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Seismic Behavior of Composite Steel-Concrete Beams in High-Risk Earthquake Zones: An Analytical and Experimental Approach

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Abstract

This study investigates the seismic performance of composite steel-concrete beams in high-risk earthquake zones through a combination of analytical modeling and experimental testing. Composite beams, which combine the strengths of steel and concrete, are increasingly utilized in structural designs due to their superior load-bearing capacity and ductility. The research emphasizes the behavior of these beams under seismic loading, focusing on critical parameters such as energy dissipation, load transfer mechanisms, and failure modes. Advanced numerical simulations are conducted to model the nonlinear behavior of composite beams, validated through full-scale experimental testing. The findings highlight the influence of connection detailing, material properties, and beam geometry on seismic performance. The outcomes provide practical recommendations for optimizing composite beam designs, ensuring enhanced safety and structural resilience in earthquake-prone regions.

Introduction

The seismic performance of structures plays a pivotal role in safeguarding human lives and infrastructure in earthquake-prone regions. Structural failures during earthquakes often lead to catastrophic consequences, including loss of life, economic disruptions, and long-term societal impacts. To address these challenges, composite steel-concrete beams have emerged as an advanced engineering solution, leveraging the complementary properties of steel and concrete. Steel offers high tensile strength and ductility, while concrete provides excellent compressive strength and stiffness. Together, these materials form a synergy that enhances energy dissipation, structural integrity, and load-bearing capacity, making composite beams an indispensable choice in seismic-resistant construction.

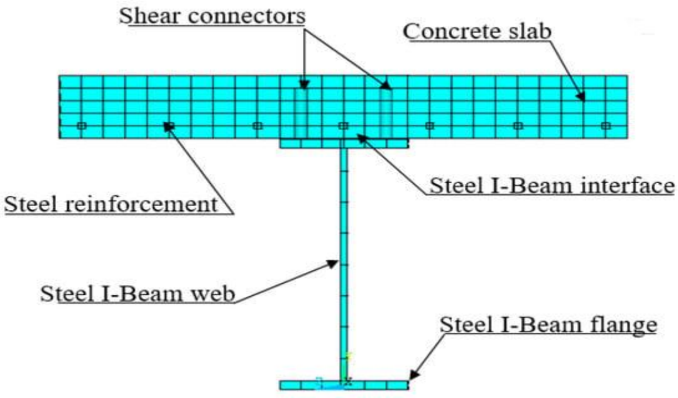

Figure1.1: Strengthened Steel–Concrete Composite Beams

Despite the widespread adoption of composite beams, their seismic behavior remains a complex area of study influenced by various parameters, including material properties, connection detailing, beam geometry, and load conditions. While previous research has contributed to understanding these factors, most studies either rely on numerical simulations or experimental analyses in isolation. The need for a comprehensive approach that integrates analytical modeling and experimental validation is critical to capturing the nonlinear, dynamic behavior of composite steel-concrete beams under seismic loading conditions.

This research addresses this gap by adopting an analytical and experimental approach to evaluate the seismic behavior of composite steel-concrete beams in high-risk earthquake zones. Advanced finite element modeling techniques are employed to simulate the dynamic and nonlinear behavior of these beams under varying seismic intensities. These simulations are then validated through rigorous experimental testing of full-scale specimens, focusing on critical performance parameters such as energy dissipation, load transfer mechanisms, and failure modes.

The outcomes of this study aim to provide actionable insights into the seismic performance of composite beams, offering practical design recommendations to engineers and architects. By optimizing material use, connection designs, and structural configurations, this research seeks to enhance the resilience and reliability of composite structures in high-risk earthquake zones, ultimately contributing to safer and more sustainable built environments.

Problem Statement

Seismic events pose a significant threat to the safety and stability of structures, particularly in high-risk earthquake zones. Composite steel-concrete beams are widely used in modern construction due to their superior strength, ductility, and energy dissipation capabilities. However, despite their advantages, the seismic behavior of these composite beams is not fully understood, especially when subjected to complex, nonlinear, and dynamic loading conditions typical of severe earthquakes.

Existing studies on composite beams primarily focus on isolated factors, such as material properties, connection designs, or beam geometry, often relying on either analytical modeling or experimental testing alone. This fragmented approach limits the ability to predict real-world performance accurately. Furthermore, the lack of validated design guidelines that account for the interaction of these factors under seismic loading increases the risk of structural failure in high-risk zones.

