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Inter-Module Connections and Global Structural Behavior of Modular Steel Buildings: A Review

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Abstract

Modular steel buildings are mainly constructed through factory prefabrication and on-site assembly. Their global structural performance is governed to a large extent by inter-module connections. Existing studies have shown that local nonlinear behaviors in connections, such as gap closure, frictional slip, semi-rigid rotation, and cyclic degradation, can be amplified into global structural effects through load-path reconfiguration and deformation compatibility. These effects include the redistribution of inter-story drift, the accumulation of residual deformation, and the formation of weak stories. As a result, they can influence seismic and wind-resistant design outcomes as well as structural robustness assessment. This paper reviews the structural forms and load-transfer mechanisms of inter-module connections in modular steel buildings. Experimental and numerical evidence on global structural behavior is systematically summarized. A performance evaluation framework oriented toward global response is then outlined, together with approaches for describing system-level coupling effects. The development of equivalent connection modeling and global analysis methods is also reviewed. Finally, research prospects are discussed from the perspectives of high-rise development, performance-based design, reparability, and robustness. The study aims to provide reference for engineering design and standardized application of modular steel buildings.

Keywords

Modular Steel Buildings; Inter-Module Connections; Global Structural Behavior; Performance Evaluation.

1. Introduction

Modular buildings have attracted wide attention because they can shorten construction time, reduce on-site disturbance, and improve quality control. However, their structural system is fundamentally different from that of conventional continuous structures. A modular system is assembled from discrete modules, as shown in Fig. 1. Structural continuity depends on the collaborative action of inter-module connections and floor joints. Therefore, the global response is highly sensitive to connection details and connection stiffness[1].

Previous studies have shown that connection type, construction tolerance, and multi-interface contact behavior are key factors that govern the global load-transfer path and ultimate limit state. Their influence becomes more pronounced under wind and seismic actions[2].

With the increasing application of modular systems in mid-rise and high-rise buildings, higher demands have been placed on connection systems in terms of calculation, verification, constructability, and maintenance. To meet these demands, research has gradually expanded from the strength and stiffness of individual connections to the coupled influence of connection nonlinearity on inter-story drift, residual deformation, stability, and robustness. This development has also promoted the refinement of evaluation indices and modeling methods.

Fig. 1 Mid-rise modular residences

2. Inter-Module Connection Systems and Load-Transfer Mechanisms

2.1 Connection Locations and Functional Classification

Inter-module connections are commonly arranged at the ends of corner columns, the ends of edge beams, and floor joints. They are responsible for vertical compressive load transfer, uplift resistance, horizontal shear transfer, and rotational restraint. Corfar et al.[3] systematically reviewed and classified connections in hot-rolled steel modular systems. They emphasized the need for a unified terminology and classification framework based on connection form and load-transfer path, so that different studies can be compared on a consistent basis.

From the viewpoint of structural load transfer, the function of inter-module connections can be further divided into three key aspects. The first is axial load transfer and uplift resistance in the vertical connection chain, which determine the continuity and integrity of stacked modular systems. The second is horizontal shear transfer, which governs the distribution of story shear among different lateral-force-resisting components. The third is rotational restraint, which determines whether effective moment transfer and frame action can be developed between edge beams and corner columns. This issue is especially important in corner-supported modular systems, where the discrete arrangement of connections and the discontinuity of floor diaphragms reduce the validity of the conventional rigid diaphragm assumption. In such cases, the global response is jointly controlled by the interaction between connections and floor systems[4].

2.2 Typical Connection Forms

Existing inter-module connections can generally be classified into bolted connections, interlocking connections, post-tensioned connections, and hybrid connections with energy dissipation or self-centering capacity.

Bolted connections are the most widely used type and have the advantage of good inspectability in practice. However, their stiffness and slip behavior are strongly influenced by hole clearance, surface treatment of friction interfaces, bolt pretension, and assembly error. In a review of bolted inter-module connections, Lacey et al.[5] pointed out that conventional stiffness estimation methods for steel connections may lead to significant errors when directly applied to modular connections. This is because modular connections usually involve multi-interface slip and multi-stage contact transition, which should be explicitly considered in both modeling and experimental calibration.

