Structural Integrity and Seismic Resilience in Beam-Column Joints: A Review

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Abstract:

Advancements in beam-column joint technologies have revolutionized structural safety and efficiency in modern construction. This study reviews experimental and analytical investigations into various prefabricated and composite beam-column joint configurations. Key innovations include joints with tie bars, resilient composite joints with replaceable buckling-restrained plates, and novel bolted connections for modular structures. Parameters such as damage patterns, hysteresis performance, stiffness degradation, and energy dissipation were evaluated through static and cyclic tests. Additional studies focused on concrete-filled steel tube joints, shape memory alloy tendons, and bio-inspired hinges for repairable seismic designs. These findings provide critical insights for optimizing joint designs, enhancing seismic performance, and advancing construction methodologies.

Key Words: Hysteresis Performance, Buckling-Restrained Cover Plate (BRCP), Finite Element Analysis, Shape Memory Alloy (SMA) Tendons, Stiffness Degradation

1. Introduction

Beam to column joints show a pivotal function in ensuring the structural stability and overall seismic resilience of buildings. These critical connection points transfer forces between beams and columns, influencing the performance of the entire structure under various loading conditions, particularly during seismic events. As buildings become taller, more complex, and are constructed in regions with high seismic activity, the demand for advanced joint technologies that can withstand dynamic forces has increased significantly.

Recent advancements in joint technology focus on overcoming traditional challenges such as inadequate load-carrying capacity, limited energy dissipation capabilities, and difficulty in repairability after damage. These advancements are driven by the need for durable, efficient, and sustainable solutions that align with the increasing adoption of prefabrication and modular construction techniques. Prefabricated and modular designs not only accelerate construction timelines but also ensure consistent quality, making them an attractive choice for modern infrastructure projects.

One key area of development is the enhancement of load-carrying capacity. Experimental and analytical studies have introduced innovative joint designs that leverage high-strength materials and optimized geometries. These designs distribute stresses more effectively and prevent early failures under heavy loading conditions. For example, the integration of high-strength double-side plates in wall-type concrete-filled steel tube (WCFTC) joints reduces material usage while maintaining or even enhancing load-bearing performance.

Energy dissipation is another critical consideration in joint design, particularly for structures in earthquake-prone regions. The capability of a joint to absorb and dissipate seismic energy determines its capacity to mitigate damage during an earthquake. Advanced designs, such as those employing replaceable buckling-restrained plates or shape memory alloy tendons, focus on maximizing energy dissipation while maintaining the structural integrity of the joint. These innovations ensure that the building can endure multiple seismic events with minimal damage, significantly enhancing its resilience.

Repairability has emerged as a vital aspect of modern joint technology. Traditional joints often require extensive repairs or complete replacement after sustaining damage, leading to increased costs and downtime. In contrast, recent developments emphasize the use of replaceable components within joints, such as bio-inspired hinges and bolted connections. These features allow damaged parts to be quickly replaced, restoring the structure's functionality with minimal disruption.

The growing emphasis on prefabrication and modular construction has further shaped the evolution of beam-column joint technologies. Prefabricated joints, designed for ease of assembly and disassembly, improve construction efficiency and ensure high-quality control. They are also adaptable to various structural configurations, making them suitable for diverse architectural designs. Moreover, modular joints often incorporate advanced materials like concrete-filled steel tubes or composite configurations, which offer superior performance compared to traditional materials.

Extensive experimental and analytical research supports these advancements, providing valuable insights into the behavior of innovative joint configurations under static and dynamic loads. Large-scale laboratory tests, finite element simulations, and real-world applications have validated the effectiveness of these designs, highlighting their potential to redefine standards in structural engineering.

2. Review of Literature

Advancements in beam-column joint technology are pivotal to enhancing the structural integrity and seismic resilience of modern buildings. This section explores into the latest research on prefabricated and composite joints, analyzing their design configurations, experimental validations, and seismic performance. Key parameters such as load-carrying capacity, ductility, and energy dissipation are examined to understand their role in optimizing joint performance. These insights aim to bridge the gap between innovative designs and practical applications in construction.

[1] Proposed prefabricated concrete column-steel beam joints connected by tie bars have been studied through static tests on five joint members. Analyses include damage patterns, hysteresis performance, and load-carrying capacities, providing insights into the behavior of such connections under applied loads.

A single-sided resilient composite beam–column joint has been introduced [2], incorporating a nonreplaceable concrete slab, a connection plate, and a replaceable buckling-restrained cover plate (BRCP). Experimental studies highlight its structural resilience and performance under seismic conditions.

A novel bolted connection for prefabricated modular structures was investigated [3] using five full-scale joint specimens subjected to cyclic loads. Finite element analysis explored variables such as bolt diameter, column flange thickness, and joint rotational stiffness, contributing to enhanced joint design.

Prefabricated concrete-filled square steel tube (CFSST) joints with fully-bolted exterior diaphragms were tested [4]. Parameters such as axial compression ratio, beam-column linear stiffness ratio, and steel tube wall thickness were examined for their impact on seismic performance.

Structural performance of joints between CHS columns and I-beams equipped with SMA tendons and steel angles was analyzed [5] through full-scale laboratory tests and numerical simulations. The re-centering and energy dissipative capabilities of these joints were key focus areas.

A composite wall-steel beam joint with a crossed U-plate connection was studied using experimental and finite element models [6]. Seismic performance indices such as hysteresis curves, ductility, and stiffness degradation were evaluated to optimize joint design.

Large-scale experimental campaigns on steel-concrete composite beam-to-column sub-assemblages examined [7] seismic performance under monotonic and cyclic loading. Variations in structural details and material qualities were analyzed to assess energy dissipation capabilities.

A novel joint design for wall-type concrete-filled steel tube (WCFTC) beams utilizing high-strength double-side plates was investigated [8]. Finite element models evaluated seismic properties, revealing steel usage reduction while maintaining load capacity.

A stiffened extended end-plate joint connecting I-beams to partially-encased composite columns was introduced [9]. The design included T-shaped hammer heads and reinforced column flanges, enhancing the seismic resistance of building frames.

An assembly joint between hybrid H-steel precast concrete beams and concrete-encased CFST columns was developed [10]. The novel configuration improved connectivity and structural performance under seismic loads.

Composite joint specimens with flush beam-flange side-plate (FBSP) connections were tested [11] under cyclic loading to determine failure modes and seismic behavior. Key performance metrics included ductility and energy dissipation capacity.

A replaceable bio-inspired hinge (RBHJ) was developed [12] for prefabricated beam-column joints, offering rotational and energy dissipation capabilities. Experimental evaluations confirmed its seismic performance and repairability.

Seismic shear behavior of joints between PEC columns and steel beams was investigated [13] through cyclic load tests. Findings include joint panel zone failures and performance indices such as stiffness degradation and ductility.

End plate connection joints between I-beams and square steel tube columns were evaluated [14]. Failure modes, energy dissipation capacity, and seismic performance metrics demonstrated the superiority of T-shaped joints over cross-shaped counterparts.

3. Conclusion

Advancements in beam-column joint technology address the multifaceted challenges of modern construction, enhancing load-carrying capacity, energy dissipation, and repairability. By aligning these innovations with the principles of prefabrication and modularity, the industry is paving the way for safer, more resilient, and cost-effective structural systems. These developments not only improve performance under seismic conditions but also contribute to the sustainability and efficiency of construction practices in the 21st century.

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