This research aims to address these gaps by investigating the seismic behavior of composite steel-concrete beams through a holistic approach that integrates advanced analytical modeling with experimental validation. By understanding the critical factors influencing their performance, this study seeks to develop practical recommendations to improve the design and resilience of composite structures in earthquake-prone regions.

Goal of Dissertation

To investigate and enhance the seismic performance of composite steel-concrete beams in high-risk earthquake zones through analytical modeling and experimental validation, with the goal of developing optimized design guidelines for safer and more resilient structures.

Importance of Composite Steel-Concrete Beams in Earthquake Engineering

- Explain the structural benefits of composite beams, such as improved strength, ductility, and energy dissipation.

- Provide examples or case studies where composite beams have proven effective or raised concerns in seismic conditions.
- Describe the importance of optimizing these beams to enhance the seismic performance of buildings and bridges.

Objectives of the Study

- To study the interaction between steel and concrete elements under seismic loads.
- To analyze the failure mechanisms of composite beams during earthquakes.
- To propose design improvements to improve seismic resistance.

Scope and Limitations

- Define the scope of the study, such as the types of composite beams analyzed (e.g., particular dimensions, materials, or connection methods).
- Clarify limitations like the range of seismic intensities tested, assumptions in analytical modeling, or constraints of the experimental setup.
- Highlight the focus on structural performance rather than ancillary factors (e.g., cost analysis or long-term durability).

Literature Survey

Fahad Baig et al., IRJET, Volume: 10 Issue: 09, 2023. "Comparative study on analysis of steel-concrete composite structure with different shear wall positions "

This study analyzes a 25m x 25m steel-concrete composite building, comparing its design with and without shear walls. The results show that the structure with shear walls at corners has minimal displacement, storey drift, and time period.

Yogita D. Madan et al., IJSDR | Volume 8 Issue 4,2023. "A review paper on seismic evaluation of building having steel concrete composite columns and rc beams"

This study examines the use of steel-concrete composite columns with reinforced concrete beams in building frames, focusing on their seismic performance using Indian standards. The rectangular building with 30 meters elevation and E345 grade steel and M30 grade concrete was designed using ETABs software. Results showed composite columns offer better ductility and earthquake resistance.

Rajan Suwal et al., NJST, Vol 22 | No. 1, 2023. "A Comparative Study of the Seismic Behavior of Composite (Steel-Concrete) and Reinforced Concrete Structure"
Steel-concrete composite construction is popular worldwide due to its low weight, high strength, and durability. However, it is not widely used in Nepal due to economic constraints. This paper compares composite and regular concrete (RC) structures for earthquake zone V buildings. Results show composite constructions are more suitable for multi-storied buildings compared to RC structures using ETABS software and linear static methods.

Tushar Chaudhari et al., Springer,2022. "Numerical and analytical methods for the design of beam-column sub-assemblies with composite deck slab"
A finite element numerical model was used to estimate the force displacement backbone curve of steel moment frame beam-column-joint subassemblies under repeated cyclic loading. A simple analytical model was developed to estimate peak strength due to slab effect. The model captured the backbone envelope of experimental tests but overestimated strength at larger displacements. The analytical model considered nonlinear deformation modes and failure modes, matching experimental strengths and failure modes. The model is suitable for research and design consideration.

Chang Wu et al., frontiers in, Volume 9, 2022. "Sectional Analysis of Reinforced Engineered Cementitious Composite Columns Subjected to Combined Lateral Load and Axial Compression"
This paper proposes a sectional analysis of Rectified Constructive Concrete (RECC) columns subjected to combined lateral load and axial compression. It uses the design theory of load capacity of eccentric compression columns and the unique constitutive model of ECC to derive calculation equations for the sectional load capacity of RECC columns. The study also constructs strength-interaction diagrams and conducts a parametric study to provide insight into the design principles of RECC columns.

V. SriAbirami et al., IJAEM, Volume 4, Issue 2, 2022. "A Review of Steel Concrete Composite Beam"
Residential buildings are primarily constructed using reinforced concrete (RCC), which is costly due to its heavy weight and hazardous formwork. However, steel concrete composite structures are popular due to their reduced costs, rapid construction, and fire protection properties. Composite beam columns have excellent earthquake resistance, making them popular in Japan. To promote successful composite construction, seismic design criteria for Indian structural systems were developed.

