasibility of mid-rise modular housing depends on integrated design strategies that coordinate architectural layout, structural systems, and connection detailing (Peng et al., 2020).

3.4 Implications for Architectural Practice

The findings of this study offer important insights for architects, engineers, and planners involved in designing modular housing systems. Rather than treating joinery as a technical detail resolved during later stages of design, connection strategies should be integrated into the conceptual design phase of modular buildings (Lawson et al., 2014).

Architectural planning must consider structural stacking logic, module dimensions, and connection accessibility to ensure efficient construction and long-term structural performance. Design strategies such as vertically aligned module stacking, tolerance-adjusting connection interfaces, and hybrid structural systems can improve the feasibility of mid-rise modular housing (Lacey et al., 2018).

In rapidly urbanizing cities, modular housing systems also provide opportunities for faster construction, reduced material waste, and improved quality control through industrialized building processes (Smith, 2010). By integrating structural joinery frameworks within modular design, architects can develop housing solutions that respond effectively to contemporary urban challenges.

3.5 Limitations of the Study

Despite its contributions, this research has several limitations. The study relies primarily on documented case studies and secondary research sources, which limits access to detailed structural data and proprietary connection technologies used in modular construction projects.

Additionally, the analysis focuses mainly on international modular housing precedents, as large-scale mid-rise modular housing projects remain limited within the Indian context (Lawson et al., 2014). This restricts the ability to evaluate locally developed modular construction systems.
Furthermore, the study does not include detailed numerical modelling or experimental testing of joinery systems, which could provide deeper insight into structural performance characteristics (Lacey et al., 2018).

3.6 Scope for Future Research

Future research could expand this study by incorporating quantitative structural analysis and numerical simulations to evaluate connection behaviour in mid-rise modular buildings. Structural modelling software and experimental testing could provide deeper insights into connection stiffness, load redistribution, and seismic performance.

Further research could also investigate modular housing applications within Indian cities through pilot projects and field studies to evaluate constructability and regulatory challenges. Such studies would help develop context-specific design guidelines for modular construction in India.

Interdisciplinary research combining architecture, structural engineering, and construction management could also explore how digital fabrication technologies and Building Information Modelling (BIM) can improve coordination between module design and connection systems (Peng et al., 2020).

3.7 Final Reflection

This research positions joinery as the critical structural interface that determines the feasibility and scalability of mid-rise modular housing systems. Through the comparative evaluation of modular precedents and the analysis of parameters such as joinery typologies, stacking logic, load transfer mechanisms, constructability, and adaptability, the study demonstrates that structural behaviour in modular buildings is fundamentally connection-driven rather than module-driven. The findings indicate that the performance of multi-storey modular systems depends on calibrated joinery capable of balancing stiffness, ductility, and tolerance absorption while maintaining continuous structural load paths (Lawson, Ogden, & Goodier, 2014; Lacey et al., 2018).

The synthesis of case study analysis and parameter-based evaluation further reveals that hybrid structural frameworks provide the most feasible configuration for mid-rise modular housing in the Indian context. Systems combining reinforced concrete stability cores with lightweight steel volumetric modules supported by semi-rigid high-strength bolted connections demonstrate improved structural robustness, better tolerance management, and enhanced constructability. The material strategy identified through the study—incorporating cold-formed steel modular frames, high-performance concrete cores, composite slim floor systems, and elastomeric tolerance interfaces—offers a practical pathway for integrating modular construction with existing Indian building practices.

Beyond technical evaluation, the research reframes modular construction as an integrated architectural-structural system rather than a purely industrialized production method. Joinery systems emerge not only as mechanical connections but as organizing elements that mediate architectural planning, structural hierarchy, and construction sequencing. This perspective expands the understanding of modular housing from a speed-driven prefabrication technique to a system-based design strategy capable of delivering resilient, adaptable, and scalable housing solutions.

In the context of rapidly urbanizing Indian cities, the proposed joinery-to-structure framework offers a conceptual and practical foundation for advancing mid-rise modular housing. By integrating architectural design logic with structural connection performance, the research contributes to ongoing discourse on industrialized construction and supports the development of efficient housing systems responsive to contemporary urban demands.

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