Interlocking connections usually combine mechanical interlocking components with bolts in order to achieve both assembly tolerance accommodation and shear transfer. Chen et al.[6][7] proposed built-in connections and rotating connections, as shown in Fig. 2. Their studies showed that interlocking and corner connection details can provide good tensile and shear resistance as well as satisfactory seismic performance, while maintaining high assembly efficiency. However, the mechanical behavior of such connections is closely related to the load-transfer path and local detailing.

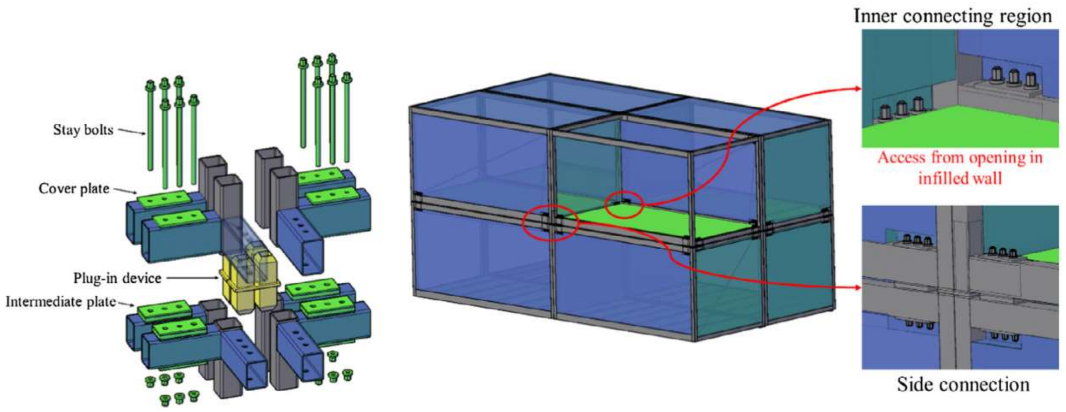

Fig. 2 Construction of inner connecting region in the proposed MSB connection

Post-tensioned connections achieve vertical continuity through post-tensioning elements arranged inside hollow columns. They have the potential to reduce on-site welding and improve construction efficiency. Sanches et al.[8] conducted experimental studies on vertical post-tensioned connections and summarized their mechanical behavior and failure characteristics. Their results showed that both connection detailing and post-tensioning level have important effects on stiffness and energy dissipation.

To achieve reparability and low residual deformation, hybrid connections have recently introduced components such as shape memory alloys and high-damping materials. These systems reflect a growing trend toward concentrating damage in replaceable parts and improving cyclic degradation and residual deformation control. However, their engineering standardization is still limited.

2.3 Major Sources of Nonlinearity

The nonlinearity of inter-module connections can be summarized into four main mechanisms, and these mechanisms usually show clear stage-dependent characteristics[9].

The first is gap closure and contact-state transition. During the early loading stage, hole clearance and assembly tolerance may prevent the connection from entering an effective load-transfer state until a certain deformation level is reached. This can lead to an abrupt change in global stiffness[10].

The second is frictional slip and the transition from friction-based transfer to bearing or shear transfer. In friction-type or interlocking connections, the stiffness and energy dissipation mechanism differ before and after slip initiation. The slip stage and pinching effect can significantly affect cyclic energy dissipation stability and residual deformation[11].

The third is semi-rigid rotation and degradation. The moment-rotation behavior of modular connections usually lies between ideal pinned and ideal rigid conditions. Under cyclic loading, both stiffness and strength may degrade. Full-scale cyclic tests have shown that semi-rigid inter-module connections can affect the load-transfer path and hysteretic degradation characteristics of the whole system through rotational compatibility[12].

The fourth is the risk of low-cycle fatigue and local buckling under repeated loading. Under cyclic action, connection regions may experience bolt relaxation, local plate buckling, and damage accumulation at weld toes or stress concentration zones. Therefore, when connections are designed as preferred energy-dissipating or replaceable components, low-cycle fatigue and local failure should be incorporated into durability and repair strategies[13][14].