Tomás Lejarraga et al., APA, Vol. 147, No. 6, 2021. "How Experimental Methods Shaped Views on Human Competence and Rationality"
In 1967, Peterson and Beach's study of statistical intuitions led to the introduction of the heuristics-and-biases research program in psychology. This program shifted the focus from learning and experience to described scenarios in behavioral decision research. This shift, influenced by the intuitive-statistician program and the heuristics-and-biases program, has significantly shaped the view of human cognition's error-proneness. The program has dominated post-1974 research, focusing on Bayesian reasoning and judgments of compound events, highlighting the importance of description in understanding human cognition.

Bhushan G. Dhurve et al., IRJMETS, Volume:03/Issue:07,2021. "Seismic analysis of reinforced concrete buildings"
Seismic excitation in a building can be assessed using various methods, including linear static analysis, eigen value analysis, response spectrum analysis, time history analysis, pushover analysis, and nonlinear dynamic analysis. Linear static analysis defines forces acting on a structure, while eigen value analysis calculates natural frequencies and mode shapes. Time history analysis determines the structure's exact response over time, while pushover analysis creates a capacity curve by integrating forces into a non-linear structural model. Nonlinear dynamic analysis evaluates component deformations for each degree of freedom.

V. Nithin et al., IJAEM, Volume 2, Issue 10, 2020. "Structural Analysis and Design of Rcc and Steel Plate Shear Wall for Multistoried Building – A Review"
Tall structures in seismic-prone areas are heavily influenced by lateral forces, making lateral stability crucial for their stability and control. The shear wall, a high-in-plane stiffness system, is often used to oppose horizontal loads and gravity loads. This paper analyzes a multistorey building in Zone IV, considering shear walls of RCC and steel plate, determining parameters like axial load, displacement, overturning moment, and stiffness for different locations.

Mir Rahman Naseri et al., IRJET, Volume: 08 Issue: 04, 2021. "A Review on Seismic Analysis of Hybrid Structures"
This article studies a high-rise hybrid structure in a seismic environment using the CSI ETABS 2019

program. It analyzes reaction continuum between RC structure and steel-concrete hybrid structure, comparing parameters like storey displacement, storey drift, and storey shear.

V. Todea et al., ELSEVIER,2021. "Experimental investigations on the seismic behavior of composite steel concrete coupled shear walls with central openings"
The study investigates the seismic behavior and performance of concrete structural walls subjected to vertical and cyclic lateral loads. It investigates the use of steel fibers reinforced concrete and various composite steel-concrete connections on the walls' hysteretic performance. The results show that embedding supplementary steel fibers in the concrete matrix can regain ductility loss due to openings and improve the performance of the composite connection between structural steel and concrete web panel.

Alireza Behnamnia et al., JCEMA,2019. "Seismic Behavior of Steel-Concrete Composite Columns Under Cyclic Lateral Loading"
Lightweight concrete, a popular flooring material in buildings, has been studied for its compressive strength and durability in acid environments. The research used pumice aggregate and 1M sulfuric acid. The addition of Nanomaterials like Nano silica and Nano clay increased the concrete's compressive strength by 1.43%. The durability of the concrete reached its maximum value with 5% Nano silica and 5% Nano lime, while losing a lower percentage of its weight. This research aims to better understand the behavior of lightweight concrete in various climatic conditions.

Venkateswar Reddy. K et al., IJEAT, Volume-9 Issue-2, 2019. "Seismic Behavior of Steel-Concrete Composite Structures"
This study explores the seismic conduct of steel-concrete composite structures, focusing on their ability to disseminate seismic energy through inelastic dislocations. The research aims to apply non-direct investigation strategies to assess building performance, identify key factors influencing seismic reactions, conduct numerically, create a modular model to represent dynamic conduct, and examine the impact of shear connectors on composite structures' conduct in seismic stacking.

Khaled Z. Sayed et al., IOSR-JMCE, Volume 16, Issue 6,2019. "Seismic Behaviors of Steel/Concrete Composite Edge Beam-Column Joints under Cyclic Loading"
The study investigates the behavior of steel-concrete composite edge joints under cyclic loading. Six specimens were tested with different types of steel sections and beams. Results showed shear failure mode at the end of encased steel sections, with tiny cracks detected. Joints with encased I sections had higher ultimate loads and better energy dissipation capacity. The study concluded that composite steel sections minimize cracks, lead to weak beam-strong column criteria, and improve seismic behavior.

