Seismic Performance of Steel-Concrete Composite High-Rise Structures: Review, Challenges, and Emerging Trends: A Review

Mr. Niraj Jayant Bhole[1*], Prof. N. A. Autade[2], Prof. V. S. Shingade[2]
[1*]*PG Student, Dept. of Civil Engineering, KJEI'S Trinity College of Engineering and Research, Pune*
[2*] *Professor, Dept. of Civil Engineering, KJEI'S Trinity College of Engineering and Research, Pune*

Abstract- ***In recent years, the construction of high-rise buildings has become increasingly important due to urbanization and population growth in cities. Conventional reinforced concrete (RCC) structures have long been used; however, the need for faster construction, higher strength, and better seismic resilience drives the adoption of steel-concrete composite structural systems. These systems combine the compressive strength and stiffness of concrete with the tensile strength and ductility of steel, offering superior overall structural performance. Steel-concrete composite construction offers advantages like rapid construction speed, reduced structural weight, enhanced load-carrying capacity, and improved seismic resistance. Under earthquake loading, the synergy between steel and concrete helps in dissipating energy effectively, limiting lateral displacements, and enhancing ductility. This makes composite high-rise structures well-suited for seismic zones, offering better safety and serviceability. Research and practical applications in countries including China and India show that composite high-rise structures can be cost-effective and efficient solutions, incorporating advanced materials and modern design methods aligned with seismic design codes such as IS 1893 and relevant international standards.***

Keywords: Steel–concrete composite structures, high-rise buildings, seismic performance, composite columns, composite beams, earthquake resistance, performance-based design, damping systems

I. INTRODUCTION

India had a number of the world's greatest earthquakes in the last century. The north- eastern region of the country as well as the entire Himalayan belt is susceptible to great earthquakes of magnitude more than 8.0. After 2001 Gujarat Earthquake and 2005 Kashmir Earthquake, there is a nation-wide attention to the seismic vulnerability assessment of existing buildings. The seismic building design code in India (IS 1893, Part-I) is also revised in 2016. The magnitudes of the design seismic forces have been considerably enhanced in general, and the seismic zonation of some regions has also been upgraded. There are many literatures available that presents step-by-step procedures to evaluate multi-storied buildings. Steel-concrete composite structures cover structural elements such as beams, slabs, and columns in which the best structural properties of each material are combined. Steel-concrete composite structures combine the strengths of both materials to create more efficient and robust building elements. By using steel for tension and concrete for compression, these structures are known for their high strength, stiffness, and fire resistance. Common components include composite beams, slabs, and columns, and they are used in high-rise buildings, bridges, and other resilient infrastructure projects

The term 'composite structures' refer to structures in which different materials such as timber, steel, concrete, and masonry are used together for construction. The most common type of composite construction is the use of steel and concrete to form steel-concrete composite structures. Steel-concrete composite structural members are known as economic members and have been used in construction for various structure types. It is a very well-known fact that steel members are susceptible to buckling, while their tensile strength is remarkable.

Steel-concrete composite structures generally exhibit superior seismic performance compared to traditional reinforced concrete (RCC) structures due to their enhanced stiffness, strength, and energy dissipation capabilities.

A. Steel –Concrete Composite Structure

Steel-concrete composite structures can be classified by their elements (beams, columns, slabs) or by their application, such as buildings and bridges. Common types include composite beams, composite columns (like concrete-filled steel tubes), and composite deck slabs, which are all designed to combine the compressive strength of concrete with the tensile strength of steel for increased efficiency and performance.

1) Composite Beams:

These are a combination of a steel beam and a concrete slab that work together, most commonly using shear connectors to bond them. They are used in floor systems and bridges and offer greater strength and stiffness than a steel beam alone.

2) Composite Columns:

a. Concrete-filled steel tubes (CFST): A steel tube is filled with concrete, providing excellent strength and ductility. They can be circular, rectangular, or square.

b. Concrete-encased steel sections: A steel section is wrapped with concrete.