These nonlinear mechanisms usually do not occur independently. Instead, they interact across multiple interfaces and form a multi-stage response chain. As a result, a single joint-level index is often insufficient to represent structural performance at the system level.

3. Research Progress and Typical Findings on Global Structural Behavior and Connection Effects

3.1 Progress in Joint and Substructure Tests

Joint and substructure tests provide fundamental data for identifying connection constitutive behavior, degradation law, and failure mode. Chen et al.[6] carried out static and pseudo-static cyclic tests on internal connections in modular steel structures and combined them with finite element analysis. Their study revealed the collaborative load-transfer mechanism between interlocking components and bolted joints, as well as the corresponding seismic behavior, and provided experimental evidence for the design and analysis of built-in inter-module connections.In addition to conventional built-in joints, Chen et al.[7] proposed a rotating inter-module connection, as shown in Fig. 3. Tension and shear tests demonstrated that this connection could provide satisfactory tensile and shear resistance while also maintaining construction convenience. Based on the test results, a corresponding load-carrying capacity calculation method was established.

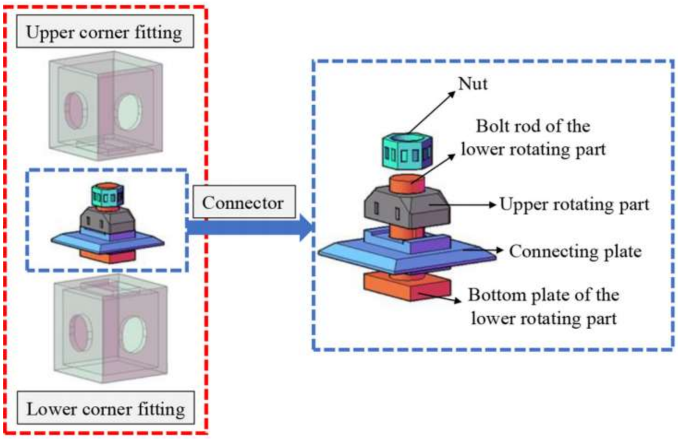

Fig. 3 Composition of connection

Sendanayake et al.[11] investigated innovative inter-module connections under monotonic and cyclic loading. Their results indicated that connection performance is not governed only by peak strength. It is also closely related to slip initiation, hysteretic energy dissipation path, and residual deformation after unloading. Sanches et al.[8] studied vertical post-tensioned modular connections and found that these connections can exhibit relatively stable hysteretic response and small residual deformation under cyclic loading. This suggests that different connection forms may differ significantly in energy dissipation mechanism and self-centering capacity.

Experimental observations show that inter-module connections commonly exhibit a slip stage, pinching effect, and various degrees of cyclic degradation. Some connection forms also show clear accumulation of residual deformation. These phenomena provide the physical basis for the subsequent development of system-level coupled indices and equivalent modeling methods.

3.2 Global Response Characteristics at the Structural System Level

At the system level, the key issue is how connection nonlinearity is amplified into changes in global displacement distribution and internal force redistribution. From both review studies and high-rise global analysis, Chua et al.[15] pointed out that the global response of modular buildings is highly sensitive to the stiffness of inter-module connections, especially translational stiffness and rotational stiffness along the loading direction.

As research advanced, Shi et al.[16] proposed a simplified model in which the connection is divided into vertical and horizontal components. Equivalent connection elements were used to represent shear and axial load transfer, and the model was validated through experimental and numerical studies.

This approach provides a practical and extendable method for inputting connection behavior into the global analysis of high-rise modular buildings.

Duan et al.[17] further studied high-rise steel modular buildings and found that the rotational stiffness of inter-module connections significantly affects internal force distribution, lateral displacement, and member demand. Their results indicate that connection parameters should not be treated only as local detailing issues, but should instead be incorporated into structural analysis as system-level design variables.

