

Comparative Evaluation Of Bolted, Plug-In Self-Lock, And Wall Beam-Strut Joints For Modular High-Rise Buildings

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Abstract: The structural performance of modular high-rise buildings significantly depends on the efficiency of connections between prefabricated units. This research presents a comparative evaluation of three joint types—bolted, plug-in self-lock, and wall beam-strut—through both theoretical analysis and MATLAB-based multi-criteria optimization. Key structural parameters, including stiffness, damping, slip resistance, and load transfer efficiency, were assessed and normalized using published literature data. Weighted suitability scores were calculated to reflect the distinct functional demands of intra-modular and inter-modular joints. The analysis revealed that bolted joints are most suitable for intra-modular connections, offering superior stiffness and slip control, while plug-in self-lock joints are best suited for inter-modular applications, owing to their high damping capacity and reliable load transfer behavior. The findings were visualized using bar charts, radar plots, and pie diagrams to support informed design decisions.

Keywords: Bolted joint, modular construction, plug-in self-lock joint, structural behavior, wall beam-strut joint.

1. INTRODUCTION

Prefabricated Modular construction technique involves the manufacturing of framed modules in controlled factory settings, followed by their transportation & assemblage on-site (Refer Fig. 1 and 2). This technique allows:

- i. Rapid construction by reducing the on-site work and speeding up the entire construction process by 30-50%
- ii. Lower construction costs by reducing material wastage due to controlled factory environment and also involves lesser labor
- iii. Higher Efficiency as off-site precision manufacturing allows material consistency and much better alignment
- iv. Risk management by reducing on-site accidents
- v. Sustainability in terms of less construction waste and ability to alter materials as per requirements

Keeping the above factors in mind, prefabricated construction has entered the infrastructure market in the recent years. However, due to lack of enough structural evidence to support the positives, prefabricated modular buildings (PMBs) offer many research gaps to academicians worldwide.



Fig. 1 On-site Construction of Modular Building



Fig. 2 Modular Blocks being placed like Lego Blocks

The structural key elements in a modular structure that need to be designed with utmost sanctity are the Modular Joints. The design and behavior of modular joints is a major area of concern for researchers in this field. These joints are primarily of two types (Refer Fig. 3 [15]):

- i. Intra-modular Joints – These joints connect the structural elements, within a module, to each other. These are primarily present at the corners of a module connecting the steel column to two perpendicular beams or may be present along the length of a module to connect bracings to the beams.
- ii. Inter-modular Joints – These joints connect two or more modules to each other, in the vertical or horizontal directions. These joints transfer loads such as gravity, wind or seismic from one module to another to maintain the structural integrity of the structure.

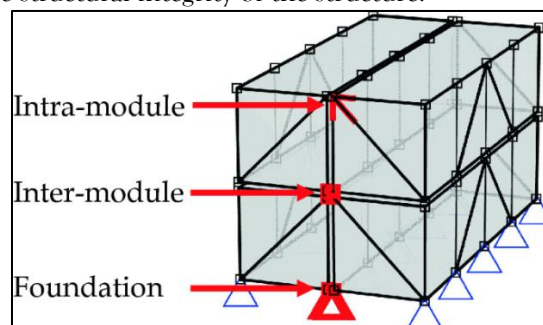


Fig. 3: Types of Connections in a Modular Building

Generally, there types of joints are used as intra- or inter-modular joints – Bolted Connections, Plug-in Self-Lock Joints and Wall Beam-Strut Joints. The present study aims to evaluate the three joints using past literature and MATLAB-based multi-criteria optimization and fill the gap regarding the selection of joints in a modular high rise based on various performance parameters including stiffness, energy dissipation, slip resistance, ease of assembly, reusability, load transfer efficiency and cost & time of installation.

2. LITERATURE REVIEW

Joints are known to play a major role in determining the dynamic characteristics of a modular structure. Studies have suggested that the type of connection determines the natural frequency, energy dissipation and damping of the modular frame. This emphasizes on the need for a rigorous method to select a joint type for inter- and intra- modular connections. Usually three types of joints are used in modular buildings – Bolted, Plug-in self-lock and Wall beam-strut joints. Each of these joints are discussed below.