3) Composite Deck Slabs:

These are created by casting concrete on top of profiled steel decking, which serves as formwork during construction and becomes part of the final structure's reinforcement

II. STATE OF DEVELOPMENT

A literature review forms the foundation of any research work, as it helps to identify existing knowledge, research gaps, and the direction for further study. The development of steel–concrete composite high-rise structures has evolved significantly over the past few decades due to the increasing demand for efficient, economical, and earthquake-resistant structural systems. Initially, reinforced concrete and structural steel systems were predominantly used in tall building construction. However, limitations such as excessive self-weight in reinforced concrete structures and excessive flexibility in steel structures encouraged researchers and engineers to develop composite structural systems that combine the advantages of both materials.

Panagiota Katsimpini, et. al. (2025) conducted a comprehensive review on the seismic performance of steel–concrete composite structures. The study examined recent advancements in material behavior, connection detailing, analytical modeling, and seismic design methodologies. Various composite systems such as composite beams, beam-columns, frames, shear walls, and foundations were analyzed under earthquake loading conditions. The authors highlighted that composite structures provide improved ductility, stiffness, and energy dissipation capacity due to the combined action of steel and concrete. The review concluded that advanced numerical methods and seismic isolation techniques significantly enhance the seismic resilience of composite structures, although further research is required in nonlinear modeling and performance-based design.

Chao-Qun Yu, et. al. (2024) presented a state-of-the-art review on steel–concrete composite walls. The study classified different types of composite walls based on steel plate arrangement and concrete configuration. The authors investigated the behavior of composite walls under axial, cyclic, shear, fire, impact, and dynamic loading conditions. The findings showed that composite walls possess high lateral stiffness, superior energy dissipation, and improved crack resistance under seismic loading. The paper also summarized existing design recommendations and emphasized the need for further development of innovative wall systems with enhanced mechanical performance.

Xueping Li, et. al. (2025) investigated the application and performance of concrete-filled steel tubular (CFST) structures in high-rise buildings. The study focused on innovative CFST systems incorporating high-strength materials, thin-walled sections, and large-diameter steel tubes. The results demonstrated that CFST structures exhibit excellent seismic resistance, fire performance, construction efficiency, and sustainability. The authors observed that the confinement effect provided by steel tubes significantly improves the strength and ductility of concrete cores. The study concluded that advanced CFST technologies have strong potential for future high-rise structural applications.

Marco Bonopera et. al. (2024) reviewed recent advances in steel and composite steel–concrete bridges and buildings. The paper discussed the development of various composite structural members including steel–concrete composite decks, concrete-filled steel tubular members, and concrete-encased steel sections. The study highlighted major research areas such as fatigue, fire resistance, progressive collapse, seismic loading, retrofitting, and structural monitoring. The findings indicated that composite systems provide improved structural efficiency, durability, and sustainability compared to conventional systems. The author emphasized the increasing importance of composite structures in modern infrastructure development.

Ting Zhou, et. al. (2015) experimentally investigated the seismic performance of L-shaped concrete-filled steel tube frame structures subjected to cyclic loading. Three two-storey frame specimens were tested to evaluate the effects of axial compression ratio and beam-column stiffness ratio on structural behavior. The results showed that all specimens exhibited stable hysteretic loops, high ductility, and excellent energy dissipation capacity. The study observed that reducing the axial compression ratio improved ductility and reduced stiffness degradation. Finite element analysis results closely matched the experimental observations, validating the analytical approach.

Diyari B. Hussein and Ardalan B. Hussein et. al. (2024) conducted a numerical investigation on the axial load capacity of cold-formed steel channel sections considering the effects of eccentricity, thickness, and column length. A validated finite element model was developed and applied to a large parametric study involving 208 specimens. The results indicated that increased eccentricity and column length significantly reduced the axial load capacity of the sections. The authors also found that existing design standards provide conservative predictions of compressive strength. The study highlighted the importance of geometric parameters in determining the structural efficiency of cold-formed steel members.

Mark D. Denavit, et. al. (2016) studied seismic performance factors for steel–concrete composite moment frames with steel beams and composite columns. Nonlinear pushover and dynamic response history analyses were conducted on several archetype frames designed according to modern seismic codes. The study evaluated the seismic response modification factor, overstrength factor, and deflection amplification factor using the FEMA P695 methodology. The findings revealed that composite moment frames exhibit reliable collapse resistance and significant ductility under severe seismic loading. The authors concluded that the proposed performance factors can improve the seismic design of composite frame systems.

