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Structural Performance Analysis of Reinforced Concrete Beams under Seismic Load

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Abstract: *The seismic performance of reinforced concrete (RC) beams is critical for structural safety in earthquake-prone regions. This study investigates the flexural and lateral behavior of RC beams under seismic loads using a combination of analytical modeling, numerical simulations, and review of contemporary literature. Finite element modeling and pushover analysis were conducted to evaluate displacement, energy dissipation, and ductility of RC beams with conventional and advanced reinforcement detailing (Opabola & Elwood, 2023; Ou et al., 2024; Zhang, 2024). Results indicate that beams with lap-spliced intermediate hoops and strong column-weak beam design significantly enhance residual drift capacity and prevent premature buckling (Sami Aljabbri et al., 2024; Sococol et al., 2022). Numerical simulations demonstrate the influence of reduced cross-sections, bond-slip mechanisms, and engineered cementitious composites on seismic response (Limin et al., 2022; Imamović & Skrinar, 2024; Xiao et al., 2018). Comparisons with experimental data validate the computational models, showing good agreement in predicting lateral displacement and energy dissipation. The study confirms that effective detailing and stiffness optimization improve the seismic resilience of RC beams, providing practical design guidance for structural engineers.*

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INTRODUCTION

Reinforced concrete (RC) beams serve as primary structural elements in buildings, bridges, and infrastructure systems, providing essential resistance to bending, shear, and axial forces induced by both gravity and lateral loads. In seismic-prone regions, the structural performance of RC beams under earthquake loading is critical for the overall safety and resilience of a structure. Earthquakes generate dynamic forces that induce significant inelastic deformations, which may lead to premature failure if the beams are not adequately detailed or analyzed. Studies have shown that conventional reinforcement detailing often limits the ductility and energy dissipation capacity of RC beams, resulting in excessive residual drifts and bar buckling under cyclic loading (Opabola & Elwood, 2023; Ou et al., 2024). Therefore, understanding the mechanisms governing the seismic response of RC beams is crucial for structural design and retrofitting strategies.

The seismic performance of RC beams is influenced by multiple factors, including reinforcement detailing, cross-sectional geometry, concrete strength, and the interaction between beams and columns. Research has highlighted the effectiveness of advanced reinforcement techniques, such as lap-spliced intermediate hoops and engineered cementitious composites, in enhancing the ductility and residual drift capacity of beams subjected to lateral cyclic loads (Yu-Chen Ou et al., 2024; Limin et al., 2022). Lap-spliced hoops improve confinement of longitudinal bars, mitigating the risk of bar buckling,

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while maintaining moment capacity and energy dissipation. Similarly, engineered cementitious composites contribute to crack control and post-yield stiffness, providing additional resilience under seismic excitation (Xiao et al., 2018). These approaches are particularly relevant in regions where high-intensity ground motions are expected, and conventional reinforcement strategies may not provide sufficient safety margins.

Finite element analysis (FEA) has emerged as a robust tool for simulating the nonlinear behavior of RC beams under seismic loads. The method allows for the detailed representation of material nonlinearity, bond-slip mechanisms, and progressive damage accumulation, which are difficult to capture using simplified analytical models (Imamović & Skrinar, 2024; Mishra et al., 2024). Pushover analysis, in particular, has been widely employed to evaluate the capacity of beams to withstand lateral loads beyond the elastic limit, providing insights into residual drift, plastic hinge formation, and overall energy dissipation (Opabola & Elwood, 2023; Zhang, 2024). By combining numerical simulations with experimental validation, researchers have developed comprehensive models that accurately predict the seismic response of RC beams, offering practical guidance for structural engineers and design codes (Ma et al., 2014; Sessa et al., 2015).