Bhavesh Joshi Shahnawaz Ansari et al., IJCET, Vol.8, No.2 ,2018. "Research on seismic behaviour of composite Steel concrete moment frames"
The European Union is promoting research on composite steel concrete moment frames to address seismic design issues, involving experimental activity and numerical model studies in large European testing installations.

Jianguo Nie et al., ELSEVIRE,2017. "Seismic behavior of connections composed of CFSSTCs and steel–concrete composite beams—experimental study"
The study tested fourteen cruciform connection specimens for seismic behavior. Results showed adequate strength with interior diaphragms but low ductility, and good deformation capacity with anchored studs. Exterior diaphragm connections had adequate strength, good ductility, and high-energy dissipation capacity, making them suitable for seismic regions.

Muhammed Sabith K et al., IJSRSET | Volume 3 | Issue 3, 2017. "Seismic Analysis of Irregular Composite Structures with Shear Connectors using ETABS"
This study examines the impact of stud shear connectors on composite structures and compares them to conventional RCC structures. The study focuses on plan irregular structures with 10-storey medium rise buildings. It analyzes the behavior of shear connectors and their variation with RCC structures to determine the best construction method. The study considers parameters like storey displacement, base shear, and mass, and uses Response Spectrum Analysis with ETABS V 16.

Abhishek Sanjay Mahajan et al., IJRET, Volume: 05 Issue: 04 ,2016. "Performance analysis of RCC and steel concrete composite structure under seismic effect"
The RCC structure is no longer suitable due to increased dead load, span rejection, and less stiffness. Engineers are exploring alternative materials, such as steel-concrete composite sections, to increase steel volume in construction. A study compares two structures using seismic analysis, linear static and nonlinear static methods. The composite has more lateral stiffness, and the non-linear static analysis shows significant variation in performance points compared to the RCC model.

K. Mukesh Kumar et al., IJSR, Volume 5 Issue 8, 2016. "Seismic Analysis of Steel Concrete Composite System and its Contrast with RCC Structures"
Composite structures made of steel and concrete are preferred over RCC and steel structures due to their

weight, larger cross sections, and resistance to earthquake loads. This comparative study compares low to high rise RCC and composite structures in seismic zone V, evaluating seismic behavior using Response spectrum and. ETABS software.

A.S. Mahajan et al., IOSR-JMCE, Volume 13, Issue 4,2016. "Behavior of RCC and Composite Structure under Seismic Loads"
The Indian structural community is yet to adopt the modern composite modeling approach in tall buildings, despite its benefits such as speedy erection, labor savings, and increased strength. A comprehensive analysis of G+20 buildings using E-tab 2015 software reveals that composite models are habitable, stable, safe, cost-effective, and efficient in using concrete and steel models.

Prof. Vijay S Sawant et al., IJIRSET, Vol. 4, Issue 4, 2015. "Survey on Comparison of Steel and Concrete Composite Beam Column Connections"
Composite constructions are popular due to their advantages over conventional concrete and steel structures. They combine the better properties of both materials, with lesser cost, speedy construction, and fire protection. A study compares steel and concrete composite building frame work in seismic performance using equivalent static and Response Spectrum methods.

The study concludes that composite frames are best suited for better seismic behavior and material cost benefits.

Varsha Patil et al., IJSER, Volume 6, Issue 12, 2015. "Structural behavior of Composite structure"
This paper explores the research on the response of structures made of reinforced cement concrete (RCC), steel, and composite materials to static and dynamic loads, primarily due to earthquake, to overcome their respective drawbacks.

LIU Jingbo et al., WECC,2008. "Seismic behavior analysis of steel-concrete composite frame structure systems"
The study investigates the seismic behavior of steel-concrete composite frame structures using a four poly-line plastic hinge mode. Different frame structures, including CL-CFST, SL-CFST, CL-ETRC, SL-ETRC, and RC frame structures, are created. Results show that the CFST frame structure has better aseismic performance, but the effect of composite frame beams on structural seismic behavior should be considered comprehensively. The study also found that RC columns can't meet the demand of "no collapsing with strong earthquake" under rare earthquakes.