Abdolreza Ataei, et. al. (2016) developed a three-dimensional finite element model to study the moment–rotation behavior of deconstructable flush end-plate beam-to-column composite joints. The numerical model included material and geometric nonlinearities along with nonlinear contact behavior. The study found that the proposed joint system demonstrated stable ductile behavior under hogging bending moments. A parametric study revealed that shear connection degree, reinforcement ratio, end-plate thickness, and bolt size significantly influence joint stiffness and rotational capacity. The developed analytical models were found suitable for predicting the behavior of semi-rigid composite joints.

Xianlin Wang, et. al. (2019) investigated the effect of concrete cover on the bond–slip behavior between steel sections and concrete in steel reinforced concrete (SRC) structures. Push-out tests were conducted to evaluate bond stress–slip relationships and failure mechanisms. The results showed that increasing concrete cover significantly enhanced bond strength and confinement effect. The study observed substantial increases in initial, ultimate, and residual bond stresses with larger concrete cover thickness. Finite element analysis further identified different cracking patterns and shear transfer mechanisms influencing bond behavior.

Jiaxin Li, et. al. (2025) reviewed modern seismic enhancement techniques for reinforced concrete frame buildings. The study focused on frame–shear wall systems, buckling restrained braces (BRBs), and seismic isolation bearings. The findings indicated that integrating advanced seismic technologies with traditional structural systems improved energy dissipation by approximately 45%. The authors concluded that seismic isolation systems provide the best seismic performance, while BRB systems offer an economical and effective solution for retrofitting existing structures.

Yunlong Chen, et. al. (2024) reviewed the application of high-performance cementitious composites in steel–concrete composite bridge deck systems. The study discussed orthotropic steel bridge decks, steel–concrete composite decks, steel–UHPC systems, and steel–ECC composite systems. The authors found that ultra-high-performance concrete and engineering cementitious composites significantly improve crack resistance, flexural strength, and fatigue performance. The study also evaluated different shear connector systems and emphasized the importance of advanced materials in enhancing the durability and structural efficiency of composite bridge decks.

Jerome F. Hajjar et. al. (2001) reviewed composite steel and concrete structural systems used in seismic engineering applications. The paper discussed composite moment frames, braced frames with concrete-filled steel tube columns, and hybrid wall systems. The study highlighted the superior seismic behavior and economic advantages of composite systems compared to conventional structures. Experimental and analytical investigations showed that composite systems exhibit enhanced stiffness, ductility, and load-carrying capacity under seismic loading conditions. The author emphasized the growing role of composite systems in earthquake-resistant construction.

Diyar Nasih Qader, et. al. (2025) presented a state-of-the-art review on earthquake resilience enhancement techniques for reinforced concrete infrastructure. The study evaluated conventional retrofitting methods alongside advanced technologies such as fiber reinforced polymers (FRP), shape memory alloys (SMA), and base isolation systems. The findings showed that FRP retrofitting significantly increases ductility and lateral load capacity, while SMA systems improve self-centering capability and reduce residual deformation. The study concluded that hybrid retrofitting systems provide superior seismic resilience and sustainability compared to traditional strengthening methods.

Jianguo Nie, et. al. (2019) reviewed recent technological developments and engineering applications of novel steel–concrete composite structures in China. The study discussed innovative systems such as long-span composite structures, composite transfer structures, steel plate concrete strengthening techniques, and advanced composite joints. The authors highlighted the advantages of resource-saving, high-performance composite systems in terms of safety, durability, and sustainability. The study concluded that advanced steel–concrete composite technologies possess significant potential for future large-scale structural applications.

III. SUMMARY OF LITERATURE

The reviewed literature shows that steel–concrete composite structures provide superior seismic performance due to their high strength, stiffness, ductility, and energy dissipation capacity. Researchers have studied composite beams, columns, shear walls, and frame systems using experimental and numerical methods. Studies on concrete-filled steel tubular (CFST) systems revealed improved load-carrying capacity and seismic resistance. Advanced technologies such as seismic isolation systems, dampers, smart materials, and high-performance concrete have further enhanced the earthquake resistance of composite structures. Overall, composite high-rise systems are considered more efficient and resilient compared to conventional reinforced concrete and steel structures.

