



Advancements and Challenges in Composite Steel-Concrete Systems for Seismic Resilience

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Abstract— Composite steel-concrete structures exhibit promising seismic performance, combining the benefits of steel's ductility and concrete's compressive strength. Research highlights key advancements in testing, analysis, and design of composite systems like RCS frames, coupled shear walls, and modular buildings. Experimental studies reveal factors influencing seismic behavior, such as floor slab effects, energy dissipation, stiffness degradation, and ductility under cyclic loads. Connections like concrete-filled square steel tubular columns and steel beams demonstrate varying performance based on diaphragm and stud configurations. Innovations like SFCB- reinforced ECC columns enhance deformation capacity and energy dissipation. Post-earthquake assessments underscore the impact of prior damage on residual capacity and repair needs. Key challenges include refining predictive models for joint shear strength and ensuring seismic resilience across diverse systems.

Keywords — Composite Steel-Concrete Systems, Seismic Performance, Stiffness Enhancement, Structural Optimization, Energy Dissipation.

INTRODUCTION

In the field of structural engineering, ensuring the stability and resilience of buildings and infrastructure against seismic activities is a crucial priority. Earthquakes pose substantial threats to urban and rural areas alike, with the potential to cause extensive loss of life, property damage, and disruption of essential services. As urbanization accelerates globally and the density of populated areas continues to increase, the demand for innovative and reliable seismic-resistant design solutions has grown more urgent. These designs aim to mitigate the devastating impacts of earthquakes and ensure the safety and functionality of structures during and after seismic events. Seismic-resistant design is a specialized discipline within structural engineering that applies advanced principles to create structures capable of withstanding the forces and displacements generated by earthquakes. These designs account for the complex dynamics of seismic waves and their interaction with buildings, ensuring that the structures can sustain significant lateral loads without catastrophic failure. A key focus is to enhance the ability of buildings to remain standing and protect occupants during seismic events, even if some structural damage is sustained.

The importance of seismic-resistant design extends beyond the protection of life and property. It is integral to preserving economic stability, as damaged infrastructure can disrupt commerce, transportation, and utilities. Furthermore, in regions prone to frequent seismic activity, such designs contribute to community resilience, enabling faster recovery after earthquakes.

Traditional construction materials such as steel and concrete have long been foundational in seismic-resistant design. Steel, known for its tensile strength and ductility, complements concrete's excellent compressive strength and durability. However, the performance of these materials can be limited by challenges such as brittleness in concrete or susceptibility to fatigue in steel under repetitive seismic loading. Consequently, the structural engineering community has explored composite materials and advanced structural configurations to overcome these limitations.

Composite Sections in Structural Design

Composite sections represent a transformative approach in structural design, particularly in the context of seismic resistance. These sections combine two or more materials to create structural elements that benefit from the unique properties of each material. By integrating materials with complementary strengths, composite sections address key challenges in traditional construction and enable innovative solutions for earthquake-resistant structures.

Steel-Concrete Composite Beams

One of the most notable applications of composite materials in seismic-resistant design is the steel-concrete composite beam. These beams combine the tensile strength and ductility of steel with the compressive strength and stiffness of concrete. The steel component, often in the form of an I-section or tubular profile, serves as the primary load-bearing element in tension. The concrete, typically cast around or atop the steel, contributes compressive resistance and improves the overall stiffness and damping capacity of the beam.

Steel-concrete composite beams offer several advantages over traditional beams. First, they achieve a higher load-carrying capacity and greater efficiency in material usage. The interaction between steel and concrete reduces the amount of each material needed to achieve a given performance level, thereby optimizing the weight and cost of the structure. Additionally, the encased steel is protected from environmental factors like corrosion and fire, enhancing the beam's durability and lifespan. From a seismic perspective, the improved stiffness and energy dissipation properties of composite beams are significant. During an earthquake, these beams can deform in a controlled manner, dissipating energy through plastic deformations in the steel and micro-cracking in the concrete. This behavior reduces the likelihood of brittle failure, making composite beams a safer and more reliable choice for seismic regions.