Haibei XIONG et al., WECC, 2004. "Experimental study on behavior of steel beam to concrete column connection in retrofitting"
A new steel beam to existing RC column connection has been developed for retrofitting, combining high-strength bolts on site. Two full-scale specimens were tested under cyclic loading, proving it achieves expected strength and seismic performance. The composite connection model was found to be satisfactory.

Gap Analysis
Seismic Performance of Composite Steel-Concrete Beams

- Limited experimental data on dynamic loading conditions.
- Incomplete understanding of material interaction during seismic events.
- Lack of comprehensive analytical models for nonlinear behavior.
- Design code limitations for seismic forces in high-risk earthquake zones.
- Limited energy dissipation analysis.
- Insufficient research on beam design optimization for improved ductility and seismic resilience.

Summary of Review
The paper "Seismic Behavior of Composite Steel-Concrete Beams in High-Risk Earthquake Zones: An Analytical and Experimental Approach" investigates the performance of composite steel-concrete beams under seismic loads. The study combines analytical modeling and experimental testing to evaluate the beams' structural integrity and energy dissipation capabilities in high-risk earthquake regions. The research emphasizes the critical interaction between steel and concrete, highlighting how the composite action enhances strength and ductility. Key findings include the influence of connection details, material properties, and beam geometry on seismic performance. The study provides recommendations for optimizing design to improve safety and resilience. The approach is valuable for advancing earthquake-resistant construction techniques.

Research Methodology
The research methodology for this study integrates both analytical and experimental approaches to comprehensively investigate the seismic behavior of composite steel-concrete beams. The methodology begins with an extensive literature review to examine existing studies on the seismic performance of composite beams, focusing on analytical modeling techniques, experimental testing methods, and the key parameters that influence performance. The review helps identify the gaps in the current understanding of the nonlinear behavior of composite beams under seismic loading conditions.

Following the literature review, advanced finite element models (FEM) will be developed to simulate the seismic behavior of composite steel-concrete beams. These models will incorporate various factors such as material properties, connection details, and beam geometries, allowing for a detailed investigation of the beams' response to seismic forces. Parametric analyses will be conducted to study the impact of different variables such as material composition, loading intensities, and boundary conditions on the overall seismic performance.

To validate the analytical models, full-scale composite steel-concrete beam specimens will be designed and fabricated for experimental testing. These specimens will be subjected to simulated seismic loading using specialized testing equipment such as shake tables or cyclic loading setups. Key performance parameters, including energy dissipation, load transfer, ductility, and failure modes, will be measured during the testing phase.

The results of the experimental tests will then be compared with the predictions from the analytical models to assess their accuracy and reliability. Any discrepancies will be addressed by refining the numerical models, and additional simulations will be performed to improve the predictions.

Data from both the experimental testing and the simulations will be analyzed to identify patterns and determine the critical factors that influence the seismic performance of composite steel-concrete beams. The effectiveness of different connection designs, material combinations, and structural configurations in enhancing seismic resilience will be evaluated.

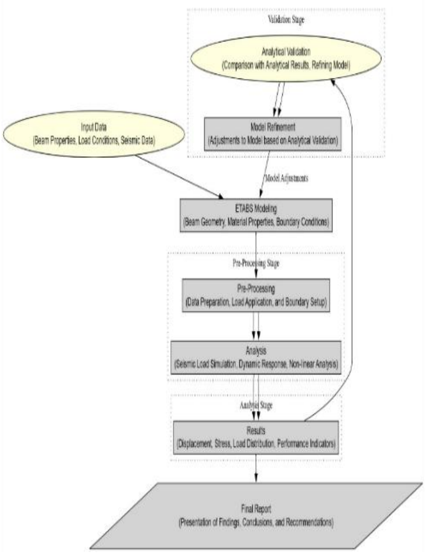

Figure1.2: Research Methodology

Based on the findings from both the analytical and experimental phases, practical design guidelines will be developed. These guidelines will aim to optimize the design of composite steel-concrete beams for improved seismic performance while considering cost-effectiveness, sustainability, and safety.

Finally, the research findings will be documented and shared through academic publications, industry seminars, and design codes, providing valuable insights for engineers and architects involved in the design of earthquake-resistant structures. This comprehensive methodology ensures a thorough understanding of the seismic behavior of composite beams, contributing to the advancement of safer, more resilient infrastructure in high-risk earthquake zones.

