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Modular Construction: An Unique Approach

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ABSTRACT: Connection in modular construction refers to the critical components that link individual modules to form a single, stable structure. These connections are essential for transferring forces, ensuring structural integrity, and providing stability against loads like wind and seismic activity. While traditional welded or bolted methods are common, research focuses on improving these connections to be more efficient, easier to assemble/disassemble, and to better handle seismic performance, with new designs like self-locking mechanisms and preload systems gaining attention. Prefabricated modular construction can be an alternative to meet the growing demand for low-cost housing due to its rapid and economical construction techniques. The structural behavior of modular connection is complex depending on the connection types and the degree of rigidity offered. In or only, or may connect both horizontally and vertically, depending to structurally behave as a single unit, it must be ensured that all the forces between modules are transferred effectively through inter-modular connections. This paper presents a review of existing techniques used in the inter-modular connections of the modular construction. The review presents a detailed discussion on the important characteristics of inter-modular connections such as geometric designs, structural performances, and current design practices etc. The pros and cons of the existing connections are reviewed in terms of the structural performances through the previously available experimental and theoretical studies. The observations and discussion presented in this review can help better understand and improve the connection behavior in the modular structural systems.

KEYWORDS: Modular Construction, Connection, Inter-modular Connection .

I. INTRODUCTION

Modular construction is a construction technique which involves the prefabrication of 2D panels or 3D volumetric structures in off-site factories and transportation to construction sites for assembly. This process has the potential to be superior to traditional building in terms of both time and costs, with claimed time savings of between 20 and 50 percent faster than traditional building techniques. Due to relatively low labour costs in some countries, traditional construction methods using on-site poured structures and brick walls are still widely employed. However, the inefficiency of these construction methods has become a barrier to economic growth in the construction industry, and with the continuous rise in labour costs, their financial advantages are gradually diminishing.

The design of connection plays a pivotal role in modular construction, as the reliability of these connections directly determines the overall structural performance. To achieve optimal results, connection designs must not only ensure structural integrity but also facilitate efficient construction processes.

Unit connections in modular construction are crucial for ensuring the overall stability, structural integrity, and performance of the finished building by tying individual modules together to form a single structure. These connections are responsible for transferring loads, providing stiffness against lateral forces like wind and seismic activity, and maintaining the building's vertical alignment.

Scope of the study:

An aim of study on unit connections in modular construction through window corners across floors would be to develop and validate a novel, high-performance inter-module connection system that is integrated into the window frame at the building's corners. This approach addresses key challenges in modular construction, such as reducing on-site finishing work, improving assembly efficiency, and enhancing the structural integrity, particularly seismic and energy performance, of multi-story modular buildings.

II. LITERATURE SURVEY

2.1 Mohammadamin Zohourian, Apurva Pamidimukkala, Sharareh ermanshachi, Deema Almaskati “Modular Construction: A Comprehensive Review,” University of Texas,2017

Modular construction has the potential to transform the construction industry, as most (80–95%) of the modules, which are considered prefabricated buildings, are manufactured off-site, which is more efficient, safe, cost-effective, sustainable, productive, and faster than traditional construction.

It is not without challenges, however, as it requires detailed and comprehensive planning, high initial costs, and navigating transportation and design constraints.

2.2 Dr. María Fernanda Gómez, Dr. Ricardo Javier Sánchez “Impact of modular construction technique on cost and time efficiency in large projects”, International Journal of Civil Engineering and Construction, 2024

These findings underscore the transformative potential of modular construction techniques globally, especially in addressing challenges in both developed and developing economies. By focusing on scalable and sustainable practices, modular construction can pave the way for innovative solutions in infrastructure development. The construction industry faces growing challenges in meeting project deadlines and controlling costs, particularly in large-scale developments.