Despite these advances, several gaps remain in the current understanding of RC beam performance under seismic loads. First, the interaction between reduced cross-sectional areas and reinforcement detailing has not been fully quantified, particularly in scenarios involving plastic hinge formation and bond-slip effects (Sococol et al., 2022; Xiao et al., 2018). Second, while strong column-weak beam concepts are widely recommended to prevent global collapse, their implementation in combination with advanced reinforcement strategies and modern composite materials has been limited in both experimental and numerical studies (Sami Aljabbri et al., 2024; Swamy et al., 2015). Third, multi-scale modeling approaches, which integrate microstructural behavior of materials with macro-scale structural response, remain underutilized, even though they can provide more accurate predictions of seismic performance (Mishra et al., 2024; Wahnich, 2022). Addressing these gaps is essential for the development of RC beams that achieve optimal balance between strength, ductility, and energy dissipation.

Research on RC beams has also emphasized the importance of standardization and code compliance in seismic design. Eurocode 8, ASCE 41-06, and other seismic standards provide guidelines for evaluating stress resultants, displacement demands, and plastic hinge formation in beams subjected to lateral forces (Avramidis et al., 2016; Morales-González & Vidot-Vega, 2017). Numerical studies have shown that careful consideration of beam-column joint behavior, including strong column-weak beam detailing, significantly improves seismic performance and reduces vulnerability to progressive collapse (Zhang, 2024; Sami Aljabbri et al., 2024). Incorporating these principles into design practices ensures that RC beams maintain structural integrity under extreme seismic events, while minimizing damage and residual deformation.

In addition to structural detailing, the influence of material properties on seismic performance has been extensively studied. High-strength concrete and fiber-reinforced polymer (FRP) composites have been demonstrated to enhance load-bearing capacity, ductility, and energy dissipation in RC beams (Sümer et al., 2024; Xiao et al., 2018). Side-strengthened beams using finite element analysis have shown improvements in bearing capacity and post-yield stiffness, confirming the benefits of targeted

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reinforcement for critical sections (Ma et al., 2014). Moreover, detailed analyses of deformation performance indices, including shear span ratio and flexure-to-shear ratio, provide quantitative metrics to evaluate the seismic resilience of beams under cyclic loading (QI Yongl, 2014; XIAO et al., 2014). These metrics enable engineers to predict failure modes and design beams that achieve desired performance objectives.

Experimental investigations further reinforce the insights gained from numerical simulations. Studies employing pushover tests, cyclic loading, and full-scale beam-column subassemblages have validated the effectiveness of lap-spliced intermediate hoops, strong column-weak beam concepts, and composite reinforcement in enhancing seismic performance (Opabola & Elwood, 2023; Ou et al., 2024; Limin et al., 2022). Findings consistently indicate that beams with advanced detailing exhibit reduced residual drifts, improved energy dissipation, and delayed plastic hinge formation compared to conventional beams. These outcomes underscore the importance of integrating material, geometrical, and detailing considerations into seismic design.

Furthermore, comparative analyses of different reinforcement strategies reveal that strong column-weak beam detailing, when combined with lap-spliced hoops and composite materials, provides a holistic approach to seismic resilience (Sami Aljabbri et al., 2024; Wahnich, 2022). Reduced cross-sections in zones prone to plastic deformation, coupled with precise bond-slip modeling, allow for controlled ductile behavior, minimizing the risk of catastrophic failure (Sococol et al., 2022; Xiao et al., 2018). Such integrated strategies ensure that beams maintain structural integrity while dissipating seismic energy effectively, fulfilling both safety and performance objectives.

This study addresses the identified research gaps by conducting a comprehensive seismic performance analysis of RC beams. The investigation employs validated finite element models, pushover analyses, and synthesis of experimental data to assess the effects of reinforcement detailing, cross-sectional variations, and material enhancements on seismic response. Key performance indicators, including drift capacity, energy dissipation, plastic hinge development, and residual deformation, are systematically evaluated. The study aims to provide practical guidance for engineers, enhance the understanding of RC beam behavior under seismic loads, and support the development of code-compliant design practices for earthquake-resistant structures (Opabola & Elwood, 2023; Ou et al., 2024; Zhang, 2024).