3.3 Floor Diaphragm Interaction and Load-Path Reconfiguration

In modular systems, the floor diaphragm is generally composed of floor slabs within individual modules. The joints between modules do not always form a continuous slab strip. This feature challenges the applicability of the conventional rigid diaphragm assumption. Slip in inter-module connections and insufficient in-plane stiffness of floor diaphragms may lead to the redistribution of lateral forces among lateral-force-resisting components, migration of inter-story drift concentration, and changes in the design force demand of structural members.

Under abnormal loading and progressive collapse scenarios, the influence of discrete floor systems and corner connection chains becomes even more significant. Chua et al.[18] showed that modular buildings differ substantially from conventional buildings with continuous floor slabs in terms of load redistribution, development of alternative load paths, and tie-force demand. The connection type and its semi-rigid characteristics can directly influence progressive collapse resistance and robustness assessment.

4. Performance Evaluation Framework and System-Level Coupling Representation for Global Response

4.1 Evaluation Indices at the Single-Connection Level

At the single-connection level, performance is usually evaluated in terms of load-carrying capacity, initial stiffness, yield and ultimate deformation, energy dissipation capacity, ductility coefficient, and failure mode. Through pseudo-static tests on blind-bolted composite side-column joints, Yang et al.[19] found that hysteresis curves, skeleton curves, stiffness degradation, and energy dissipation capacity can comprehensively characterize connection performance under cyclic loading. These indices can be used not only for comparing different connection details, but also for calibrating equivalent constitutive models.

Batukan et al.[20], in their study on modular steel structures equipped with ductile slip-friction joints, further pointed out that for connections with slip and energy dissipation characteristics, peak load or initial stiffness alone is insufficient for evaluation. Slip initiation force, stiffness during the slip stage, unloading and reloading paths, pinching effect, and cyclic degradation parameters can also have significant influence on the global drift response and residual deformation of the structure. Therefore, these path-dependent indices should be clearly reported in connection tests and explicitly considered in subsequent model calibration.

4.2 Coupled Performance Indices at the Structural System Level

For global performance assessment of modular structures, more important indices are those that can reflect how connection nonlinearity is transmitted to system response.

The first category includes global lateral deformation indices, such as maximum inter-story drift ratio, the vertical distribution pattern of inter-story drift, the degree of drift concentration, and the degradation curve of global lateral stiffness. Lacey et al.[21] studied the effects of connection stiffness on wind-induced and seismic responses of modular steel structures. Their results showed that connection stiffness, especially translational stiffness along the principal loading direction, has a significant influence on both inter-story drift and global lateral displacement. Therefore, lateral deformation indices should be regarded as the most basic control indices at the system level.

The second category includes post-earthquake functionality-related indices, such as residual inter-story drift, overall residual lateral displacement, reparability classification indices, and their relationship with the distribution of connection damage. Deng et al.[22] showed in their study on self-centering and repairable modular connections that controlling post-earthquake residual deformation and concentrating damage in replaceable components are key to rapid post-earthquake repair of modular structures. Therefore, in design oriented toward functional recovery, residual response indices should be considered alongside conventional strength and deformation indices.

The third category includes energy dissipation and degradation indices, such as equivalent damping ratio, cyclic energy dissipation stability, rates of strength and stiffness degradation, and cumulative damage measures. Batukan et al.[20] showed that different connection forms can alter the hysteretic shape and energy dissipation mechanism of modular steel structures. Whether a connection can maintain stable energy dissipation capacity under repeated cyclic loading directly affects seismic performance and post-earthquake damage level.

The fourth category includes integrity and robustness indices, such as redundancy of key connection chains, reserve tie capacity, ability to develop alternative load paths, and risk indicators for disproportionate collapse. Chua et al.[18] studied the robustness of steel modular buildings under column loss scenarios and found that connection type and load-transfer characteristics have significant effects on load redistribution paths and progressive collapse resistance. Swami et al.[23] further showed that connection performance and modular column form jointly determine the overall robustness of the structure under abnormal loading. Therefore, robustness indices must be evaluated at the system level and linked to connection selection.