2.3 Shubham Jadhav, Amit Kadam, Mahesh Dangat, Swapnil More, Mayur Tanpure, “Analysing Precast & Modular Construction with respect to design and cost”, IJCRT 2022

The article considers temporary methods of using modular units in construction. The advanced world experience in the construction of modular buildings is analyzed. It is emphasized that modular construction has the potential to shorten project design and engineering time, reduce costs and improve construction productivity. The installation of modular buildings is cost-efficient, safe and eco-friendly. Modern modular systems are based on using not only large elements such as «block rooms» but various small 3D building elements.

2.4 Islam Gharaibeh, Rahman Azari , Gregory Pavlak “A Review of Modular Construction Role in Reducing Buildings' Environmental Impacts”, Research gate,2025

As one of the largest contributors to greenhouse gas emissions, the construction industry faces increasing pressure to adopt more sustainable practices. In this context, Modular Construction (MC) has emerged as a promising sustainable process of industrializing construction activities, where different tasks can be transferred into off-site facilities and automated, regulated, and controlled within a specific environment. The potential benefits of MC extend beyond improved productivity, quality, and cost efficiency, encompassing waste and environmental footprint reduction.

2.5 Devika Sumithran , Nivetha John , Dr.A.Kumar, “Study of modular building construction using Primavera”, IJETS™2023

This research studies the need and importance of modular building construction in this fast developing countries like India. In this research firstly we study about the basic principles and criteria's to be used in the modular construction technique. The pros and cons of construction of modules are also studied

III. PROBLEM STATEMENTS

- Difficulty in Fast Assembly of Modular Units
- Alignment Issues Between Stacked Modular Units
- High Cost of Structural Connectors
- Difficulty in Disassembling Modular Buildings
- Inefficient Use of Structural Components
- Limited Innovation in Modular Floor-to-Floor Connections

IV. OBJECTIVES

- **To develop an innovative connection method for modular construction**

To design a new structural connection system that joins two modular units using **window corner bolt joints**.

- **To simplify the assembly process of modular buildings**

To create a connection technique that allows **quick and easy installation of stacked modular units** during construction.

- **To reduce construction time and labor requirements**

To minimize the complexity involved in traditional modular connections by using **simple bolts and nuts for joining modules**.

- **To improve alignment between stacked modules**

To ensure proper **vertical alignment of upper and lower modular units** through corner window connection points.

- **To make the structure easily disassemblable and reusable**

To design a connection system that allows **easy removal of bolts**, enabling relocation or reuse of modular units.

- **To provide a cost-effective connection system**

To reduce the need for expensive connectors or welding by using **simple mechanical fastening techniques**.

- **To demonstrate the feasibility of the proposed connection method**

To build a **small prototype model** and show that the window corner bolt connection can effectively hold modular units together

V. STRUCTURAL MATERIALS

5.1 Steel : Steel is the most common material for multi-story modular construction, prized for its strength, durability, and a high strength-to-weight ratio. Cold-formed steel: Light steel C-sections are frequently used for load-bearing walls in low- to mid-rise buildings (up to 10 stories). Hot-rolled steel: Heavier square hollow sections (SHS) or rectangular hollow sections (RHS) are often used for corner posts and beams in high-rise buildings or those requiring larger open spaces.

5.2 Concrete : Precast concrete is used for highly durable, fire-resistant, and sound-insulating modular units, such as those used for hotels or dormitories. However, the extreme weight of these modules presents logistical challenges for transportation and crane lifting.

5.3 Timber : Wood-framed modules are commonly used for low- to mid-rise residential buildings.

5.4 Light-framed wood: Uses lightweight wood studs and trusses, which are cost-effective but have height and span limitations. Mass timber: Engineered wood products like Cross-Laminated Timber (CLT) are increasingly used for their sustainable properties and superior strength in mid-rise projects

VI. PROTOTYPE DEVELOPMENT

6.1 Development of Scaled Modular Units : Two modular units representing **lower floor and upper floor** were fabricated using mount board, each unit included :

- Window openings at corner locations
- Structural frame representation
- Proper alignment surfaces for stacking

6.2 Creation of Window Corner Connection Points : Special attention was given to the window corner regions, where :

- Holes were provided at lintel level of the lower module
- Corresponding holes were aligned at sill level of the upper module

This setup replicates the actual connection concept.