Design & Modelling

The design and modeling phase of this study focuses on developing a robust framework to simulate and evaluate the seismic performance of composite steel-concrete beams. This phase combines detailed design considerations with advanced computational modeling to ensure accurate representation of the composite beam behavior under seismic loading.

The first step in the design process involves selecting the appropriate beam geometry, material properties, and connection details that are representative of real-world applications in high-risk earthquake zones. Composite steel-concrete beams are typically designed with a steel section (such as an I-beam) that is connected to a concrete slab, with the two materials working together to resist loads. The design will incorporate varying beam dimensions, connection configurations, and material strengths to investigate their influence on seismic behavior.

For the modeling phase, advanced finite element analysis (FEA) techniques will be employed to simulate the structural response of the composite beams under seismic loading. The beams will be modelled using a combination of linear and nonlinear elements to capture the complex interactions between the steel and concrete components. The nonlinear modeling will account for material behavior under cyclic loading, as well as potential failure mechanisms such as yielding, cracking, and bond-slip between the steel and concrete. The modeling process will also consider the boundary conditions and load profiles representative of seismic events. A range of seismic loadings, including varying intensities and frequencies, will be applied to the model to assess the beam's response under different earthquake scenarios. The material properties will be defined using realistic values based on standard design codes, with particular attention paid to the strength and ductility of both steel and concrete in seismic conditions.

The connection detailing, which is critical to the overall seismic performance of composite beams, will be incorporated into the model. Various connection types, such as shear studs or welded connections, will be examined to determine their effectiveness in transferring loads between the steel and concrete components during seismic events.

Once the model is established, a series of parametric studies will be conducted to explore the impact of different design variables, such as beam geometry, material properties, and connection types, on the seismic behavior. The findings from the numerical simulations will be used to identify the optimal design parameters for maximizing the seismic resilience of composite steel-concrete beams.

The design and modeling phase will be followed by validation through experimental testing, where full-scale composite beams will be tested under controlled seismic conditions. The experimental results will provide valuable insights to refine the numerical models and ensure their accuracy in predicting the actual seismic behavior of composite beams. This integrated approach will help in developing a comprehensive understanding of the design factors that contribute to the seismic performance of composite steel-concrete beams.

Expected Outline

The expected outline for the review paper begins with an **Introduction**, where the background of seismic challenges in earthquake-prone regions will be introduced, emphasizing the importance of composite steel-concrete beams in earthquake-resistant design. This section will also define the objectives of the review and outline the structure of the paper to guide the reader through the content.

The paper will then move to a section on the **Seismic Behavior of Composite Steel-Concrete Beams**, exploring the fundamental properties of both steel and concrete in composite beams, and how they interact under seismic loading. It will examine key factors influencing seismic performance, such as material properties, connection detailing, and beam geometry, as well as the energy dissipation and load-bearing capabilities of these beams during seismic events.

Next, the **Analytical Modeling of Seismic Behavior** section will review the numerical methods used for modeling composite beams, particularly finite element analysis, and discuss the challenges in capturing nonlinear behavior under seismic loading. The section will also examine previous studies that have used analytical models to predict the seismic performance of composite beams and how these models have been validated through experimental data.

Following this, the **Experimental Testing of Composite Beams** section will review the various experimental methods used to evaluate the seismic performance of composite beams, such as cyclic loading tests, shake table tests, and full-scale specimen testing. Key performance parameters like energy dissipation, failure modes, and ductility will be discussed, along with findings from past research that have contributed to understanding composite beam behavior under seismic loads.

The paper will also address **Design Guidelines and Standards**, providing an overview of current design codes and standards for composite steel-concrete beams in seismic zones. This section will analyze the strengths and limitations of existing guidelines and offer recommendations for improving the seismic design of composite beams, drawing on case studies of real-world applications.

The review will then explore the **Gaps and Challenges in Current Research**, identifying areas where understanding of composite beam behavior under seismic loading is limited. It will discuss challenges in both modeling and experimental validation and highlight areas that require further investigation to improve seismic resilience.

In the **Future Research Directions** section, the paper will propose areas for future studies aimed at enhancing the seismic performance of composite beams. This will include advancements in computational modeling techniques, experimental methodologies, and innovations in materials and design strategies for improved seismic resilience.
The review will conclude with a **Conclusion** summarizing the key findings, discussing their implications for the design and performance of composite steel-concrete beams in seismic regions, and offering final thoughts on improving the seismic safety of structures using composite beams.

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