LITERATURE SURVEY

1. Composite steel-concrete systems, such as concrete-filled steel tubes (CFTs), steel-reinforced concrete (SRC), and composite wall systems, offer superior seismic performance by combining the strengths of both materials. The steel resists tension and flexure, while the concrete efficiently handles compression, resulting in high strength, ductility, and energy dissipation. Recent research focuses on enhancing connections, such as split-tees and pass-through designs, improving reliability under cyclic loading. Systems like S-RCW (partially-restrained steel frames with concrete infill walls) demonstrate cost efficiency, ease of repair, and redundancy under seismic demands. Advances in computational modeling and experimental studies are refining design provisions, paving the way for wider application in high-rise and seismic-prone regions. Challenges like bond strength and shrinkage effects are also being addressed for optimization.

2. The CSRC structural system effectively transfers lateral forces through studs, diagonal compression struts, and steel frames, with studs carrying 80- 90% of lateral loads and steel frames sharing 10- 20%. Overturning moments are mainly resisted by steel frames, with a minor contribution from the infill walls. The system demonstrates strong energy dissipation, primarily through cracking in infill walls, yielding steel members, and the fracture of studs. Design recommendations emphasize the importance of headed studs, their strategic placement, and the need to consider their fatigue life to ensure structural performance.

3. Research on Reinforced Concrete-Steel (RCS) frames has emphasized the seismic performance of unique beam-column connections through experimental tests, finite-element analysis, and updated design guidelines. Key findings highlight enhanced ductility, energy dissipation, and shear strength using advanced materials like carbon fiber wraps and steel band plates. Updated guidelines focus on deformation limits, performance-based seismic design, and the integration of high-strength materials, ensuring structural safety under seismic loads. Future research aims to refine finite-element methods and explore braced frame designs for greater resilience.

4. The study examines the residual seismic capacity of a ten-story steel-concrete composite frame under varying damage levels caused by seismic intensities. Using a fiber element model and nonlinear time history analysis, it reveals that pre-existing damage, especially at higher levels, leads to increased lateral deformations, stiffness degradation, and reduced internal forces in beams and columns. While lower damage levels meet safety standards, structures with higher damage levels exhibit significant strength loss and residual deformation, necessitating detailed safety evaluations and potential strengthening measures after intense earthquakes. These findings emphasize the importance of assessing post-earthquake structural stability.

5. Research on Reinforced Concrete-Steel (RCS) frames has focused on improving their seismic performance, particularly through the study of beam-to-column connections under cyclic loading. Studies have highlighted the importance of joint details, such as cover plates and stiffeners, in enhancing strength and stability. Advanced simulations and experiments have shown that RCS frames, including beam-column-slab connections, exhibit strong seismic resilience, with improved energy dissipation and shear strength. Future research will focus on refining finite element models, exploring high-strength materials, and expanding performance-based seismic design approaches to further optimize RCS frame performance in seismic zones.

6. Concrete-filled steel tubular columns (CFSSTCs) offer several advantages, such as preventing local buckling and enhancing stiffness. Research on CFSSTC connections reveals that those with interior diaphragms show stable behavior but limited ductility, while exterior diaphragm connections exhibit better load-bearing capacity and energy dissipation. Connections with anchored studs have lower strength and energy dissipation due to weaker tension transfer. Displacement analysis shows that the joint displacement ($r\Delta_j$) is dominant, with shear deformation increasing significantly in connections with exterior diaphragms, while interior diaphragm connections fail due to inadequate flexural capacity.