6.3 Simulation of Bolt Connection Mechanism : A bolt-type connection system was simulated using Small rods/pins to represent :

- M16 high tensile bolt
- Washer and nut arrangement

The bolt was :

- Inserted from **lintel level of lower module**
- Passed through aligned corner frames
- Tightened at **sill level of upper module (inner side)**

6.4 Representation of Inner Side

Accessibility : The model clearly demonstrates that :

- The connection is made **after the final window frame boundary**
- All operations are performed **from inside the module**
- No external access is required

6.5 Demonstration of Assembly Process

The model was used to practically show

- Stacking of upper module over lower module
- Alignment of window corners
- Insertion and tightening of bolt
- Stability after connection

6.6 Verification of Concept Feasibility : Through the model, it was observed that

- The connection provides **proper alignment**
- Assembly is **simple and quick**
- The system is **reusable and detachable**



VII. METHODOLOGY

7.1 Design of Units :

To design bolted connections at the window corners of modular units across floors, engineers must address the challenge of limited access for assembly and ensure the connections provide sufficient vertical and lateral load resistance. A common solution involves using a combination of vertical structural rods and specially designed connector plates installed within the floor and ceiling cavities at the corner posts. Connection design details

7.2 Vertical connection system :

Hollow structural section (HSS) columns : Modular units are typically constructed with HSS (Square or Rectangular) steel sections at the corners. The columns are the primary compression members and provide a conduit for the vertical bolts.

Vertical threaded rods : High-tensile steel threaded rods, also known as stay bolts, are passed through the hollow core of the HSS columns. These rods span multiple stories and are coupled together using couplers, allowing for connection from the top of the modules.

Post-tensioning : Post-tensioned bolted connections are used to create a strong clamping force between the module floor and ceiling sections, which sit atop one another. This preload enhances the stiffness and load-bearing capacity of the joint.

Fasteners : Different fasteners can be used, including:

Blind bolts : Used in locations with limited or one-sided access, such as connecting the plate to the HSS column.

High-tension (H/T) bolts : Used where access is available, such as connecting the plates to the C-shaped steel floor beams.

7.3 Horizontal connections at the window corner :

Interlocking elements: Novel interlocking mechanisms can be integrated into the connector plates to aid in the horizontal alignment of the modules.

Bolted plates: Simple plate connections are commonly used to fasten adjacent modules together horizontally. These are bolted on-site to the side plates of the modules. For window corners, these plates can be designed to transfer in-plane forces around the window opening.

7.4 Design considerations for window corner connections :

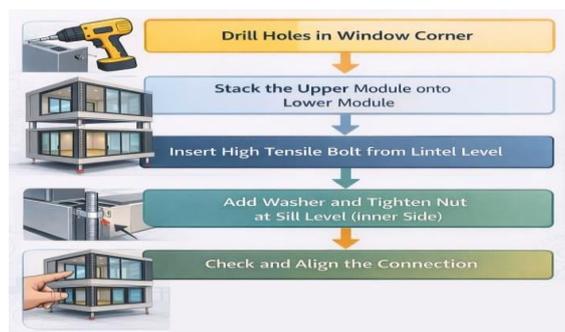
7.4.1 Access and constructability : Since window corners limit external access, the connection must be designed for one-sided assembly, using methods like blind bolts and vertically inserted stay bolts. The design must account for construction tolerances using slotted holes where needed, though this can allow for unwanted slip in the joint

7.4.2 Structural integrity and load resistance :

The connections must be robust enough to ensure the integrity of the assembled structure and redistribute loads, especially in the event of a column failure. The bolted system must effectively transfer gravity loads (compression) and lateral loads (shear and tension from wind or seismic forces) across the floors. The pre-tensioning of the vertical rods ensures initial stiffness and prevents slip under service loads.

7.4.3 Finish integration :

The design must account for the architectural finishes and internal walls that are prefabricated off-site, ensuring connection is accessible during assembly but hidden in the final state.