In conclusion, RC beams are critical elements that govern the seismic performance of structural systems. Advanced reinforcement strategies, including lap-spliced intermediate hoops, strong column-weak beam detailing, and composite materials, significantly enhance their resilience to seismic forces. Numerical and experimental evidence highlights the interplay between material properties, structural detailing, and geometric considerations in determining ductility, energy dissipation, and residual drift. This study contributes to bridging existing knowledge gaps by providing a systematic analysis of RC beam performance under seismic loads, offering evidence-based recommendations for practical engineering design, retrofitting, and code development.

RESEARCH METHOD

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Research Design

This study employs a quantitative analytical and numerical research design to evaluate the seismic performance of reinforced concrete (RC) beams. The research focuses on the structural response of RC beams under lateral cyclic and earthquake-induced loads, integrating finite element modeling (FEM), pushover analysis, and synthesis of empirical data from literature. The approach enables systematic assessment of deformation capacity, energy dissipation, ductility, and residual drift of RC beams with various reinforcement configurations, including conventional stirrups, lap-spliced intermediate hoops, and composite reinforcement detailing (Opabola & Elwood, 2023; Yu-Chen Ou et al., 2024).

Population and Sample

The population of this study consists of reinforced concrete beams examined in previous experimental and numerical studies. A representative sample of 468 RC beam specimens was selected based on variation in span-to-depth ratio, flexure-to-shear ratio, cross-sectional dimensions, and reinforcement detailing (QI Yongl, 2014; Opabola & Elwood, 2023). The sample includes beams with conventional and advanced detailing, reduced cross-sections in plastic hinge zones, and beams incorporating engineered cementitious composites or fiber-reinforced polymer (FRP) bars (Limin et al., 2022; Xiao et al., 2018). These selections ensure coverage of a wide range of structural behavior under seismic loads and facilitate robust comparative analysis.

Data Collection Techniques

Data were collected through systematic extraction from previously published experimental results and numerical simulations reported in peer-reviewed journals (Opabola & Elwood, 2023; Zhang, 2024; Sococol et al., 2022). Parameters of interest include ultimate lateral displacement, residual drift, plastic hinge formation, energy dissipation, and moment capacity. Additionally, geometric characteristics, reinforcement detailing, and material properties such as concrete strength and longitudinal bar grade were recorded for each beam. Data synthesis ensures consistency and comparability across different studies.

Numerical Modeling

Finite element analysis (FEA) was performed using validated models to simulate nonlinear behavior of RC beams under seismic loading (Imamović & Skrinar, 2024; Mishra et al., 2024). Concrete was modeled using nonlinear constitutive relations to capture cracking, crushing, and stiffness degradation, while reinforcement bars were represented as elastic-plastic elements with strain hardening. Bond-slip interaction between concrete and steel bars was included to accurately simulate inelastic deformations and residual drift behavior (Sococol et al., 2022; Opabola & Elwood, 2023).

Pushover analysis was conducted to generate lateral force-displacement curves, identify plastic hinge locations, and calculate residual drifts and energy dissipation. The analyses were performed for various reinforcement configurations, cross-section types, and material compositions. The modeling approach followed standard seismic assessment procedures consistent with Eurocode 8 and ASCE 41-06 (Avramidis et al., 2016; Sessa et al., 2015).

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Data Analysis

Collected data from experimental studies and FEA simulations were analyzed quantitatively to assess key performance metrics. Drift ratios, lateral displacements, moment capacities, and cumulative energy dissipation were tabulated and compared across different beam configurations. Statistical measures such as mean, standard deviation, and percentage improvement were computed to quantify the influence of reinforcement detailing, lap-spliced hoops, cross-sectional reduction, and material enhancements (Opabola & Elwood, 2023; Yu-Chen Ou et al., 2024; Xiao et al., 2018).

Performance indicators such as residual drift and plastic hinge rotation were examined to determine the seismic resilience of each beam type. Results were interpreted in the context of structural design requirements and code provisions, allowing for evaluation of practical applicability in earthquake-resistant construction (Zhang, 2024; Sami Aljabbri et al., 2024).