7. The study focused on the seismic response of a 9-story building with reinforced concrete (RC) walls and modular frames. Nonlinear modeling was used to simulate the building's behavior under earthquake loading, with an emphasis on modular connections and seismic collectors. The results showed that inter-module connections had weak bending restraint, leading to separation and sliding, and that plasticity developed significantly in the RC walls, particularly at the base. The analysis also revealed that shorter periods in the structure caused higher responses and increased forces in seismic collectors, particularly at the bottom story due to plasticity in the RC walls. Additionally, the ASCE 7-16 code's design method underestimated accelerations at lower stories, and a revised approach was suggested for better safety.

8. The study examined the seismic behavior of a six-story composite frame building in Beijing, focusing on its performance under vertical and lateral cyclic loading. The tests showed that the structure maintained good composite action between steel beams and concrete slabs, with minimal yielding and effective energy dissipation. Despite damage, including weld fractures and column deformation, the frame demonstrated strong seismic performance, with high ductility and stable strength. The results indicated that the first-story components experienced higher internal forces, highlighting the need for reinforcement in lower stories, while the shear lag effect in the slabs was significant at ultimate loading.

9. This study examines the seismic performance of SFCB-reinforced ECC and concrete columns under cyclic loading, highlighting their comparison with traditional steel bar-reinforced columns. SFCB-reinforced ECC columns show improved load-carrying capacity, deformation capacity, and energy dissipation, but with reduced energy dissipation at later stages due to bond-slip behavior. ECC columns demonstrated better damage resistance and delayed crack initiation, while concrete columns

experienced severe and matrix crushing. The study concludes that while increasing FRP content in SFCB improves stiffness and load capacity, it reduces energy dissipation, and SFCB-reinforced ECC columns experience rigid-body rotation, affecting deformation and repairability

10. This study investigated the seismic performance of composite steel-concrete shear walls with central openings, comparing them to conventional reinforced concrete and solid shear walls. Results showed that the inclusion of steel fiber reinforced concrete (SFRC) enhanced ductility and energy dissipation, particularly in walls with openings, while solid walls exhibited the highest load-bearing capacity and stiffness. The use of welded steel profiles and steel fiber reinforcement improved the overall seismic behavior by reducing shear failures and cracking in coupling beams. The study concluded that composite steel-concrete walls offer superior performance, but further research is needed to evaluate additional factors like axial load ratios and concrete strength.

11. This study investigates the seismic performance of partially encased composite (PEC) columns and their beam-column joints, highlighting the advantages of PEC members in strength and cost efficiency. Experimental testing of S and W joint specimens revealed good shear deformation capacity but emphasized the need to prevent shear failure in joint panel zones during earthquakes. The current T/CECS 719-2020 design code provides conservative shear strength predictions, as it overlooks the contribution of column flanges and confined concrete. The study recommends design improvements like horizontal stiffeners, extended end-plates, and high-strength ductile concrete, along with further research to refine shear strength prediction models for better seismic resilience.

CONCLUSION

Composite steel-concrete systems, like concrete-filled steel tubes (CFTs) and steel-reinforced concrete (SRC), combine the strengths of steel and concrete, offering excellent seismic performance due to high strength, ductility, and energy dissipation. They resist tension and flexure effectively while handling compression efficiently. Research has focused on enhancing connections like split-tees and diaphragms to improve stability under cyclic loads. Systems like SRC frames with infill walls are cost-efficient and easy to repair. Reinforced Concrete-Steel (RCS) frames show strong energy dissipation, particularly at beam-column connections, and advanced materials like steel bands and carbon wraps enhance their shear and seismic strength.

Studies on modular frames reveal weaknesses in inter-module connections, leading to sliding and bending issues under seismic loads. Concrete-filled steel tubular columns (CFSSTCs) prevent buckling and increase stiffness, with exterior diaphragm connections showing better energy dissipation. Analysis of tall composite frames and modular systems under seismic forces highlights the need for detailed safety evaluations, especially for damaged structures. Future research focuses on improving computational models, using high-strength materials, and refining seismic design codes for greater resilience and safety in seismic zones.

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