VIII. EXPERIMENTAL RESULTS

8.1 Structural performance :

load-bearing capacity: Analyze how the connections at window corners transfer and withstand structural loads, including gravity, wind, and seismic forces. This can involve testing prototype connections under various axial, shear, and moment loads.

Evaluate connection methods: Compare the effectiveness of different types of connections used at the corners, such as bolted plates, welded joints, interlocking mechanisms, and proprietary blind fixings.

8.2 Thermal performance : Identify and mitigate thermal bridging: Investigate how the highly conductive materials of the structural frame at window corners create thermal bridges, leading to heat loss or gain. Use infrared thermography to identify and quantify heat leaks.

8.3 Evaluate insulation and detailing : Assess the effectiveness of insulation and detailing strategies at the window jambs, sills, and heads to maintain a continuous thermal envelope and improve energy efficiency.

8.4 Analyze condensation risk : Study the risk of interstitial condensation within the wall assembly at window corners, which can lead to moisture damage, mold growth, and a reduction in insulation performance.

8.5 Acoustic performance :

Measure sound transmission : Quantify the sound transmission loss through the window corner connections, which can be a weak point in the facade's overall acoustic performance.

Study sound flanking paths : Investigate how sound can bypass the primary wall and window assembly by traveling through the structure at the corner, and evaluate methods for breaking these flanking paths.

8.6 Construction and assembly efficiency :

Assess on-site assembly: Evaluate the ease and speed of assembling and connecting modular units at the window corners on-site.

Review manufacturing tolerances: Investigate how manufacturing tolerances affect the fit and performance of the connections at the factory and on-site.

IX. CONCLUSION

9.1 The present study successfully achieved the objective of developing an **innovative connection method for modular construction** using window corner bolt joints. A **physical prototype model** was designed and fabricated to demonstrate the feasibility of the proposed system.

9.2 The project effectively simplified the **assembly process of modular units** by introducing a bolt-based connection that can be installed from the **inner side of the window**, eliminating the need for complex external connections. This directly contributes to the objective of **reducing construction time and labor requirements**.

9.3 Proper **alignment between stacked modules** was achieved through the use of predefined window corner connection points, ensuring stability and ease of installation. The proposed system also fulfilled the objective of **cost-effectiveness**, as it utilizes simple mechanical components such as bolts, nuts, and basic framing elements.

9.4 Additionally, the connection method supports **easy disassembly and reusability**, making it suitable for modular and relocatable structures. The internal accessibility of the connection enhances **safety and maintenance**, while also preserving the external aesthetics of the structure.

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9.5 Modular construction through bolted connection in floors has the potential to transform, expand, and enhance the construction sector by increasing its efficiency, cost effectiveness, quality control, safety, and sustainability while reducing the time required for construction.

9.6 The analysis revealed that the most significant benefits of modular construction include a reduction in construction time by approximately 50%, cost savings of up to 20%, and a reduction in material waste by more than 80%.

9.7 Additional benefits identified include improved workplace safety, lower rework rates, enhanced energy efficiency, and decreased carbon and water usage.

9.8 The study also identified major challenges faced during the implementation of bolted connection.

9.9 These challenges include transportation complexities, limited design flexibility due to an early design freeze, fragmented supply chains, high initial costs, and a shortage of experienced professionals.

The study addressed each of these challenges with practical strategies supported by the literature.

9.10 A key contribution of this study is the systematic linking of specific challenges with practical mitigation strategies, grounded in recent research.

9.11 By establishing clear connections between problems and solutions, the study provides construction stakeholders with actionable knowledge to guide their decision-making and implementation processes.

9.12 Additionally, it emphasizes the role of digital technologies such as AI, BIM, blockchain, and digital twins in optimizing various aspects of modular construction, from logistics and planning to connection design and lifecycle management.

9.13 This study offers a structured synthesis of the current modular construction literature, laying the groundwork for future empirical investigations into connection design, life cycle cost analysis, and long-term performance assessments.

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