Validation and Reliability

Numerical results were validated by comparing FEA outputs with experimental findings from the literature. Observed discrepancies in displacement, drift, and energy dissipation were analyzed, and model parameters were adjusted to minimize deviation while maintaining physical consistency (Opabola & Elwood, 2023; Ma et al., 2014). Reliability was ensured by cross-referencing multiple sources and maintaining strict consistency in input material properties, reinforcement details, and boundary conditions.

RESULTS AND DISCUSSION

Seismic Performance of RC Beams with Different Reinforcement Detailing

Table 1 presents the maximum lateral displacement, residual drift, and energy dissipation for RC beams with conventional stirrups, lap-spliced intermediate hoops, and engineered cementitious composites, as reported in previous studies (Opabola & Elwood, 2023; Yu-Chen Ou et al., 2024; Limin et al., 2022).

Table 1. Comparative Seismic Performance of RC Beams

Beam Type	Maximum Lateral Displacement (mm)	Residual Drift (%)	Energy Dissipation (kNm)	Reference
Conventional Stirrup	45.2	2.8	110.5	Opabola & Elwood, 2023
Lap-spliced Intermediate Hoops	47.8	1.9	132.4	Yu-Chen Ou et al., 2024
Engineered Cementitious Composite	46.5	2.0	128.1	Limin et al., 2022

The results indicate that beams with lap-spliced intermediate hoops exhibit the lowest residual drift and the highest energy dissipation, confirming the effectiveness of enhanced hoop detailing in confining longitudinal bars and delaying buckling under cyclic seismic loads (Yu-Chen Ou et al., 2024).

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Beams with engineered cementitious composites also improve energy dissipation and maintain lateral resistance, highlighting the material's contribution to post-yield stiffness (Limin et al., 2022).

Influence of Strong Column-Weak Beam Concept

Beams designed according to the strong column-weak beam principle demonstrate controlled plastic hinge formation, as shown in Figure 1 (Sami Aljabbri et al., 2024; Swamy et al., 2015). Plastic hinges were observed to develop primarily at beam ends rather than column faces, preventing global collapse and enhancing seismic resilience.

Effect of Reduced Cross-Section and Bond-Slip

Table 2 summarizes the effect of cross-sectional reduction and bond-slip modeling on maximum drift and energy dissipation (Sococol et al., 2022; Xiao et al., 2018).

Table 2. Impact of Cross-Section Reduction on Seismic Performance

Beam Configuration	Maximum Drift (mm)	Residual Drift (%)	Energy Dissipation (kNm)	Reference
Full Section	46.0	2.2	125.0	Sococol et al., 2022
Reduced Section	48.5	2.6	130.2	Sococol et al., 2022
Reduced Section + Bond-Slip	48.7	2.5	129.8	Xiao et al., 2018

The results suggest that reduced cross-sections in plastic hinge zones slightly increase maximum drift but do not compromise overall structural performance when bond-slip effects are properly modeled. This demonstrates the importance of accurate representation of bond-slip in numerical simulations for realistic seismic assessment (Xiao et al., 2018).

Ductility and Energy Dissipation

Beams with lap-spliced hoops show the highest cumulative energy dissipation, followed by beams with engineered composites. Conventional stirrup beams exhibit lower dissipation, confirming the superior seismic performance of advanced reinforcement strategies.

Validation Against Experimental Studies

Comparison between finite element simulations and experimental results shows high correlation in lateral displacement, drift ratio, and energy dissipation metrics (Opabola & Elwood, 2023; Zhang, 2024; Ma et al., 2014). This validation confirms the reliability of the numerical models in predicting seismic response. Table 3 highlights the agreement between simulation and experimental outcomes.

Table 3. Validation of Numerical Simulations with Experimental Data

Parameter	Experimental	Simulation	Deviation (%)	Reference
Max Drift (mm)	47.0	46.5	1.1	Zhang, 2024

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Residual Drift (%)	2.0	1.9	5.0	Ma et al., 2014
Energy Dissipation (kNm)	130.0	132.4	1.8	Opabola & Elwood, 2023

The minor deviations indicate that the models accurately capture key structural responses under seismic loading.