4.3 Mapping between Evaluation Indices and Design Objectives

Evaluation indices can only truly serve engineering design when they are clearly mapped to design objectives. For seismic design, emphasis should be placed on inter-story drift ratio, energy dissipation stability, strength and stiffness degradation, and prevention of brittle failure. Since changes in connection stiffness can significantly alter global displacement response, connection parameters should be treated as important design variables in seismic design.

For repairable design, greater attention should be paid to residual inter-story drift, residual lateral displacement, and whether damage can be concentrated in replaceable parts. The self-centering and repairable connection proposed by Deng et al.[22] shows that if residual deformation can be limited and damage can be localized after an earthquake, repair efficiency and reusability of the structure can be substantially improved.

For high-rise design, in addition to strength and deformation requirements, attention should also be given to global stability, wind-induced vibration comfort, and the influence of connection stiffness on dynamic characteristics. Srisangeerthanan et al.[24] pointed out that with increasing building height, connections are no longer only local details, but become key factors that affect the accuracy of global analysis and the reliability of structural design.

For robustness-oriented design, tie capacity, alternative load paths, and the potential propagation of local failure under abnormal loads should be incorporated into a unified framework. Chua et al.[18] showed that without a consistent evaluation framework matched to system characteristics, different studies may reach substantially different conclusions on the robustness of modular structures. This inconsistency limits the application of research findings in engineering design and standardization. Therefore, future studies should establish a unified mapping relationship among connection test indices, global analysis indices, and design performance requirements so as to improve comparability and engineering reliability.

5. Equivalent Connection Modeling and Global Analysis Methods

5.1 Constitutive Representation of Semi-Rigid and Slip Behavior

In the global analysis of modular steel structures, it is usually difficult to directly incorporate refined contact models of connections into full-structure calculations. Therefore, translational springs, rotational springs, or their combinations are often used to represent equivalent connection stiffness in different degrees of freedom. Bilinear, trilinear, or degradation-included constitutive relationships are then adopted to describe slip initiation, stiffness transition, and cyclic degradation.

Chua et al.[15] proposed a translational spring model for vertical modular connections in high-rise modular buildings. By comparing the results with those from global frame analysis, they showed that the equivalent translational stiffness of the connection can effectively reflect inter-module load transfer and lateral response. This finding indicates that stiffness components in critical directions should be retained in global analysis, while non-critical degrees of freedom may be simplified when justified.

For connections with obvious slip characteristics, ideal rigid or ideal pinned assumptions are often unable to represent the actual mechanical behavior. Nadeem et al.[10] studied self-locking inter-module connections and showed that these connections exhibit clear staged slip behavior during loading. Their force-displacement response is jointly affected by connection form, contact transition, and slip control mechanism. Therefore, simplified constitutive models should explicitly include slip initiation, stage-dependent stiffness change, and nonlinear evolution during loading. This also suggests that the key to constitutive modeling is not the complete reproduction of local details, but the accurate capture of stage-dependent features that are most sensitive to global response.

5.2 Incorporation of Component-Based Models into Global Analysis

From the perspective of engineering application, global analysis should be able to reflect the influence of connection nonlinearity on structural response, while also controlling modeling complexity and computational cost. For this reason, a common approach is to decompose the connection according to its dominant load-transfer paths and then incorporate equivalent connection elements or nonlinear springs into the global finite element model.

Shi et al.[16] separated the connection into horizontal and vertical functional components and established corresponding equivalent elements. Their results showed that when the dominant connection stiffness and force-transfer mechanisms are properly retained, the simplified model can achieve good agreement with refined modeling results in terms of lateral displacement and internal force distribution. This provides support for applying component-based equivalent models to engineering analysis.

In addition to conventional bolted connections, studies on prestressed or preloaded connections also reflect a technical route that proceeds from joint testing to simplified modeling and then to global structural analysis. Yu et al.[25] carried out experiments on prestressed modular connections and found that moment-transfer capacity is closely related to insert layout, steel strand arrangement, and section size. Based on the test results, they proposed a simplified strength model, which shows that complex connections can be reduced to equivalent expressions suitable for structural analysis through parameter-based generalization.