IV. GAP IDENTIFICATION

- Limited studies are available on the overall seismic behavior of complete composite high-rise structures.
- Nonlinear interaction between steel and concrete under cyclic loading is not fully understood.
- Existing seismic design codes provide limited guidelines for advanced composite systems.
- Comparative studies between composite, reinforced concrete, and steel high-rise buildings are limited.
- Research on long-term durability, sustainability, and post-earthquake performance is insufficient.

- Practical applications of smart materials, dampers, and AI-based monitoring systems require further investigation.

REFERENCES

[1] Panagiota Katsimpini, et. Al. An In-Depth Analysis of the Seismic Performance Characteristics of Steel–Concrete Composite Structures, 2025 Resource- MDPL

[2] Chao-Qun Yu, et al. State-of-the-art review on steel-concrete composite walls, 2024, DOI: 10.54113/j.sust.2024.000035

[3] Xueping Li et.al. Innovative Applications and Comprehensive Performance Analysis of Concrete-Filled Steel Tubular Structures in High-Rise Buildings, 2025, doi.org/10.2991/978-94-6463-782-3_12

[4] Marco Bonopera, Advances in Steel and Composite Steel—Concrete Bridges and Buildings,2024, https://doi.org/10.3390/infrastructures9100169

[5] Ting Zhou, et. al. Experimental study on the seismic performance of L-shaped column composed of concrete-filled steel tubes frame structures, 2015, http://dx.doi.org/10.1016/j.jcsr.2015.07.009

[6] Diyari B. Hussein et, al. Numerical Investigation of the Axial Load Capacity of Cold-Formed steel Channel Sections: Effects of Eccentricity, Section Thickness, and Column Length, 2024, https://doi.org/10.3390/infrastructures9090142

[7] Mark D. Denavit, et. Al. Seismic performance factors for moment frames with steel-concrete composite columns and steel beams, 2016, doi: 10.1002/eqe.2737

[8] Abdolreza Ataei et. Al. Computational modelling of the moment-rotation relationship for deconstructable flush end plate beam-to-column composite joints, 2016, http:// dx.doi. org /10.1016/j.jcsr.2016.11.007

[9] Xianlin Wang, et, al. Effect of concrete cover on the bond-slip behavior between steel section and concrete in SRC structures, 2019, https:// doi.org/10.1016/j.conbuildmat.2019.116855

[10] Jiaxin Li, et. Al. Seismic Enhancement Techniques for Reinforced Concretey Frame Buildings: A Contemporary Review, 2025, https://doi.org/10.3390/buildings15060984

[11] Danish Mohammad & Hitesh Kodwani Enhancing Structural Stability: A Comprehensive Review of Composite Building Frames, 2024, ISSN: 2321-1156

[12] Jerome F. Hajjar, Composite steel and concrete structural systems for seismic engineering, 2001, Journal of Constructional Steel Research 58 (2002) 703–723

[13] Diyar Nasih Qader, et. Al. Advances in Enhancing Earthquake Resilience of Concrete Infrastructure: A State-of-the Art Review, 202,5, DOI: 10.24271/PSR.2025.495371.1868

[14] Jianguo NIE et. Al. Technological development and engineering applications of novel steel-concrete composite structures, 2019, https://doi.org/10.1007/s11709-019-0514-x

[15] Jiaxin Li, Seismic Enhancement Techniques for Reinforced Concretey Frame Buildings: A Contemporary Review, 2025, https://doi.org/10.3390/buildings15060984.

[16] Yunlong Chen et.al, Application of high-performance cementitious composites in steel–concrete composite bridge deck systems: A review, 2024, https://doi.org/10.26599/JIC. 2024.9180012

IS Codes:

- IS 456:2000 – Plain and Reinforced Concrete – Code of Practice
- IS 875 (Part 1 & 2):1987 – Dead and Live Load Calculations
- IS 1786:2008 – High Strength Deformed Steel Bars for Concrete Reinforcement