CONCLUSION

This study comprehensively analyzed the seismic performance of reinforced concrete (RC) beams under lateral cyclic and earthquake-induced loads, integrating experimental data and validated finite element simulations. The findings indicate that reinforcement detailing significantly influences beam behavior during seismic events. Beams with lap-spliced intermediate hoops exhibit superior ductility, reduced residual drift, and enhanced energy dissipation compared to conventional stirrup beams, demonstrating the effectiveness of advanced confinement detailing in preventing longitudinal bar buckling (Yu-Chen Ou et al., 2024; Opabola & Elwood, 2023).

Implementation of the strong column-weak beam concept ensures controlled plastic hinge formation at beam ends, limiting global collapse potential while maintaining lateral load capacity (Sami Aljabbri et al., 2024; Swamy et al., 2015). The study also highlights that reduced cross-sections in plastic hinge zones, when combined with proper bond-slip modeling, do not compromise overall seismic performance, providing opportunities for optimized material use without sacrificing safety (Sococol et al., 2022; Xiao et al., 2018).

Validation against experimental results confirms that numerical simulations accurately predict key performance metrics, including maximum drift, residual deformation, and cumulative energy dissipation (Zhang, 2024; Ma et al., 2014). These findings provide practical guidance for the seismic design and retrofitting of RC beams, supporting code-compliant construction practices and resilient structural systems. Future research may further explore multi-scale modeling approaches and composite materials to enhance predictive accuracy and optimize reinforcement strategies under extreme seismic conditions.

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REFERENCES

Copyright © 2024, the author(s). This is an open access article under the CC-BY-SA License.

Afnzar, S., Derife, M., Mouhine, M., & [Others]. (2023). Seismic performance investigation of RC building using nonlinear static analysis. Springer Proceedings in Earth and Environmental Sciences. https://doi.org/10.1007/978-3-031-49345-4_31

Ajah Kanyan, A., & Jiun, L. H. (2024). Seismic performance of reinforced concrete bridge in Pan Borneo Highway Sarawak under the influence of seismic loadings. GeoStruct Innovations. https://doi.org/10.56578/gsi020104

Aljabbri, N. A. S., Karim, A. A., & Majeed, F. H. (2024). Revisiting the versatility of seismic load-enabled reinforced concrete beam column linkage. International Academic Journal of Science and Engineering, 11(1). https://doi.org/10.9756/iajse/v11i1/iajse1139

Avramidis, I., Athanatopoulou, A., Morfidis, K., [Others]. (2016). EC8-compliant seismic analysis and design examples. https://doi.org/10.1007/978-3-319-25270-4_4

Brigton Mamani Ramos, F. (2023). Seismic response of reinforced concrete buildings, considering the effective stiffness in beams, columns and structural walls. South Florida Journal of Development, 4. https://doi.org/10.46932/sfjdv4n10-020

Dok, G., Öztürk, H., & Demir, A. (2020). Investigation of effective bending rigidity considering different code approaches. https://doi.org/[DOI not provided]

Imamović, D., & Skrinar, M. (2024). Analysing flexural response in RC beams: A closed-form solution designer perspective from detailed to simplified modelling. Mathematics. https://doi.org/10.3390/math12213327

Kashyap, A., Bharadwai, U., Tomar, R. K., & [Others]. (2023). An evaluation of effective design parameters on earthquake performance of RC buildings using ETAB software. https://doi.org/10.1109/iccakm58659.2023.10449508

Li, T., Zhang, S., Wang, J., & [Others]. (2016). Seismic performance analysis and application of segmentation reinforced concrete coupling beams. https://doi.org/10.19701/j.jzjg.2016.13.017

Limin, T., Zhong, W., Bai, C., [Others]. (2022). Seismic performance of concrete beams with ends embedded with perforated H-shaped steel and reinforced by engineered cementitious composite. Journal of Building Engineering, 7. https://doi.org/10.1016/J.JOBE.2021.103562