A. Bolted Connections

Bolted Joints (Refer Fig. 4 [17]) are the most common types of joints used in modular construction as they provide ease of installation, scope of reusability and structural & mechanical simplicity. These joints, however, may lag in performance under cyclic loads due to microslip and loss of stiffness. Studies by Liu et al (2017), Wang et al (2019), Chen et al (2020), and Abdelhamed (2025) repeatedly suggested that bolted connections must be adopted for modular housing, proving its structural integrity by numerical simulations and experimental validations.

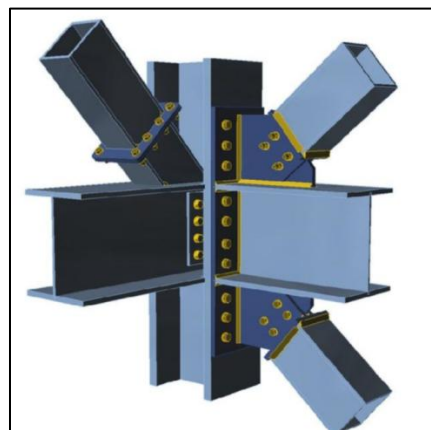


Fig. 4 Bolted Connections

B. Plug-in Self-Lock Joint

Plug-in self-lock joints (Refer Fig. 5 [4]) are adopted in modular construction as they make the process of installation easier and faster. Nadeem et al (2023) and Dai et al (2019) validated the use of these connections as inter-modular joints by demonstrating its excellent performance under cyclic loads using FEA and experimental calibration.

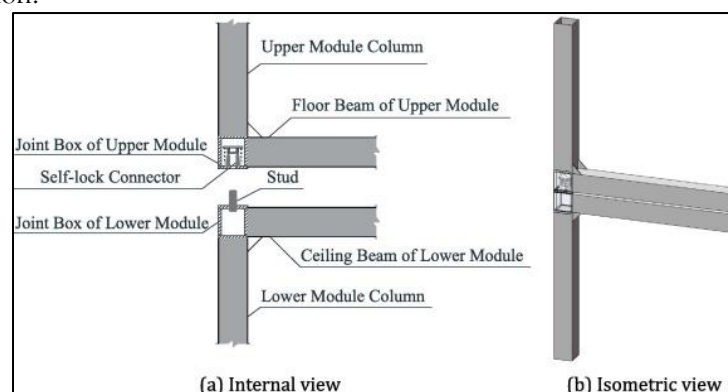


Fig. 5 Plug-in Self-Lock Joint

C. Wall Beam-Strut Joint

Traditionally used in underground structures, wall beam-strut joints (Refer Fig. 6 [11]) are now being applied to high-rise modular buildings, owing to their high stiffness and load transfer efficiency. These joints are known to provide robust resistance to lateral loads and are therefore considered useful in high-rise modular structures where seismic forces are known to act on the structure.

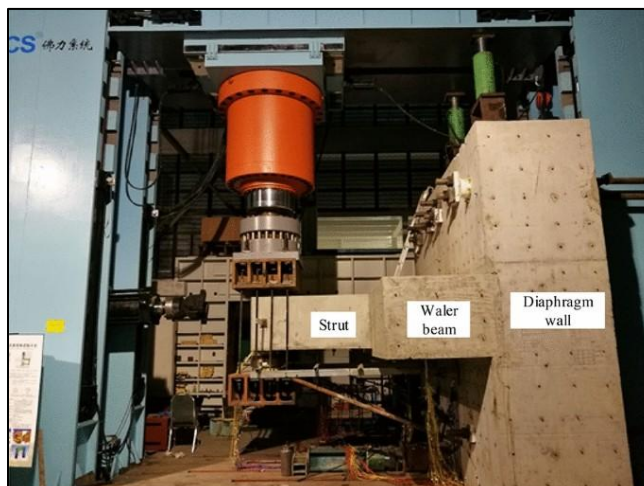


Fig. 6 Wall Beam-Strut Joint

3. METHODOLOGY

This study performs a physics-based comparative assessment of the three commonly used modular joint types - Bolted, Plug-in self-lock and Wall beam-strut joints. The current adopted methodology consists of two stages - (i) analytical derivation of the joint performance matrix and (ii) MATLAB Optimization using the multi-criteria decision making approach implemented by the AHP-TOPSIS method.

The AHP (Analytic Hierarchy Process) allows us to assign weights to each structural parameter in a logical manner, thereby determining its importance. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is used to rank the alternatives on the basis of performance of the above parameters. The combination of these two techniques provides a powerful multi-criteria decision making approach.