Lee et al.[26] proposed a bolted-free preloaded connection that introduces preload through long-rod bolts and special connectors. Combined experimental and numerical analyses showed that once the dominant parameters of a novel connection can be identified in a stable manner, it can also be incorporated into the simplified modeling framework for global analysis.

5.3 Uncertainty and Parameter Identification

Pretension force, friction coefficient, hole clearance, and assembly error all involve significant uncertainty. These factors directly control slip initiation and residual deformation. Experimental studies on interlocking connections have specifically discussed the influence of hole clearance and assembly tolerance on shear-slip behavior. The findings indicate that construction deviation introduces scatter at the connection level and further affects the reliability of global response prediction. Therefore, equivalent connection models should be accompanied by parameter identification and sensitivity analysis methods. Key parameters should also be transformed into measurable and verifiable construction and inspection indices.

6. Structural Detailing and Quality Control for Engineering Design

6.1 Design Considerations for Connection Details

In engineering design, the functional allocation of connections should follow the main structural load-transfer path. Priority should be given to ensuring shear transfer and uplift resistance in key connection chains. The need for moment transfer and the strategy for semi-rigid design should then be determined according to the target performance.

For systems designed with reparability as a major objective, a hierarchical design philosophy of damage concentration and replaceability may be adopted, so that plastic deformation and degradation are confined to replaceable components. Studies on hybrid connections and cyclic tests provide both structural solutions and performance evidence for this approach. At the same time, they also indicate the need to balance structural complexity and engineering feasibility.

6.2 Key Construction and Inspection Control Measures

The performance of inter-module connections depends strongly on construction quality. For friction-type high-strength bolted connections, the treatment of friction surfaces, the application of pretension, and the reinspection procedure should be strictly controlled. For interlocking connections, assembly tolerance, positioning accuracy, and contact surface condition should be properly controlled[14]. For post-tensioned connections, attention should be paid to the tensioning level and long-term relaxation effect. Reviews on bolted modular connections have emphasized that without construction and inspection provisions consistent with the connection mechanism, the upper-bound performance observed in laboratory tests is difficult to achieve reliably in practice.

6.3 Recommended Engineering Design Procedure

Based on existing studies, the engineering design of inter-module connections may be summarized as a closed-loop process driven by target performance. First, according to the design objectives related to seismic resistance, wind-induced vibration, reparability, or robustness, the control indices and verification scenarios at the system level should be defined. Second, connection systems should be selected and refined in accordance with the structural load-transfer path and construction conditions.

After the connection type has been selected, representative joint testing, simplified model calibration, and global analysis verification should be carried out in sequence, so that connection performance can be transformed into parameters suitable for global structural analysis. Corfar et al.[27] conducted cyclic tests on hybrid connections and showed that a novel connection can only serve global structural analysis and structural optimization after its dominant load-transfer mechanism, damage mode, and key control parameters have been clearly identified.

Therefore, the core of this design process is to establish a consistent chain among connection test parameters, global model input, and construction inspection indices. The key parameters proposed at the design stage should be calibratable through testing, applicable in global analysis, and measurable, controllable, and verifiable during construction and inspection. Only when this closed loop is established can research findings on modular steel connections be effectively transformed into practical engineering design methods.

7. Summary

The multi-stage nonlinear behavior of inter-module connections, including gap closure, frictional slip, and semi-rigid degradation, is a major source of variation in the global lateral response of modular steel structures. These effects should be explicitly considered in both evaluation and modeling.

System-level studies have shown that global response is sensitive to connection stiffness, especially translational stiffness along the loading direction. The choice of connection model can significantly affect the predicted wind-induced and seismic response.

The trend toward taller modular buildings has promoted the development of connection modeling from refined contact models to component-based equivalent models. One promising approach is to divide the connection into vertical and horizontal components and introduce them into the global model through equivalent connection elements.

The performance evaluation framework should be extended from single-connection indices to system-level coupled indices. Particular attention should be given to inter-story drift redistribution, residual deformation, degradation behavior, and the ability to form alternative load paths for robustness. A consistent link should also be established between these evaluation indices and construction quality control.

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