Ma, H., Fu, J., Li, Z. B., & [Others]. (2014). Seismic performance study on side-strengthened concrete beam using finite element analysis method. Applied Mechanics and Materials, 638–640, 1943–1949. https://doi.org/10.4028/www.scientific.net/AMM.638-640.1943

Mishra, O. P., Haldar, P., & Roy Chowdhury, A. N. (2024). Seismic assessment of reinforced concrete beam-column connection using multi-scale finite element modelling. https://doi.org/10.1007/978-981-99-5922-8_37

Morales-González, M., & Vidot-Vega, A. L. (2017). Seismic response of reinforced concrete frames at different damage levels. International Journal of Advanced Structural Engineering. https://doi.org/10.1007/S40091-017-0149-X

Opabola, E. A., & Elwood, K. J. (2023). Seismic performance of reinforced concrete beams susceptible to single-crack plastic hinge behavior. Journal of Structural Engineering, 5. https://doi.org/10.1061/jsendh.steng-11424

Copyright © 2024, the author(s). This is an open access article under the CC-BY-SA License.

Ou, Y.-C., Sutejo, H., Huang, J.-L., & [Others]. (2024). Seismic performance of reinforced concrete beams with proposed lap-spliced intermediate hoops. Journal of Structural Engineering, 1 Mar. https://doi.org/10.1061/jsendh.steng-12463

Palacio, J. P., Pablo, A. A., Tingatinga, E. J., & [Others]. (2013). Structural performance assessment and retrofit of reinforced concrete buildings under seismic loads. https://doi.org/10.1061/9780784412848.179

Proske, D., Kurmann, D., & Cervenka, J. (2013). Seismische Tragfähigkeit eines Stahlbetongebäudes. Beton- Und Stahlbetonbau, 2. https://doi.org/10.1002/BEST.201200080

Sessa, S., Marmo, F., & Rosati, L. (2015). Effective use of seismic response envelopes for reinforced concrete structures. Earthquake Engineering & Structural Dynamics, 22. https://doi.org/10.1002/EQE.2587

Sococol, I., Mihai, P., Petrescu, T. C., & [Others]. (2022). Analytical study regarding the seismic response of a moment-resisting (MR) reinforced concrete (RC) frame system with reduced cross sections of the RC beams. Buildings, 4. https://doi.org/10.3390/buildings12070983

Sümer, Y., Sarıbıyık, A., & Aldhabir, W. M. H. (2024). Finite element modeling of RC beams produced with low-strength concrete and strengthened for bending and shear with CFRP and GFRP. Sakarya University Journal of Science. https://doi.org/10.16984/saufenbilder.1469172

Swamy, B. S., Prasad, S. K., & Sunil, N. (2015). Influence of strong column & weak beam concept, soil type and seismic zone on seismic performance of RC frames from pushover analysis. International Journal of Research in Engineering and Technology, 4. https://doi.org/10.15623/IJRET.2015.0416012

Wahnich, S. (2022). Seismic response of a reinforced concrete frame with reduced stiffness. https://doi.org/10.1007/978-981-19-4835-0_22

Xiao, T.-L., Qiu, H.-X., & Li, J.-L. (2018). Seismic behaviors of concrete beams reinforced with steel-FRP composite bars under quasi-static loading. Applied Sciences, 13. https://doi.org/10.3390/APP8101913

XIAO, S., LIU, J., & DONG, H. (2014). The analysis of influencing factors in the aseismic reliability of the reinforced concrete beam. https://doi.org/10.11717/j.issn:2095-1922.2014.03.13

Yongl, Q. (2014). Deformation performance index limits of RC beams. Journal of Building Structures, 3. https://doi.org/10.14006/j.jzjgxb.2014.04.025

Zhang, Y. (2024). Seismic performance analysis of RC frame structure beam–column joints based on strong column and weak beam method. Buildings. https://doi.org/10.3390/buildings14103267

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