A. Selection of Evaluation Parameters

The following six parameters, as described in Table 1, were selected to evaluate the structural performance of the three joint types.

Table 1. Performance Parameters for Joint Optimization

Parameter	Unit	Description
Stiffness	KN/mm	Resistance to deformation
Energy Dissipation	%	Critical for seismic resilience; higher energy dissipation ensures minimum structural damage
Slip Resistance	mm	Displacement between connected parts
Ease of Assembly	1 - 10 Rank	Ranking based on speed of assembly, simplicity and level of skilled labor required
Reusability & Demountability	0 or 1	Binary score; 1 if easily reusable/demountable, 0 otherwise
Load Transfer Efficiency	%	Effectiveness in transferring axial/lateral loads; estimated based on load continuity, mechanical interlock and rigidity

B. Modeling of Joint via Spring-Damper Equivalence

Each joint has been simplified to an idealized mechanical model comprising of axial springs, dampers and frictional interfaces, thereby enabling the derivation of structural performance characteristics of the three joint types using fundamental mechanical equations.

Stiffness Calculation (k)

Joint Stiffness is calculated using axial or bending stiffness expressions depending on the type of joint. For example, the stiffness of a bolted connection is given by:

$$k = \frac{n \cdot A_b \cdot E_b}{L_b}$$

Where, n = 4 bolts,

$$A_b = \pi r^2 = \pi (8 \text{ mm})^2 = 201 \text{ mm}^2$$

$$E_b = 2 \times 10^5 \text{ MPa}$$

$$L_b = 25 \text{ mm}$$

Therefore, k = 643.2 KN/mm (bolted connections).

Similar mechanical equations were applied to plug-in self-lock and wall beam-strut joints using contact mechanics and beam theory.

Slip Resistance (Δ_{slip})

It is calculated using frictional resistance and joint stiffness. For bolted connection,

$$\Delta_{slip} = \frac{\mu \cdot T_{bolt}}{k}$$

Where, $\mu = 0.3$,

$$T_{bolt} = 25 \text{ KN}$$

Therefore, $\Delta_{slip} = 0.006 \text{ mm}$

Plug-in self-lock joint has lower slip resistance due to interference fit while wall beam-strut has zero slip due to monolithic continuity.

Energy Dissipation (ζ)

Energy dissipation is represented by an equivalent damping ratio (ζ). These values replicate the ability of a joint to dissipate energy under cyclic loading.

$\zeta = 0.05$ for bolted, 0.13 for plug-in and 0.07 for wall beam-strut.

Constructability Parameters

- Ease of Assembly (1 – 10): Assigned on the basis of tools, labor and alignment sensitivity
- Reusability (0 or 1): Defined by whether the joint can be demounted and reused.
- Load Transfer Efficiency (%): Estimated based on load continuity, mechanical interlocking and rigidity.

The calculated values of all parameters for the three joint types are tabulated in Table 2.

Table 2. Analytical Values of Parameters

Parameter	Bolted	Plug-in Self-lock	Wall Beam-Strut
Stiffness (KN/mm)	643.2	200	1000
Energy Dissipation	0.05	0.13	0.07
Slip Resistance (mm)	0.006	0.003	0.00
Ease of Assembly	8	10	4
Reusability & Demountability	1	1	0
Load Transfer Efficiency (%)	65	85	95

C. Parameter Normalization and Weight Assignment

All parameters were normalized to a 0-10 scale to enable equal comparison. For positive performance indicators (e.g., stiffness, dissipation), min-max normalization was applied:

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}}$$

For negative indicators (e.g., slip resistance), inverse scaling was used:

$$x' = \frac{x_{\max} - x}{x_{\max} - x_{\min}}$$

This ensures higher normalized scores always indicate better performance. The normalized matrix, as derived, is tabulated in Table 3 below. Fig. 7 depicts the radar plot of the normalized parameters for all three joint types.

Table 3. Normalized Parameter Matrix

Parameter	Bolted	Plug-in Self-lock	Wall Beam-Strut
Stiffness	0.554	0.000	1.000
Energy Dissipation	0.000	1.000	0.250
Slip Resistance	1.000	0.500	0.000
Ease of Assembly	0.667	1.000	0.000
Reusability & Demountability	1.000	1.000	0.000
Load Transfer Efficiency	0.000	0.667	1.000

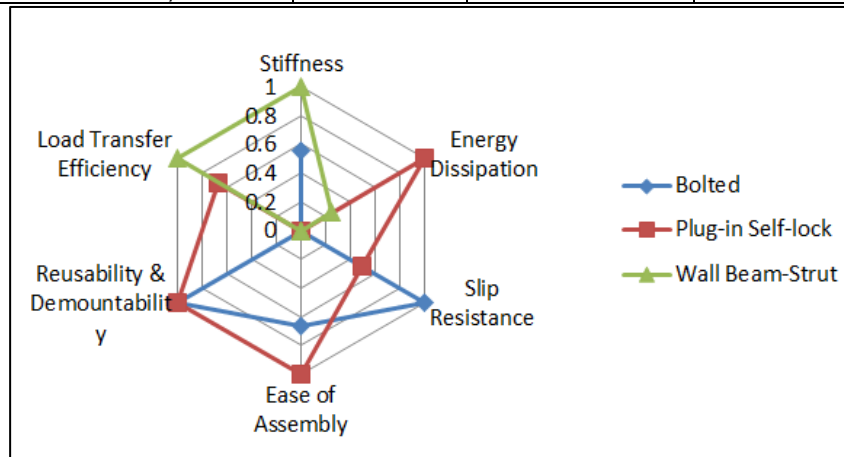


Fig. 7: Radar Plot of the Normalized Parameters of the Joints

D. AHP-TOPSIS Optimization Framework

The placement of joint – inter- or intra-modular – determines the importance of parameters. Therefore, weights are assigned to the parameters based on function of the joint, structural priorities and findings from published literature. Further, these weights are validated using AHP and expert judgement.

Two different weight vectors were used for inter- and intra-modular joints. These are tabulated in Table 4 below. Fig. 8 depicts the pie chart of the AHP weights for inter- and intra-modular joints.

Table 4 Assigned Weight Matrix

Parameter	Intra-Modular Weights	Inter-Modular Weights
Stiffness	0.25	0.15
Energy Dissipation	0.05	0.30
Slip Resistance	0.25	0.05
Ease of Assembly	0.20	0.05
Reusability & Demountability	0.20	0.10
Load Transfer Efficiency	0.05	0.35
Total	1.00	1.00

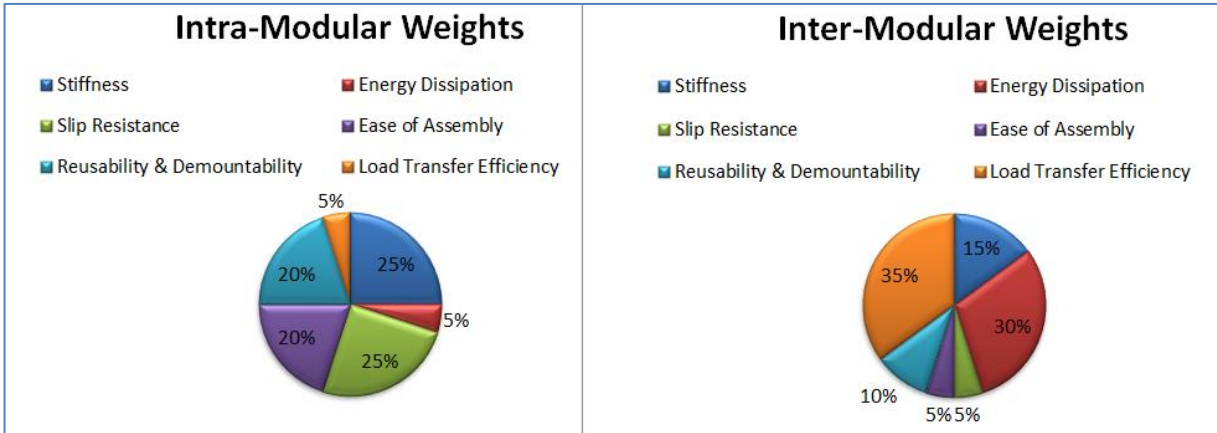


Fig. 8: AHP Weights for Inter- and Intra-Modular Joints

E. Final Rankings and Implementation

The normalized matrix is then multiplied by weights and TOPSIS ranking is computed by measuring each joint type's Euclidean distance from the ideal and the non-ideal solutions, to obtain the final scores. All calculations, normalization and optimization are implemented on MATLAB and the final ranking of joints thus obtained is tabulated in Table 5 and can also be interpreted with the help of Fig. 9.

Table 5. Final Ranking

Joint Type	Intra-Modular Score	Inter-Modular Score
Wall beam-strut	0.549	0.609
Plug-in Self-lock	0.536	0.674
Bolted	0.472	0.223

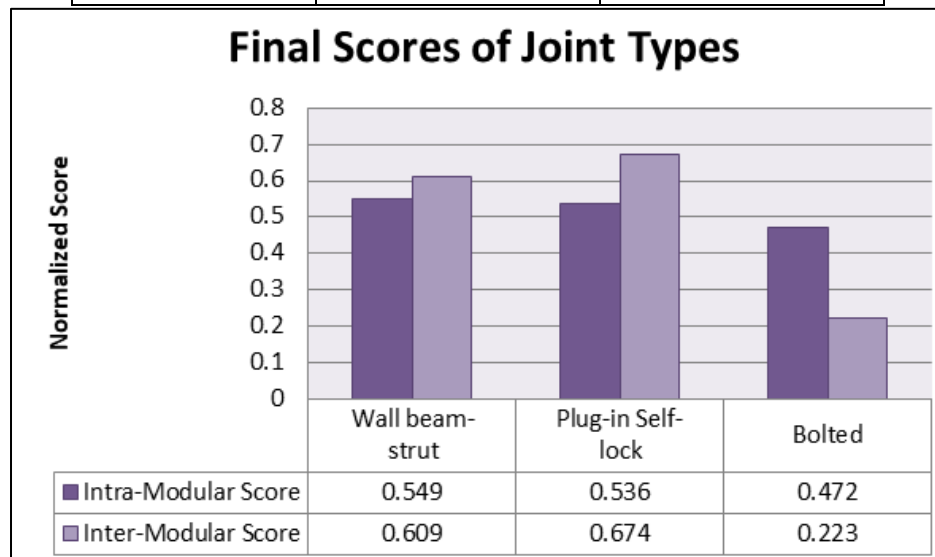


Fig. 9: Final Normalized Scores of Joint Types

4. Interpretation of Results

The following section interprets the analytical findings and the MATLAB Optimization results for the comparative analysis of the three joint types – bolted, plug-in self-lock and wall beam-strut joints. The three joints have been analysed to define their use as inter- and intra-modular joints based on various structural parameters. The final scores, as obtained in Table 5, are interpreted below:

Intra-Modular Application

The wall beam-strut joint has emerged as the top performer in intra-modular connections with a high score of 0.549, closely followed closely by both, plug-in self-lock (0.536) and bolted connections (0.472). While the structural superiority of the wall beam-strut connection is undeniable since these joints exhibit highest stiffness, perfect slip resistance and exceptional load transfer efficiency. However, their practical application in modular construction is limited due to poor constructability, lack of reusability and high installation time. Further, intra-modular joints are fabricated in controlled factory settings before transferring the module to site. It can be argued that neither wall beam-strut joint nor plug-in self-lock connection offers the advantages of a bolted connection.

A bolted joint has high repeatability, can be easily inspected and can be installed in minimum time. The numerous practical advantages of a bolted connection easily outweigh the minor differences in numerical score.

Inter-Modular Application

The plug-in self-lock joint, with the highest score of 0.674, clearly outperforms the wall beam-strut joint (0.609) and bolted connection (0.223). This reiterates the fact that this connection type is an ideal solution for inter-modular joints as it high energy dissipation, excellent slip control, robust load transfer and rapid site assembly interface.

5. CONCLUSIONS

Based on the analytical derivation and AHP-TOPSIS normalization and optimization of the numerical results, the Bolted joint may be recommended for intra-modular connections. This joint type offers high stiffness (643.2 KN/mm), relatively strong slip resistance (0.006 mm) and is quick & easy to assemble, disassemble and reuse, making it ideal for factory fabricated modular construction.

For inter-modular connections, plug-in self-lock joint is the most suitable. It has an excellent energy dissipation ($\zeta = 0.013$), good load transfer efficiency (85%) and rapid on-site deployment, as is required in modular buildings.

Although the wall beam-strut joint scores highest overall, it is not recommended for modular construction due to its requirement for on-site welding, increased installation time and no reusability, making it incompatible with modular construction principles.

6. Scope of Further Research

Future studies can expand on this work by incorporating experimental validation of joint performance under real seismic loads. Finite Element Modeling (FEM) of the joints can be conducted for detailed stress analysis and failure prediction. Further, life-cycle cost analysis including maintenance and retrofitting could enhance decision-making.

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